Iris Lewandowski *Editor*

Bioeconomy

Shaping the Transition to a Sustainable, Biobased Economy

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In collaboration with

Nicole Gaudet · Jan Lask · Jan Maier · Boris Tchouga · Ricardo Vargas-Carpintero

Springer OPEN UNIVERSITY OF HOHENHEIM

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Introduction

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Baroque Castle of the University of Hohenheim © Ulrich Schmidt

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Feeding a growing population is one of the major challenges of the twenty-first century. However, 200 years ago, it was this very same challenge that initiated the foundation of the University of Hohenheim in 1818. Three years earlier, in 1815, the volcano Tambora erupted in Indonesia. This local geological event had tremendous impact on the global climate. The eruption ejected huge quantities of ash into the atmosphere, causing two 'summers without sun'. In Europe, lower temperatures led to poor crop growth, resulting in famine and riots. On 20 November 1818, King Wilhelm I of Württemberg founded an agricultural education and research station at Hohenheim, with the aim of contributing to regional food security by educating farmers and developing better agricultural production methods.

Since then, the University of Hohenheim has grown continuously and today consists of three faculties, namely, the Faculty of Agricultural Sciences, the Faculty of Natural Sciences and the Faculty of Business, Economics and Social Sciences. Research and education is still focused on societal and environmental challenges, such as food security and climate change. Building on this basis, the 'bioeconomy' has recently emerged as a leading theme for the University of Hohenheim.

The bioeconomy, often referred to as 'biobased economy', encompasses the production of biobased resources and their conversion into food, feed, bioenergy and biobased materials. A biobased value chain includes the primary production of biobased resources, their conversion to higher-value goods via processing and commercialisation on the market. This involves a variety of sectors and brings together different scientific disciplines and stakeholders. Thus, the field of the bioeconomy is fertile ground for inter- and transdisciplinary research. Interdisciplinary research into the bioeconomy is based on the collaboration of different disciplines across the biobased value chain including agricultural science, natural science, economics and social science. This systemic approach enables the assessment of complex challenges from an environmental, social and economic perspective. In addition, transdisciplinary approaches support the ambition of the bioeconomy to contribute to overcoming some of the most relevant societal challenges and the underlying paradigm of switching from an economy based on fossil raw materials to a new, innovative and sustainable economy based on biogenic resources.

Due to the importance of inter- and transdisciplinary competences in the bioeconomy and the need for an appropriate knowledge base, the demand for professionals specifically educated in this field is growing. For this reason, in 2014, the University of Hohenheim established the first international Bioeconomy Master program, designed to train the experts required for a successful transition.

This textbook is a joint venture aiming to explore important aspects of the bioeconomy from the perspective of Hohenheim's educators and students and offers an orientation guideline for the future. It provides specialised knowledge in relevant disciplines as well as the systematic approaches required to shape bioeconomic projects and activities. Issued on the occasion of the 200th anniversary of the University of Hohenheim, it will be made available globally to all students and professionals aiming to drive the bioeconomy for a more sustainable future.

Part I

Bioeconomy Concepts and Research Methods

Context

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Abstract

The future bioeconomy is expected to drive the transition towards a more sustainable economy by addressing some of the major global challenges, including food security, climate change and resource scarcity. The globally increasing demand for food in particular, but also materials and renewable energy, necessitates innovative developments in the primary sectors. Innovations will need to generate more resource-use-efficient technologies and methods for increasing productivity in agriculture, forestry and aquaculture without jeopardizing the Earth's carrying capacity and biodiversity. The bioeconomy exploits new resources by building on renewable biomass. Through this, the introduction of innovative and resource-use-efficient production technologies and the transition to a sustainable society, it helps to substitute or reduce the use of limited fossil resources, thereby contributing to climate change mitigation.

Keywords

Climate change • Natural resources • Planetary boundaries • Population growth • Food security • Global challenges

Learning Objectives
In this chapter you will:

- Get an overview of the main challenges of the twenty-first century.
- Identify the interrelations between the causes of these challenges.
- Understand how the bioeconomy can contribute to meeting these challenges.

In the course of 1 year, the Earth travels 940 million km around the sun, from which it receives 1366 W/m^2 of solar radiation (2,500,000 EJ per year). Of this, 0.25% is transformed into usable biomass through the process of photosynthesis. The Earth's vegetation sequesters about 175 petagrams (175,000,000,000,000 kg) of carbon a year, equivalent to about 300,000 billion tons of biomass (Welp et al. 2011).

Before humankind discovered fossil oil, coal, gas and uranium and learnt how to put them into use, biomass covered all human needs for food, energy and materials.

2.1 Fossil Resources and Climate Change

The use of fossil resources fuelled industrialization, which was driven by technical and economic processes causing a shift from mainly agrarian towards industrial production. However, the availability of fossil resources is limited and its use resulted in negative environmental effects.

There are an estimated 37,934 EJ of fossil energy reserves and 551,813 EJ of fossil energy resources globally (Fig. 2.1, BGR 2015). Reserves are the amounts of energy sources that have been determined with high accuracy and are economically exploitable. Resources are the amounts of an energy resource for which there is geological evidence, but which are

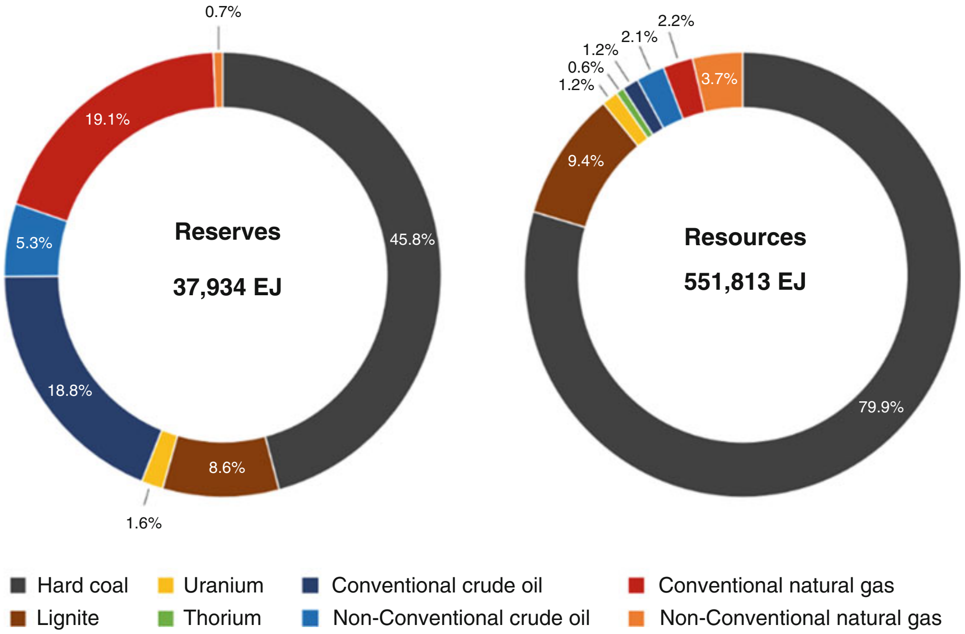


Fig. 2.1 Fossil reserves and resources, determined for 2014 (BGR 2015)

either economically or geologically not exploitable. Currently, fossil energy reserves exceed the global primary energy consumption of 540 EJ 70 times. However, crude oil, which is also required for material uses, makes up only 24% of fossil reserves (BGR 2015) and is therefore expected to be the first fossil resource to deplete.

Fossil Resources

Fossil resources include coal, petroleum, natural gas, oil shales, bitumens, tar sands and heavy oils. All contain carbon and were formed as a result of geological processes acting on the remains of organic matter produced by photosynthesis (see Sect. 5.1.1), a process that began in the Archean Eon more than 3 billion years ago. Most carbonaceous material occurring before the Devonian Period (approximately 415 million years ago) was derived from algae and bacteria (https://www.britannica.com/science/fossil-fuel).

Fossil resources were formed from biomass through geological processes that occurred several million to billion years ago. For this reason, they have a high carbon content (see Table 2.1). With every ton of fossil oil or coal burnt and transformed to energy, about 0.8 tons of carbon are oxidized, and 3 tons of carbon dioxide (CO_2) are released into the atmosphere (Table 2.1).

The atmospheric concentrations of the major greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have shown increases of 40%, 150% and 20%, respectively, since the year 1750 (IPCC 2014). These increases are mainly driven by the combustion of fossil fuels, deforestation and soilborne greenhouse gas emissions. Between 1970 and 2010, CO_2 emissions from fossil fuel combustion and industrial processes accounted for the largest share (78%) of the increase in GHG emissions (IPCC 2014). Today, electricity and heat production, industry and land-use-related activities (agriculture, forestry, land use change) are the sectors that contribute most to the so-called global warming potential (GWP), which is expressed in CO_2 equivalents

Table 2.1 Carbon contents of fossil resources and amounts of carbon dioxide (CO_2) and other greenhouse gases (GHG) emitted when fossil fuels are used energetically

		Greenhouse gas emission (t/t)[b]		
Fossil resource	% carbon (C)[a]	CO_2	N_2O	CH_4
Hard coal	71.6	2.6	0.000027	0.000040
Lignite	32.8	1.2	0.000012	0.000018
Petroleum	84.8	3.1	0.000127	0.000025
Natural gas	73.4	2.7	0.000048	0.000005

[a] IPCC (2006)

[b] Authors' own calculation based on IPCC (2006)

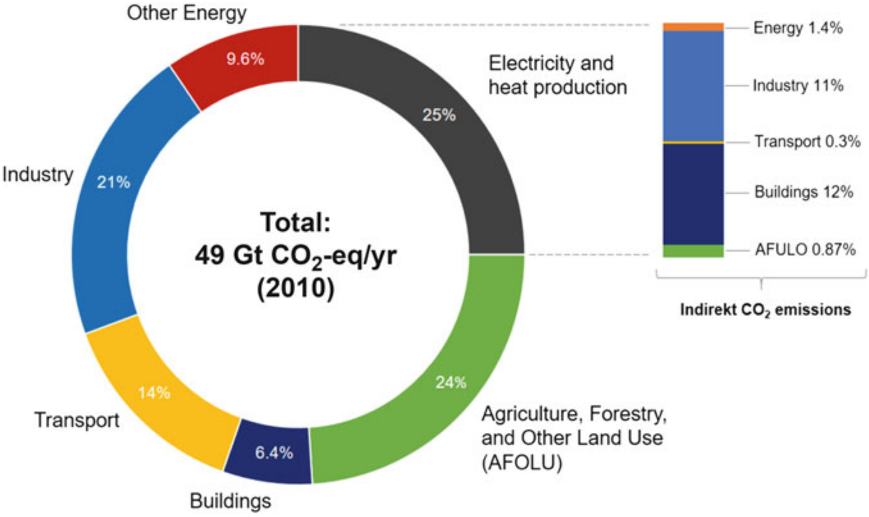


Fig. 2.2 Total anthropogenic greenhouse gas (GHG) emissions (gigatons of CO_2 equivalent per year, $GtCO_2$-eq/year) from economic sectors in 2010 (based on IPCC 2014)

(Fig. 2.2). CO_2 equivalents include the weighted effect of CO_2 ($GWP_{100\ year} = 1$), CH_4 ($GWP_{100\ year} = 28$) and N_2O ($GWP_{100\ year} = 265$) on global temperature. The higher the $GWP_{100\ year}$, the more a molecule of a GHG contributes to global warming and climate change (see Box 2.1) over 100 years.

Box 2.1 Climate Change

Greenhouse gases (GHG) in the atmosphere lead to the so-called greenhouse effect. The Earth's surface absorbs some of the energy from sunlight and heats up. It cools down again by giving off this energy in a different form, called infrared radiation. This infrared radiation escapes back to space, but, on the way, some of it is absorbed by GHG in the atmosphere, thus leading to a net warming of the Earth's surface and lower atmosphere (Fig. 2.3).

The direct and indirect effects of the increasing atmospheric concentration of GHG and concomitant increasing global temperatures are manifold and include (IPCC 2014):

- Ocean warming and acidification (through uptake of CO_2)
- Melting of the Greenland and Arctic ice sheets

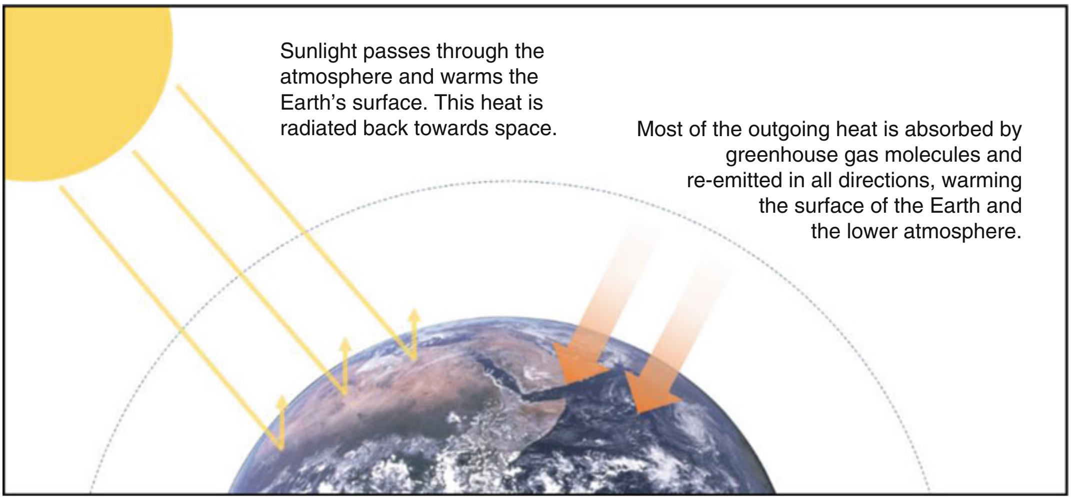


Fig. 2.3 How greenhouse gases lead to global warming (adapted from: http://climate.nasa.gov/causes/)

- Sea level rise (1.5–1.9 mm/year), threatening coastal communities and ecosystems
- Glacial retreat
- Decreased snow cover and increased permafrost temperatures
- Reduction in precipitation and increased occurrence of drought, especially in areas already critically affected by water limitation
- Extreme and unpredictable weather events such as storms and flooding
- Anticipated negative temperature, drought and other (e.g. diseases) impacts on agriculture, potentially leading to yield losses
- Negative impact on human health through deteriorating air and water quality, increasing the spread of certain diseases and altering the frequency or intensity of extreme weather events

The Intergovernmental Panel on Climate Change (IPCC) formulated a "climate goal" of 2 °C—the increase in global temperature that should not be exceeded in order to avoid disastrous global effects. To ensure CO_2-induced warming remains below 2 °C would require cumulative CO_2 emissions from all anthropogenic sources to remain below about 3650 $GtCO_2$ (1000 GtC); over half this amount had already been emitted by 2011 (IPCC 2014). One high potential GHG mitigation option is the use of biobased instead of fossil resources.

2.2 Biobased Resources

The resources produced and used in a biobased economy all contain carbon (C). Therefore, they can replace those fossil resources that contain carbon, i.e. coal, oil and natural gas.

In the following sections, biobased resources are defined as all resources containing non-fossil, organic carbon, recently (<100 years) derived from living plants, animals, algae, microorganisms or organic waste streams (see Sect. 5.1 for a more detailed description of biobased resources).

Biobased Resources
Biobased resources are of biological origin and stem from biomass. This biomass can be untreated or may have undergone physical, chemical or biological treatment.

Biomass
Biomass stems from living or once-living organisms including plants, trees, algae, marine organisms, microorganisms and animals.

Excluded are materials embedded in geological formations and/or fossilized.

Both biobased and fossil resources are derived from biomass that has been built through the process of photosynthesis (see Sect. 5.1). During that process, CO_2 is taken up by plants or algae with the help of light energy. Plants and algae convert light to chemical energy by integrating carbon (C) into their organisms. The carbon bound in fossil fuels was thus taken up from atmospheric CO_2 several million or billion years ago. By contrast, biobased resources are composed of recently grown biomass where there is a short time span of 1 to <100 years between the withdrawal of CO_2 from the atmosphere and its release back into the atmosphere. Therefore, biomass is often considered "CO_2 neutral" because the same amount of CO_2 is bound and then released again within a short period of time.

With an annual increment of 300,000 billion tons of biomass, biobased resources form a very large and, because they grow back, theoretically unlimited resource. However, their production necessitates the use of natural resources, mainly land, soil, water and plant nutrients.

2.3 Planetary Boundaries and Limitation of Natural Resources

Climate change is one of the nine planetary boundaries (Fig. 2.4) that the UN (Steffen et al. 2015) has characterized as demarcating the carrying capacity of the Earth and the vulnerability of global natural resources. According to these, climate change and land system change processes are already beyond the safe operating space. However, there are two categories that are at even higher risk. These are biosphere integrity (in particular genetic diversity) and biogeochemical flows (specifically nitrogen and phosphorus flows to the biosphere and oceans as a result of various industrial and agricultural processes) (see Box 2.2).

Box 2.2 Planetary Boundaries
"The planetary boundaries concept presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come" (http://www.stockholmresilience.org/research/planetary-boundaries.html):

1. Stratospheric ozone depletion
2. Loss of biosphere integrity (biodiversity loss and extinctions)
3. Chemical pollution and the release of novel entities
4. Climate change
5. Ocean acidification
6. Freshwater consumption and the global hydrological cycle
7. Land system change
8. Nitrogen and phosphorus flows to the biosphere and oceans
9. Atmospheric aerosol loading

(http://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html)

Integrity here refers to "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr and Dudley 1981, p. 56). It therefore has a functional as well as a quantitative (number of species and individuals) component (Angermeier and Karr 1994).

Agriculture—the primary source of food and feed and an important sector in the bioeconomy—has been responsible for

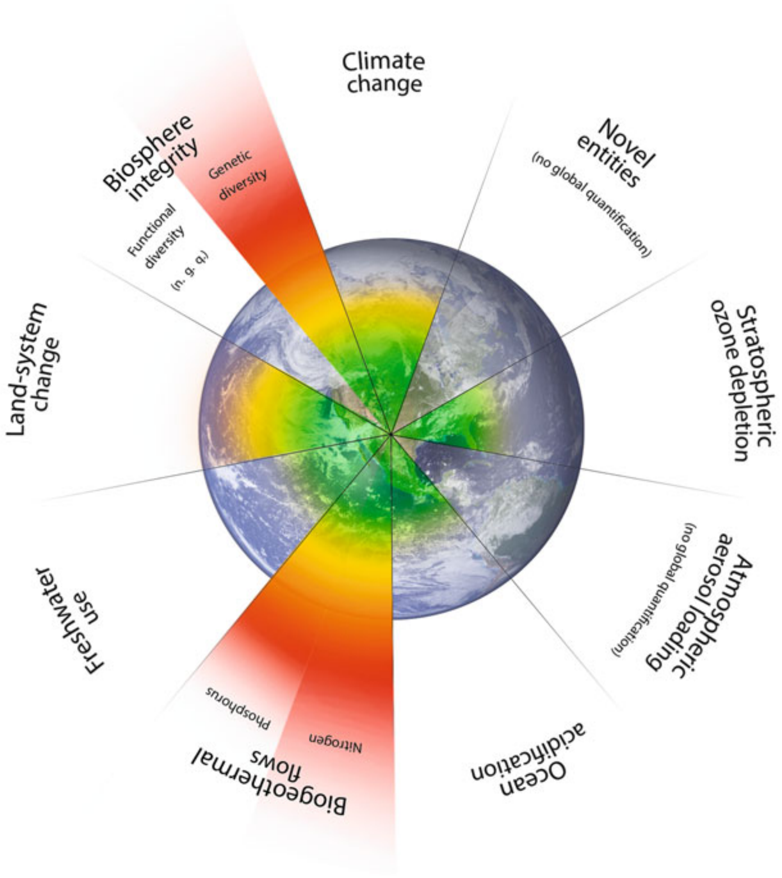


Fig. 2.4 The nine planetary boundaries. The *green-shaded* area represents the safe operating space

significant biodiversity losses. Key drivers of the decline in biodiversity and in conservation and ecosystem services are increased pesticide, herbicide and fertilizer use, increased landscape homogeneity associated with regional and farm-level specialization, drainage of waterlogged fields, loss of marginal and uncropped habitat patches and reduced fallow periods (Hilger et al. 2015; Lambin et al. 2001). The current high rates of ecosystem damage and extinction can be slowed by efforts to protect the integrity of living systems (the biosphere), enhancing habitat and improving connectivity between ecosystems while maintaining the high agricultural productivity that humanity requires (Steffen et al. 2015).

Other natural resources necessary for agricultural production are also under threat. While the production of agricultural goods increased 2.5–3 times over the last 50 years, the agricultural land area has only expanded by 12% (FAO 2011). Because more than 40% of the increase in food production stems from irrigated areas, water use has also increased. Today, 70% of all water withdrawn from aquifers, streams and lakes is used for agricultural production, leading to water scarcity in many areas of Asia, northern and southern Africa and western North America (FAO 2011). Intensive agricultural use and deforestation has also led to soil degradation processes, such as erosion. Very degraded soils are found especially in semiarid areas (sub-Saharan Africa, Chile), areas with high population pressure (China, Mexico, India) and regions undergoing deforestation (Indonesia) (UNEP 1997). Finally, the plant nutrient phosphorus (P) is also expected to become a limited natural resource for crop production. Phosphate fertilizer used in agriculture is mainly produced from rock phosphate (RP). However, RP is a finite resource, as with all mined resources. For this reason, in 2014, the EC added it to the list of critical raw materials (EC 2014).

Natural Resources
Natural resources occur naturally on the Earth. They include (a) biotic resources, stemming from living organisms (mainly plants and animals) and organic material (also fossil), and (b) abiotic resources from nonliving and inorganic material, such as air, soil, water, sunlight and minerals.

Because the bioeconomy makes direct use of natural resources—especially soil, land, water and nutrients—and therefore depends on their availability, it is at the focus of the sustainability debate. Only a bioeconomy that makes responsible use of natural resources, including their efficient use, conservation, restoration and recycling, can contribute to the transformation to a more sustainable economy. For this process, the bioeconomy will have to drive innovations further towards sustainable agricultural intensification. This is defined as “producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services” (Pretty et al. 2011). Sustainable agricultural intensification necessitates the use of innovative methods to produce modern varieties, fertilizers and crop protection measures. This aspiration is in line with recent trends, which show that about 70% of total factor productivity in agriculture is derived from innovations and only about 12% from land area extension. Also, other sectors producing biomass, such as forestry and aquaculture, need to apply sustainable production methods.

A sustainable bioeconomy cannot be achieved merely through replacing fossil resources by biobased resources to the maximal possible extent. It also requires that the replacement of fossil fuels by biobased resources results in an overall more sustainable economy.

2.4 Population Growth and Food Security

It is projected that the world’s population will increase from the current seven billion people to nine billion by 2050 (FAO 2011, Fig. 2.5). Today (2017), almost one billion people are undernourished, particularly in sub-Saharan Africa (239 million) and Asia (578 million) (FAO 2011). In addition to the demands of the growing population, economic development, especially in the emerging economies, leads to increasing consumption of meat. That means the trend towards increasing meat consumption in the emerging economies of Africa and Asia, and the concomitant increase in global meat production (Fig. 2.6) will continue. It is estimated that by 2050 an extra billion tons of cereals and 200 million tons of livestock products will need to be produced annually (Bruinsma 2009). However, meat production requires more land than crop production. To produce 1 kg of meat, 3–100 kg of biomass is required, depending on which animals and production systems are used (Smeets et al. 2007). Therefore, future projections anticipate the need to increase food production by 70% globally and by 100% in the developing economies (FAO 2011).

In food production, quantity is not the only criterion; quality is also important. One of the first quality management steps in the biobased value chain is the protection of crop and animal health. This is aimed not only at delivering good quality foodstuffs but also at increasing productivity and reducing losses in the production, storage, transport and processing of biomass. Even before food discarded at consumer level is

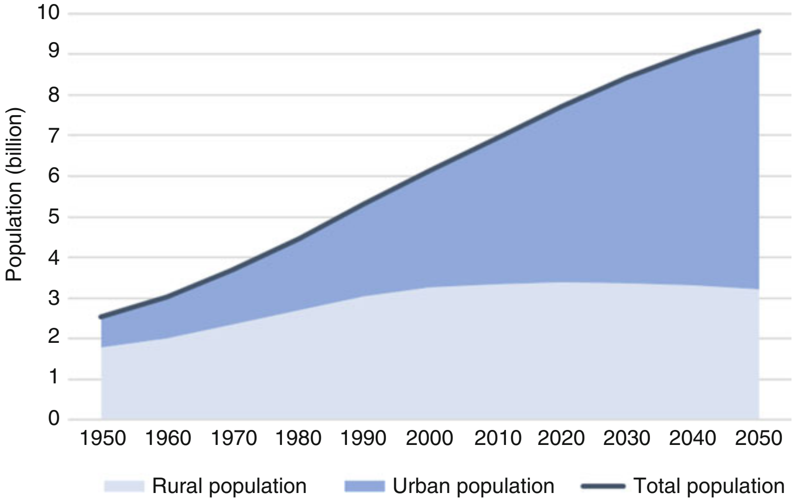


Fig. 2.5 World population trends for 1950–2050 (UNEP 2014)

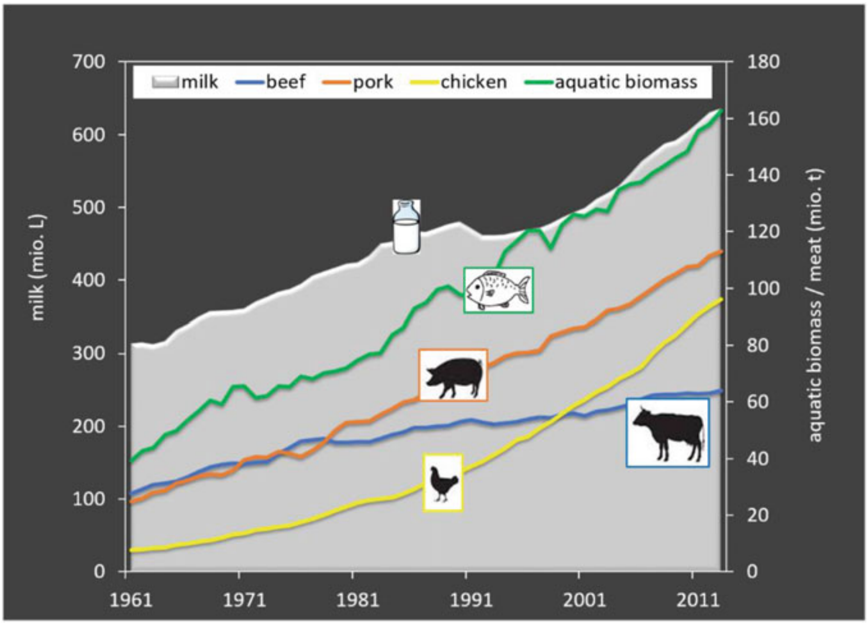


Fig. 2.6 Global meat, milk and fish (including crustaceans, molluscs and echinoderms) production for 1961–2011 (UNEP 2014; FAO 2015)

considered, food losses along the supply chain are estimated to be as high as 35% for cereals and more than 50% for perishable products such as roots, tubers, fruits and vegetables (Aulakh and Regmi 2013). Avoiding such losses requires disease-resistant varieties, effective crop protection measures and better training of farmers to apply these technologies, infrastructure for storage and transportation, and efficient processing and conversion methods.

The transition to a knowledge-based bioeconomy also depends on consumers being aware of the nature and characteristics of biobased products. Otherwise, they will neither be able to identify more sustainably produced products nor will they be willing to pay a higher price for higher-value goods. The process of raising awareness will also result in a more conscious choice of higher-quality, healthier products with a lower environmental impact and possibly in a reduction in meat consumption.

The availability of sufficient high-quality food for a growing population is thus not only a matter of sufficient production but also of appropriate use and food consumption patterns. The question of fair food distribution and adequate access of all people to food determines food security. In addition, today's hunger is not caused by insufficient global food production but by politically driven distribution problems.

2.5 The Role of the Bioeconomy in Dealing with Global Challenges

Bioeconomy is the sustainable and innovative use of biomass and biological knowledge to provide food, feed, industrial products, bioenergy, and ecological and other services. As such, it has the function of providing sufficient food of adequate quality and renewable resources to a growing population and at the same time making sustainable use of natural resources. The bioeconomy can help meet global challenges in the following ways:

- As non-renewable fossil resources are finite and have a high climate change impact, we need to meet our demands for food, products and energy through renewable resources. Foodstuffs and renewable materials can only be supplied by biomass from agricultural and forestry production as well as from aquaculture. Renewable energy on the other hand, to which bioenergy presently contributes 73% [biomass accounts for about 14% of global final energy consumption, REN21 (2016)], can also be supplied through solar, wind, geothermal, hydro or tidal energy.
- In a sustainable bioeconomy, the use of biobased resources should be optimized with regard to two main criteria. First, the demand for high-quality food for the world's population should be satisfied. Second, the remaining biobased resources should ideally be allocated with regard to the maximal ecological, social and economic benefit. This holistic approach in resource allocation is a major pillar of a sustainable bioeconomy and can serve as a blueprint for sustainable and general resource allocation strategies.
- Because land use presently contributes 24% of anthropogenic GHG emissions and a large part of biodiversity losses, agricultural and forestry land use management needs to be improved in a sustainable way. Climate-smart production methods need to be applied that make use of soil carbon sequestration and innovative technologies that reduce emissions and ecological impacts. These result in GHG mitigation and are often associated with improved efficiencies, lower costs and environmental co-benefits (Smith et al. 2007). In the bioeconomy, resource supply has to be sustainable, and therefore the use of biobased resources should only be implemented where these perform more sustainably than the fossil alternative.
- The global demand for more and higher-quality food and the limited availability of land and natural resources necessitate a thrust on innovation in agricultural, forestry, aquaculture and other forms of biomass production as well as biomass processing and use. This has to result in more efficient and less resource-consuming production methods along biobased value chains. Through a knowledge-based approach, more efficient and sustainable production methods must be applied in order to manage natural resources sustainably and increase productivity.
- The ubiquitous nature of biomass offers the possibility of creating modern jobs in rural areas, thus counteracting both the limited geographical distribution of accessible fossil resources and the current concentration of job and income opportunities in urban areas. The bioeconomy will enable areas poor in fossil but rich in biobased resources to improve income and development opportunities. The development of innovative technologies will

also generate new jobs with a modern profile (e.g. digitalization).
- The limited, and in part already overstretched, planetary boundaries render a shift to a more sustainable economy imperative, which makes better and responsible use of the Earth's resources. The change to a sustainable economy requires environmentally aware consumers, who steer economic activities through their targeted preferences and choices, and an overall sustainability-conscious behaviour of all stakeholders. Bioeconomy has become the guiding concept for large areas of economic development and societal transition so urgently needed to achieve this goal.
- The bioeconomy goes far beyond the idea of creating a biobased economy. It also builds on sustainable development through the application of biological and systems knowledge and the generation of innovations to develop a sustainable economy. This is not a sectoral approach in which only economic activities are considered that use biobased resources. Instead, the concepts of life cycle thinking and value chain approaches, resource use efficiency and recycling are applied to all production activities. Therefore, the bioeconomy is an integrated and forward-looking approach striving for an overall economic system optimization.

The bioeconomy can contribute to meeting global challenges through its nature as an economy building on renewable resources, biological knowledge, innovation and knowledge generation and through holistic approaches that think along value chains and in value nets. This means that the bioeconomy does more than just follow traditional pathways of biomass production, conversion and use. First, it must lead the way towards an innovative and sustainable use of the Earth's limited resources. Second, it has to provide guidelines for the societal transition towards sustainable development.

Review Questions

- What are the consequences, advantages and disadvantages of the use of fossil resources?
- How can the use of biobased resources overcome the shortcomings of fossil resources?
- How can the production of biobased resources help to keep the carrying capacity of the Earth within the planetary boundaries or, where they have already been exceeded, to fall back to within the boundaries?
- What are the potential contributions of the bioeconomy to meeting major global challenges?
- What conditions would be necessary for a sustainable bioeconomy?

References

Angermeier PL, Karr JR (1994) Biological integrity versus biological diversity as policy directives. BioScience. https://doi.org/10.2307/1312512

Aulakh J, Regmi A (2013) Post-harvest food losses estimation-development of consistent methodology. First meeting of the scientific review committee of the food and agricultural organization of the UN. Accessed 22 Dec 2014

BGR (2015) Energy study 2015. Reserves, resources and availability of energy resources (19). The Federal Institute for Geoscience and Natural Resources (BGR), Hannover, 172 p

Bruinsma (2009) The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? In: FAO expert meeting. https://doi.org/10.1016/B978-0-323-10199-8.00006-2

European Commission (2014) Report on critical raw materials for the EU – critical raw materials profiles. In cooperation with Claudia Wulz (ENTR). European Commission, Brussels

FAO (2011) The state of the world's land and water resources for food and agriculture (SOLAW) – managing systems at risk. Food and Agriculture Organization of the United Nations, London

FAO (2015) Fisheries and Aquaculture Department, Statistics and Information Service FishStatJ: Universal software for fishery statistical time series

Hilger T, Lewandowski I, Winkler B et al (2015) Seeds of change: plant genetic resources and people's livelihoods. In: Agroecology, INTECH open science open minds, Rijeka, Croatia, pp 123–146

IPCC (2006) Guidelines for national greenhouse gas inventories. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) Prepared by the national greenhouse gas inventories programme. IGES, Miura

IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK , Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, 151 pp. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf. Accessed 31 Dec 2016

Karr JR, Dudley DR (1981) Ecological perspective on water quality goals. Environ Manag 5(1):55–68. https://doi.org/10.1007/BF01866609

Lambin EF, Turner BL, Geist HJ et al (2001) The causes of land use and land cover change: moving beyond the myths. Glob Environ Change 11(4):261–269

Pretty J, Toulmin C, Williams S (2011) Sustainable intensification in African agriculture. Int J Agric Sustain. https://doi.org/10.3763/ijas.2010.0583

REN21 (2016) Renewables 2016 global status report. REN21 Secretariat, Paris. ISBN: 978-3-9818107-0-7

Smeets EMW, Faaij APC, Lewandowski IM et al (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energy Combust Sci. https://doi.org/10.1016/j.pecs.2006.08.001

Smith P, Martino D, Cai Z et al (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation, contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Steffen W, Richardson K, Rockstrom J et al (2015) Planetary boundaries: guiding human development on a changing planet. Science. https://doi.org/10.1126/science.1259855

UNEP (1997) In: Middleton N, Thomas D (co-ordinating eds) World Atlas of desertification. Copublished in the US, Central and South America by John Wiley, London, New York, c1997

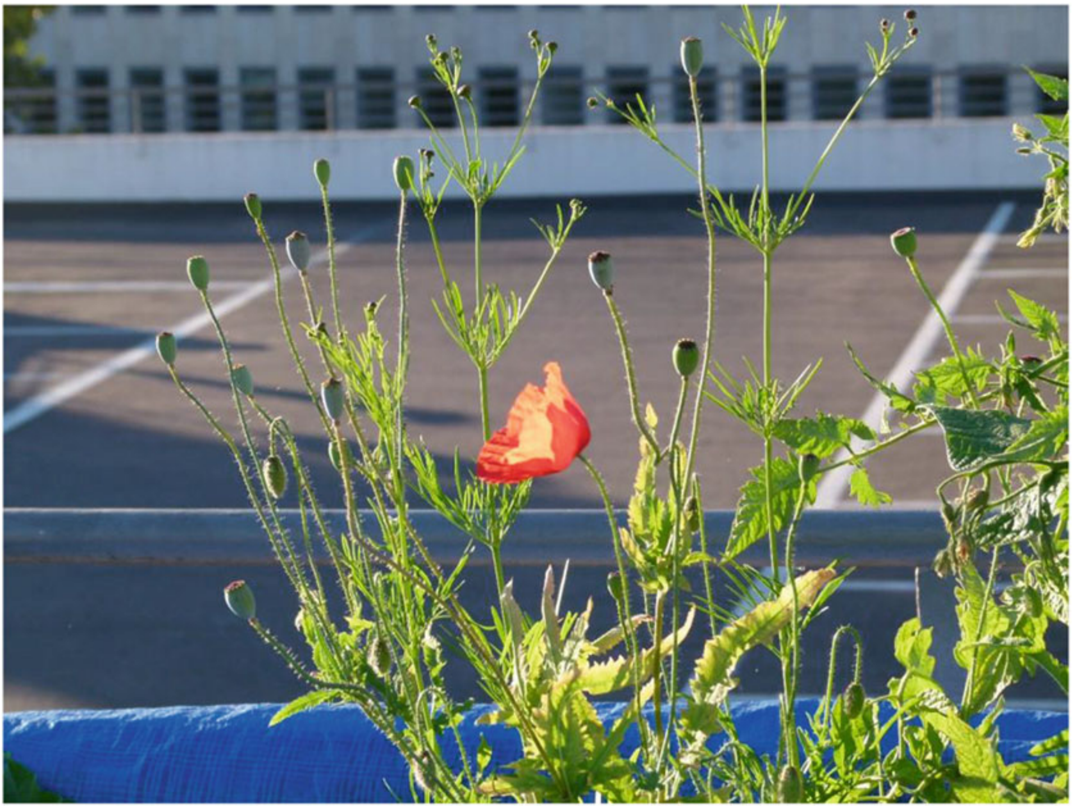
UNEP, Bringezu S, Schütz H, Pengue W, O'Brien M, Garcia F, Sims R, Howarth R, Kauppi L, Swilling M, Herrick J (2014) Assessing global land use: balancing consumption with sustainable supply. In: A report of the working group on land and soils of the International Resource Panel. UNEP

Welp LR, Keeling RF, Meijer HAJ et al (2011) Interannual variability in the oxygen isotopes of atmospheric CO_2 driven by El Niño. Nature. https://doi.org/10.1038/nature10421

Bioeconomy Concepts

3

Regina Birner



Urban gardening on a parking deck in Stuttgart. © Ulrich Schmidt

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Abstract

This chapter consists of three sections. The first section deals with the origin and evolution of the concept of the bioeconomy. It starts by tracing the first uses of the terms bioeconomics and bioeconomy and goes on to review the development of the concept of the "knowledge-based bioeconomy" in the European Union before discussing the rise of the bioeconomy as a global concept. A shift from a "resource substitution perspective" of the bioeconomy to a "biotechnology innovation perspective" is identified. Critical views of the bioeconomy are discussed, distinguishing a "fundamental critique" and a "greenwashing critique" of the bioeconomy. The first section of this chapter also reviews the relations between the concept of the bioeconomy and the concepts of "sustainable development", "green economy", "circular economy" and "societal transformation". The second section of the chapter discusses the bioeconomy strategies that an increasing number of countries around the world have adopted in recent years. This section uses a competitiveness framework to classify different elements of the bioeconomy strategies. The third section of the chapter is concerned with bioeconomy governance, focusing on the different actors in the bioeconomy, the ways in which they interact and the governance challenges that they are confronted with.

Keywords

Bioeconomy concepts • Knowledge-based bioeconomy • Bioeconomy strategies • Bioeconomy governance

Learning Objectives

This chapter should enable the reader to:

- Define the term bioeconomy.
- Understand the origin and evolution of the concept of the bioeconomy.
- Be familiar with diverse perspectives on the bioeconomy.
- Understand the relation between the concept of the bioeconomy and the concepts of sustainable development, green economy, circular economy and the great societal transformation.
- Classify the components of bioeconomy strategies and policies.
- Identify the key stakeholders of the bioeconomy and understand their relations.
- Understand key challenges of bioeconomy governance.

3.1 The Concept of the Bioeconomy: Origin and Evolution

3.1.1 The First Use of the Terms "Bioeconomics" and "Bioeconomy"

The use of the term "bioeconomics" can, according to Bonaiuti (2014, p. 54), be traced back to Zeman, who used the term in the late 1960s to designate an economic order that appropriately acknowledges the biological bases of almost all economic activities. As Bonaiuti (2014, p. 54) further explained, Georgescu-Roegen "liked the term and from the early 1970s made it the banner summing up the most important conclusions he had come to in a lifetime of research". An essential element in Georgescu-Roegen's use of the term bioeconomics was his concern that unlimited growth would not be compatible with the basic laws of nature (Bonaiuti 2014, p. 54).

This use of the term "bioeconomics" is rather different from the early use of the term "bioeconomy", which referred to the use of biological knowledge for commercial and industrial purposes. As pointed out in Chap. 4, one can consider this rather contrasting use of the two terms as an "irony of fate". According to von Braun (2014, p. 7), the term was first defined by the two geneticists Juan Enriquez Cabot and Rodrigo Martinez. A paper published by Enriquez in the *Science* magazine in 1998 (Enriquez 1998) is also quoted as a source for this use of the term (Gottwald 2016, p. 11). In this paper, which is entitled "Genomics and the World's Economy", Enriquez discusses that the application of the discoveries of genomics will lead to a restructuring in the role of companies and industries "in a way that will change the world's economy". He outlined "the creation of a new economic sector, the life sciences" in this paper (Enriquez 1998, p. 925). Though this paper does not use the term "bioeconomy", the source represents one of the roots of the concept of bioeconomy: advancements in the biological sciences and in biotechnology, which have the potential to transform many industrial production processes. The view that the "biological revolution" would eventually transform the industry was, however, not new at that time. The "industrial impact of the biological revolution" was already formulated in the early 1980s (Glick 1982).

3.1.2 The Development of the Concept of the "Knowledge-Based Bioeconomy" in the European Union

Even though the term bioeconomy was first introduced by scientists concerned with the industrial consequences of advancements in biology, the major reason why bioeconomy became an important policy concept in Europe was a deliberate decision by staff members of the European Commission to promote this concept. One of the key actors in this effort was Christian Patermann, the former Program Director of "Biotechnology, Agriculture and Nutrition" in the Directorate General for Research, Science and Education of the European Commission. According to his own account, the term "bioeconomy" was used by a conference of Ministers of Environment.[1] The term had not been further specified by the members of that conference, but Patermann and his colleagues realized that the concept had a unique potential as a policy concept that would allow the EU to respond to new opportunities. One opportunity was making economic use of the emerging new potential of using biotechnologies, as indicated above. Another opportunity inherent in the concept of the bioeconomy is the replacement of fossil-based resources by bio-based resources, both for energy and for material use. In the early 2000s, decision-makers in the EU felt a strong incentive to find new concepts, because the need for increasing agricultural productivity to meet future needs for food and biomass was not very well recognized at the time. Funding for agricultural research, which is key to increasing agricultural productivity, had declined throughout the 1990s in spite of the emerging need to produce biomass for other uses than food (Geoghegan-Quinn 2013).

In developing the concept of the bioeconomy in the EU, the label "knowledge-based" was added so that it became the "knowledge-based bioeconomy". The label "knowledge-based" was in line with the EU innovation policy that prevailed at the time. At a meeting in Lisbon in 2000, the European Council had made a commitment to establish "the most competitive and dynamic, knowledge-based economy in the world" (EU 2000). As pointed out in Sect. 3.1.4 in

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[1] Personal communication with Dr. Christian Patermann, 29.04.2013, Berlin.

more detail, the concept of the knowledge-based economy reflects the vision of achieving economic growth through high-technology industries, which requires investments in innovation and highly skilled labour.

The efforts of the EU to promote the concept the knowledge-based bioeconomy proved remarkably successful. In 2005, the European Commission held a conference entitled "New Perspectives on the Knowledge-Based Bio-Economy" (EC 2005). At this conference, Janez Potočnik, the European Commissioner for Science and Research, gave a speech entitled "Transforming life sciences knowledge into new, sustainable, eco-efficient and competitive products" (Potočnik 2005). In the so-called Cologne Paper of 2007, this title has been quoted as a definition of the knowledge-based bioeconomy. The Cologne Paper was based on a workshop held under the German Presidency of the Council of the European Union in 2007 in the city Cologne. The workshop was attended by experts from research organizations and companies covering different fields, including crop production, biotechnology, bioenergy and biomedicine (EU 2007). The Cologne Paper emphasized the two dimensions of the bioeconomy mentioned above:

- On the one hand, the paper identified the role of biotechnology as "an important pillar of Europe's economy by 2030, indispensable to sustainable economic growth, employment, energy supply and to maintaining the standard of living" (EU 2007, p. 4). One can label this dimension of the bioeconomy "the biotechnology innovation perspective".
- On the other hand, the Cologne Paper stressed the use of crops as "renewable industrial feedstock to produce biofuels, biopolymers and chemicals" (EU 2007, p. 4). The paper also envisaged that "by 2020, in addition to the then mature gasification technologies, the conversion of lignocellulosic biomass by enzymatic hydrolysis will be standard technology opening up access to large feedstock supplies for bioprocesses and the production of transport fuels". One can label this dimension of the bioeconomy "the resource substitution perspective".

The changing emphasis of these two perspectives over time is further discussed in Sect. 3.1.4. The development of the concept of the bioeconomy was accompanied by increased funding, especially in the EU's Framework Programs for Research and Technological Development, most notably in the current 8th Framework Program, which is entitled "Horizon 2020" (EC 2013).

The development of the bioeconomy concept by the institutions of the EU was mirrored by efforts to establish this concept in the EU member states. Germany, for example, established a Bioeconomy Council at the federal level in 2010 under the leadership of the Federal Ministry of Education and Science (BMBF). In 2010, a "National Research Strategy BioEconomy 2030" was published (BMBF 2010), and the federal government pledged to spend 2.4 billion euros for bioeconomy research until 2016 (BMBF 2014, p. 9). In 2013, Germany published a "National Policy Strategy on Bioeconomy". The policy had the subtitle "Renewable resources and biotechnological processes as basis for food, industry and energy", which reflects both the biotechnology innovation perspective and the resource substitution perspective mentioned above (BMEL 2013).

Other European countries also developed policies and strategies related to the bioeconomy. However, there was considerable variation regarding the extent to which these policies and strategies were specifically focused on the bioeconomy or rather on related aspects, such as biotechnology or renewable energy. For example, by 2015 neither France nor Great Britain nor Italy had a strategy that specifically focused on the bioeconomy (BÖR 2015a). Finland, in contrast, had already published a bioeconomy strategy in 2014. Austria and Norway, to mention two other examples, were in the process of preparing a dedicated bioeconomy strategy in 2015 (BÖR 2015b).

3.1.3 The Rise of the Bioeconomy as a Global Concept

The EU is not the only region of the world where the concept of the bioeconomy has been promoted since the early 2000s. As already mentioned in Sect. 3.1.1, the term bioeconomy was probably first used at a meeting of the American Association for the Advancement of Science in 1997. In 2012, the Obama administration released an official strategy on the bioeconomy entitled the "National Bioeconomy Blueprint" (White House 2012). This strategy defines the bioeconomy as follows:

> A bioeconomy is one based on the use of research and innovation in the biological sciences to create economic activity and public benefit. The U.S. bioeconomy is all around us: new drugs and diagnostics for improved human health, higher-yielding food crops, emerging biofuels to reduce dependency on oil, and biobased chemical intermediates, to name just a few. (White House 2012, p. 7)

This definition also reflects the two perspectives of the bioeconomy discussed above, the biotechnology innovation perspective and the resource substitution perspective. Other countries, including both industrialized and developing ones, also published bioeconomy-related policies and strategies in the first two decades of the twenty-first century. For example, Malaysia published a "Bioeconomy Transformation Program" in 2012, and South Africa released a bioeconomy strategy in 2013 (BÖR 2015b). While the number of countries that have dedicated bioeconomy policies is still limited, there are a large number of countries that have strategies related to biotechnology and/or to renewable resources (BÖR 2015b). Figure 3.1 gives a global overview of the state of bioeconomy strategy development achieved in 2017.

In December 2015, the first Global Bioeconomy Summit was held in Berlin. The event was organized by the German Bioeconomy

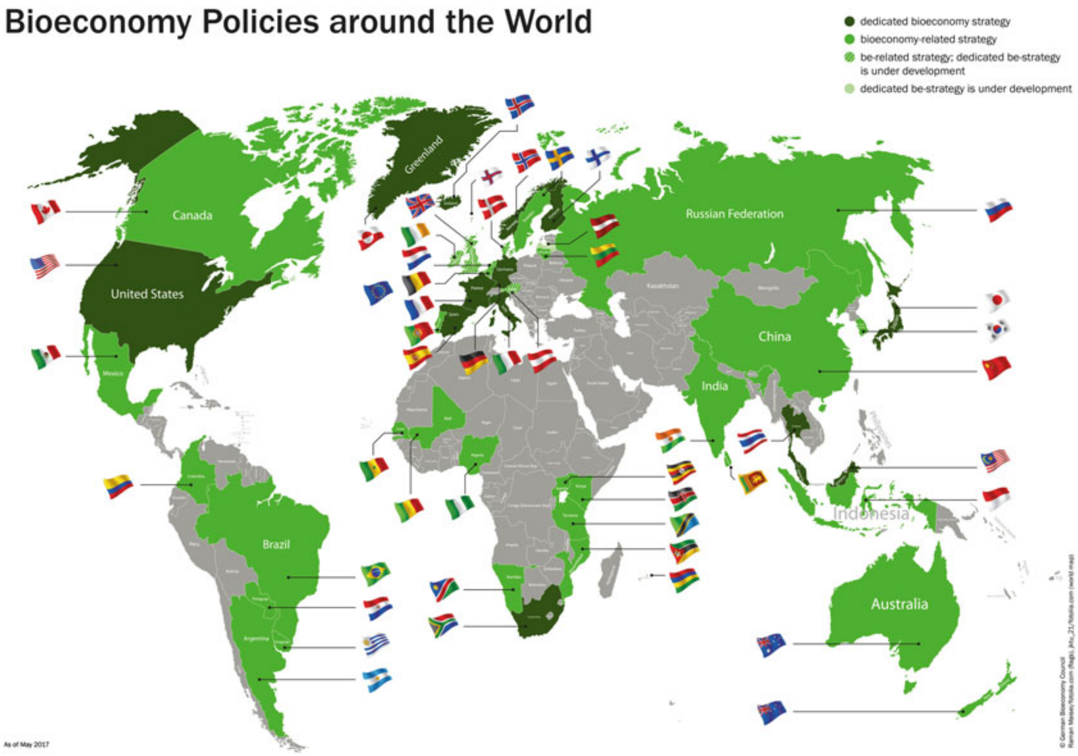

Fig. 3.1 Bioeconomy policies and strategies established by 2017 (BÖR 2017)

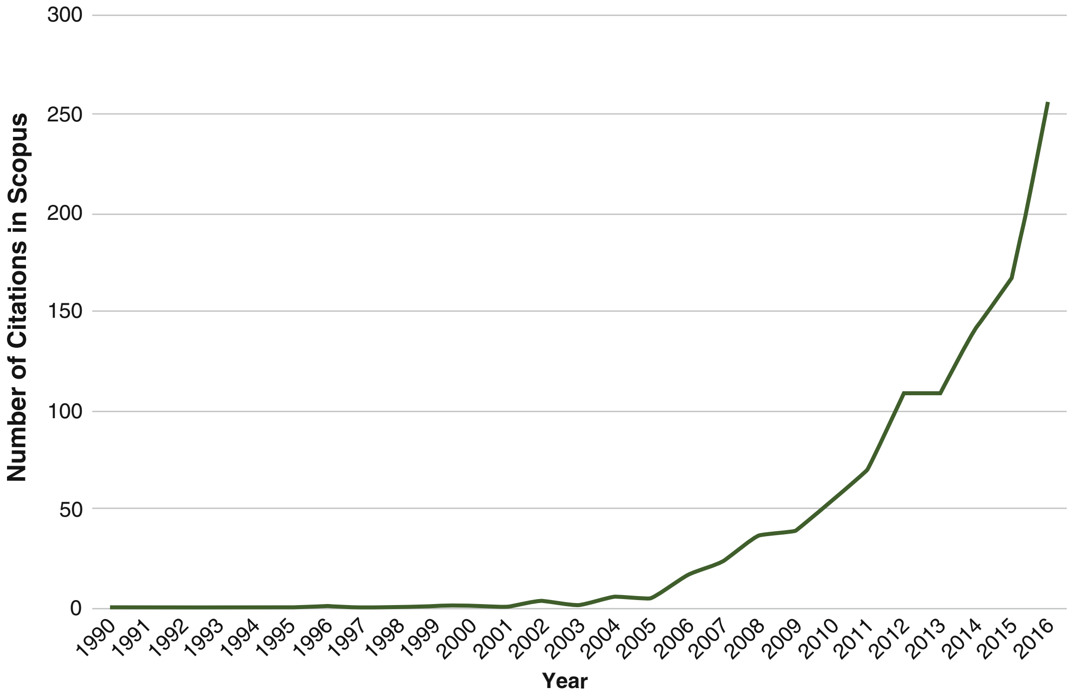

Fig. 3.2 Number of publications listed in Scopus that refer to the bioeconomy. Note: The diagram captures the number of entries that have one of the following expressions in titles, abstracts or keywords: “bio-based economy”, “biobased economy”, “bioeconomy” or “bio-economy”. Source: Compiled by the authors based on Scopus

Council in collaboration with an international advisory committee. It brought together more than 700 bioeconomy experts from more than 80 countries (BÖR 2015c, p. 4).

The rise of the bioeconomy as a global concept is not only reflected in the increasing number of countries that have bioeconomy-related strategies and policies but also in the scientific literature. As shown in Fig. 3.2, the number of publications listed in Scopus that refer to the bioeconomy has increased rapidly from 2005 onwards.

3.1.4 Changing Perspectives on the Bioeconomy

As shown above, the development of the concept of the bioeconomy was characterized by two perspectives: (1) the resource substitution perspective and (2) the biotechnology innovation perspective. Table 3.1 indicates how the emphasis on these two perspectives changed over time. Even though biotechnology innovation was recognized from the very beginning as an opportunity for the bioeconomy, the resource substitution perspective was more prominent in the first decade of the twenty-first century.

One driving force behind the resource substitution perspective was the concept of “peak oil”, which implies that oil extraction rates had reached its peak and that extraction rates would fall after the peak, while oil prices would continuously increase (Bardi 2009). A rising price of oil increases the comparative advantage of using biomass for energy and material use. This line of reasoning promoted the resource substitution perspective of the bioeconomy.

Figure 3.3 illustrates the resource substitution perspective of the bioeconomy. This diagram was developed by the German Bioeconomy Council in 2010 (BÖR 2010). Essential

Table 3.1 Changing perspectives of the bioeconomy

Perspectives	Resource substitution perspective (first decade of the twenty-first century)	Biotechnology innovation perspective (second decade of the twenty-first century)
Relation to fossil resources	"Peak oil", scarcity of fossil energy resources	New exploration technologies for oil; low, volatile prices
Major driving forces	Expectation that prices will continue to increase	Paris climate agreement Advances in the biological sciences
Overall rationale	Resource substitution	Innovation for sustainable development

Source: Prepared by the author based on BÖR (2014)

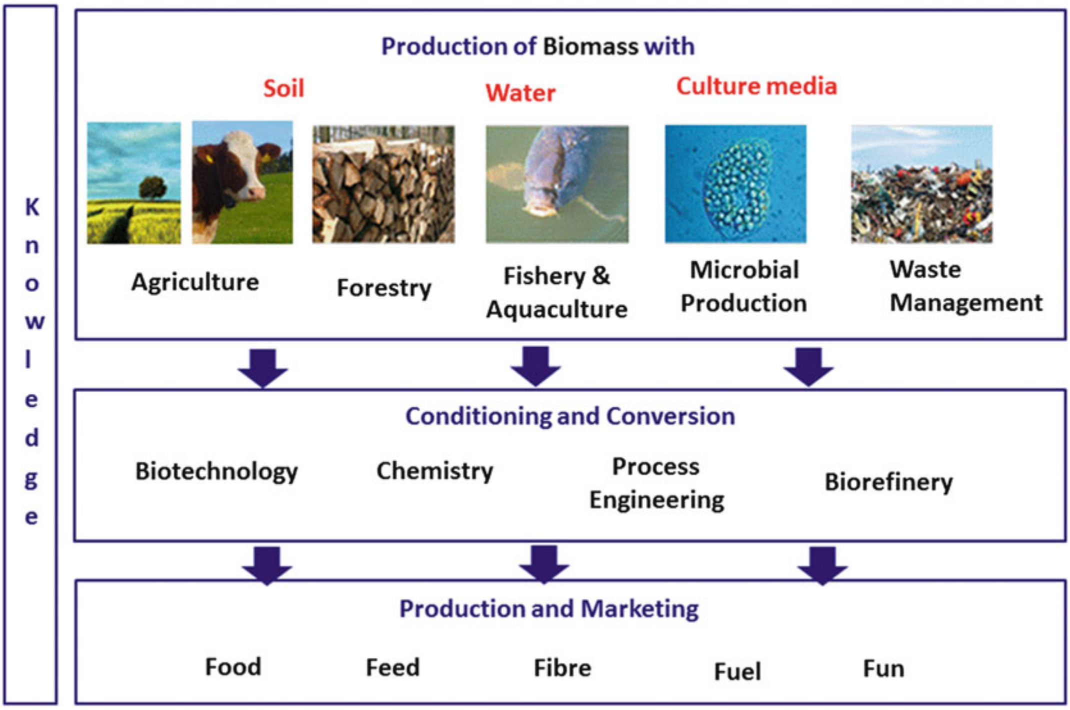

Fig. 3.3 The resource substitution perspective of the bio-economy. Source: BÖR (2010, p. 15)

components of the bioeconomy are, as seen in Fig. 3.3, the production of biomass in various forms, its conditioning and conversion using different procedures and the production and marketing of food, feed, fibre fuel and "fun". The term "fun" refers to products such as flowers.

The oil price crisis of 2007/2008 reaffirmed the "peak oil" perception. The increasing use of food crops for biofuel contributed to the spike in food prices that was observed following the oil price crisis. This development was primarily promoted by high oil prices (Headey and Fan 2008). Biofuel policies, such as biofuel subsidies and mandates to add biofuel to commercial petrol, became subject to increasing criticism, as research established the impact that they can have on food prices (de Gorter et al. 2013).

These developments had two important implications for the bioeconomy: First, the potential tension between ensuring food availability and using biomass for energy purposes became an important topic in the public policy debate surrounding the bioeconomy, as further discussed below. Second, increasing attention was paid to the need to increase the productivity of biomass production and to develop options for producing and using biomass that are not in conflict with food availability. Such options include second-generation technologies and the use of by-products and waste products for bioenergy production.

Both energy and food prices fell considerably after 2010, and they also became more volatile as compared to the 1990s (Kalkuhl et al. 2016). The development of the oil price remains difficult to project (Baumeister and Kilian 2016), but in view of the prevailing low oil prices, scarcity of oil was no longer a prominent argument for the resource substitution perspective (Table 3.1). Climate protection became the major argument for substituting fossil-based resources. While this argument was not new (e.g. WBGU 2011), the Paris Agreement under the United Nations Framework Convention on Climate Change became a major rationale for resource substitution (see Table 3.1).

While resource substitution, thus, remains important, the emphasis has shifted to the biotechnology innovation perspective of the bioeconomy. Accordingly, the opportunity to make economic use of innovations in biotechnology and, more generally, in the life sciences has become a major rationale for the bioeconomy in recent years. An example for this shift in perspective is a Strategy Paper published by the German Federal Bioeconomy Council in May 2014, which includes the following section:

> Originally, the concept of a biobased economy was promoted in the light of expected rapidly depleting petrol, gas and coal reserves. However, the move into bioeconomy is no longer driven predominantly by expectations of rising prices of fossil fuels. In view of the exploitation of new fossil reserves and due to energy efficiency improvements, this argument has become less pressing but it nevertheless remains strategically essential. Without major adjustments, the continued emission of greenhouse gases and the related changes in climate conditions will irreversibly damage the global ecosystem and will involve incalculable economic risks. (BÖR 2014, p. 1)

The role of the bioeconomy as an important element in moving towards a more sustainable economic system is an issue further discussed in more detail in Sect. 3.1.6.

3.1.5 Arising Criticism of the Concept

The global rise of the concept of the bioeconomy has not been without its critics. One can distinguish two major types of criticism, which one can label the “fundamental critique” and the “greenwashing critique”. An example of the fundamental critique is the writings by Birch and co-authors (Birch 2006; Birch et al. 2010). They criticize the bioeconomy as the “neoliberalization of nature”. The authors analyse the emerging discourse of the knowledge-based bioeconomy in the EU and criticize that the development of the concept has been dominated by what they refer to as a “neoliberal ideology”. Accordingly, the criticism of the bioeconomy concept is linked to a more general critique of “a neoliberal regime in which market values are installed as the over-riding ethic in society and the market rule is imposed on all aspects of life” (Birch 2006, p. 4). Related to this type of criticism is the claim that the concept has been promoted to pursue the interest of big companies, which are interested in commercializing innovations in the life sciences and in applying technologies that are contested in society, such as genetic engineering and synthetic biology. An example of this criticism is a paper by Gottwald and Budde that was published in 2015 on the occasion of the Global Bioeconomy Summit of 2015. These authors also argue that the bioeconomy would promote “land grabbing” and threaten world food security (Gottwald and Budde 2015).

The second type of criticism is not fundamentally opposed to the concept of the bioeconomy but rather warns against the use of this concept for “greenwashing”. An example of this type of criticism is a report by the World Wide Fund for Nature published in 2009 (WWF 2009), which is entitled “Industrial biotechnology—More than green fuel in a dirty economy?” This report acknowledges the potential of the bioeconomy to make modern economic systems more environmentally sustainable, but points out that the approaches that have been promoted under the label bioeconomy do not necessarily realize this potential. The thrust of this criticism is to ensure that the label "bio" is not misused to portray an essentially non-sustainable economic system as environmentally friendly, but to ensure that innovations in the life sciences are indeed used to ensure a transition towards a sustainable economic system.

The rising criticism against the bioeconomy may have contributed to two trends in the development of the bioeconomy concept, which have become prominent in recent years. One is to embed the concept of the bioeconomy more explicitly into the broader concepts of sustainable development and the green economy. The second trend is a shift in focus from the supply side of the bioeconomy to the demand side, i.e. a shift from technological innovations and companies that commercialize them to the consumers and to society at large. Both trends are described below in more detail.

3.1.6 "Greening" the Bioeconomy

The early definitions of the bioeconomy quoted above did not include explicit references to environmental goals, even though environmental sustainability was implicitly assumed both in the biotechnological innovation perspective and in the resource substitution perspective. As the bioeconomy concept was further developed the second decade of the twenty-first century, it was increasingly recognized that environmental goals need to be explicitly included into the concept as the use of biotechnological innovations and the use of bio-based resources are not "automatically" more environmentally friendly than alternative options. The increasing criticism of the use of bioenergy, which was associated with the food price crisis of 2008/2009 (see above), is a particularly pronounced example of this shift in emphasis.

3.1.6.1 Bioeconomy and Sustainability

The increasing concern about ensuring sustainability is reflected in an adjustment of the definition of the bioeconomy. The Communiqué of the Global Bioeconomy Summit of 2015, which was entitled "Making Bioeconomy Work for Sustainable Development", includes the following statement:

> Bioeconomy is defined in different ways around the world. We have not aimed for a unified definition but note that an understanding of 'bioeconomy as the knowledge-based production and utilization of biological resources, innovative biological processes and principles to *sustainably* provide goods and services across all economic sectors' is shared by many. (Bioeconomy Summit 2015, p. 4, emphasis added)

The reference to sustainability can be placed within the context of the wider societal goal of "sustainable development". This concept had entered the international policy agenda already in the 1980s. The UN Commission on Environment and Development defined "sustainable development" in its report "Our Common Future" as follows:

> development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (WCED 1987, p. 41)

The Commission on Environment and Development is also known as the Brundtland Commission, named after its chair, Gro Harlem Brundtland, who was then prime minister of Norway and first political leader who came to this position after having been a minister of environment before. As Brundtland points out, the commission aimed at bringing two major concerns together, which had been emerged in the international agenda in previous decades but were hitherto treated rather independently: the concern about environmental problems in industrialized countries on the one hand and the concern about poverty and population pressure in developing countries on the other hand (WCED 1987). The definition of sustainable development reflects the goal to address these two concerns jointly.

The concept of sustainable development was reaffirmed at the "International Conference on Environment and Development" in Rio de Janeiro in 1992, also referred to as the Earth

Summit. At this conference, the representatives of more than 170 nations passed a major global action program called “Agenda 21”, which had four program areas: social and economic dimensions; conservation and management of resources; strengthening major groups, including civil society organizations; and means of implementation (UN 1992). The Agenda 21 promoted the notion that “sustainable development” has three dimensions: an economic, a social and an environmental dimension. Accordingly, the principle that the bioeconomy has to be sustainable covers not only the environmental dimension but also the economic and social dimension. The concept of sustainability and its relevance is further discussed in Sect. 8.2.

3.1.6.2 The Bioeconomy as a Component of the Green Economy

At the Rio+20 Conference in Rio de Janeiro in 2002, the participants adopted a resolution entitled “The future we want” (UN 2012). This resolution reaffirms the principle sustainable development, and it highlights the concept of the “green economy” as “one of the important tools available for achieving sustainable development” (UN 2012, p. 10). The United Nations Environment Program (UNEP) defined a green economy:

> as one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities [. . .] In its simplest expression, a green economy can be thought of as one which is low carbon, resource efficient and socially inclusive. (UNEP 2011, p. 16)

In the academic literature, the concept of the green economy has a long history (see review by Loiseau et al. 2016). The question arises as to how the concept of bioeconomy is linked to the concept of the green economy. Ultimately, this is a matter of definition. One option is to consider the bioeconomy as an integral component of the green economy. According to this view, one may consider renewable energy sources that do not rely on biological resources, such as wind and solar energy, as part of the green economy but not as part of the bioeconomy. Figure 3.4 illustrates this conceptualization.

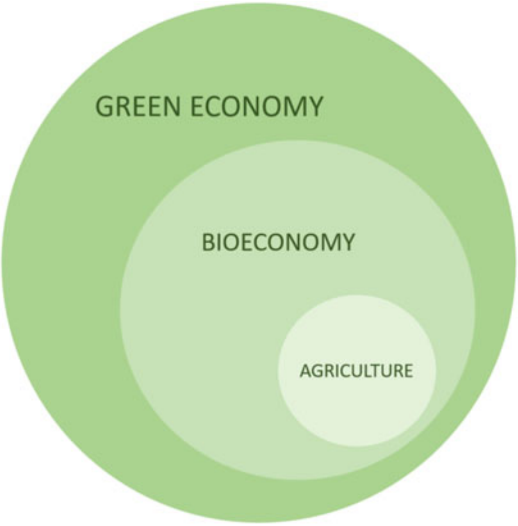

Fig. 3.4 The bioeconomy as a component of the green economy. Source: Authors

In the UN resolution “The world we want” mentioned above, the international community also agreed on a process to establish sustainable development goals as a follow-up to the Millennium Development Goals that were agreed upon in 2000 and covered the time period until 2015 (UN 2012, p. 46ff). A set of 17 “Sustainable Development Goals” (SDGs) were adopted by the UN in 2015. Section 8.2 further discusses the role of the SDGs for the bioeconomy.

3.1.6.3 Bioeconomy and the Principles of the Circular Economy

Next to the concept of the green economy, another concept has gained prominence in recent years, which is related to the bioeconomy: the concept of a “circular economy”. The Communiqué of the Global Bioeconomy Summit mentioned above emphasizes the need to align the principles of a sustainable bioeconomy with the principles of a circular economy, which “would involve systemic approaches across sectors (i.e. nexus thinking), particularly innovation policy measures that aim at optimizing Bioeconomy value networks and minimizing waste and losses" (Bioeconomy Summit 2015, p. 5).

This concept of the circular economy was popularized in a classical textbook on environmental economics by David Pearce and Kerry Turner in 1989 (Pearce and Turner 1989). These authors trace it back to a landmark essay by Kenneth Boulding published in 1966, in which Boulding emphasized the need to manage the economy not as an open system but as a "spaceship", where "man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form" (Boulding 1966, p. 11). Boulding's concepts are further discussed in Sect. 10.2. As a recent review shows, the concept of the circular economy has mostly been associated with the adoption of closing-the-loop production patterns within an economic system, and with aims to increase the efficiency of resource use, placing a specific focus on urban and industrial waste (Ghisellini et al. 2016, p. 11). As such, the concept of the circular economy is narrower in scope than the concepts of the green economy and the bioeconomy. The demand to link the bioeconomy with the principles of the circular economy can, however, play an important role in ensuring that the bioeconomy is, indeed, sustainable. Moreover, the focus on renewable resources and on biotechnological innovations, which are central elements of the bioeconomy, can play an important role in implementing the principles of the circular economy.

The goal to link the bioeconomy with the principles of a circular economy has also led to the development of the concept of a "biomass-based value web" (Virchow et al. 2016). This concept takes into account that the cascading use of biomass and the use of by-products from the processing of biomass lead to an interlinkage of different value chains. These can be analysed as a "value web". Scheiterle et al. (2017) present a case study of Brazil's sugarcane sector. Figure 3.5 illustrates the concept of a value web based on the sugarcane biomass. As can be seen from the diagram, the by-products from the processing of sugarcane, such as filter cake, vinasse and bagasse, are used for the generation of biogas or bioelectricity instead of being disposed as waste. These by-products can also be used for new types of bioeconomy products, such as flavours or pharmaceuticals, thus opening new branches in the biomass-based value web.

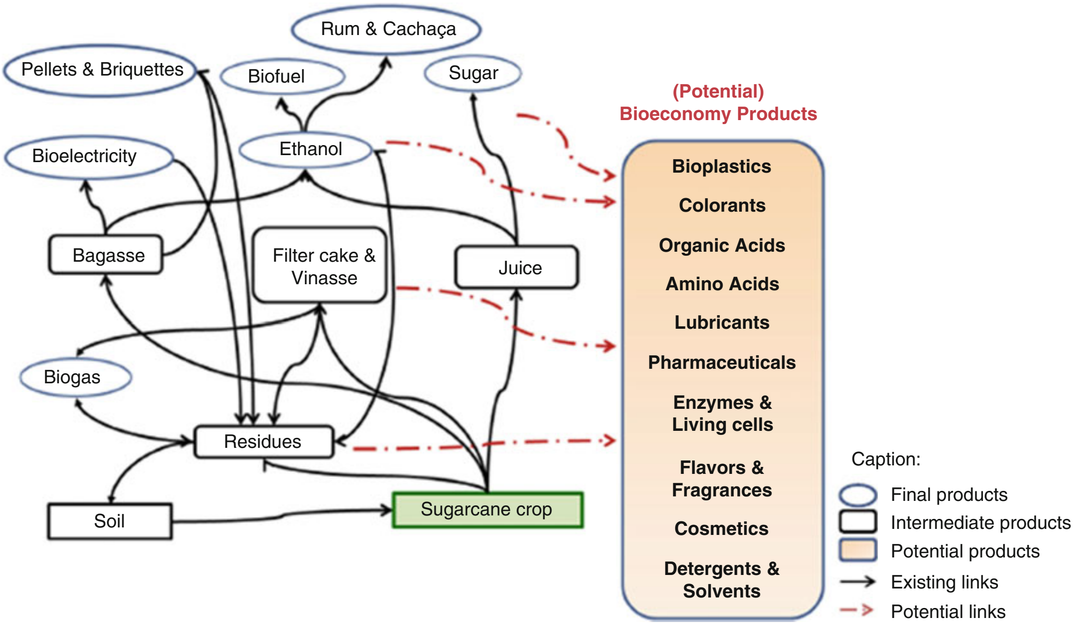

Fig. 3.5 Biomass flows in a value web based on biomass from sugarcane. Source: Scheiterle et al. (2017, p. 6)

3.1.7 Bioeconomy as an Element of a "Great Societal Transformation"

As can be seen from the above definitions, the development of the bioeconomy concept was initially characterized by a focus on the "supply side" of the bioeconomy, that is, by a focus on the supply of goods and services that are based on biological resources and biotechnological processes. In recent years, more emphasis has been placed on the demand side of the bioeconomy and, more generally, on the role of the bioeconomy in society.

Figure 3.6 represents a more holistic view of the bioeconomy, which takes people—as consumers and citizens—explicitly into account. This diagram was developed by a team from the University of Hohenheim as basis for the Master's program "Bioeconomy", which started in 2014.

As shown in the diagram, preferences and values of people, which translate into needs and demands for (new) bio-based products, are as essential for the bioeconomy as is the production of those products. This holistic view of the bioeconomy requires a transdisciplinary systems analysis. The issue of transdisciplinarity is dealt with in Chap. 4.

Taking the societal embeddedness of the bioeconomy a step further, one can also consider the bioeconomy as an element in a process of societal transformation, which is ultimately required to transform the current economic system into one that is economically, environmentally and socially sustainable. The recognition of the challenges involved in this transformation has led to the hypothesis that it will not be sufficient to create economic incentives and implement conducive environmental policies. What is ultimately required is "a great societal transfor-

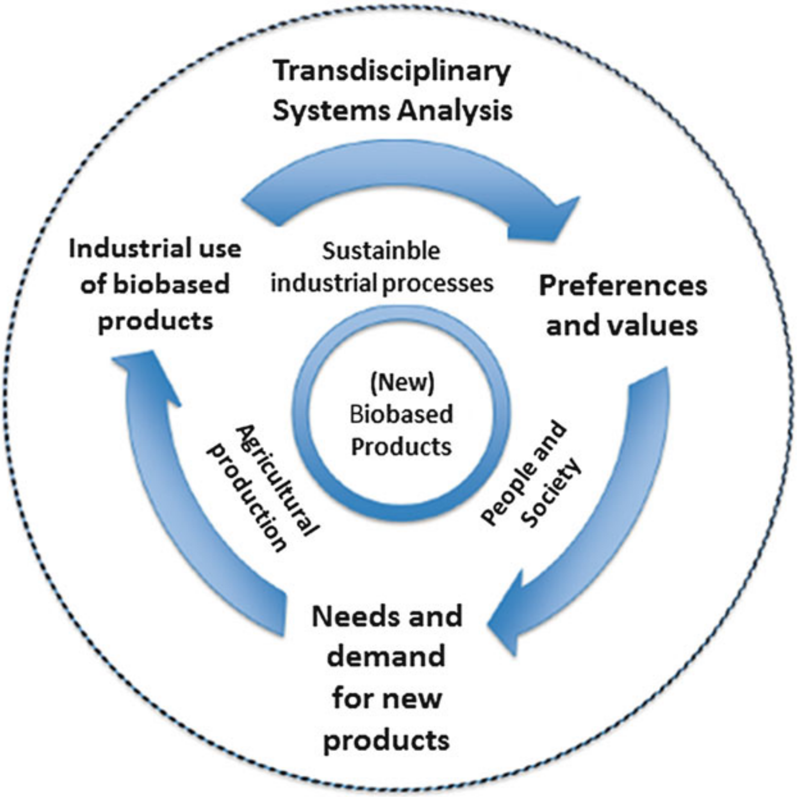

Fig. 3.6 Holistic concept of the bioeconomy. Source: University of Hohenheim (2013)

mation", which "encompasses profound changes to infrastructures, production processes, regulation systems and lifestyles, and extends to a new kind of interaction between politics, society, science and the economy" (WBGU 2011, p. 1).

In line with this thinking, Fig. 3.7 places the bioeconomy in a larger historical context. In this perspective, the bioeconomy is conceptualized as an essential element in a new era that will ultimately replace the industrial society. As shown

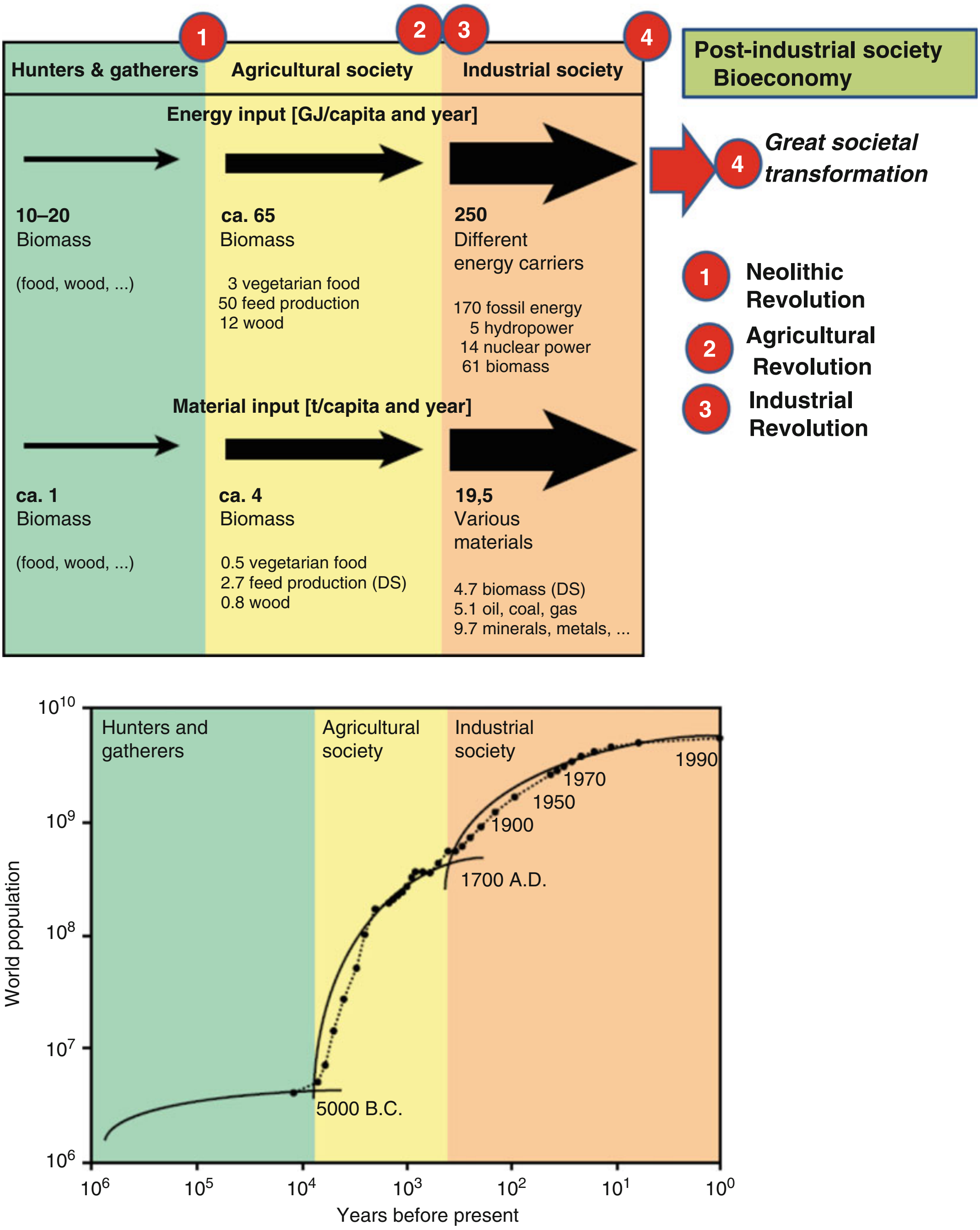

Fig. 3.7 The bioeconomy as an element in societal transformation. Source: Adjusted from WBGU (2011, p. 86)

in Fig. 3.7, the industrial society followed the agricultural society, which in turn had followed the society of hunters and gatherers. The industrial society was made possible by the industrial revolution and agricultural revolution that preceded it. The agricultural society, in turn, was made possible by the Neolithic Revolution. As shown in Fig. 3.7, the agricultural society and the industrial society were associated with a substantial increase in energy and material use. The lower part of Fig. 3.7 indicates that the transitions to the agricultural and to the industrial society were associated with a steep increase in world population, which has slowed down only in the later phases of the industrial society. Since the transitions to the agricultural and the industrial society were caused by so-called revolutions, it appears justified to assume that the shift to the bioeconomy requires a similar large-scale change. This line of thinking is reflected in the idea of a "great societal transformation" mentioned above (WBGU 2011).

3.2 Bioeconomy Strategies

As pointed out in Sect. 3.1.3, an increasing number of countries have adopted bioeconomy strategies or bioeconomy policies. Since the two terms are often used interchangeably, the term "bioeconomy strategies" is used in the following to refer policy documents or strategy documents that have officially been released by national governments or parliaments. The rationale for government intervention in support of the bioeconomy is further discussed in Sect. 10.2. To better understand the bioeconomy strategies that governments have developed, it is useful to take the comparative advantage into account that a country has for developing different components of the bioeconomy. The "diamond model" developed by Porter (1990) provides a conceptual framework, which can be used for determining the competitive advantage of a country's bioeconomy (Birner et al. 2014). Figure 3.8 displays an adapted version of Porter's diamond model.

3.2.1 Basic Elements of a Bioeconomy Strategy

The four basic elements of the "diamond" model, which determine the competitive advantage of a country for developing its bioeconomy, are (1) factor conditions; (2) demand conditions; (3) firm structure, strategy and rivalry; and (4) related and supporting industries. Bioeconomy strategies typically aim to promote the bioeconomy by targeting several or all of these

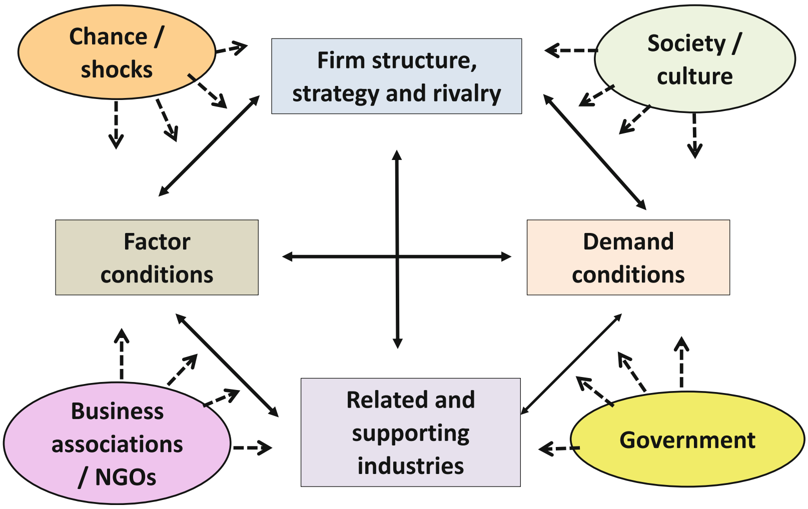

Fig. 3.8 The diamond model of comparative advantage. Source: Adapted from Porter (1990, p. 127), published in Birner et al. (2014, p. 5)

four groups of factors. The Global Competitiveness Report of the World Economic Forum (2016) provides a wide range of indicators related to these groups of factors for 138 countries. Though the indicators are not specific for the bioeconomy, they are still a useful source of information for countries to assess the general conditions for the development of their bioeconomy.

3.2.2 Upgrading Factor Conditions for the Bioeconomy

Based on Porter (1990), one can distinguish five types of factor conditions, which are relevant for the development of the bioeconomy:

1. *Natural conditions*: A country's endowment with land and its agroclimatic conditions have a large influence on a country's competitive advantage for the production of biomass. Countries with large land endowments, favourable agroclimatic conditions and low population density typically have a comparative advantage for emphasizing the resource substitution perspective of the bioeconomy as they can have the potential to produce biomass for bioenergy and bio-based materials (e.g. bioplastic) on a large scale and at comparatively low cost. Brazil, which has a competitive advantage for producing sugarcane, is an example for this type of countries. Countries that have access to marine resources may emphasize these resources in their bioeconomy-related strategies. Norway is an example (BÖR 2015b, p. 108). Countries with less favourable natural resource conditions and/or limited land resources will have to focus more on biotechnology innovation than on resource substitution to develop their bioeconomy.
2. *Labour resources*: While the basic natural conditions cannot be influenced by government interventions, governments can have a large influence on the qualification of their labour force for the bioeconomy, especially by investing in education and professional training. The development of the bioeconomy requires specific skill sets, and education programs need to be adjusted and developed to enable the labour force to gain those skills. As an example, the University of Hohenheim in Stuttgart, Germany, introduced as an interdisciplinary Master's program called "Bioeconomy" in 2014. In Porter's framework, such investments in education are referred to as "factor upgrading"—which is an important strategy that countries can use to improve their competitive advantage for the development of their bioeconomy.
3. *Knowledge resources*: One of the most important instruments that governments can use to develop their bioeconomy is investment in public research on bioeconomy to foster innovations. The concept of the "knowledge-based bioeconomy" discussed above emphasizes this aspect. Accordingly, investments in research and innovation are an important element of most bioeconomy-related strategies (BÖR 2015a, b). Since research by the private sector also plays a key role for developing the bioeconomy, creating a conducive environment for research in the private sector is important as well.
4. *Capital resources*: The development of the bioeconomy relies on investments along the entire value chains for bioeconomy products, including research, product development and marketing. The availability of capital, especially venture capital for risky investments, is therefore an essential condition for the development of the bioeconomy.
5. *Infrastructure*: Governments can also support the development of the bioeconomy by providing a supportive infrastructure, especially in terms of transport as well as information and communication technologies (ICTs). An important task is the identification of infrastructure needs that are particularly relevant for the bioeconomy strategy selected.

3.2.3 Strengthening the Demand for Bioeconomy Products

An important incentive for the development of the bioeconomy is a strong demand of consumers for bio-based products. Governments can foster this demand by promoting labels for bio-based products that facilitate consumer choice and by conducting information campaigns and fostering social dialogue. Governments can also implement rules for public procurement that strengthen the pubic demand for bio-based products. The analysis of national economy strategies around the world conducted by the German Bioeconomy Council (BÖR 2015a) showed that such demand-side instruments play an important role in many bioeconomy strategies. An interesting example of this approach is the BioPreferred® Program of the United States Department of Agriculture (USDA). This program combines a voluntary labelling initiative for bio-based products with mandatory purchasing requirements for federal agencies and their contractors, which encompasses 97 product categories (https://www.biopreferred.gov/BioPreferred/).

3.2.4 Fostering Competition Among Bioeconomy Firms

It is an important insight from Porter's (1990) analysis that a strong competition of companies in their home countries fosters their international competitive advantage because such competition forces them to be innovative and strategic. At times, governments chose to select and subsidize "champions" and protect them from competition. However, as Porter's comparative historical studies show, this strategy has hardly ever been successful in enabling companies to gain international competitive advantage. This insight can be applied to the bioeconomy, as well. Fostering competition among firms engaged in the bioeconomy and restricting market dominance among them can be seen as an important element of a bioeconomy strategy. The review of bioeconomy strategies by the German Bioeconomy Council indicates, however, that this aspect has attracted relatively limited attention, so far (BÖR 2015a, b).

3.2.5 Strengthening Bioeconomy Clusters

A striking feature of the bioeconomy strategies around the world is the emphasis that they place on the development of clusters (BÖR 2015a, b). The concept of industry clusters or innovation clusters is based on the insight that the development of the bioeconomy requires a strong and regionally integrated network of industries that are related and supporting each other along the value chain, e.g. by providing specialized inputs and services. Clusters also benefit from a close interaction of research organizations, start-up companies that are often spin-offs of research organizations and companies that have the capacity to engage in product development and access large markets. Historical experience indicates that governments have limited capacity to create clusters from scratch. A more promising strategy is to identify emerging clusters and supporting them (Porter 1990). Bioeconomy clusters may also form regional networks. An example is the "3BI intercluster", a partnership of bioeconomy clusters located in France, Germany, the Netherlands and the United Kingdom (http://www.3bi-intercluster.org/home/).

3.2.6 Using Chances and Shocks as Opportunities for Bioeconomy Development

The comparative historical studies of Porter (1990) have shown that factors that are beyond the control of economic and political actors can play an important role in determining the competitive advantage of an industry. These factors may be positive ("chances"), such as discoveries that offer unexpected opportunities for the bioeconomy, or negative ("shocks"), such as sudden price changes or natural disasters (see

Fig. 3.8). These insights from general economic studies can also be applied to the bioeconomy. Ultimately, it depends on the actions of governments and/or private businesses whether opportunities that arise from chances or shocks are effectively used. For example, the oil price crisis of 1973 induced the government of Brazil to establish a National Alcohol Program in 1975, which subsequently played an important role in the development of Brazil's sugar-based bioeconomy (cf. Scheiterle et al. 2017). Likewise, the nuclear disaster of Fukushima in 2011 was a major factor behind the political decision of the German government to get out of nuclear energy and focus on renewable energy, a decision referred to as "Energy Turn" (Energiewende).

3.2.7 Considering Sociocultural Factors

As indicated in Fig. 3.8, sociocultural factors play an important role for the development of the bioeconomy, as well. Just as chances and shocks (see above), these factors are also beyond the immediate control of political or economic actors. Yet, they can influence the development of the bioeconomy in various ways. A case in point is genetically modified organisms (GMOs). Proponents of GMOs argue that they can play an important role in the bioeconomy, e.g. by improving the efficiency of producing or converting biomass. However, in most countries of Europe, the use of GMOs in agriculture is not accepted by consumers, and, therefore, GMOs are not used in agriculture. This exclusion of a technology for sociocultural reasons may, however, foster the efforts to develop alternative technologies, such as crop breeding methods based on statistical methods. Countries may then gain a competitive advantage in such alternative technologies.

3.3 Governance of the Bioeconomy

The previous sections of this chapter have dealt with the questions of how the bioeconomy can be defined, how the concept has evolved and how the bioeconomy can be promoted. This final section deals with the question of bioeconomy governance. The term governance is used here to refer to the institutions, processes and actors that are relevant for the development of the bioeconomy.

3.3.1 Overview

Figure 3.9 displays a conceptual framework that can be used to analyse the bioeconomy governance. The framework distinguishes between three different types of organizations: organizations of the private sector, organizations of the public sector and civil society organizations, which are referred to as the "third sector". Research organizations are mostly public sector organizations. They are depicted separately in view of their important role for the knowledge-based bioeconomy. The media are also depicted separately in view of their role in political processes. Typically, they are organizations of the private sector. Citizens are placed in the centre of the diagram. They are closely interlinked with all sectors, as further discussed below.

The development of the bioeconomy depends on the various interactions among the different actors depicted in Fig. 3.9. The different actors may have converging or conflicting interests, which will result in political and economic processes that may be more or less conducive to the bioeconomy. The governance of the bioeconomy is an interesting new area of research. Existing studies have focused on selected aspects, e.g. the governance of biofuel policies (see, e.g. Bailis and Baka 2011). However, comprehensive studies on the governance of the bioeconomy are still scarce. Therefore, the following sections provide conceptual considerations, which may be explored in more detail by empirical studies in the years to come.

3.3.2 Private Enterprises and Business Associations

In a market economy—which is after the fall of the Soviet Union the dominant economic system

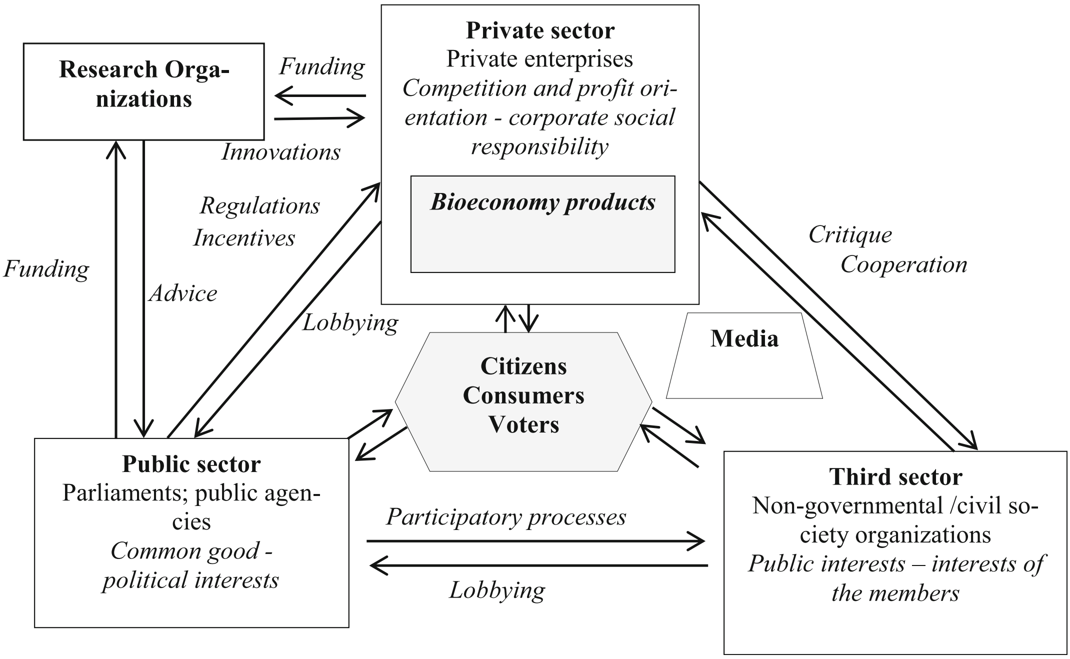

Fig. 3.9 Governance of the bioeconomy. Source: Author

in most countries of the world—private companies are, next to the consumers, the main actors in the bioeconomy. Bioeconomy products and services are, as indicated in Fig. 3.9, mostly produced by private companies. They are subject to competition and they need to make profit to survive, but they can also exercise corporate social responsibility. An interesting potential of the bioeconomy lies in the fact that the bioeconomy creates new opportunities for a wide range of different types of private sector companies—ranging from the small start-up that explores new biotechnology innovations to the well-established large-scale manufacturers of consumer goods that may decide to introduce bio-based materials.

One of the challenges of bio-based companies is the fact that they are distributed across many different industry branches and that they are, therefore, not represented by traditional industry associations. Companies that engage in the production of bio-based products may even face stiff competition, both economically and politically, from companies that rely on fossil-based resources. However, over time, companies that are engaged in the bioeconomy may form new types of business associations and start to play a role in lobbying for the bioeconomy.

As indicated in Fig. 3.9, bioeconomy companies can benefit from government policies, such as support programs. The various strategies that governments can use to support the bioeconomy fall under the linkages between private and public sector depicted in Fig. 3.9. Bioeconomy companies may also benefit from research on bioeconomy that is funded by the public sector, and they may co-fund research together with the government. Bioeconomy companies and their associations may lobby the government with the aim to induce the government to support the development of the bioeconomy. However, companies that rely on fossil resources may lobby the government, as well, which may slow down the development of the bioeconomy.

3.3.3 Consumers/Citizens/Voters

In a market economy, consumers are, next to companies, the main economic actors in the bioeconomy. Therefore, policy instruments, such as labels for bio-based products, can play an important role in promoting the bioeconomy, as mentioned above. In the political system, consumers also play a central role as citizens and voters. If they are interested in the bioeconomy, they may consider the extent to which political parties foster the development of the bioeconomy and this may influence their voting decision. Citizens may also be critical of the bioeconomy, as discussed in Sect. 3.1.5. Citizens become more effective political actors, however, if they organize themselves in the form of civil society organizations, as discussed in the next section. Figure 3.9 also indicates that they are influenced by the media, which may report positively or negatively about the bioeconomy.

3.3.4 Public Sector Organizations

As has been discussed in Sect. 3.2, public sector organizations can play an important role in fostering the development of the bioeconomy. Governments can use various policy instruments to promote the bioeconomy, as discussed above. Governments may use the existing public administration to implement bioeconomy strategies, or they may create special agencies. So far, special agencies have mostly been established for specific components of the bioeconomy, such as renewable resources or biofuels. As further discussed below, the coordination between different ministries and agencies constitutes one of the governance challenges of the bioeconomy.

3.3.5 Research Organizations

Research organizations that carry out research related to the bioeconomy are typically public sector organizations, as mentioned above. However, they often enjoy a degree of independence that sets them apart from other government agencies. They play an important role for the bioeconomy, especially by conducting research using public funding. They may, however, also receive funding from the private sector and engage in joint research activities. As discussed in Chap. 4 in more detail, research organizations can involve a wide variety of stakeholders beyond industry partners by applying transdisciplinary research approaches. Members of research organizations may also influence government policies and public opinion by participating in Scientific Advisory Councils related to the bioeconomy.

3.3.6 Third Sector Organizations

Civil society organizations, also referred to as non-governmental organizations (NGOs), play an important role in democratic systems. Since they differ from both public and private organizations in terms of organizational structure and the nature of their interests, they are often referred to as “third sector”. NGOs typically pursue public interests, such as environmental protection or social justice, which correspond to the interests of their constituents. They are based on principles of collective action and are often organized in networks rather than hierarchical structures. They interact with government, e.g. by lobbying or by participating in other ways in policy processes, e.g. by being members of round tables. Since the bioeconomy is still emerging, NGOs that specifically pursue public interests related to the bioeconomy have hardly emerged yet. However, well-established environmental organizations have started to deal with the bioeconomy. As has been pointed out in Sect. 3.1.5, some of them view the bioeconomy rather critically. This is, however, not necessarily an obstacle. To the contrary, by taking a critical perspective, NGOs can play an important function in creating pressure to ensure that the bioeconomy is indeed environmentally sustainable (see Sect. 3.1.6).

3.3.7 Governance Challenges

As can be derived from Fig. 3.9, the bioeconomy is governed by a network of actors from different sectors that have partly aligned and partly conflicting interests. They interact through a variety of processes, which leads to various governance challenges. Three types of governance challenges are discussed here in more detail.

Political Economy Challenges Governments can play a far-reaching role by creating conducive frame conditions for the development of the bioeconomy, as has been pointed out above. However, governments are themselves subject to a variety of forces, such as lobbying by industry groups and civil society organizations, which may not necessarily be in favour of the bioeconomy. Bioeconomy policies are, thus, the outcome of conflicting political processes. Examples of such controversial policy fields include biofuel policies (Deppermann et al. 2016) or biotechnology regulations (see, e.g. Richardson 2012).

Participatory and deliberative policy processes have a considerable potential in improving the policy processes related to the bioeconomy. An example is the EU BIOSTEP project, which aims at "Promoting Stakeholder Engagement and Public Awareness for a Participative Governance of the European Bioeconomy" (www.bio-step.eu). The project is supported by the European Union. Mustalahti (2017) presents an interesting recent example from Finland of including citizens in the forest-based bioeconomy with the aim to ensure responsive governance.

Coordination Challenges Another challenge of bioeconomy governance is coordination. Fostering the bioeconomy requires collaboration among different ministries, such as the ministries in charge of the economy, agriculture, the environment as well as research and education. Setting up inter-ministerial working groups may help to address this challenge, as the example of such a group in the German federal government shows. There is, however, also a need to establish coordination mechanisms across the public, the private and the third sectors and across different levels of government, especially in federal systems. At present, such coordination mechanisms are still emerging.

Global Bioeconomy Governance Global governance mechanisms for the bioeconomy will be essential to address global concerns, such as reconciling food security with an increasing production of biomass and agreeing on joint international standards for ensuring sustainability in the bioeconomy. Even though there is increasing global interest, as documented by the Global Bioeconomy Summit of 2015, global governance mechanisms still need to be developed. This may require a better integration of the concept of bioeconomy into the global processes related to sustainable development, which are coordinated by the United Nations (see Sect. 3.1.6).

Review Questions

- How is the bioeconomy defined and how did this concept evolve over time?
- What characterizes the resource substitution perspective of the bioeconomy on the one hand and the biotechnology innovation perspective on the other hand?
- Which types of criticism have been formulated against the concept of the bioeconomy?
- What are the relations between the concept of the bioeconomy and the concepts of sustainable development, green economy, circular economy and the great societal transformation?
- What are the policy instruments that governments can use to promote the development of the bioeconomy?
- Who are the main actors in the bioeconomy, and through which types of processes do they interact with each other?
- What are some challenges regarding the governance of the bioeconomy?

References

Bailis R, Baka J (2011) Constructing sustainable biofuels: governance of the emerging biofuel economy. Ann Assoc Am Geogr 101(4):827–838. https://doi.org/10.1080/00045608.2011.568867

Bardi U (2009) Peak oil: the four stages of a new idea. Energy 34(3):323–326. https://doi.org/10.1016/j.energy.2008.08.015

Baumeister C, Kilian L (2016) Forty years of oil price fluctuations: why the price of oil may still surprise us. J Econ Perspect 30(1):139–160

Bioeconomy Summit (2015) Communiqué of the global bioeconomy summit 2015: making bioeconomy work for sustainable development, Berlin

Birch K (2006) The neoliberal underpinnings of the bioeconomy: the ideological discourses and practices of economic competitiveness. Genomics Soc Policy 2 (3):1–15. https://doi.org/10.1108/00242530610667558

Birch K, Levidow L, Papaioannou T (2010) Sustainable capital? The neoliberalization of nature and knowledge in the European "knowledge-based bio-economy". Sustainability 2(9):2898–2918. https://doi.org/10.3390/su2092898

Birner R, Isermeyer F, Lange C et al (2014) Die Wettbewerbsfähigkeit der Bioökonomie in Deutschland nachhaltig stärken. Hintergrundpapier German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

BMBF (2010) National research strategy bioeconomy 2030 – our route towards a biobased economy. Federal Ministry of Education and Research (BMBF), Berlin

BMBF (2014) Wegweiser Bioökonomie. Bundesministerium für Bildung und Forschung (BMBF) (Federal Ministry of Education and Research), Berlin

BMEL (2013) National policy strategy on bioeconomy – renewable resources and biotechnological processes as a basis for food industry and energy. Federal Ministry of Food and Agriculture in Germany (BMEL), Berlin

Bonaiuti M (2014) Bio-economics. In: D'Alisa G, Dematia F, Kallis G (eds) Degrowth: A vocabulary for a new era. Routledge/Taylor & Francis Group, Abingdon/Oxon, pp 52–55

BÖR (2010) Bio-economy council report 2010: bio-economy innovation. German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

BÖR (2014) Positions and strategies of the German bioeconomy – decided at the 8th session of the council 14.5.2014 German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

BÖR (2015a) Bioeconomy policy – synopsis and analysis of strategies in the G7. German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

BÖR (2015b) Bioeconomy policy (Part II) – synopsis of national strategies around the World German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

BÖR (2015c) Global bioeconomy summit conference report – for a global sustainable bioeconomy. German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

BÖR (2017) Bioeconomy policies and strategies established by 2017. Diagram prepared by the German Bioeconomy Council (Bioökonomierat – BÖR), Berlin

Boulding KE (1966) The economics of the coming spaceship earth – environmental quality in a growing economy. In: Jarrent H (ed) Essays from the sixth resources for the future forum on environmental quality in a growing economy. Johns Hopkins University Press, Baltimore, pp 3–14

de Gorter H, Drabik D, Just DR (2013) How biofuels policies affect the level of grains and oilseed prices: theory models and evidence. Glob Food Sec 2 (2):82–88

Deppermann A, Offermann F, Puttkammer J et al (2016) EU biofuel policies: income effects and lobbying decisions in the German agricultural sector. Renew Energy 87:259–265. https://doi.org/10.1016/j.renene.2015.10.005

EC (2005) New perspectives on the knowledge-based bio-economy – conference report. European Commission (EC), Brussels

EC (2013) Horizon 2020 – the EU framework programme for research and innovation. European Commission, Brussels

Enriquez J (1998) Genomics and the world's economy. Science 281(5379):925–926. https://doi.org/10.1126/science.281.5379.92

EU (2000) Lisbon European Council 23 and 24 March 2000 – Presidency Conclusions Council of the European Union Lisbon. http://www.consilium.europa.eu/en/uedocs/cms_data/docs/pressdata/en/ec/00100-r1.en0.htm. Accessed 15 July 2017

EU (2007) En route to the knowledge-based bio-economy ("Cologne Paper") German Presidency of the Council of the European Union (EU), Cologne

Geoghegan-Quinn M (2013) Role of research and innovation in agriculture. Speech at the European Parliament on June 4 2013, Brussels

Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J Clean Prod 114:11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Glick JL (1982) The industrial impact of the biological revolution. Technol Soc 4(4):283–293. https://doi.org/10.1016/0160-791X(82)90005-7

Gottwald FT (2016) Bioeconomy – a challenge to integrity. In: Westra L, Gray J, D'Aloia A (eds) The common good and ecological integrity: human rights and the support of life. Earthscan/Routledge, London/New York, pp 22–35

Gottwald F-T, Budde J (2015) Mit Bioökonomie die Welt ernähren? Institut für Welternährung – World Food Institute e.V., Berlin

Headey D, Fan S (2008) Anatomy of a crisis: the causes and consequences of surging food prices. Agric Econ 39(Suppl 1):375–391. https://doi.org/10.1111/j.1574-0862.2008.00345.x

Kalkuhl M, von Braun J, Torero M (2016) Volatile and extreme food prices, food security and policy: an overview. In: Kalkuhl M, von Braun J, Torero M (eds) Food price volatility and its implications for food security and policy. Springer Open, Cham, pp 3–31

Loiseau E, Saikku L, Antikainen R et al (2016) Green economy and related concepts: an overview. J Clean Prod 139:361–371. https://doi.org/10.1016/j.jclepro.2016.08.024

Mustalahti I (2017) The responsive bioeconomy: the need for inclusion of citizens and environmental capability in the forest based bioeconomy. J Clean Prod. https://doi.org/10.1016/j.jclepro.2017.06.132

Pearce DW, Turner KR (1989) Economics of natural resources and the environment. Johns Hopkins University Press, Baltimore

Porter M (1990) The competitive advantage of nations. Free Press, New York

Potočnik J (2005) Transforming life sciences knowledge into new sustainable eco-efficient and competitive products. Speech held at the Conference on Knowledge-based Bio-economy Brussels 15 September 2005 at the European Commission Brussels

Richardson B (2012) From a fossil-fuel to a biobased economy: the politics of industrial biotechnology. Environ Plan C: Polit Space 30(2):282–296

Scheiterle L, Ulmer A, Birner R, et al (2017) From commodity-based value chains to biomass-based value webs: the case of sugarcane in Brazil's bioeconomy. J Clean Prod (forthcoming). https://doi.org/10.1016/j.jclepro.2017.05.150

UN (1992) Agenda 21. United Nations Conference on Environment and Development Rio de Janeiro Brazil 3 to 14 June 1992. https://sustainabledevelopment.un.org/outcomedocuments/agenda21. Accessed 15 July 2017

UN (2012) The future we want. Resolution adopted by the General Assembly United Nations Sixth Session 22 September 2012 A/Res/66/288

UNEP (2011) Towards a green economy: pathways to sustainable development and poverty eradication. United Nations Environment Programme (UNEP). https://www.unep.org/greeneconomy. Accessed 15 July 2017

University of Hohenheim (2013) Concept for the Development of an M.Sc. Program "Bioeconomy". Unpublished manuscript. Stuttgart

Virchow D, Beuchelt TD, Kuhn A et al (2016) Biomass-based value webs: a novel perspective for emerging bioeconomies in Sub-Saharan Africa. In: Gatzweiler FW, von Braun J (eds) Technological and institutional innovations for marginalized smallholders in agricultural development. Springer, Berlin, pp 225–238

von Braun J (2014) Bioeconomy and sustainable development – dimensions. Rural 21(2):6–9

WBGU (2011) World in transition: a social contract for sustainability German advisory council on global change (Wissenschaftlicher Beirat für Globale Umweltveränderungen – WBGU), Berlin

WCED (1987) Our common future. World Commission on Environment and Development (WCED)/Oxford University Press, Oxford

White House (2012) National Bioeconomy Blueprint. Washington, DC

World Economic Forum (2016) The global competitiveness report 2016/2017. World Economic Forum, Geneva

WWF (2009) Industrial biotechnology – more than green fuel in a dirty economy? World Wide Fund for Nature (WWF), Copenhagen

4

Inter- and Transdisciplinarity in Bioeconomy

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Abstract

In this chapter, characteristics and definitions of inter- and transdisciplinary research are presented and discussed with specific attention to bioeconomy-related policy discourses, concepts and production examples. Inter- and transdisciplinary research approaches have the potential to positively contribute to solving complex societal problems and to advance the generation

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of knowledge relevant for innovative solutions. As a key concept for integrating different disciplines across social and natural sciences within a common research project, we present principles, models and examples of system research and highlight systems practice with the help of the farming systems and the socioecological systems approaches. Next, we concretise inter- and transdisciplinary research practice as a three-phase process and operationalise cooperation of scientists and stakeholders in bioeconomy contexts. Specific attention is given to a differentiated understanding of knowledge. The chapter is closed with a reflection on the role researchers play in inter- and transdisciplinary research and the impacts created by norms and values emanating from science.

Keywords
Inter- and transdisciplinarity • Wicked problems • Types of knowledge • Systems thinking • Socioecological systems • Bioeconomy research

Learning Objectives
In this chapter, you will:

- Learn how inter- and transdisciplinary approaches contribute to knowledge generation in bioeconomy-related research.
- Understand system concepts' potential to integrate distinct disciplinary views in joint research.
- Reflect upon researchers' roles and tasks when interacting with others societal actor groups in common projects.

4.1 Introduction: Why Inter- and Transdisciplinarity in Bioeconomy?

In the first section of this chapter, we present our understanding of 'bioeconomy' as a political and societal discourse, as a concept constructed in complex interactions of public and private actors from both economy and civil society spheres within regions, nations and in international contexts. It is with this understanding in mind that we then argue for inter- and transdisciplinary research approaches.

4.1.1 Bioeconomy as a Political Strategy for Sustainable Growth

Following the early interpretations of 'bioeconomics' of Zeman and Georgescu-Roegen in the 1970s of the last century, the term was meant to designate 'a new economic order' which appropriately acknowledges the biological bases of (almost) any economic activities (Bonaiuti 2015). Apparently, the intention was not to encourage economic development and growth but to warn of the ecological and the sociocultural damages induced and to replace the prevailing economic model. Since then, the term 'bioeconomy' has become prominent in politics, science and economy (cf. Chap. 3), and it is a certain 'irony of fate' that Western nations make use of the 'bioeconomy concept' to promote and foster research and innovation processes with the aim to establish a better 'biobased' economic development and growth (e.g. BMBF 2010; OECD 2009; Staffas et al. 2013).

As a prominent example, the European Commission portrays the bioeconomy as a key component for smart and green growth. Utilising the results of the public consultation, the EC published a combined strategy and action plan document in 2012 entitled 'Innovating for Sustainable Growth: A Bioeconomy for Europe'. In this paper, bioeconomy is described as relying on ‘the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy’, and comprising a broad array of economic sectors and branches, such as ‘agriculture, forestry, fisheries, food and pulp and paper production, and parts of chemical, biotechnological and energy industries’ (European Commission 2012, p. 5). The report states further the economic importance of the bioeconomy in terms of annual turnover and employment creation and also emphasises the strategical importance of the sector for the future of the European Union. More concretely, the strategy aims to improve the knowledge base for the bioeconomy, encourage innovation to increase natural resource productivity in a sustainable manner and assist the development of production systems that mitigate and adapt to the impacts of climate change. Importantly, the policy document calls for a strategic, comprehensive and coherent approach to deal with the complex and interdependent challenges related to the bioeconomy in Europe, such as competition between different biomass uses and potential impact on food prices. ‘The Bioeconomy Strategy focuses on three large areas:

- The investment in research, innovation, and skills
- The reinforcement of policy interaction and stakeholder engagement
- The enhancement of markets and competitiveness in bioeconomy sectors’ (European Commission 2012, p. 12).

In a similar way, the German national bioeconomy strategy emphasises the use of biomass for multiple purposes and also stresses the waste recycling as a major strategic field (BMEL 2014). More generally, the strategy highlights the objectives both to meet societal challenges such as world population growth, climate change and the loss of soil fertility and biodiversity as well as transforming the economy from a dependence on fossil resources towards a ‘circular’ or ‘recycling’ economy. Cross-cutting and thematic policy areas are thus interwoven (Table 4.1).

Political bioeconomy strategies have thus a strong focus on scientific development and equally underline the necessity of stakeholder integration and engagement. However, underlying innovation models seems to frequently be rather traditional models of exogenous innovation development with a strong focus on diffusion of innovation. Explicitly, this is visible in a chapter title ‘Advancing from Lab to the Market’ of the White House Bioeconomy Blueprint (2012). The innovation concept is presented with more details in Chap. 11.

Within a social sciences’ perspective, bioeconomy can be understood as a policy discourse (see excursus box) that selects and defines societal problems (problem framing) and creates a ‘performative narrative’, i.e. a convincing story that offers solutions in this respect. The bioeconomy discourse combines various (environmental, economic and social) problem streams. With regard to environmental issues, it particularly addresses climate change and the limited availability of non-renewable (fossil) resources. These issues are connected with the socioeconomic challenge of growing demand for resources due to the global population growth and increasing incomes. In combination, these processes require a change of the economy (towards a bio-based economy) and growing productivity at the same time.

Table 4.1 Cross-cutting and thematic policy areas

Cross-cutting policy area	Thematic policy area
Coherent policy Information and public dialog Primary and vocational education	Sustainable production of renewable resources Processes and value chains Growing markets and innovation Competition of land uses International context

Box 4.1 Discourses

'Discourse' has originally been used as a concept for sequential analysis of the flow of conversations. Then, the concept has become a much broader interpretation by the work of Michel Foucault (a French philosopher, 1926–1984), who defined discourse as 'systems of thoughts composed of ideas, attitudes, courses of action, beliefs and practices that systematically construct the subjects and the worlds of which they speak'. Foucault traced the role of discourses in wider social processes of legitimisation and power, emphasising the construction of current truths, how they are maintained and what power relations they carry with them. Foucault argued that discourse is a medium through which power relations produce speaking subjects and a practice through which power structures are reproduced. Thus, power and knowledge are interrelated, and therefore every human relationship is a struggle and negotiation of power.

Foucault's analysis has inspired discourse analysis in many fields, and it has become an integral part of political analysis in particular through the work of Maarten Hajer (a Dutch political scientist). He defined a policy discourse as ensemble of ideas, concepts and categories through which meaning is given to social and physical phenomena. It is produced and reproduced through an identifiable set of practices. In a policy arena, different, competing policy discourses may be identified. A policy discourse is produced and maintained by a discourse coalition, a group of actors that, in the context of an identifiable set of practices, shares the usage of a particular set of story lines over a particular period of time (Foucault 1981; Hajer 1995).

In EU and in German political discourses, sometimes the idea of a knowledge-based economy is used as an implicit concept to bioeconomy, which is a reference to ideas of the knowledge society (see Chap. 3). Most obviously, this concept is interpreted in a way that 'knowledge' is identical to 'scientific knowledge', which reflects the strong roles that scientists are supposed to occupy in the bioeconomy. However, as stated in the first chapter, developing solutions for an innovative and sustainable use of the Earth's limited resources is only one part, the other is to understand and guide targeted societal changes and transformations.

4.1.2 Addressing Wicked Problems Related to the Bioeconomy Transition

Bioeconomy discourses claim to address complex societal problems and challenges in which environmental, economic and social dimensions are dynamically interwoven in both, conflictive or mutually enhancing manners. In the literature, this type of challenges is also qualified as 'wicked problems' (Batie 2008). Thus, proposed technological solutions, e.g. the use of renewable instead of fossil material, have to be understood as embedded in new institutional structures (regimes), e.g. consumption patterns, and supported and conditioned by evolving mental frames and knowledge structures, e.g. individually and socially held values and norms, before effectively contributing to the expected social outcomes (efficiency and distribution of costs and benefits). To develop a bioeconomy can be understood as a transition process or a process of social change within societies (Geels 2002) that starts from wicked problems. Such a transition process targets to voluntarily change individual and collective behaviours respective practices of individual and collective actors through the enhancement of problem solving and innovation adoption and diffusion processes (cf. also Sect. 11.1).

To develop a conceptual scheme for such change processes, first, a generic understanding is necessary of what 'a problem' is. Then, we

Fig. 4.1 Problem solving—basic structure (adapted from Hoffmann et al. 2009, p. 63)

show factors and give examples of what determines a complex or wicked problem in order to demonstrate the multiple aspects to be taken into account. From human psychology concepts, a problem is defined as a perceived discrepancy, a cognitive gap between a desired and an actual state, for which no routinised solution (operation) exists (Hoffmann et al. 2009).

So, a first important insight is that problems are not objectively present but perceived by individuals (=actors) and determined by their subjective understandings and interests. As shown in Fig. 4.1, the basic structure of a problem situation consists of four components: the actual and the desired, targeted state and the operation(s) that may change the actual to a desired state; the fourth component is the feedback loop from the desired future state to the actual state which reflects the assumption how the desired state will influence of the current situation. In other words, it is the expectation about the impact of the desired state. Thus, this step is highlighting that a problem-solving process might not always come to an end when the desired state is achieved (and has become the actual state) (Hoffmann et al. 2009). A problem is given, if one or—what is also possible—several of these components are unknown to the actor(s).

Analysing the nature of a problem more in detail, its origin may then be caused by either lack of knowledge or by conflicting or incompatible values. As the figure shows, both options may occur in every step, e.g. lack of knowledge may exist with regard to desired state (what should be the share of bio-based materials in the construction sector?) or the valuation of possible desired states and operations (is it ethically acceptable to make use of animals for the production of hormones?). Another challenge may be to coherently understand and address the actual state, e.g. how to judge and assess the current national production of bioenergy? Actors may face great difficulties to address such a challenging quest only on the basis of what is considered 'facts' and might want to consider values and norms, e.g. with regard to the protection of natural resources. Actors may be tied in familiar social contexts in multiple ways. They may ignore relevant information ('group think') or are unable to change behaviour due to normative expectations by reference groups. Also, actors may identify themselves strongly with a certain status quo, so that they are reluctant to change behaviour, which would challenge their status (e.g. diversification of farm activities in order to increase income may be connected with changing gender roles). Finally, problem solving is also a personal cognitive capability. Actors often are overconfident with regard to their own capabilities (skills) and their capacities (e.g. time, money) to solve problems (e.g. car drivers are in general overconfident about their own driving skills). Overconfidence is particularly problematic in risky choice situations (overconfident actors often take higher risks). However, under-confidence in particular with regard to low-status groups (poor, marginalised) may also be possible and lead to a situation where actors do not solve perceived problems despite the fact that they have both the capacities and the capability to act. These various aspects may all contribute to the perception and description of a problem and cause that frequently 'there is no consensus on what exactly the problem is' (Batie 2008, p. 1176)—a typical feature of wicked problems.

Summarising, addressing wicked problems in the context of bioeconomy, requires both an analytical understanding of what the core components of the respective problem are and a synthetic view of how the various mutual understandings of the people engaged with the problem can be related and integrated. An example of an interdisciplinary problem view is presented in the excursus box. A conceptual approach of how to develop an integrated understanding is presented in Sect. 4.3 on systems thinking and systems practice.

Box 4.2 Interdisciplinary Problem-Solving Approach (Example)

For students, it can be especially interesting how the problem-solving approach is explored by other students. Zhang and Shen (2015) introduce an example of 16 interviews conducted with the graduates of 3 disciplinary backgrounds (physics, chemistry and biology) who explain their experience in dealing with 2 interdisciplinary problems on the topic of osmosis. Even though the majority of the students honestly express their sceptical opinion about one or both disciplines in which they are not specialised in, in the end, they admit the value of the interdisciplinary approach in dealing with complex issues:

- Firstly, all scientific fields are interconnected to some extent and 'boundaries between subjects are artificial' (epistemological perspective).
- Secondly, to conceive almost any world problem, a comprehensive view based on many disciplines must be considered (practical perspective).
- Thirdly, interdisciplinarity can serve as a tool which supports the learning process as it gives students an opportunity to see 'a broader picture' regarding a particular problem (educational perspective).

The authors provide the graphs and detailed descriptions of the interviews with quotes (read more—https://doi.org/10.1080/09500693.2015.1085658).

As has been argued in the previous sections, the challenge of transition to bioeconomy, of addressing the respective problems appropriately and of responding to questions arising from changing production and consumption patterns not only involves researchers but requires active engagement of many other actors. 'A close communication between politics, business, science and civil society, as well as the preparation of policy decisions' is necessary (BMEL 2014, p. 45). Furthermore, 'a knowledge-based dialogue on controversial issues' has to consider general public's interests and demands (BMEL 2014, p. 47). Spreading awareness about changes and innovations in the society, keeping people informed, 'strengthening open-mindedness' is also important (BMEL 2014, p. 10).

Inter- and transdisciplinary research approaches are considered to have the potential to positively contribute to addressing and working on complex societal problems and to considerably advance the generation of effectively implementable knowledge (Agyris 2005) relevant for innovative solutions. In the following section, these approaches are presented.

Further Reading

Staffas L, Gustavsson M, McCormick K (2013) Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches. Sustainability 5:2751–2769

Useful Links

BMEL (Federal Ministry of Food and Agriculture of Germany) (2014) National policy strategy on bioeconomy. Renewable resources and biotechnological processes as a basis for food, industry and energy. http://www.bmel.de/SharedDocs/Downloads/EN/Publications/NatPolicyStrategyBioeconomy.pdf?__blob=publicationFile. Accessed 25 Dec 2016

European Commission (2012) Directorate-General for research and innovation. Innovating for sustainable growth: a bioeconomy for Europe. http://bookshop.europa.eu/en/innovating-for-sustainable-growth-pbKI3212262/. Accessed 12 Jan 2016

OECD (Organisation for Economic Co-operation and Development) (1996) The knowledge-based economy. http://www.oecd.org/sti/sci-tech/theknowledge-basedeconomy.htm. Accessed 17 Sep 2017

4.2 Terms and Backgrounds of Inter- and Transdisciplinary Research

As argued above, a societal transition to a more sustainable way of production and resource use in the frame of the bioeconomy paradigm requires a successful cooperation of a broad range of actors from various societal subsystems and a meaningful integration of scientific and practical knowledge. Hence, science's contribution to the solution of the problems consists necessarily of multifaceted and integrated approaches, or in short, of inter- and transdisciplinary research (Brand 2000; Hirsch Hadorn et al. 2008). In the following, we briefly present definitions and then elaborate on principles and key characteristics of inter- and transdisciplinary knowledge generation in the context of bioeconomy.

4.2.1 What Is Meant by Interdisciplinarity, What by Transdisciplinarity?

At first sight, scientific disciplines seem to be easily separable entities of subject matters, such as biology, chemistry, economics, history, etc., that are shaped by common rules and internally passed down procedures of knowledge generation. However, we also can observe a continuous disciplinary differentiation and itemisation that is expressed, for example, in extended titles of academic chairs. From a social science perspective, scientific disciplines can be considered as institutions that shape the way in which people do research in a certain thematic field and on a range of topics (following Castán Broto et al. 2009). Here, the term institution is defined as a set of conventions, norms and formal rules that 2005, as quoted in Castán Broto et al. (2009). Hence, a discipline is a result of shared understandings, practices and conventions that have been accumulated and compiled over time.

Interdisciplinarity
Scientific research that relates a number of disciplines and transgresses the broader fields of humanities and natural sciences. (Knierim et al. 2010; Tress et al. 2007)

Doing joint research as a group of researchers with different disciplinary backgrounds is usually denoted as 'multidisciplinary'. *Multidisciplinarity* refers to a research that addresses a question or an issue from a variety of disciplinary perspectives, without purposefully integrating the various findings. Results of this type of research consist usually of added disciplinary pieces without synergies rather than a connected composition (Pohl and Hirsch-Hadorn 2008a, b). As an example, we see that in the policy strategy 'Innovating for Sustainable Growth: A Bioeconomy for Europe' (2012), the EU develops 12 crucial actions among which one is 'increasing cross-sectoral and multi-disciplinary research and innovation' (European Commission 2012).

Interdisciplinarity involves different disciplinary approaches to research in a conceptually coordinated way where the disciplinarily guiding assumptions and research concepts ('worldviews') are made explicit and mutually connected. Thus, interdisciplinarity implies overcoming classical boundaries and reorganising scientific questions and knowledge (Mittelstraß 1987). With an interdisciplinary approach, 'facts and findings' from each discipline are critically evaluated in light of the 'facts' from the other disciplines, and the attempt is made to integrate discipline-specific knowledge into a larger whole. The broader the range of disciplines involved, and especially if both natural and social sciences' researchers participate, the more challenging is this step of knowledge integration.

Box 4.3 Examples of Interdisciplinary Studies

A number of applied studies are carried out within the interdisciplinary project ‘Spatial Humanities’ (funded by the European Research Council) whose main goal is stated as ‘developing tools and methods for historians and literary scholars’ who use the geographic information systems (GIS). In their research work, the interdisciplinary team combined computational linguistics, cultural geography and spatial analysis. Thus, the project implemented methodologies in an interdisciplinary way that allowed to investigate unstructured material from historical literature and official documents. Visit the project’s webpage via http://www.lancaster.ac.uk/fass/projects/spatialhum.wordpress/.

Another example for collaboration of an interdisciplinary team (ecologists, anthropologists and economists) is given by Lockaby et al. (2005). The project WestGa consists of several studies devoted to the ‘urban development of forested landscapes’ in the Southeastern United States taking into account land use, ecosystems, biodiversity as well as social and policy aspects related to the process. The WestGa projects help to analyse roots and consequences of many-sided issues associated with the ‘relationships between urban development and natural resources’ and design solutions for them. Read more—https://www.auburn.edu/~zhangd1/RefereedPub/Urbanecosystems2005.pdf.

Podestá et al. (2013) describe two interdisciplinary multinational research projects which investigate relations ‘between climate variability on interannual to decadal scales, human decisions, and agricultural ecosystems in the Argentine Pampas’. In both cases, the problem-driven cooperative work of the scientists from diverse fields (climate science, oceanography, physics, statistics, agronomy, geography, anthropology, sociology, agricultural economics, psychology, epistemology and software engineering) together with social stakeholders plays the main role in achieving the outcomes. These are ‘implementation of new climate diagnostic products, multiple talks and articles for non-scientific audiences, and various tailor-made instructional efforts (e.g., workshops on the fundamentals of decision-making)’. The participants of the projects agree that the intense interdisciplinary collaboration, especially with the involvement of stakeholders (transdisciplinary approach, to be described below), can be very demanding and energy-consuming, starting with the common formulation of a problem, choosing cross-disciplinary methods to be used in research, formation of a team and others. The obstacles stem from differences in ‘styles of thought, research traditions, techniques and language’ of involved actors. However, despite the difficulties, the interdisciplinary approach facilitates in keeping a systemic view and looking at problems from a range of perspectives. Read more—https://doi.org/10.1016/j.envsci.2012.07.008.

Finally, *transdisciplinarity* broadens a research’s scope into another study dimension as beside the orientation towards real-life problems; this approach also seeks to integrate lay or non-academic knowledge with scientific one. This understanding is expressed in the definition of Lang et al. (2012, p. 27) where ‘transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge’.

Box 4.4 Example of Transdisciplinary Research

On the challenge of adapting agricultural systems to the effects of climate change, Bloch et al. (2016) show how farm-specific innovations and adaptive measures are developed in a transdisciplinary research approach. In a cyclical process of analysis, planning, action and reflection, the network of researchers and organic farmers repeatedly used participatory analyses tools to structure the transdisciplinary innovation and adaption process. First, a group of organic farmers identified as main weaknesses the water and nitrogen supply likely to be worsened by climate change; then, farm-specific adaption measures were identified and tested by conducting on-farm 27 experiments at 6 organic farms in teams of researcher and practitioners. By evaluating and thus adjusting and retesting the measures in consecutive trials, new farming methods were developed to increase diversification and decrease risk in organic farming practices. Along with the iterative process, the network was expanding towards actors from advisory services and farmers' associations, and the collective learning process led to changes in attitudes and behaviour. The participating organic farmers proved to be active partners; their openness to innovation and their approach to problem solving make them well suited to transdisciplinary research. In adapting regions to climate change, these kinds of stakeholders will play a decisive role. https://doi.org/10.1007/s13165-015-0123-5

Transdisciplinarity

A specific form of interdisciplinarity in which boundaries between and beyond disciplines are transcended and knowledge and perspectives from different scientific fields as well as non-scientific sources are integrated (Bergmann et al. 2010).

Thus, the interface between society and science is a key constituent which implies not only the necessity to create mutual understandings but to go far beyond towards interaction and collaboration among the various actors.

Rosenfield (1992, p. 1351) revealed a narrower understanding when she defined transdisciplinarity as 'jointly work of researchers using shared conceptual framework drawing together disciplinary-specific theories, concepts, and approaches to address common problems'. Clearly, this definition is almost similar to the above developed description of 'interdisciplinarity' and points at the difficulty that, in some scientific communities, the terms are blurred and no clear distinction is made in this regard. However, nearly 25 years later, a certain stock of transdisciplinary publications can be acknowledged which also allows to summarise 'three core features of transdisciplinary research: (1) complex real-world problems, (2) collaborations, and (3) evolving methodologies' (Zscheischler and Rogga 2015, p. 32).

Finally, we conclude the range of definitions with a more pragmatic one given by Jahn et al. (2012, p. 4): 'A reflexive research approach that addresses societal problems by means of interdisciplinary collaboration as well as the collaboration between researchers and extra-scientific actors; its aim is to enable mutual learning processes between science and society; integration is the main cognitive challenge of the research process'. Definitions have the important function in academia to standardise understandings and by this provide a solid common ground for cooperation. Nevertheless, there may be contested or conflicting perspectives within a group of scientists. Hence, the search for a common definition is important in order to determine agreements, but also differences in looking at the world and explaining phenomena. Consequently, for an inter- or transdisciplinary team, it is important not to impose common definitions but to deal with definitions in a flexible way and to explore and identify the ‘common epistemological ground’, i.e. the common conceptual understanding of cause–effect relations. The multifaceted systems theory is well suited to structure this working step (see Sect. 4.3).

4.2.2 Backgrounds of Inter- and Transdisciplinary Research

There is an increasing concern about the usability of research outputs and a quality divide between lay and scientific knowledge is contested. Instead, there is a growing conviction that solving real-world problems requires the integration of multiple forms of knowledge. This includes the acknowledgment of practical, local, tacit knowledge as a valuable resource but in particular also the integration of social and natural sciences perspectives.

Previously, the emergence of modern science was closely connected with the development of modern societies. The paradigm of scientific discovery had become the dominant mode of innovation in the modern world. It was built on the hegemony of theoretical and experimental science, and sometimes science has been seen as the only location of innovation and discovery. This model of science is built on a set of principles, such as the autonomy of scientists, which is also considered being the basis for internally driven taxonomy of disciplines, the ability of purely scientific problem definitions and the assumption that scientific knowledge is objective and can be used irrespective of the context. Although this model has been fundamentally contested already (e.g. Kuhn 2012), it is still widely prevailing in both academic communities and the interested public.

The paradigm of scientific discovery is closely connected to transfer of knowledge or transfer of technology (TOT) model that assumes a one-directional diffusion of new knowledge and innovation from science to other parts of society (Hoffmann et al. 2009). This paradigm and the corresponding model of diffusion of innovation has been criticised on various occasions (e.g. Hoffmann 2007). In a groundbreaking ethnographic study (*The Manufacture of Knowledge*), Knorr-Cetina (1981) demystified science. She demonstrated that science is not a purely rational, cognitive process, but scientific knowledge is a social process and practice which is embedded in a trans-scientific field. Researchers have to make series of choices (about research objectives, methods, sampling, publishing strategies etc.) that are bound to social factors (e.g. external evaluators, local research traditions, funding opportunities). Thus, science can be studied like any other social field, and in particular, the assumption of science providing objective, transferable and decontextualised, all-round applicable knowledge has to be taken with caution. Further examples for pioneer research on knowledge generation outside science were provided by Karl Polanyi (1886–1964) and Clifford Geertz (1926–2006) who worked on tacit and on local knowledge. Tacit knowledge is defined as knowledge that is difficult to transfer to another person by means of writing it down or verbalising it (‘we can know more than we can tell’), so it is opposed to explicit knowledge. Examples are all handicrafts, where actors may develop incredible skills, which can only be learnt through practice. Local knowledge can be understood as a shared way of interpreting the world and, thus, relates to basic ideas of social constructivism (Geertz 1973). Here, the meaning of ‘local’ is not defined precisely but relates knowledge to people, places and contexts. Since knowledge is always culturally bounded and thus socially constructed, there is no universal knowledge; hence, the universality claim of scientific knowledge is questioned; and science is considered as a social practice, among others (Knorr-Cetina 1981). As a consequence, there may be different worldviews, and thus, ‘knowledge’ and projects that support social or societal change may become ‘battlefields of knowledge’ (Long and Long 1992), in which competing interpretations of reality struggle to become the orthodox or dominant view.

Table 4.2 Expert versus lay knowledge (compilation of the authors)

	Expert (scientific, explicit)	Lay (local, personal, tacit, practical, traditional)
Context	Decontextualised	Contextualised/situated
Epistemology	Objective	Socially constructed
Generation	Systematic research/science	Practical experience
Codification	Highly codified	Uncodified/tacit
Valuation	Academic discourse	Communities of practice
Roles	Experts	Practitioner
Policy approach	Top-down, exogenous development	Bottom-up, endogenous development

The different types of knowledge are often condensed in a dualistic typology of expert versus lay knowledge (Table 4.2).

4.2.3 Acknowledging Preconditions and Bases of Inter- and Transdisciplinary Research

Transdisciplinary research has a relatively young history: In Germany, it was especially the increasing (political) request for sustainability research which encouraged and strengthened inter- and transdisciplinary research approaches. Starting from the late 1990s, a series of correspondingly targeted calls and programs from the German Ministry of Education and Research (BMBF) can be noted, and the first prominent projects were related to agricultural landscape research (Müller et al. 2002; Hoffmann et al. 2009). Also, in Austria and Switzerland, large-scale transdisciplinary research programs were funded, and, step by step, a certain body of common understanding, principles and core approaches was discussed in books and papers (Brand 2000; Hirsch Hadorn et al. 2008; TA 2005; GAIA 2007). At that time, several authors noted general deficits in the philosophy of science and epistemological basis related to inter- and transdisciplinarity; Grunwald and Schmidt (2005, p. 5) lamented that 'a lot had been said about inter- and transdisciplinarity, some has been practiced, little is reflected and understood'; they called for methodological canonisation and routines.

The number of sustainability-related inter- and transdisciplinary studies has drastically increased since then and international journals publishing such research have become more widespread, such as 'sustainability' or 'ecology and society'. However, most frequently, papers report on experiences from single projects and describe case studies while comparative or even quantifying research is still at its beginning (Schmid et al. 2016; Zscheischler and Rogga 2015).

From the presented definitions and their conceptual foundations, we can conclude that mutual understanding and joint conceptual bases appropriate to cross-disciplinary boundaries are necessary constituents for successful inter- and transdisciplinary approaches. In the following section, systems thinking and systems practice are introduced as theoretical concepts and practices with the aim to support inter- and transdisciplinary teams in joining and relating interests, objectives and understandings for successful cooperation.

Further Reading

Hirsch Hadorn G, Hoffman-Riem H, Biber-Klemm S, Grossenbacher-Mansuy W, Joye D, Pohl C, Wiesmann U, Zemp E (2008) Handbook of transdisciplinary research. Springer, Dordrecht

Lang JD, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ (2012) Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain Sci 7(1):25–43

Zscheischler J, Rogga S (2015) Transdisciplinarity in land use science—a review of concepts, empirical findings and current practices. Futures 65:28–44

4.3 Systems Thinking, Systems Practice

4.3.1 Systems Theory

Systems theory is a disciplinary transgressing idea for the study of the abstract organisation of phenomena, independent of their substance, type or spatial or temporal scale of existence. It investigates both the principles common to all complex entities and the (usually mathematical) models which can be used to describe them. We propose to use systems analysis as an abstract way to conceptualise how various world views and understandings can be connected in trans- and interdisciplinarity research projects. Systems thinking thus provides the necessary bases for linking multiple sources of knowledge and some general concepts that help to reflect and structure transdisciplinary research. In the following, we give an eclectic overview based on economic, sociological and natural sciences' conceptualisations of systems (Huber 2011; Schiere et al. 2004).

Generically, systems consist of basic elements, which may be of a similar type (e.g. humans in human societies) or different types (e.g. animal and plants in an ecosystem). The elements of a system are connected to each other by specific relations or forms of interactions (e.g. communication, predator–prey relations, information, energy and material flows). Any relationship can be interpreted as a form of communication and exchange of information. Any communication requires a signal and a receiver. The receiver will respond to the signal in one way or another. Communication does not necessarily imply awareness or consciousness. In technical systems, the components communicate among each user even though they are not aware what 'they are doing'. Instead, a sensor perceives a signal. In the case of living systems, this may require the ability of elements to identify and select among different behaviours and/or states of other elements (information processing). Relations therefore are selective in the way that certain states are recognised and others are ignored. An example for a living system is given in the excursus box below.

Box 4.5 The Fox–Mouse Predator–Prey Relation Perceived with a System Concept
In the fox–mouse relation, the only relevant information for a fox is the availability of mice (yes/no coded as 0,1). Further properties of mice are irrelevant (e.g. gender, personal character, family status, age). The availability of mice is not a signal that mice intend to send. The information about the availability of mice will influence the reproduction behaviour of foxes. This will again have an effect on the presence of foxes, which will have an impact on the availability of mice. The fox–mouse relationship may be understood as a subsystem in a wider ecosystem.

Thus, information can be described as perceived data, to which meaning is ascribed by the element (Schiere et al. 2004). Information processing has an effect in the way that certain states or behaviours will trigger sequential operations. However, a system only emerges, when the response of receiver will be observed by the original sender and or other elements of the system, and this reciprocal communication will be reproduced over time. Only then, systems form identifiable entities that can be clearly separated from their context, the system's environment. The separation of systems and their environment requires the existence of boundaries.

Systems thinking has proven its usefulness as a general meta-theoretical approach that seeks to depart from linear thinking in order to model complexity. Initially, it extends the model of simple causation (cause–effect) by introducing feedback loops (reciprocity) and linkages to other entities. Feedback loops and linkages between several elements are necessary but not sufficient to characterise a group of elements as systems. In systems, the elements interact in ways that new collective patterns and regularities emerge such that larger entities hold properties the individual elements do not exhibit ('the system is more than the sum of its part'). This phenomenon is usually referred to as emergence.

Thus, systems thinking provides a huge potential for transdisciplinary research as it offers options to connect phenomena of different kinds. Usually, this connection implies a hierarchy in the sense that systems are constituted by elements, which are of a different kind. The connection is referred to as 'structural coupling'. Emergent systems are structurally coupled with the entities, on which they are built. Structural coupling describes a nondeterministic relationship, in which the emergent system does not recognise the existence of the lower-order entities. For example, the human consciousness and cognitive abilities are based on neurobiological processes. However, what we think is independent from the neurobiological processes (nondeterminism) and, at the same time, our consciousness is unable to observe that the neurons of our brain are working (Fig. 4.2). For the study of wicked problems in bioeconomy, such a system understanding is relevant as it enables people to connect the material phenomena related to bio-based technologies (e.g. bioinformatics resulting in the possibility of monitoring and steering living organism) to interpretation and sense-making of human activities (here: institutions and ethics of bio-engineering) and by this to relate technological change to pathways of societal transformation.

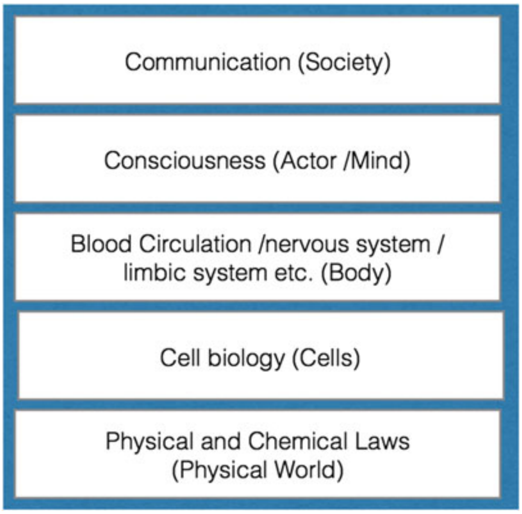

Fig. 4.2 Example for emergent phenomena

In sum, we can describe systems as emergent entities with identifiable boundaries, in which the elements are linked in reciprocal ways, which are structurally coupled to its elements, and that can be nested in larger systems and/or consist of subsystems.

4.3.2 Differentiating Systems

As it has been mentioned in the beginning of this section, system analysis is a way to address complexity. Systems can be distinguished regarding their own complexity. The complexity of systems is associated with the attributes of its elements, relations as well as the system-context relations. Due to the disciplinary multitude of systems theories, there are many ways of how to differentiate the system notion. In the following, we present a few attributes that commonly serve for differentiating systems and which are of use in the context of inter- and transdisciplinary research.

Openness

One way to categorise systems is about their openness or the closure of a system's boundaries. In engineering, closed systems are such, for which required inputs and/or outputs are controlled. Examples of closed systems:

- A computer network is closed in the sense that digital data transfer is only possible between a defined set of computers, while energy and user input is required.
- A greenhouse can be organised in a way that no water and nutrients can escape (matter); thus, it is an independent, self-sufficient entity; however, at the same time, heat (energy) is constantly exchanged with the environment (Fig. 4.3).

Fig. 4.3 Greenhouse, a closed system (the University of Hohenheim, photographer Sacha Dauphin)

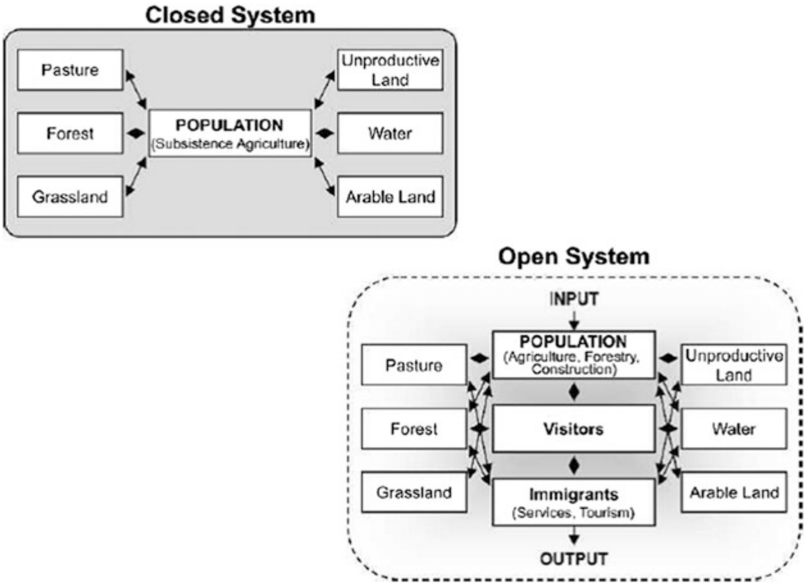

Fig. 4.4 Shift from closed system to open system (Messerli and Messerli 2008)

An open system is a system that has external interactions with its environment also for its core relationships. Hirsch Hadorn et al. (2008) provide an example of a change from rather closed rural system (1860) to an open one (twentieth century) during the society's development and modernisation over time. Because of the flows 'of people, capital, energy, technology, information, goods and services in many different forms', linkages in the land use system behave in a more complicated way, and even areas considered as conventionally 'unproductive' are used more and more often, e.g. for tourist and conservation purposes (Fig. 4.4).

Leakages in both directions, emissions and absorption of matter or information, may have a significant effect on system performance. Thus, boundary maintenance is commonly both a core issue of evaluation and assessment, and an intervention strategy. Technological approaches in the bioeconomy that seek to improve productivity and sustainability usually try to reduce openness of production systems by creating closed systems to gain direct control over emissions and absorptions. However, such direct interventions are in many situations not possible or cause other adversities. Then, only indirect approaches of system steering are possible. Transdisciplinary research is closely related to situations, in which the openness of system boundaries must be maintained since the negative externalities of closure may exceed its benefits.

Goals and Functions

Another way of looking at systems is focussing on systems' goals or functions. Goals are states that systems try to achieve and maintain, despite obstacles or perturbations. There are mainly two contexts when goals are commonly labelled functions. Firstly, in diversified systems like organisms, subsystems may provide a specialised function to the maintenance of the whole. Here, function is connected to division of labour. Secondly, functions of systems may be ascribed goals. For instance, ecosystem services or the function of a machine are no entities of the system itself but ascribed to the systems by humans. In such cases, assessments of system performances may tell us as much about humans who assess as about the system performance itself. The term 'goal' is more commonly applied, when some degree of intentionality is assumed. Particularly, human social systems (e.g. organisations) are often treated as goal-oriented entities. In contrast, physical systems (e.g. planet system or atoms) are usually considered as unintentional, in the way that they are solely determined by physical laws. Describing things in terms of their apparent purpose or goal is called teleology. Regarding system assessment, we find that in biology, the evaluation focus is shifting away from outputs and inputs towards persistence and maintenance over time. This shift is connected to a specific characteristic of living and ecological systems that is called autopoiesis. Autopoiesis refers to a system capable of reproducing and maintaining itself (self-organisation). The components (elements/subsystems) of such system are produced by internal components or through the transformation of external elements by internal components. For example, a bee colony is an autopoietic system that internally reproduces its elements (queen, drones, worker bees (house bees, guards, field bees), bee hive) and actively transforms external components (nectar, pollen, etc.) to components (feeding, building material).

Autopoietic systems are operatively closed in the sense that certain internal operations are required to maintain the system. Systems structures are built and modified by internal operations. More importantly, autopoiesis is connected with the ability to adapt to environmental changes (adaptive systems). This requires sensory feedback mechanisms and the development of an adaptation that is a change of behaviour patterns and/or structural changes. In the example, a bee colony is storing honey and reduces its size during winter as a response to seasonal food availability. The opposite of autopoiesis is called allopoesis. A car factory is an allopoetic system that uses raw materials (components) to generate a car (an organised structure), which is something other than itself (the factory). Autopoietic and allopoetic systems rely on a distinction that goes back to biologists and systems thinker Hugo Maturana (born in 1928) and Francisco Varela (1946–2001).

System Assessment

This focus on survival, self-organisation and adaptivity in the study of living and ecosystems has triggered the debate on a different types of assessment criteria such as equilibrium, stability and resilience that also have been influencing other sciences, particularly, economics (think of the idea of market equilibriums in general economy) and sociology (Table 4.3). The concept of system equilibrium is perhaps the oldest approach applied. An equilibrium is a state in which all forward reactions (flows, potentials)

Table 4.3 Characteristics of equilibrium, stability and resilience (compilation of the authors based on Schiere et al. 2004)

Equilibrium	All forward reactions (flows, potentials) equal all reverse reactions, so that the state of a system remains stable May only be achieved in closed systems
Stability	An absence of excessive fluctuations of outcomes Outcomes of systems remain in a defined range of parameters
Resilience	Capacity of an (eco)system to respond to a perturbation or disturbance by resisting damage and recovering quickly

Table 4.4 Simple and complex systems (based on Schiere et al. 2004)

	Simple	Complex
Elements	Small number of elements	Large number of elements
	Attributes of the elements are predefined	Element attributes are variable
Interactions/relations	Few interactions	Many interactions
	Linear interactions	Non-linear interactions
	Elements are loosely coupled	Elements are strongly coupled
	No feedback loops	Feedback loops
	Simple relations	Multiplicity of relations
Subsystems	Few, simple subsystems	Nested, complex subsystems
Boundaries	Closed	Open
Time	Static	Dynamic, pattern stability

equal all reverse reactions, so that the state of a system remains stable. However, such a state may only be achieved in closed systems. A more moderate concept, stability, thus has been applied to highlight the absence of excessive fluctuations of outcomes. In this sense, outcomes of systems remain in a defined range of parameters. However, these concepts are more important for engineering and the physical world. Ecosystem resource has shown that outcomes may vary considerably, and, if they vary, radical shifts may occur not only due to external shocks but as a normal condition (consider summer and winter aspects of ecosystems in the North or the dry season/rainy seasons in the South). For the analysis of such systems, the concept of resilience has been widely adopted. It is defined as the capacity of an (eco)system to respond to a perturbation or disturbance by resisting damage and recovering quickly (Schiere et al. 2004).

Table 4.4 presents selected opposing characteristics in a simplified way. To make this distinction operational, qualities such as ‘small’ or ‘large’ number or ‘few’ or ‘many’ interactions would need quantification. The more complex systems, the more direct interventions will induce side effects, and the less they are likely to succeed.

Finally, one debate connected with systems approaches is that about the ontological status of a system. There is a position that systems are ‘real’. Thus, a system is understood as existing in the real world; it has ontological status, i.e. exists independent from an observer. The alternative viewpoint is that systems are analytical constructions by the observer. The elements, relations and boundaries of the system are defined by the observer, who has a certain interest in the analysis. Thus, systems can be considered as systems of interests. Science or any other societal community define system perspectives to analyse certain types of problems. In this sense, systems are socially constructed entities (by a group rather than by an individual).

For example, from a biological perspective, it seems at a glance self-evident that the human is defined by the boundaries of the body. However, the body is settled by microbes that may be both dangerous (e.g. viruses) and helpful (e.g. millions of bacteria that support our digestion) but are inside of our body. Such a definition also excludes the fact that we rarely meet naked humans. So, does the clothing that definitely is functional under certain climatic conditions belong to a 'real definition' of being human? From a psychological viewpoint, a definition of being human includes the concept of personality that comprises its cognitive abilities, the character and patterns of behaviour. According to systems thinking, human culture can be understood as an emergent phenomenon that is structurally coupled to the biophysical world (Fischer-Kowalski and Weisz 1999). In the field of socio-environmental studies, the interfaces of human–nature relations have become particularly important. Frameworks to analyse socioecological systems include entities such as nature objects, materials, etc. as well as humans and social systems (cf. Sect. 4.3.4).

4.3.3 Systems in Social Sciences

So far, most research for the bioeconomy is in natural and engineering sciences. However, as a research approach that fundamentally aims at changing societal phenomena and conditions (transformation), transdisciplinary research projects are undertaken to change perceptions, knowledge and behaviour of human beings, thus targeting social systems. Moreover, transdisciplinary research projects themselves are social systems, in which groups of individuals communicate in order create new knowledges and to solve complex socioecological and sociotechnical problems (cf. excursus box in this section). Therefore, we introduce two approaches in social sciences, which have applied systems thinking to the analysis of societal problems.

Social Systems as Action Situations

The American Sociologist Talcott Parsons (1902–1979) has introduced systems thinking to sociological analysis (Parsons 1991[1952]). His concern was the analysis of social action. An action is a special type of behaviour that is related to some subjective meaning or intention. Even further, a social action refers to an 'act' which considers the actions and reactions of other individuals. Thus, according to Parsons, the basic elements of a system are 'acts'. An act requires an actor, an end/outcome, a future state of affairs towards which the process of action is oriented and an action situation, which is defined by 'conditions' of action, and actors' 'means', and that allows alternatives or choices. The latter implies that actors' individual orientations are relevant. Actions are usually not isolated events but must be seen in relation to the actions of other individuals. Thus, a 'social system is a system of processes of interaction between actors, it is the structure of the relations between the actors as involved in the interactive process which is essentially the structure of the social system. The system is a network of such relationships' (Parsons 1991[1952], p. 15).

One important point is that social systems develop stable patterns that are rather independent from the individual actors. Through stable patterns emerging from repeated interactions, rules or norms evolve. In more complex social systems, such norms become generalised, appear as collectively shared knowledge and form complex normative structures rather independent from individuals. Thus, social systems are emergent phenomena, which are constituted by norms, roles and institutions. From the perspective of an individual, the social systems appear as given structures. Actors will orient their actions not only towards action outcomes, as utilitarian (economic) theories suggest, but actions will also follow a normative orientation taking third-party actions and expectations into account. Parsons thus distinguishes motivational orientations that refer to needs and benefits of individuals and normative orientations.

Since there are many possible action situations, actors face the problem to interpret situations, to know, which rules to apply. Therefore, actors must share knowledge and understand signs and symbols, which help to identify the nature and the meaning of situations. These shared knowledge and beliefs and the expressive symbols together form the cultural system. Thus, values, beliefs and symbols must be considered in the analysis of social action situations. Referring to our former discussion, one could say that the cultural system is the basis for information flows and communication process in social systems.

Like the social system, the cultural system provides comparatively abstract structures that from the perspective of the individual may appear as given. While social structures provide institutions, Parsons calls cultural structures of symbolic signification generalised media of interaction. The prototype and most highly developed example of generalised media of social interaction is language. Parsons argues that social action situations can be seen as (action) systems, in which the personal, the social and the cultural systems are tied together and interpenetrate each other. At a later stage, he added the biological organism as a fourth system. All systems shape action situations by providing orientations (motivations, normative expectations, values, instincts) as well as structures (abilities/resources, rules, media, physical conditions).

Social Systems as Communication Situations
While Parsons developed his systems theory starting from the analysis of social action situations, the German sociologist and systems thinker Niklas Luhmann (1927–1998) has shifted the perspective to the analysis of the reproduction of social systems (Luhmann 2013). One could say, while Parsons is focussing on the single acts and social organisations at a given point in time, Luhmann is interested in the perpetuation and continuation of social processes in the flow of time. Central to his analysis is the connectivity of events. Rather than to ask how systems shape actions, he asks how systems emerge out of individual acts. Thus, his concern is less about the person that acts but more about the other actors that observe, interpret the act and may react or do not react. Accordingly, the central element of systems is not action but communication.

Communication does not necessarily imply that observers have to respond to the initial ‘actor’ directly. For instance, if a player of your favourite football team scores, thousands of spectators will shout; some might hug their neighbour, the goal will be discussed at homes, in the media and your work place; betters will lose or win; and football fans might engage in violent disputes. Thus, an initial act may initiate further, rather diverse activities and outcomes. But how are these activities connected? The answer is shared meaning. All the diverse reactions and following communications and activities require that actors understand the meaning of the goal (even it might be difficult to explain it). Thus, social systems are ‘systems of meaning’.

Luhmann’s concept of social system deviates from Parsons’ model in another important regard. It focusses on the separation of system and environment and emphasises the concept of autopoiesis. Communication is the operation that reproduces specific social systems. Social systems are a continuous flow of related, meaningful communication. Communication creates connected communication, or communication ‘produces’ new communication. In this sense, social systems are autopoietic, since system elements reproduce its elements. The boundaries of a social system are not physical but are produced and reproduced in a communication situation itself. The evaluation criteria are thus moving away from outcomes and stability towards boundary maintenance and resilience. Meaning can be understood as mechanism to select communication and to define criteria to further maintain, continue and reproduce it. Alternatively, one could say that systems refer to a specific rationale or internal logic where communication requires knowledge about the meaning of a communication as well as communication rules. The reproduction of meaning through communication also requires that meaning must be recognisable. For instance, academic disciplines are subsystems of the academic system, since they share a common rationality of science (the difference between true/not true), but have established different research focusses, methodologies, specialist languages and forms of communication.

For Luhmann, communication media are particularly important, and he distinguishes between circulation media and symbolically generalised communication media. Circulation media (oral speech, writing, modern telecommunication, etc.) define the form of communication. The most important aspects of circulation media are the boundedness or separation of communication from time and space and therewith the actors, which can be included in a communication system. Symbolically generalised communication media (SGCM) or success media are important to motivate actors to engage in communications, particularly when these are connected with partly negative consequences. SGCM are binary coded which allows a binary distinction between systems. The main social systems are the political system (binary code power/no-power), economic system (money/no money), science (truth/false) and law (legal/illegal).

Box 4.6 Transdisciplinary Research as a Communicative Interaction System

The following example will help to explain Luhmann's understanding of social system: A transdisciplinary research project on a bioeconomy-related issue brings people together from different 'backgrounds' (academy, businesses, policy, etc.). Such backgrounds may be understood as different social systems, which follow different rationales. Academics seek for truth (according to their disciplinary standards), business people will look at issues assessing implications for profits and policymakers judge the process from the perspective of maintaining/gaining political power. The transdisciplinary research is not a social system itself but rather an interaction system, in which different systems overlap and constitute a temporary social structure.

The circulation media used are oral communication in meetings, written documents, maps, images or calculations produced by the participants. The use of these media can be very demanding for some, who 'in their worlds' apply different media or media in a different way. Due to the diversity of viewpoints and ways to use media, there is a considerable chance that communication might fail. Project participants may not understand each other and get frustrated or conflicts may evolve.

This interpretation of a transdisciplinary project gives some hints, what kind of issues should be addressed and how results should look like. Firstly, the group has to acknowledge and accept the differences. The process is about understanding the diversity of viewpoints, knowledges, languages and motivations. After the project, everybody will return to his or her own world and must live with the outcomes. Thus, solutions must be designed in ways that they create connectivity between formerly separated worlds, without changing (too much) the worlds (business people will continue to seek for profit, academics for higher reputation and policymakers for voters) (cf. Sect. 4.4).

Summarising, it can be concluded that systems theory is a powerful and extremely productive conceptual approach in the sense that it set manifold impulses for the creation of linkages and the integration of knowledge among various disciplines and groups of professional actors. Hence, systems theory is considered as a key ingredient. Systems-theory-based conceptual frameworks can provide a solid basis to inter- and transdisciplinary research. In the next section, we demonstrate how system concepts are applied in interdisciplinary research practice, making use of two prominent examples.

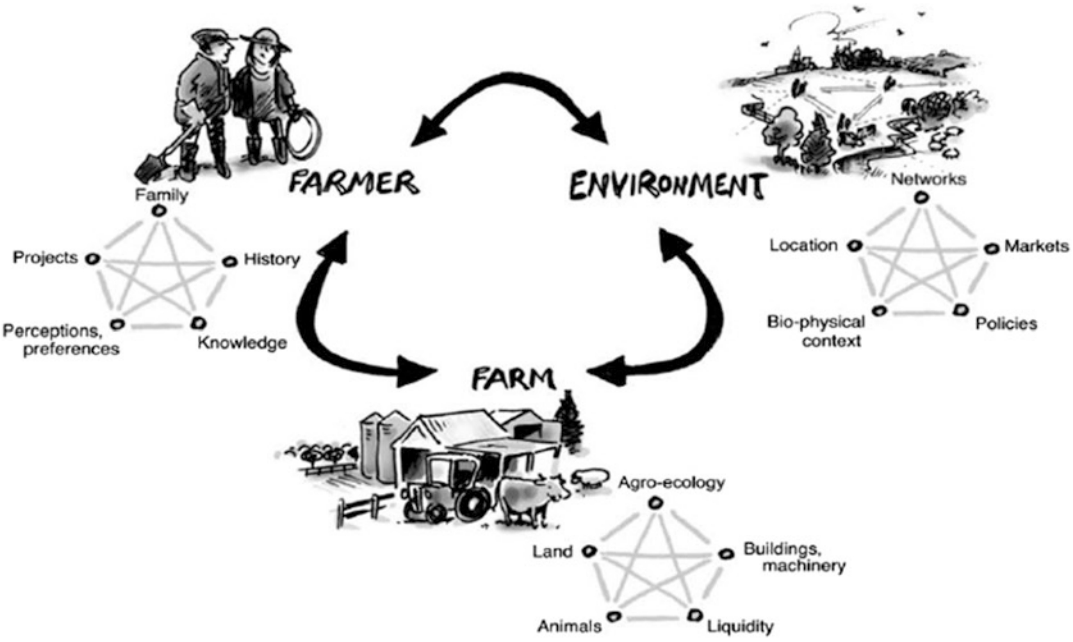

Fig. 4.5 Farming systems approach (Darnhofer et al. 2012, p. 4)

4.3.4 Systems Practice

How system concepts are put into research praxis and provide a conceptual framework for inter- and transdisciplinary research is demonstrated with the help of examples from two scientific communities, the farming system research community and the Ostrom Workshop at the Indiana University of Bloomington.

The Farming Systems Approach

The farming systems approach proposes an analytical framework combined with a methodological approach in the field of agricultural sciences in order to understand the interactions between components of farms or larger agricultural systems. The components may include material objects (e.g. soils, plants, animals, buildings, financial means, etc.) as well as subjective perceptions, values and preferences, i.e. how farmers 'make sense' of their practices. The focus on interactions also emphasises that a farm cannot be studied in isolation, and to understand the farming practices, the farm needs to be understood as embedded in a territory, a locale and a region, with its specific agro-ecological setting, economic opportunities and cultural values (see Fig. 4.5).

The farming systems approach has three core characteristics:

- It uses systems thinking. Situations deemed 'problematic' are understood as emergent phenomena of systems, which cannot be comprehensively addressed by using only a reductionist, analytical approach. It requires thinking about the interconnections between a system's elements, its dynamics and its relation with the environment. It studies boundaries, linkages, synergies and emergent properties. The aim is to understand and take into account interdependencies and dynamics. It means keeping the 'bigger picture' in mind, even when a study focusses on a specific aspect or subsystem.
- It relies on interdisciplinarity. Agronomic sciences (crop production, animal husbandry) are working closely with social sciences at micro- and mesoscale levels (sociology, economics, political sciences, human geography,

landscape planning, etc.). Farming systems research is thus distinct from multidisciplinary research, which can provide complementary insights (e.g. informing the development of new production methods).

- It builds on a participatory approach. Integrating societal actors (farmers, extension agents, civil society organisations, associations, etc.) in research is critical to understand 'real-world' situations, to include the goals of various actors and to appreciate their perception of constraints and opportunities. The participatory approach also allows integrating local and farmers' knowledge with scientific knowledge, thus fuelling reciprocal learning processes (Darnhofer et al. 2012; Janssen 2009).

Farming systems research explicitly strives to join the material–technical dimension and the human dimension of farming. The aim is to take into account both the 'things' and their meaning. This requires understanding the structures and the function of systems simultaneously as 'objective' (things, and their interactions, existing in a context) and as 'subjective' (i.e. relating to the different socially contingent framings).

The Socioecological Systems Approach

A comprehensive understanding of complex human–natural resources' interaction especially at a regional scale and involving collective decision-making and governance issues was the core interest of Elinor and Vincent Ostrom and continues through the 'workshop in political theory and policy analysis' in Indiana University Bloomington which they initiated. This community of researchers uses socioecological systems (SES) approaches as analytical frameworks that support the understanding of environmental degradation problems such as an irrigation-related, regional drop of the water level, the depletion of coastal fish sources or soil erosion related to harmful agricultural practices as complex issues. 'Characteristically, these problems tend to be system problems, where aspects of behaviour are complex and unpredictable and where causes, while at times simple (when finally understood), are always multiple. They are non-linear in nature, cross-scale in time and space, and have an evolutionary character. This is true for both natural and social systems. In fact, they are one system, with critical feedbacks across temporal and spatial scales' (Ostrom 2007, p. 15181).

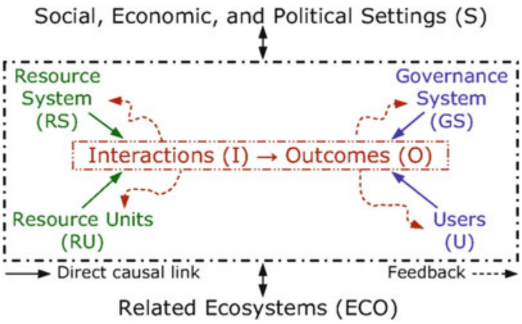

Fig. 4.6 SES (Ostrom 2007, p. 15182)

SES frameworks are built around the analysis of action situations similar to those defined by Parsons (Sect. 4.3.3). They have been developed in order 'to clarify the structure of an SES so we understand the niche involved and how a particular solution may help to improve outcomes or make them worse. Also, solutions may not work the same way over time. As structural variables change, participants need to have ways of learning and adapting to these changes' (Ostrom 2007, p. 15181). Figure 4.6 summarises the influencing factors at a very high level of aggregation into an analytical framework that seeks to define common characteristics of SES and to draw on both social sciences as well as natural sciences.

Similar to the farming systems research framework, the generic SES framework (1) relies on systems thinking appropriate to address complex governance problems and (2) makes use of a range of disciplinary expertise that is interdisciplinary combined. While there is no explicit mention on whether and how participatory methods and stakeholder involvement processes are to be included, it gives very detailed instructions for a multilevel governance understanding and analysis of nested action systems and institutional

Fig. 4.7 Systems practice in interdisciplinary research (Ison 2010, Fig. 4.3.4; adapted from Checkland 1999 and Checkland and Poulter 2006, Fig 4.1.9)

arrangements. By this, the framework is appropriate to substantiate conceptual reflections in transdisciplinary teams addressing societal transition towards sustainable development.

4.3.5 Making Systems Practice Effective

Although uncontestably, developing a systems concept is a key constituent for a comprehensive appraisal and analysis of a perceived challenge, it is only one ingredient to systems practice despite others. As shown in Chap. 11, a broad range of key competences is related to professionals in bioeconomy. Here, we concentrate on those important in the context of research and follow Ison (2012), who emphasises the important role (s) and agency of the researchers engaged as system practitioners. Especially, it is the researcher who makes conceptual and definition choices and determines by these possible outcomes. Ison (2012, p. 145) stresses that (1) reflection about such steps in the making of research and (2) reflexivity about 'why we do what we do' are essential to link the researcher's perspective with the 'situation outside of our selves' (Ison 2012, p. 147). Thus, reflexivity is necessary in order to understand one's role in contributing to or inducing systemic change. Building on these conceptual premises, it becomes obvious that when a researcher develops a system concept appropriate to guide a research, compiling (1) boundary judgements, (2) hierarchies of systems and subsystems, (3) different elements and their relationships, (4) purposes and (5) performance criteria, this is a system composition, which represents 'the person and their system of interest' (Ison 2012, p. 151). Essentially, such systems practice requires an open and curious attitude of the researcher towards the implications and consequences of one's own study interests, epistemological awareness and flexibility in using concepts (Fig. 4.7).

4.4 Inter- and Transdisciplinary Research Practice

When outlining the principal characteristics of inter- and transdisciplinary research practice in bioeconomy, we emphasise commonalities more than differences of the two approaches. These common components thus comprise the integrative design of the research, the team collaboration of the involved actors, the joint conception of the research problem and the necessity of integrating and synthetising knowledge from various disciplines and sources (Jahn et al.

2012; Zscheischler and Rogga 2015). The distinction mainly consists in the professional orientation of the involved actors: in the case of interdisciplinarity, all actors have a professional background in academia, and scientific interests dominate, whereas in the case of transdisciplinarity, stakeholders and actor groups also partake, and a range of diverse outcomes are expected, including those of practical value for real-life questions (cf. Sect. 4.1). Differences in interests and impacts resulting for the researchers in particular are addressed in Sect. 4.5. Here, we present essential principals and steps of transdisciplinary research practice as structured by Lang et al. (2012) in three main phases (Fig. 4.8):

- The problem framing and team building phase
- The co-creation of solution-oriented transferable knowledge phase
- The (re)integration and application of created knowledge phase

4.4.1 The Problem Framing and Team Building Phase

By its very definition, inter- and transdisciplinary research starts with the perception of a (somehow) complex real-life problem (Sect. 4.1.2). We propose as example the bioeconomy-related question whether and under what conditions agriculture provides raw materials for the construction sector. The framing of such a problem and the composition of a team that engages in inter- or transdisciplinary research on this behalf is mutually interwoven: so, a perceived problem may constitute the starting point for the composition of a team which then will together specify and define this problem with more details. For

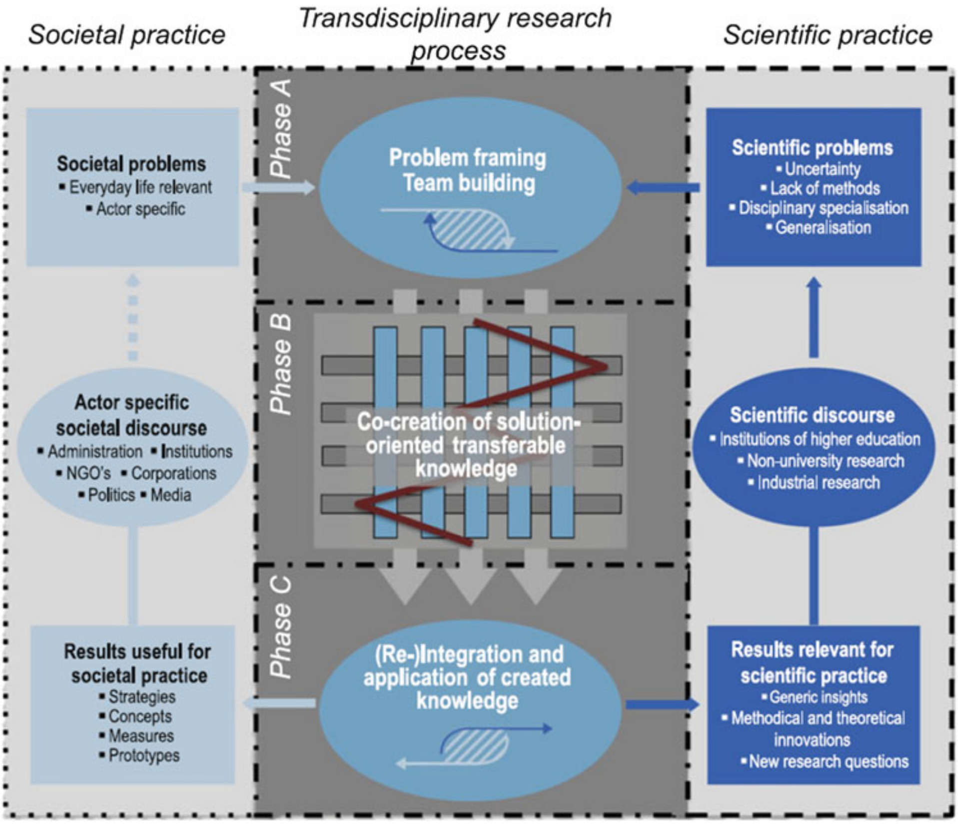

Fig. 4.8 Conceptual model of an ideal–typical transdisciplinary research process (Lang et al. 2012, p. 28)

example, if the perceived challenge is located in the agricultural production sphere predominantly, then agronomists and farm economists might be the first ones to be involved but also farmers. If in contrast, the perceived challenge is located in the technological procedure of integrating new materials into known construction processes, construction engineers and material processing experts might be involved at first hand. Next question then could be how the market would react, so that marketing experts and potential consumers would be required. From these short considerations, it becomes evident that a range of actors has to be included in order to obtain a more complete understanding of a problem situation. And consequently, an interdependency is revealed between the actors describing the research problem and the way it is perceived and embedded into cause–effect relations and the expected results and outcomes of the study. Summarising, the very first challenge of inter- and transdisciplinary research is to frame a problem appropriately and to unite a group of scientists (and other actors) whose composition is sufficiently broad and deep in its expertise to generate meaningful answers. In transdisciplinary studies, such a straight problem orientation has proven an effective instrument for successful identification and mobilisation of stakeholders (Knierim 2014).

So, once the problem is—at least initially—encircled and a number of concerned actors identified, the second and consecutive challenge of the first research phase is to set up the team's collaboration and to concretely implement the cooperation. In other words, how to practise a working procedure that allows both individual and group performances, so that the expertise of all actors involved can unfold? What exactly will be studied and how? What will be the responsibilities and tasks of the various actors? How will the results be determined? Clearly, these skills cannot be learned through books or taught in lectures but require a reflexive learning-by-doing approach. One basis for such skills can be a targeted team work training where steps of an action-oriented research process are practised separately and evaluated in mixed teams' settings. This is the case of the UHOH bioeconomy master. Another option for a learning context is to introduce the problem- and project-based learning approach (Barrett 2005; Savery 2006) as a key feature.

Specific to transdisciplinary research is the integration of actors other than scientists. A widely used term for these actors is 'stakeholders'. Stakeholders are persons, groups or collective actors with interests in and/or influence on the addressed issue (see also Sect. 4.2.3). According to this definition, a fundamental stakeholder classification proposes groups according to (1) problem ownership, (2) actors who have interest in outcomes and (3) the actors' ability to act and to influence and shape project outcomes. Thus, stakeholder identification in transdisciplinary research necessitates both an understanding of the research question, so that boundaries of the social and ecological system can be established, and an overview of required resources, rights and capabilities that are necessary to successfully complete the project. It is an iterative process, where stakeholders might be added as the analysis continues. In practice, it is often not possible to identify all concerned stakeholders, and it is necessary to draw a line at some point, based on predetermined and well-defined decision criteria, to stop the selection and recruitment process (Gerster-Bentaya 2015; Grimble and Wellard 1997).

In order to appropriately address practitioners and to understand and assess roles, agencies and power constellations of actors involved, a stakeholder analysis is an essential step (Gerster-Bentaya 2015). With regard to the categorisation of stakeholders, the first question to be addressed is: Who classifies them? In the case of top-down 'analytical categorisations', stakeholders are classified by researchers or experts, while bottom-up 'reconstructive methods' allow the categorisations and parameters in a stakeholder analysis to be defined by the stakeholders themselves. General stakeholder classification criteria may be based on interest and influence, legitimacy and resources and networks or types of activities. The influence–interest (II) matrix is commonly used to categorise stakeholders according to their interest and influence (Fig. 4.9).

Although this II matrix is very intuitive, many analyses fail to identify important stakeholders due to an insufficient clarification of 'interests' and sources of 'influence'. The level of interests is mainly about achieving benefits, but it is also about avoiding burdens. In the constructed case of agricultural raw materials for the construction sector, competing producers, e.g. from forestry would be considered as stakeholders too. Benefit and burden sharing is central to any type of projects. However, benefits and burdens may be direct and immediate or indirect and long term. Also, not all impacts are material. Cultural impacts are usually symbolic and immaterial (e.g. social recognition). Also, interest does not necessarily imply active involvement. Sometimes, actors are not aware of possible costs and benefits or incapable of acting and thus appear to be 'passive' (Nagel 2001). Actors may be able to influence the outcome of a project even if they do not have an interest in project outcomes.

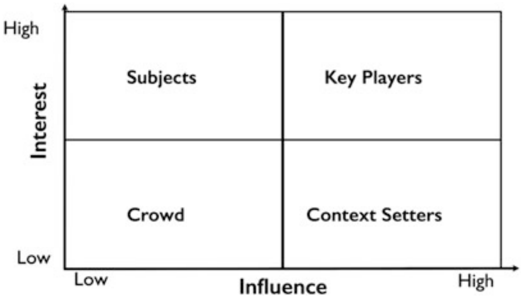

Fig. 4.9 System for classifying stakeholders according to interest and influence (Grimble and Wellard 1997, p. 176)

Influence can be based on multiple sources of power. Legitimacy (of defining rules) is an important source of power. It is often linked to an institutional position with ascribed or acquired rights, e.g. which are formalised by law such as public sector organisations or landowners. Sometimes legitimacy may derive from the task being undertaken or through public consent or from bodies which are considered to be legitimate (e.g. scientific organisations, 'moral' institutions). Resources are knowledge, expertise and capabilities, as well as material resources that allow the key stakeholder to exert a formative influence on the issue and the research objective or to manage and monitor access to these resources (e.g. experts, funding institutions, media). Finally, influence may derive from social connections and the number and quality of relationships to other actors who are under obligation to or dependent on the stakeholder. In Table 4.5, a selection of stakeholders is presented to exemplify the categories 'context setters', 'subjects' and 'key players'.

Table 4.5 Examples of stakeholder types (compilation of the authors)

Context setters	Funding organisations Relevant public administration that is not directly involved in the project Political parties/organisations Representative organisations from relevant sectors (national/international) Research community Governmental agencies
Subjects	Public/target groups Private sector organisations and individuals who have a current or potential future vested interest in an area Neighbourhood Contractors
Key players	Local municipalities/regional administrations Landowner/local businesses that may implement solutions NGOs representing target groups Project team/employees

4.4.2 The Co-creation of Solution-Oriented Transferable Knowledge

Thomas Jahn (2008) has highlighted four integration dimensions of the transdisciplinary research process. The cognitive-epistemic (or knowledge) dimension is the connection and amalgamation of discipline-specific as well as scientific and non-scientific knowledge. The social and organisational dimension means identification and acknowledgement of interests and activities of project partners. Stakeholder analysis is the core tool of this dimension (cf. Sect. 4.4.1). The communicative dimension refers to the heterogeneous communication practices and community-specific terminologies. Participatory measures are central to this dimension. Finally, factual and technical dimension means the integration of partial solutions into a common socially and normatively embedded joint framework.

In the following, we will primarily focus on the communicative dimension, while aspects of the cognitive–epistemic and the factual and technical dimension will be dealt with in the final section.

Integration through communication requires a stakeholder management strategy and plan with a focus on communicative interactions, participation and involvement procedures that also includes an ongoing ‘stakeholder monitoring’. Such a strategy may be built on differentiated forms of involvement of different actors or groups of actors. Stakeholder roles may be classified according to the ways their knowledge is included into the research process or, in other words, along the degree of participation realised (Knierim et al. 2010; Pretty 1995). In the most basic forms of interaction between researchers and other actors, stakeholders may be treated as learners and as (rather passive) recipients of information or knowledge adaptors. Even though transdisciplinary research does not simply intend to transfer knowledge, the group of stakeholders, which are not actively included in the research process, can be quite large. Stakeholders may also be a source of information. Most commonly through interviews and surveys, but also via focus groups or internet forums the viewpoints and experiences of stakeholders, who are otherwise not directly involved, may be collected, and made accessible to the research project. Similarly, stakeholders may be understood as experts of their own lives, livelihoods and experiences and thus have a consulting role. However, more in line with an equal-partner understanding of actors is the involvement of stakeholders as research collaborators in transdisciplinary studies. For instance, they may be included as practice partners, which provide access to their own life world, experiences and knowledge about how to deal with addressed challenges. Even further, stakeholders may be part of the research process contributing to the research by collecting data specifically for the purpose of the research. While research collaboration in its basic forms

Table 4.6 A typology of participation levels in research projects (modified following Pretty 1995, p. 1252)

Type of participation	Characteristics of type
Manipulative participation	Actors inclusion is a pretext, they have no functional role
Passive participation	Actors are considered as ‘learners’, they receive information
Participation by consultation	Actors contribute with information by answering to questions of knowledge, perceptions, opinions, etc. They have no part in decision making on the project’s issues
Participation for material incentives	Actors contribute to research with information and/or labour etc. and receive in turn material advantages and resources
Functional participation	Actors are involved as their competences, resources and/or societal positions are relevant to the aim of the project. They may have an influence in the research design and decision-making processes related to the project’s implementation
Interactive participation	Actors participate as equal partners throughout the research phases, participate in decision-making and share responsibilities and resources

only treats stakeholders as helpers, they may also be involved as creative actors who actively contribute to the development of the research design and interpretations. Irrespective of other types of involvements, a main role of stakeholders in transdisciplinary research projects is that of validators of research findings (cf. Table 4.6).

Most obviously, the practical ways how actors are involved in the joint research and development process of a transdisciplinary study are determinative for the participation realised. Here, Pohl and Hirsch Hadorn (2008a) differentiate between ‘forms of transdisciplinary collaboration’ and ‘means of integration’ based on their experiences as transdisciplinary researchers. The three ways to implement transdisciplinary cooperation are common group learning, deliberation among experts, and integration by a subgroup or individual. While in the first case cooperation happens as a whole group learning process, in the second case, team members with relevant expertise on the components of the problem join their views in form of a deliberative process. In the third case, the act of integration happens through the work of a specific subgroup or an individual who work(s) on the behalf of all (Pohl and Hirsch Hadorn 2008a, p. 115). As ‘means of integration’, the authors propose four ‘classes of tools’: mutual understanding, theoretical concepts, models and products (ibid). Obviously, the question of mutual understanding is one of having a common language, of seeking to avoid too specific, disciplinary terms and of spending time for explanation and listening. Secondly, ‘challenges in integration are about creating or restructuring the meaning of theoretical and conceptual terms to capture what is regarded as relevant in problem identification and framing. Therefore, a second group of integration “tools” comprises theoretical notions [theoretical concepts], which can be developed by (1) transferring concepts between fields, (2) mutually adapting disciplinary concepts and their operationalisation to relate them to each other, or (3) creating new joint bridge concepts that merge disciplinary perspectives’ (ibid, p. 116). As third means of integration, Pohl and Hirsch Hadorn (2008a) propose models—ranging on a continuum from purely quantitative (mathematical) to purely qualitative (descriptive) and they emphasise that ‘(semi-)qualitative system dynamics models are often developed in a collaborative learning process among researchers and other stakeholders, aiming at a shared understanding of the system, its elements and their interactions’. In this regard, we refer to the use of a conceptual frame as presented in the Sect. 4.3.4. Finally, as a fourth means, products are designated, which can be of any kind such as marketable products, knowledge-sharing devices or even institutions, etc.

4.4.3 (Re)integration and Application of Created Knowledge

Interdisciplinary integration raises the issues of the compatibility and connectivity of discipline-specific knowledge. Integration in this sense has to be seen in both directions. On the one hand, a joint definition of ‘study objects’ and scientific models is required, which goes beyond disciplinary perspectives. On the other hand, the new knowledge has also to be transferred back into disciplinary discourses. Similarly, the integration of research results comprises, in one respect, summarising and validation of case specific knowledge with regard to problem under investigation. The evaluative focus from such a perspective is on usability. In another vein, scientists have to, at least partly, retransfer the new knowledge in discipline-specific context. This requires the identification of generalisable, nomothetic parts of knowledge (Lang et al. 2012).

Research outcomes of transdisciplinary research (concepts, methods and products) are evaluated from two different perspectives. Firstly, outcomes are assessed with regard to their usability, their practical relevance. Local actors care for their case and not for any general knowledge. To solve the problem ‘in principle’ would not be acceptable to the audience and the local actors who push the case. Thus, each case has its individual value, because the involved actors are engaged in solving their specific issue, not a general problem! Secondly, scientists search for the more general features of a case and the advancement of scientific knowledge in general. The evaluative question here is ‘are the cases telling us that some nomothetic lessons can be learned despite their situational conditions, or that lessons can be learned because they are embedded in real world contexts?’

As it has been outlined in the earlier sections, the origins of the concept of transdisciplinarity lie in a perceived mismatch between types of knowledge produced in the field of sciences and the demand for problem-solving solutions of society. This mismatch can partly be traced back to the type of (generalised) knowledge generated through sciences and the neglect of actors’ practical, often tacit and context-specific, knowledge. Also, science has increasingly specialised in an escalating number of disciplines. While this specialisation has allowed to catalyse scientific knowledge growth, it has increasingly become a hindrance for the solution of ‘real’-world problems, which usually combine multiple dimensions in a complex manner. Therefore, solutions require the integration of different perspectives.

In practice, it is argued that for solving ‘real’-world problems, three different types of knowledge are needed. They go across scientific disciplines as well as beyond purely scientific knowledge: system, target and transformation knowledge. Systems knowledge can be seen as an understanding of the nature of a problem, the causalities and conditioning context. In the example of bio-based construction materials, knowledge about the production and the processing of these materials would fall in the ‘systems knowledge’ category. Scientific knowledge is particular important for the analysis of problems, while the definition of the problem may derive from science but also from the societal context (lifeworld) itself. However, local actors may also hold and contribute substantial practical knowledge about many aspects of the functioning of the investigated system, e.g. do farmers have practical knowledge about how to produce best on their land and under the given natural and climatic restrictions. Target knowledge is defined as an understanding of actors, their interests, concerns and capacities, and it is developed on the basis of values and norms that guide decision-making. Social research may be used to describe the social sphere, but, again, the actors themselves share a detailed knowledge about its nature. So, the question whether and to what share fossil energy or renewable material-based resources shall be used in construction is one that is solved based on target knowledge. Finally, transformative knowledge provides answers about changing practices and institutions. While the first two types of knowledge are describing the status quo, and may help to define a desired future state, the transformative knowledge is crucial in order to describe a path, the operational steps from the current to a desired state (cf. Fig. 4.1). While the systems and target knowledge form a necessary prerequisite and—at least in principal—can be undertaken in purely disciplinary scientific research manner, transformative knowledge can be understood as the essence of transdisciplinary research, in which multiple forms of scientific/practical and multidisciplinary perspectives are combined and transformed.

4.5 Researchers’ Norms, Values and Agency in Inter- and Transdisciplinary Bioeconomy Research

In Sect. 4.1, the important role of inter- and transdisciplinary research for Western societies’ bioeconomy strategies was outlined. In other words, interactive knowledge creation and innovation development are core concepts related to bioeconomy politics and programs. Thus, scientists’ roles and tasks for the advancement and implementation of bioeconomy may not be underestimated but, on the contrary, need to be explicitly addressed and taken seriously in all consequences. As was argued in Sects. 4.3 and 4.4, the conceptual backgrounds of inter- and transdisciplinary research and its design and implementation are predominantly authored by members of the academic communities. So, what are the norms and values and how do scientists' roles and tasks impact and influence the process and the results of inter- and transdisciplinary research?

In the following, these questions will be discussed referring to two key characteristics of inter- and transdisciplinary research: (1) the way how participation is put into practice and (2) the design and agreement of the conceptual framework.

4.5.1 Researchers Norms, Values and Practices with Regard to Participation

There is empirical evidence that besides classical scientific procedures, researchers in inter- and even more in transdisciplinary research settings frequently adopt multiple roles, such as 'facilitation of the working process', 'mediating among heterogeneous interests', 'consulting practitioners about possible solutions', 'communicating results to decision makers', etc. Whether or not these roles and functions are consciously adopted or ascribed by the environment, they imply that researchers give up their classical distant observatory and reflective attitude and become active in communication and interaction (Knierim et al. 2013). Hereby, values and norms about how effective communication and decision-making take place become relevant and impact on the individual behaviour in communication and interaction settings. For example, Schmid et al. (2016) have shown that scientists with a positive attitude towards transdisciplinary research conducted more interactive events with practitioners than their colleagues who were more sceptical towards transdisciplinary research. One key determinant in this regard is the question whether or not researchers affirm the necessity of and practice an 'open process' attitude in cooperation with other actors. Considering participation as an 'open' or 'emerging process' (Greenwood et al. 1993, p. 179) means that when a research process starts, it is not predetermined to which degree the interactive cooperation among the actors will be realised but that it evolves in the course of the work. Besides, the same authors argue it is the (social science) researchers' capacity and responsibility to behave in a way that a maximum of participation can be reached in such collaboration processes. This requires a high degree of trust in one's own and others capacity to bear and to deal with uncertainty. A second necessary skill is reflexivity expressed as a continuous attention for the procedural part of the research. Here, the will to learn not only about contents from other disciplines but also about methods and procedures for adequate and effective communication and collaboration among various actors is a prerequisite.

Reflexivity and Engagement
A key quality of researchers with responsibility in a transdisciplinary research process is mental openness for perceiving a situation repeatedly anew and to act within this systemic context, on the basis of reflexivity (see Sect. 4.3.3). Engaging for an appropriate degree of participation of all other actors involved constitutes a second necessary ingredient for successful cooperation (see Table 4.6). Both practices require a positive attitude towards communication and interaction in social systems.

Given the fact that scientists are frequently the drivers of transdisciplinary research settings and processes, it is not surprising that they come—intended or unintendedly—in charge of designing and managing the collaboration process. Manifold questions have to be tackled in a transparent way, such as: Who defines the research agenda? Which interests are reflected in the research agenda and which interests are perhaps ignored? A further issue is the accountability of science. If science autonomously defines the research process and its quality criteria, is there any chance for the society to influence the research process and the nature of the outcomes?

Summarising, the expectations on researchers involved in inter- and transdisciplinary studies are uncontestably higher than those on classical researchers: they are more divers with regard to methodological skills and practices at hand, and they imply a certain readiness to reveal and reflect upon one's sociopolitical norms and values that guide actions with societal relevance (Knierim et al. 2013).

4.5.2 Researchers' Roles in the Design and Implementation of Conceptual Ideas and Frameworks

As argued in Sect. 4.4, the success of collaboration among various actors and actor groups throughout a transdisciplinary research process strongly depends on a common understanding of the nature of the problem studied and the appropriate concepts that guide the structuring of the problem and related solutions (cf. - Chap. 11). Hence, there is a process of conceptualisation which is (at least) guided (if not determined) by the involved scientists: (1) it starts with the development of a general understanding of what 'bioeconomy' is (cf. Sect. 4.1.1) and how the studied problem relates to it, it continues with the judgement for which bioeconomy questions and challenges research resources should be allocated and it concretises even more in the conceptual framework concept that orients an inter- or transdisciplinary research. Throughout these steps, the researcher (s) strongly and more or less explicitly shapes the way bioeconomy research is understood and realised. Thus, researchers are important drivers in the process of the 'institutionalisation of bioeconomy' because they themselves contribute to the creation and stabilisation of institutions as:

- Developers of aims and objectives in bioeconomy-related research
- Knowledge and innovation creators related to bioeconomy
- Facilitators of stakeholders' participation in such research.

Institutions can be defined in various ways. In abstract words, they are 'prescriptions that humans use to organize all forms of repetitive and structured interactions' (Ostrom 2005, p. 3). So, in general, certain social functions are assigned to institutions such as creating stability and reliability among people. The process of creating institutions (institutionalisation) in modern societies is often interpreted as a process of establishing and assigning new rationality criteria to specialised action arenas. In a sociological perspective, the transition to a bio-based economy requires the institutionalisation of, e.g. recycling or of a preference of biomass usage over fossil resources, etc.

Box 4.7 Institutions

A more general definition sees institutions as a set of stabilised social practices/ interactions. This may be an individual morning ritual (breakfast with coffee, cleaning the teeth), an institutionalised social group activity or interaction (e.g. having a joint family breakfast at 7 a.m.), collective structure (the family as a social institution) or even a wider organised social structure (e.g. the educational system).

In a narrow sense, institutions are often defined as the 'rules of the game', thus referring to the normative order of individual practices and social interactions. From this perspective, institutions reduce the social complexity and ease individual choices (routine) but also social interactions, since actors do not have to negotiate all aspects of action situations. The establishment of a normative order requires a process of socialisation, in which actors learn (internalisation) an established normative order. Thus, institutions are related to knowledge in the way that they require actors' knowledge to function, but also offer values, meaning and knowledge to actors about 'why' and 'how to act'. Institutions also require external control and sanctioning (rewards as well as punishment) mechanism (governance).

Through their engagement when developing conceptual frameworks for research in bioeconomy, scientists contribute to this institutionalisation process. For example, when conceiving the invention of 'new' products or production processes, scientists do implicitly or explicitly also cause the emergence of 'property rights' on the result. Three fundamental steps in this process are captured with the terms 'reification' and 'commodification'.

Reification is the process of making something 'real'. Bioeconomy is based on the creation of new 'objects' of interest for society (e.g. new bio-based materials out of existing 'waste', enzymes, DNA, etc.). A prominent example in this regard is DNA: The DNA was always there, but only its recognition and the development of technical tools for its manipulation have transformed DNAs into objects of interest for society. The processes of reification primarily triggered ethical debates: in how far are we morally authorised to transform nature objects, parts of bodies, etc. into parts/materials for human usage? Commodification means transformation of formerly non-traded objects into tradable commodities (e.g. blood, organs, waste). Commodification requires the assignment of property rights to new (property) objects. The concept of bioeconomy is based on an extensive process of commodification of objects (e.g. patenting of DNA code), which were formerly regarded as gifts (organs/blood) or waste (a non-property/'res nullius') and which are now transformed into valuables.

In most cases, the role of individual researchers with respect to the institutionalisation of bioeconomy is by far not that influential as the one s/he has on the degree of interactive participation in the cooperation process. Here, it is the multitude of choices and decisions taken by a certain number of researchers engaged in bioeconomy which results in orientations of objectives, channelling of funds and finally institutionalisation of conceptualisations and research practices. Nevertheless, as there is obviously some definition power and impact on shared understandings on scientists' side, also this part has to be recognised, openly addressed and—where necessary negotiated—in inter- and transdisciplinary research projects.

Summarising, this section showed that researchers' impact on processes, outputs and outcomes of inter- and transdisciplinary research should not be underestimated. On the contrary, it is important to take the various roles, functions and tasks, which arise in the process of participatory cooperation, as serious as possible and to accept and perform or reject (and if necessary delegate) them openly (Knierim et al. 2013) in order to come to meaningful and reliable results that are relevant and appropriate to solving practical problems within the society.

Review Questions

- What is 'a problem'? Why is it important to understand the nature of 'wicked problems' in the context of bioeconomy?
- What is meant by multi-, inter- and transdisciplinary research? What are differences and similarities among these research approaches?
- How do you explain 'a system'? How is this concept used in social and in natural sciences? Why is a system concept a good basis for inter- and transdisciplinary research?
- What are characteristics of inter- or transdisciplinary research processes, which characteristic phases can be detected, which responsibilities result for scientists?

References

Agyris C (2005) Actionable knowledge. In: Knudsen C, Haridimos T (eds) The Oxford handbook of organisation theory. Oxford University Press, Oxford, pp 423–452

Barrett T (2005) Understanding problem-based learning. In: Barrett T, Mac Labhrainn I, Fallon H (eds) Handbook of enquiry & problem based learning. AISHE and CELT, NUI Galway, Galway

Batie SS (2008) Wicked problems and applied economics. American Journal of Agricultural Economics. 90 (5):1176–1191. https://doi.org/10.1111/j.1467-8276.2008.01202.x

Bergmann M, Jahn T, Knobloch T et al (2010) Methoden transdisziplinärer Forschung: Ein Überblick mit Anwendungsbeispielen. Campus Verlag, Frankfurt am Main

Bloch R, Knierim A, Häring AM et al (2016) Increasing the adaptive capacity of organic farming systems in the face of climate change using action research methods. Org Agric 6(2):139–151

BMBF (Federal Ministry of Education and Research of Germany) (2010) National research strategy bioeconomy 2030. Our Route towards a biobased economy. https://www.bmbf.de/pub/National_Research_Strategy_BioEconomy_2030.pdf. Accessed 15 Feb 2017

BMEL (Federal Ministry of Food and Agriculture of Germany) (2014) National policy strategy on bioeconomy. Renewable resources and biotechnological processes as a basis for food, industry and energy. Available from: http://www.bmel.de/SharedDocs/Downloads/EN/Publications/NatPolicyStrategyBioeconomy.pdf?__blob=publicationFile. Accessed 25 Dec 2016

Bonaiuti M (2015) Bio-economics. In: D'Alisa G, Demaria F, Kallis G (eds) Degrowth: a vocabulary for a new era. Routledge/Taylor & Francis Group, New York, pp 25–28

Brand KW (ed) (2000) Nachhaltige Entwicklung und Transdisziplinarität: Besonderheiten, Probleme und Erfordernisse der Nachhaltigkeitsforschung. Analytika-Verlag, Berlin

Castán Broto V, Gislason M, Ehlers MH (2009) Practising interdisciplinarity in the interplay between disciplines: experiences of established researchers. Environ Sci Policy 12(7):922–933. https://doi.org/10.1016/j.envsci.2009.04.005

Checkland PB (1999) Soft systems methodology: a 30 year retrospective. Wiley, Chichester

Checkland PB, Poulter J (2006) Learning for action. A Short definitive account of soft systems methodology and its use for practitioners, teachers and students. Wiley, Chichester

Darnhofer I, Gibbon D, Dedieu B (2012) Farming systems research: an approach to inquiry. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems into the 21st century: the new dynamic. Springer, Dordrecht, pp 3–31

European Commission (2012) Innovating for sustainable growth: a bioeconomy for Europe. Directorate-General for Research and Innovation, the EU. http://bookshop.europa.eu/en/innovating-for-sustainable-growth-pbKI3212262/. Accessed 12 Jan 2016

Fischer-Kowalski M, Weisz H (1999) Society as hybrid between material and symbolic realms. Toward a theoretical framework of society–nature interaction. Adv Hum Ecol 8:215–251

Foucault M (1981) The order of discourse. In: Young RJC (ed) Untying the text: a post-structuralist reader. Routledge/Kegan & Paul, Boston/London, pp 48–78

GAIA (2007) Schwerpunkt Transdisziplinarität. GAIA 16 (1):27–65

Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31:1257–1274

Geertz C (1973) Thick description: toward an interpretive theory of culture. In: The interpretation of cultures: selected essay. Basic Books, New York

Gerster-Bentaya M (2015) Stakeholder analysis. In: Giseke U, Gerster-Bentaya M, Helton F, Kraume M, Scherer D, Spars G, Amraoui F, Adidi A, Berdouz S, Chlaida M, Mansour M, Mdafai M, Helten F (eds) Urban agriculture for growing city regions. Connecting Urban-rural spheres in Casablanca. Routledge, Abingdon

Greenwood DJ, Foote White W, Harkavy I (1993) Participatory action research as a process and as a goal. Hum Relat 46(2):175–192

Grimble R, Wellard K (1997) Stakeholder methodologies in natural recourse management: a review of principles, contexts, experiences and opportunities. Agric Syst 55(2):173–193

Grunwald A, Schmidt JC (2005) Method(olog)ische Fragen der Inter- und Transdisziplinarität. Wege zu einer praxisstützenden Interdisziplinaritätsforschung. Technikfolgenabschätzung – Theorie und Praxis 2 (14):4–16

Hajer MA (1995) The politics of environmental discourse: ecological modernization and the policy process. Clarendon Press, Oxford

Hirsch Hadorn G, Hoffman-Riem H, Biber-Klemm S et al (2008) Handbook of transdisciplinary research. Springer, London

Hoffmann V (2007) Book review on Rogers, E.M. Diffusion of innovations. J Agric Educ Ext 13 (2):147–158

Hoffmann V, Gerster-Bentaya M, Christinck A et al (2009) Handbook: rural extension, Basic issues and concepts, vol 1. Margraf Publishers GmbH, Weikersheim

Huber J (2011) Allgemeine Umweltsoziologie, 2nd completely revised edition. VS Verlag für Sozialwissenschaften, Wiesbaden

Ison R (2010) Systems practice: how to act in a climate-change world. Springer, London

Ison R (2012) Systems practice: making the systems in farming systems research effective. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems into the 21st century: the new dynamic. Springer, Dordrecht, pp 141–157

Jahn T (2008) Transdisziplinarität in der Forschungspraxis. In: Transdisziplinäre Forschung.

Integrative Forschungsprozesse verstehen und bewerten. Campus Verlag, Frankfurt/New York, pp 21–37

Jahn T, Bergmann M, Keil F (2012) Transdisciplinarity: between mainstreaming and marginalization. Ecol Econ 79:1–10

Janssen K (2009) Implicit sociology, interdisciplinarity and systems theories in agricultural science. Sociol Rural 49(2):172–188. https://doi.org/10.1111/j.1467-9523.2009.00486x

Knierim A (2014) Stakeholder involvement for developing adaption innovations in rural areas: examples from Berlin-Brandenburg. In: Prutsch A, McCallum S, Swart RJ (eds) Climate change adaptation manual: lessons learned from European and other industrialised countries. Routledge, Oxfordshire, pp 128–135

Knierim A, Pintar M, Skerratt S et al (2010) The InnoLand approach: experimental research and action in Europe's rural regions. In: Wiggering H, Ende HP, Knierim A, Pintar M (eds) Innovations in European rural landscapes. Springer, Berlin, pp 11–24

Knierim A, Baasch S, Gottschick M (eds) (2013) Partizipation und Klimawandel: Ansprüche, Konzepte und Umsetzung. Oekom, Munich

Knorr-Cetina K (1981) The manufacture of knowledge: an essay on the constructivist and contextual nature of science. Pergamon Press, Oxford

Kuhn TS (2012) The structure of scientific revolutions. 50th Anniversary Edition, 4th edition. University of Chicago Press, Chicago

Lang JD, Wiek A, Bergmann M et al (2012) Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustainable Science 7 (1):25–43

Lockaby BG, Zhang D, McDaniel J et al (2005) Interdisciplinary research at the urban–rural interface: the WestGa project. Urban Ecosyst 8(1):7–21

Long N, Long A (1992) Battlefields of knowledge: the interlocking of theory and practice in social research and development. Routledge, London

Luhmann N (2013) Introduction to systems theory. Polity Press, Cambridge

Messerli B, Messerli P (2008) From local projects in the Alps to global change programmes in The mountains of the world: Milestones in transdisciplinary research. In: Hirsch Hadorn G, Hoffman-Riem H, Biber-Klemm S, Grossenbacher-Mansuy W, Joye D, Pohl C, Wiesmann U, Zemp E (eds) Handbook of transdisciplinary research. Springer, London, pp 43–62

Mittelstraß J (1987) Die Stunde der Interdisziplinarität. In: Kocka J (ed) Interdisziplinarität: Praxis – Herausforderung – Ideologie. Suhrkamp, Frankfurt am Main

Müller K, Toussaint V, Bork HR et al (2002) Nachhaltigkeit und Landschaftsnutzung. Neue Wege kooperativen Handelns, Margraf Verlag, Weikersheim

Nagel UJ (2001) Actor involvement in extension – who actually decides what? In: Hoffmann V (ed) 50 Years of Hohenheim extension studies. Margraf Verlag, Weikersheim, pp 59–65

OECD (Organisation for Economic Co-operation and Development) (1996) The knowledge-based economy. General distribution OECD/GD (96)102, Paris. Available from: https://www.oecd.org/sti/sci-tech/1913021.pdf. Accessed 25 Dec 2016

OECD (Organization for Economic Co-operation and Development) (2009) The bioeconomy to 2030. Designing a policy agenda. http://biotech2030.ru/wpcontent/uploads/docs/int/The%20Bioeconomy%20to%202030_OECD.pdf. Accessed 15 Feb 2017

Ostrom E (2005) Understanding institutional diversity. Princeton University Press, Princeton

Ostrom E (2007) A diagnostic approach for going beyond panaceas. Special feature in going beyond panaceas. Proc Natl Acad Sci 104(39):15181–15187

Parsons T (1991) The social system. With a new preface by Bryan S. Turner. Routledge, London

Podestá GP, Natenzon CE, Hidalgo C et al (2013) Interdisciplinary production of knowledge with participation of stakeholders: a case study of a collaborative project on climate variability, human decisions and agricultural ecosystems in the Argentine Pampas. Environ Sci Policy 26:40–48. https://doi.org/10.1016/j.envsci.2012.07.008

Pohl C, Hirsch-Hadorn G (2008a) Methodological challenges of transdisciplinary research. Nat Sci Soc 16:111–121

Pohl C, Hirsch-Hadorn G (2008b) Gestaltung transdisziplinärer Forschung. Sozialwissenschaften und Berufspraxis 31(1):5–22

Pretty JN (1995) Participatory learning for sustainable agriculture. World Dev 23(8):1247–1263

Rosenfield PL (1992) The potential of transdisciplinary research for sustaining and extending linkages between health and social sciences. Soc Sci Med 35:1343–1357

Savery JR (2006) Overview of problem-based learning: definitions and distinctions. Interdiscip J Probl Based Learn 1(1). https://doi.org/10.7771/1541-5015.1002

Schiere JB, Groenland R, Vlug A et al (2004) System thinking in agriculture: an overview. In: Rickert K (ed) Emerging challenges for farming systems – lessons from Australian and Dutch agriculture. Rural Industries Research and Development Corporation, Barton

Schmid JC, Knierim A, Knuth U (2016) Policy-induced innovations networks on climate change adaptation – an ex-post analysis of collaboration success and its influencing factors. Environ Sci Policy 56:67–79

Staffas L, Gustavsson M, McCormick K (2013) Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches. Sustainability 5:2751–2769

TA (Technikfolgenabschätzung – Theorie und Praxis) (2005) Schwerpunktthema – Method(olog)ische Fragen der Inter- und Transdisziplinarität – Wege zu einer praxisstützenden Interdisziplinaritätsforschung 2(14)

Tress G, Tress B, Fry G (2007) Analysis of the barriers to integration in landscape research projects. Land Use Policy 24(2):374–385. https://doi.org/10.1016/j.landusepol.2006.05.001

White House (2012) National bioeconomy blueprint. The USA, Washington. http://www.eesi.org/files/national_bioeconomy_blueprint_april_2012.pdf. Accessed 29 Jan 2017

Zhang D, Shen J (2015) Disciplinary foundations for solving interdisciplinary scientific problems. Int J Sci Educ 37(15):2555–2576

Zscheischler J, Rogga S (2015) Transdisciplinarity in land use science – a review of concepts, empirical findings and current practices. Futures 65:28–44

Part II

Knowledge Base for Biobased Value Chains

5 Biobased Resources and Value Chains

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The bioeconomy uses the resources biomass—originating directly or indirectly from plants, microorganisms or animals—and biological knowledge. A bioeconomist requires knowledge of these resources to be able to plan the resource supply strategy for a bioeconomic activity, to decide which biomass resource is best suited for a specific biobased product chain and how these product chains can be optimized. This chapter describes the characteristics of biomass, important technologies for the designing of these characteristics and the use of data and biological knowledge.

In the second part of the chapter, the concept of biobased value chains and their integration into value nets is addressed. Examples of value chains from food, bioenergy, biomaterial and biochemical applications are used to demonstrate how biomass is integrated into different biobased product chains.

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5.1 Biobased Resources

Christian Zörb and Iris Lewandowski

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Abstract Biobased resources are all resources containing non-fossil, organic carbon, recently (<100 years) derived from living plants, animals, algae, microorganisms or organic waste streams. These are summarized in the term "biomass". This section describes the formation of biomass through the process of photosynthesis. Biobased resources can be classified and characterized according to their origin (e.g. plant, animal) and the sector (agriculture, forestry or waste) in which they are produced. However, for the integration into specific biobased product chains, the most relevant classification of biomass is according to its major component, i.e. starch, sugar, lignocellulose, oil or protein.

There are various options for tailoring biomass properties to user demands. This section considers breeding, green biotechnology and genetic engineering. Synthetic biology uses the tools of genetic engineering and biotechnology to construct completely new functional units or systems with desired properties. The bioeconomy also makes use of biological knowledge, described here as the combination of biological data and its interpretation, often by means of bioinformatics, and the understanding of naturally occurring mechanisms (bionics).

Keywords Biomass; Biomass production; Biobased resources; Biomass use; Plant modification

Learning Objectives

After studying this chapter, you should:

- Understand the process of biomass formation.
- Be able to characterize the resource base of the bioeconomy.

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- Have gained an overview of techniques to design biomass characteristics.
- Understand the concept of biological knowledge.

Biomass Concepts: Different Perspectives

The concept of biomass was introduced in the year 1927 by a publication of the German zoologist Reinhard Demoll (1882–1960): "By biomass we term the quantity of substance in living organisms per unit of surface or volume" (Demoll 1927). Currently, there is no consensus on the general definition of "biomass". A simple and widely used biological definition is "organic matter derived from living, or recently living organisms". This definition may be too broad to be of use as an exact definition for this bioeconomy textbook. Let us focus on different perspectives of what constitutes biomass. Even in ecology, there is no standard definition of biomass. One reason is that biomass changes as organisms interact with each other and with their abiotic environment. Instead, a colourful variety of ecological biomass concepts exists side by side.

A Biologist's Perspective

When considering the term "biomass", a biologist would first think of carbohydrates (e.g. starch, sugar), proteins (e.g. storage proteins from grains), fats and oils (e.g. from oil seeds) and other secondary plant compounds. These substances are secondary metabolites of (plant) tissue, many examples of which can be found in biochemistry textbooks. Primary plant metabolites are compounds produced from the sugars formed by photosynthesis and used for metabolism. By contrast, secondary metabolites are not involved in primary metabolism but are responsible, for example, for the structure and functioning of a cell or organism. Higher plants probably build around 100,000–150,000 different secondary compounds including a diverse range of proteins, sugars, sugar alcohols, vitamins, fats, oils, amino acids, organic acids, nucleic acids, phenolic compounds, odours, pigments, etc. There are many interesting substances within these classes that may be (re) discovered in the bioeconomy as valuable compounds for polymer chemistry or possibly even pharmacy.

A Chemist's Perspective

A chemist would like to see a molecular formula to describe carbohydrates, proteins, fats and other secondary substances showing the chemical elements incorporated by autotrophs (see Fig. 5.1 and section "Photosynthesis") together with an amount of binding energy. However, unfortunately, there is no chemical formula for the general definition of biomass. Physicists or agronomists may calculate the energy value of a certain biomass fraction, from a maize field, for example, using an equation for the heating value of biomass based on its components, but this is also only part of the "what is biomass" story.

A Technologist's Perspective

Technologists see biomass as a source of energy. Therefore, they mostly think of plant-based materials not used for food or feed applications, specifically lignocellulosic biomass. Although technical biomass definitions include only biotic substances that can be used as energy sources, a number of different energy-related biomass terms and definitions still exist. Biomass can be used for energy either directly via combustion to produce heat or indirectly after conversion to various forms of biofuel. There are several methods of converting biomass into biofuels, and these are broadly classified into thermal, chemical and biochemical methods (see Chap. 7 for description of conversion technologies).

Our Definition of Biomass

In Sect. 2.2, biobased resources were defined as all resources containing non-fossil, organic carbon, recently (<100 years) derived from living plants, animals, algae, microorganisms or organic waste streams. These are summarized in the term "biomass". Biomass can be further defined as plant or animal tissue or tissue-based material, microorganisms and the substances produced from them as well as organic molecules (primarily) formed by (photosynthetic) organisms such as carbohydrates (e.g. sugars), proteins, fats, fibre, vitamins and other secondary plant metabolites. This includes edible biomass, such as starch-, sugar- and oil-rich biomass and nonedible lignocellulosic biomass from dedicated crop production, residues and organic wastes. Today, the term “biomass” is most frequently used to refer to organic material utilized for energy production and other nonfood applications such as the production of biogenic materials and chemicals. In the following text, we use a more general definition of biomass, which includes edible as well as nonedible organic material.

5.1.1 Biomass: Its Origin and Characterization

Photosynthesis

Primary production is the process that directly or indirectly supports virtually all life on Earth. Primary biomass is formed by the conversion of carbon dioxide (CO_2) and water through the autotrophic processes of photosynthesis (performed by plants and green algae) and chemosynthesis (performed by some microorganisms). Of these two processes, photosynthesis is the more important. In this process, autotrophic organisms take up CO_2 and water and convert them into carbohydrates with the help of light energy (photons). Thus, light energy is converted into chemical energy through the integration of carbon (C) into the organism’s substance (assimilation). The final products of photosynthesis are C6 sugars (hexoses) and oxygen. Figure 5.1 shows the chemical equation summarizing the complete process.

$$6CO_2 + 6H_2O \underset{Chlorophyll}{\overset{Light}{\rightarrow}} C_6H_{12}O_6 + 6O_2$$

CO_2: carbon dioxide; H_2O: water; $C_6H_{12}O_6$: glucose

Fig. 5.1 Photosynthesis

Glucose is used as a resource in internal plant biochemical processes to form various other molecules through subsequent biochemical reactions, which also incorporate macro- and micronutrient elements into the plant substance. It is estimated that plants can build up around 100,000–150,000 different chemical substances, many of which have not yet been identified but could be interesting in a future bioeconomy. However, not all of these substances are available in sufficiently high quantities or concentrations. Biotechnological methods may make it possible to increase the production and concentration of target molecules by plants and microorganisms.

The first step in biomass formation is the absorption of light by the chlorophyll molecule. Photosynthetic electrons are used for the assimilation of CO_2 and the formation of carbohydrates such as sugars in plant cells. However, not all absorbed energy electrons can be converted to chemical energy in the form of sugars. There are energy losses in the process of photosynthesis, for example, the heat produced by metabolism, and energy consumption through photorespiration and other processes such as the Mehler reaction (for further information, see Taiz et al. 2015). Therefore, the maximal efficiency of photosynthesis is estimated to be about 12%. However, this is a theoretical maximum (Radmer and Kok 1977) that can never be achieved by a growing crop, even if all adverse factors such as disease, predation, inadequate inorganic nutrient supply and suboptimal water supply are mitigated. Wilhelm and Selmar (2011) calculated a conversion efficiency of photosynthetic energy into biomass of only about 8% (Fig. 5.2).

Given the above-mentioned energy losses in biomass formation, it is of vital importance that available biomass is used as efficiently as possible. Here, three approaches for efficient biomass production and use are suggested:

- Focusing on the production of valuable (biochemical) substances by plants and algae. An effective strategy would be the production of valuable organic substances (such as glycolate, omega-3 fatty acids, lutein) by algae.

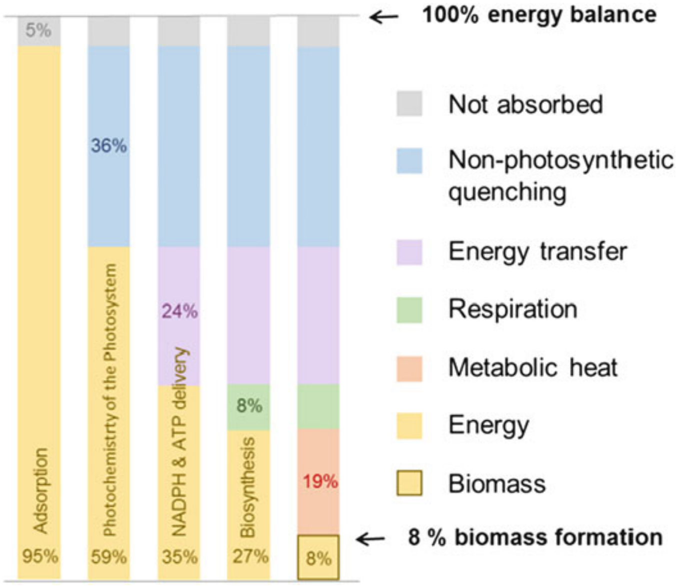


Fig. 5.2 Energy balance of biomass production. Bars represent photosynthetic energy absorbed and the various energy losses by transformation into biomass. Hundred percent is the maximum photosynthetic active energy (based on Wilhelm and Selmar 2011)

Microalgae in particular have a higher photosynthetic efficiency because the light absorption of small algal cells (unicellular algae) is generally better than that of larger algae.

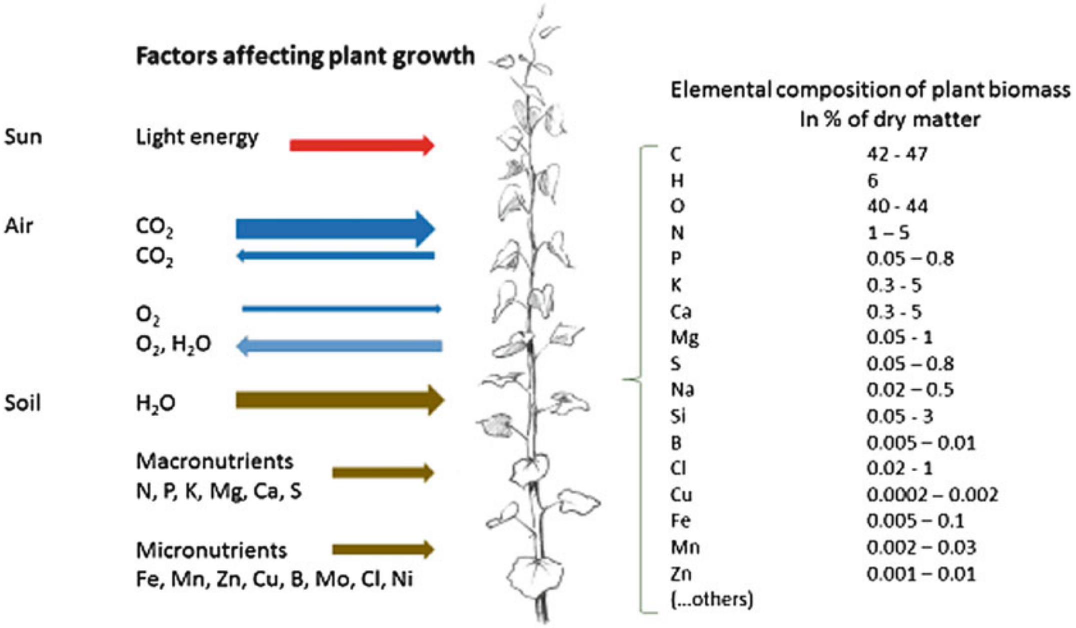
- Supporting the efficiency of crop production through optimal crop management, improved harvest technologies and the avoidance of biomass losses in the supply chain (see Sect. 6.1).
- Applying breeding and biotechnological methods to supply varieties that make optimal use of factors necessary for growth and that are tailored to the production of specific products (e.g. metabolites, proteins) at high concentrations in the biomass.

All biological material (or biomass) is essentially derived from inorganic molecules or ions that are assimilated into the biological tissue of autotrophic (primary) organisms (plants and microorganisms) through photosynthetic or chemosynthetic processes. Organisms that perform primary production are called “autotrophs” because they are self-feeding and use light as an energy source. In the process of photosynthesis, they take up CO_2 and convert it into chemical energy with the help of sunlight. These organisms provide the basis for secondary biological organisms, i.e. heterotrophs. Heterotrophs (animals, humans, fungi, most bacteria) rely on the consumption of either the products of autotrophs or whole autotrophic organisms.

Biomass is formed primarily from carbon (C), oxygen (O) and hydrogen (H) (Fig. 5.1). These are assimilated from air and water. In addition, mineral macronutrients are essential for plant growth and development and thus biomass formation. The main macronutrients necessary for the production of biomass by primary organisms are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S). These elements are also the major components of plant fertilizers, mostly in the form of ammonium, nitrate, urea, phosphate and potassium salts. Further important elements are the so-called plant micronutrients, which are essential but only in very small quantities—mostly at concentrations three orders lower than that of macronutrients. They include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl) and nickel (Ni). Other elements that can be beneficial for plant growth in niche environments are silicon (Si), cobalt (Co), selenium (Se) and sodium (Na) (Fig. 5.3).

Biomass Characterization

Biomass resources can be classified according to their origin, i.e. whether they come from plants, animals or microorganisms. Not only



Elemental composition of plant biomass
In % of dry matter

C	42 - 47
H	6
O	40 - 44
N	1 – 5
P	0.05 – 0.8
K	0.3 - 5
Ca	0.3 - 5
Mg	0.05 - 1
S	0.05 – 0.8
Na	0.02 – 0.5
Si	0.05 - 3
B	0.005 – 0.01
Cl	0.02 - 1
Cu	0.0002 – 0.002
Fe	0.005 – 0.1
Mn	0.002 – 0.03
Zn	0.001 – 0.01
(...others)	

Fig. 5.3 Factors affecting plant growth and elemental composition of plant biomass (adapted from Lewandowski and Wilhelm 2016)

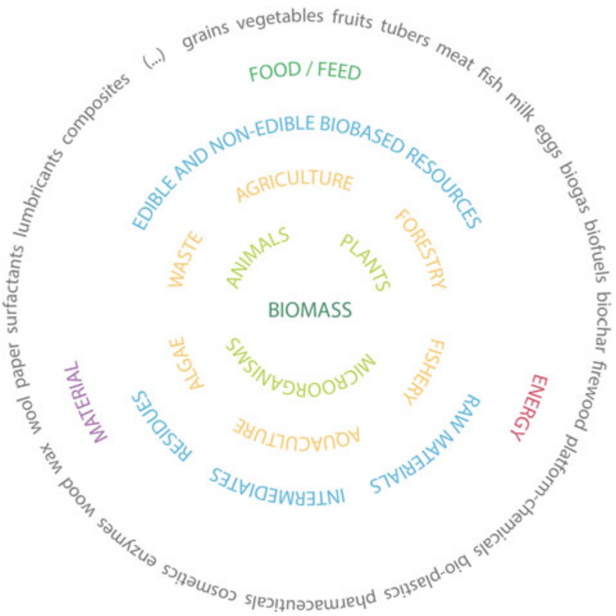


Fig. 5.4 Biobased resources. Plant, animal and microorganism biomass is produced in different primary sectors of the bioeconomy. These biomass resources are processed to food, feed, energy or raw materials. Examples of products used in the bioeconomy are seen in the outer circle

Table 5.1 Classification criteria for biomass resources

Organisms which produce biomass	Sector of biomass production	Major biomass components (molecular formula)
Plants Animals Microorganisms	Agriculture Forestry Fishery and aquaculture Algae and microorganisms Waste	Sugars (e.g. glucose, $C_6H_{12}O_6$) Starch $(C_6H_{10}O_5)_n$ Cellulose $(C_6H_{10}O_5)_n$ Hemicelluloses (e.g. xylose, $C_5H_{10}O_5$) Lignin (coumaryl alcohol, $C_9H_{10}O_2$; coniferyl alcohol, $C_{10}H_{12}O_3$; sinapyl alcohol, $C_{11}H_{14}O_4$) Oils (triglycerides, e.g. oleic acid, $C_{18}H_{34}O_2$) Proteins (amino acids, e.g. alanine, $C_3H_7NO_2$)

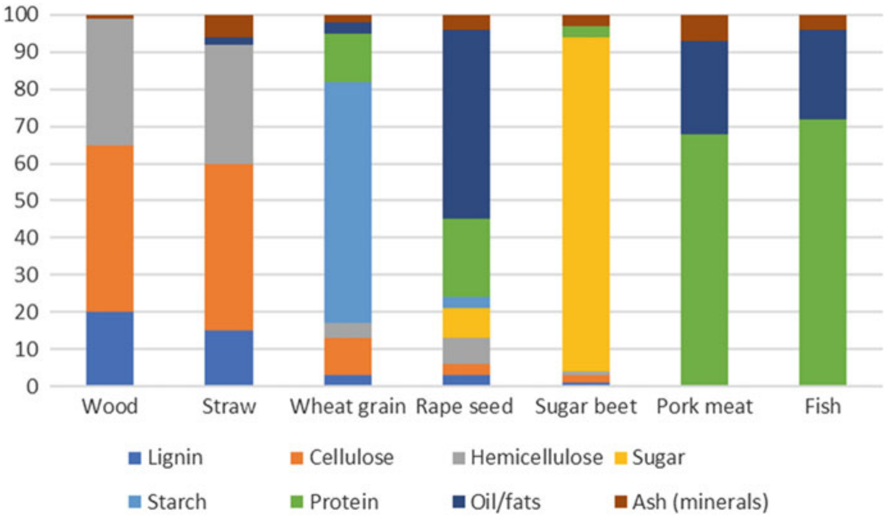


Fig. 5.5 Main components of different biomasses (in % of dry matter)

the requirements for their production (see Sects. 6.1.9, 6.1.10 and 6.4) are different but also the characteristics of their products. This is not only relevant from a processing point of view but also from an ethical point of view, for example, meat is not an "acceptable" biomass for vegetarians.

Biomass resources can also be classified according to the sector in which they are produced, e.g. as agricultural, forestry or waste biomass (Fig. 5.4). The biomass supply chains in each sector vary from a practical point of view. But also from an ethical point of view, it makes a difference whether biomass has been classified as waste or whether it comes from the agricultural sector. The use of waste biomass is generally considered beneficial, whereas agricultural biomass has the primary task of producing food. In the latter case, a careful decision needs to be made on the best use of the biomass to avoid competition with food supply. The energetic use of edible biomass, such as vegetable oil, for the production of biofuels has received particular criticism. For this reason, biomass is also classified into "edible" and "nonedible" in terms of suitability for human consumption.

The most relevant classification of biomass for its integration into specific biobased product chains is according to its major component, i.e. starch, sugar, lignocellulose (lignin + cellulose + hemicellulose), oil or protein (Table 5.1). All of these contain mainly C, H and O. Only proteins, being a combination of different amino acids, also contain N and some contain S (Table 5.1).

Figure 5.5 shows the major components of different biomasses. These vary considerably between lignocellulosic biomasses (such as wood and straw), starch-rich biomasses (e.g. wheat grain), oil-rich biomasses (e.g. rape seed), sugar-rich biomasses (e.g. sugar beet) and protein-rich biomasses (e.g. pig meat and fish).

Finally, biomass can also be characterized according to its physical conditions into "wet" and "dry" or "solid" and "liquid" biomass. The physical properties of biomass determine the requirements for its harvest, transport, storage and processing (see Sect. 7.3). Generally, wet biomass is more perishable than dry biomass. It requires a higher transport effort (because more water is transported) and additional processing before storage, such as drying or ensiling (e.g. maize is ensiled for feed and biogas applications).

Global Biomass Use

Currently, it is estimated that about 11.4 billion tonnes of biomass are produced annually on agricultural land and from forests. Of this, 18% stems from wood, 40% from agricultural production, 30% from pasture and 12% are by-products (FAOSTAT 2014; Raschke and Carus 2012). The largest part of this biomass is comprised of cellulose (5.62 billion tonnes, 49%). Other important biomass feedstocks are sugar/starch (2.63 billion tonnes, 23%), protein (1.23 billion tonnes, 12%) and fat (0.51 billion tonnes, 4%) (FAOSTAT 2014; nova Institut 2015). About three quarters of the total biomass produced by agriculture is used as feed to produce 115, 90 and 60 million tonnes of pig, chicken and cattle meat, respectively, and 640 million litres of milk (Fig. 5.6).

5.1.2 Techniques for Improving or Designing Biomass Characteristics

Breeding

Humans started to cultivate plants as they began to settle about 10,000 years ago. It was beneficial

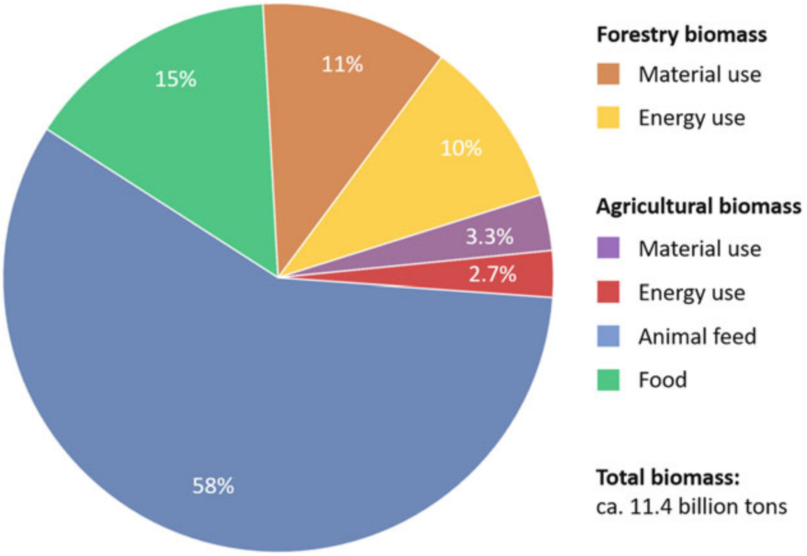


Fig. 5.6 Worldwide use of harvested forestry and agricultural biomass in 2008 (based on Raschke and Carus 2012)

for them to have food stored throughout the whole year, to consume when less or no freshly produced food was available. This enabled them to survive in unfavourable climates where naturally grown plant-based food was only available in a particular season. Early farmers already started breeding wild plants and selecting the genotypes with the best performance in terms of high yield, non-shedding seeds and resistance to biotic and abiotic stress (e.g. drought). They developed many of our most important plants, such as wheat, maize (corn), rape and rice. Today, breeding is still the most important prerequisite for sufficient and sustainable food production.

Breeding is the improvement of crop varieties and animal breeds—in terms of yield, resistance to pests and diseases, fertility, product quality or adaptation to different production conditions—through breeding methods. These are classified as either “conventional” or “genetic engineering” methods. Conventional breeding seeks to provide improved varieties or breeds by selection and directed crossing. Genetic engineering (or genetic modification) uses biotechnological techniques to alter the genome (genetic material) of the organism.

Green Biotechnology

Biotechnology is “any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use” (UN Convention on Biological Diversity, Art. 2). Green biotechnology is the application of such techniques in agricultural processes. An example is the use of genetic engineering methods to design transgenic plants able to grow in particular environments characterized by the presence (or absence) of specific (bio)chemicals.

Genetic Engineering

Genetically modified organisms (GMOs) are organisms that have had their genomes altered, either in a way that does not occur naturally or in a natural but accelerated way. To produce a GMO, specific characteristics can be changed using laboratory-based techniques to delete or alter particular sections of DNA (deoxyribonucleic acid, contains the genetic information, e.g. genes, regulatory elements). An organism’s characteristics can also be changed by introducing new pieces of DNA into its genome. These can originate from the same or another, non-related species. The latter results in a transgenic organism, i.e. one that contains genes from a different species. Breeding progress is usually faster and more specific when biotechnological methods are used.

GM techniques can be applied to crops to modify the chemical structure of polymers such as starch, lignin or other fibres. The modification of proteins or metabolites for use in the chemical industry, building industry or in pharmacy is also possible. The use of plant-based antibodies to human or animal diseases has been applied in practice for two decades. The advantage of using GM crops for pharmaceutical purposes is that the agents can be produced in greenhouses or fermenters, and official regimentation is much lower than for field trials. Most varieties of a number of major crops, including soybean, maize and cotton, commonly grown in the USA, Brazil, China, India or elsewhere, have been genetically modified. However, GM crops are usually not well accepted by the general public, and, in Europe, their production in the field is highly restricted. In addition, GMO production is not permitted in organic agriculture. The recently developed gene-editing method CRISPR/Cas9 used in plant breeding is a biotechnical method for cutting out (knocking out) genes without leaving a trace or for specifically altering or adding genes or gene pieces in order to introduce the desired properties. The status of crop varieties produced by this method is the subject of current discussion. The question arises whether these organisms should still be considered genetically modified if only parts of the genes have been cut out or altered without introducing genetic material from other organisms or if genetic material from other species was only temporarily introduced for intermediate breeding steps (e.g. early flowering in trees) and then removed again.

Breeding and genetic modification can be categorized according to the nature of the conferred traits. Input traits are those that affect crop performance without changing the nature of the harvested product. Examples include resistance to pests, viruses, bacteria, fungi or insects, tolerance to abiotic stresses (e.g. soil-borne metals, salinity, drought, heat) and a higher nutrient use efficiency resulting in higher yields of biomass or target products.

Output traits change the quality of the crop product itself, e.g. by altering the starch, protein, vitamin or oil composition to improve the nutritional value. This may be, for example, through an increase in vitamins, omega-3 fatty acids or antioxidants, a decrease in saturated fats or an improved amino acid balance. Other output-trait-related targets include an enhanced level of essential minerals (Fe, Zn), the elimination of allergenic proteins, improved taste, longer shelf life and the introduction of novel food products. Output traits may also focus on the (small-scale) production of biomass for biopharming, sold at premium price.

5.1.3 Biological Knowledge

The discipline of biology was established around 1800 as the “science of life”. Biological research produces large sets of data on different scales, ranging from genetic information to biodiversity and the interactions between species, landscapes and climates. Biological knowledge is the combination of biological data and the interpretation of its meaning. Traditionally, such data were interpreted by a person; however, today the interpretation of large-scale data sets is only possible with the help of computers due to the sheer volume of data. This is mostly done by bioinformatics—the use of computational and mathematical techniques to store, manage and analyse biological data (Kaminski 2000). A major area of bioinformatic application is the analysis of DNA and protein sequences and structures in order to characterize the linked functions. The term “omics data” is also used to refer to this type of bioinformation. There are data available for genomics, proteomics, metabolomics, ionomics and several other -omics. The term “big data” is also used for large quantities of biological data but can also be applied to other areas than genetic information, such as data for analysing human health and interactions with various factors including nutrition and the environment. Omics data are often used for breeding purposes, e.g. for the identification of genes that code for important traits such as crop resistance to pathogens, and animal health or quality parameters. Big data sets can be used, for example, to describe the pharmacological relevance of particular substances, e.g. those produced by plant cultures, either GM or conventional. This is of great value for a knowledge-driven, biobased economy because it can help to provide practical information for developments in medicinal or food crop production. An example is the use of biobased genomic data for the design of a plant-tissue-based antibody (immune globulin) for the treatment of cancer. For this purpose, the binding specificity of the antibody to its target was calculated from a bioinformatic-based data set (genomic and proteomic data). The designed gene sequence for the antibody was then introduced into tobacco cell culture in fermenters, where the protein (i.e. the antibody) was expressed (for further details, see Ma et al. 2005).

Biological knowledge also includes the understanding of naturally occurring mechanisms (bionics). A prominent example is the so-called lotus effect. This describes the self-cleaning properties of the lotus plant (*Nelumbo nucifera*) that results from the ultrahydrophobicity of its leaves. Technical application of this mechanism is used for paints, coatings, roof tiles, fabrics and other surfaces that can stay dry and clean themselves. Biologization is the integration of such natural concepts into economic development, the application of biological and life science innovations and the development of products and solutions by means of life sciences. Biologization and digitalization (seen in the example of bioinformatics above) are often considered as convergent and potentially synergetic processes.

Synthetic Biology

Synthetic biology goes beyond the application of existing biological mechanisms and knowledge. It uses the tools genetic engineering and biotechnology to construct completely new, not naturally occurring biological functional units or systems with desired properties or remodel existing biological systems for new tasks (Kircher et al. 2017). For example, recent technological advances have enabled scientists to produce new sequences of DNA from scratch. Through the application of modern engineering principles and the use of computers and chemicals, organisms can be designed that are suitable for technical purposes, for example, the direct production of biofuels or precursor chemicals for pharmaceutical drugs. Synthetic biology offers new opportunities in the bioeconomy, e.g. for the supply of products that cannot be produced economically by chemical processes or for which there are no natural synthesis methods (Kircher et al. 2017).

Review Questions

- What are the major resources used in the bioeconomy?
- How can biological knowledge be applied?
- Describe the energy balance of biomass production through the process of photosynthesis.
- Which plant nutrients are important for biomass formation?
- Which input and output traits are relevant for plant modification?

5.2 Biobased Value Chains and Networks

Ralf Kindervater, Ursula Göttert, and
Dominik Patzelt

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Abstract In order to describe bioeconomic activities, the term biobased value chain is often used by policymakers (European Commission, A bioeconomy strategy for Europe. Working with nature for a more sustainable way of living. European Commission, 2012; BMBF 2011), organizations (GBS, Communiqué of the global bioeconomy Summit, 2015) and researchers. In the bioeconomy, value chains are built on biological resources and therefore called "biobased". This chapter addresses the fundamental concept of value chains and investigates unique characteristics of biobased value chains.

Keywords Value chain; Biobased value chain; Value network; Cascading use; Biorefinery

5.2.1 Introduction to Value Chain

There are manifold concepts and notions to describe the relationship and interdependencies among players within an industry sector. For instance, supply chain, (global) value chain, market chain, value web or global commodity chain. While most of these concepts have considerable overlapping meanings and/or can be used interchangeably, in bioeconomy most commonly the term "biobased value chain" is used (Nang'ole et al. 2011; Kaplinsky and Morris 2002).

The first standardized approach to investigate the link between players in agricultural production systems and to visualize their relationship

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through a metaphorical chain was made by the French Institut National de la Recherche Agronomique (INRA) and the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) with their concept of *filiére* (French for thread) in the 1970s. The concept was developed as an analytical tool to study the organization of farmers and processors (Nang'ole et al. 2011).

In the 1980s Michael E. Porter established the term *value chain*. He conceptualized the organization of a firm as a system made up of subsystems, each with inputs, transformation processes and outputs (Porter 1985). Each (sub) system involves the acquisition and consumption of resources, i.e. money, labour, materials, equipment, buildings, land, administration and management (Fig. 5.7).

While Porter's value chain definition puts an emphasis on only *one actor* (the firm), newer conceptions expand the scope of the term to achieve a more holistic picture. This broader conception of the term includes the range of activities and complex interactions of *various actors* (M4P 2008) and is rather related to the concept of *filiére*. In a context of worldwide integration, the term global value chains arose (Kaplinsky und Morris 2002).

With respect to these newer conceptions, Kaplinsky and Morris (2002) define value chains as following:

> The value chain describes the full range of activities which are required to bring a product or service from conception, through the different phases of production (. . .), delivery to final consumers, and final disposal after use.

Following this, a value chain generally starts with the extraction or production of a raw material and the logistics to transport it to the first point of processing. Then the chain continues step by step with each following intermediate product until the final product is reached, marketed, sold to the customer and serviced over its lifetime. The visualization usually follows a left-to-right orientation with each step depicted in an arrow-shaped box.

Raw materials such as crude oil have to undergo a large number of transformation steps before they result in the final (e.g. plastic) product. As such, "complete" value chains would be very long and incomprehensible. To avoid this, value chains are often simplified by grouping activities. This makes it easier to read the value chain but also leads to a loss of detail. In Fig. 5.8 a simplified biobased value chain is shown, including primary production, conversion and market. Features of biobased value chains are discussed in Sect. 5.2.2.

Value chains are often also called "value-added chains". This reflects the fact that, from an economic point of view, there is typically an increase in value with each step applied. The value chain approach allows stakeholders to understand the cost structure and the socioeconomic value of a product in a comprehensive and transparent way.

For additional information about the value-adding process, a value chain may be complemented by a product chain, a process chain and an information flow. Product chains aim to visualize the transformation from the raw material(s) over intermediates to the final product(s). Process chains display the processes which are applied to receive all needed intermediates. Simultaneously, the value-adding activities entail information about economic figures, social indicators and the environmental

Fig. 5.7 The original value chain model of Michael E. Porter (based on Porter 1985)

Fig. 5.8 Simplified biobased value chain

impact. An example for biobased plastics production is shown in Fig. 5.9.

As mentioned above, for reasons of simplicity, the value chain has a linear form. For more complex products, such as cars, machines, buildings and packaging solutions, a simple value chain is not optimal for the depiction of the manufacturing procedure, as many different materials derived from different processes are used. Here, it is better to introduce the concept of “components” and define the manufacture of a complex product as the assembly of several components, with the production of each component being shown in a linear value chain. The complete production process can then be illustrated in a so-called value network (or - value-added network), which integrates multiple value chains. Figure 5.10 shows the example of a value-added network for the manufacture of biobased car parts and biomethane as fuel.

In the bioeconomy, due to the vast applicability of biobased raw materials, value networks can also be used to illustrate and thus gain a better understanding of the production paths in the manufacture of complex goods from a particular renewable raw material, e.g. wood. Forestry wood consists of several base materials, such as cellulose, lignin, hemicellulose and other chemical substances depending on the type of tree. A value network makes it possible to describe the manufacturing of complex products derived from multicomponent raw materials. It also allows side streams of residual components (e.g. lignin in paper production) to be displayed, which may occur at any stage in the production process. Thus, value networks provide a holistic view of the production process of complex goods and can be used to develop production scenarios (see Sect. 9.2) for a sustainable bioeconomy, following a zero-waste strategy and cradle-to-cradle concepts. A detailed understanding of value networks is also essential to gain the necessary information for successful innovation processes, e.g. in the replacement of fossil by renewable resources. Whenever a raw or intermediate material is replaced, the transition to the next value step has to be evaluated and properly planned. Any misfits may cause a break in a value chain, inhibiting the smooth integration of new raw materials into an existing production process.

The value chain approach is related to the competence of system thinking (see Sect. 4.3) and the central idea of life-cycle assessments (see Sect. 8.3). It attempts to portray the impact of a product on its environment and the interdependencies of production systems.

5.2.2 Characteristics of Biobased Value Chains

Bioeconomic concepts focus on the sustainable and efficient use of renewable, biological resources. *Cascading use* is considered to be a central concept of the bioeconomy, and efforts are taken to apply it to biobased value chains (Odegard et al. 2012). Generally, cascading is about optimizing the functional and consecutive use of biomass with respect to present conditions and future alternative applications. By means of efficiency, cascading aims at the maximization of socioeconomic value given the constraint of resource limitation (Haberl and Geissler 2000). However, the term is interpreted in various ways.

Firstly, it could be understood as an efficient use of biomass for different purposes in time. For instance, the use and recycling of paper including different applications is an already established case.

Secondly, cascading may be considered as the prioritization of high (socioeconomic)-value biomass applications. This means that plant biomass

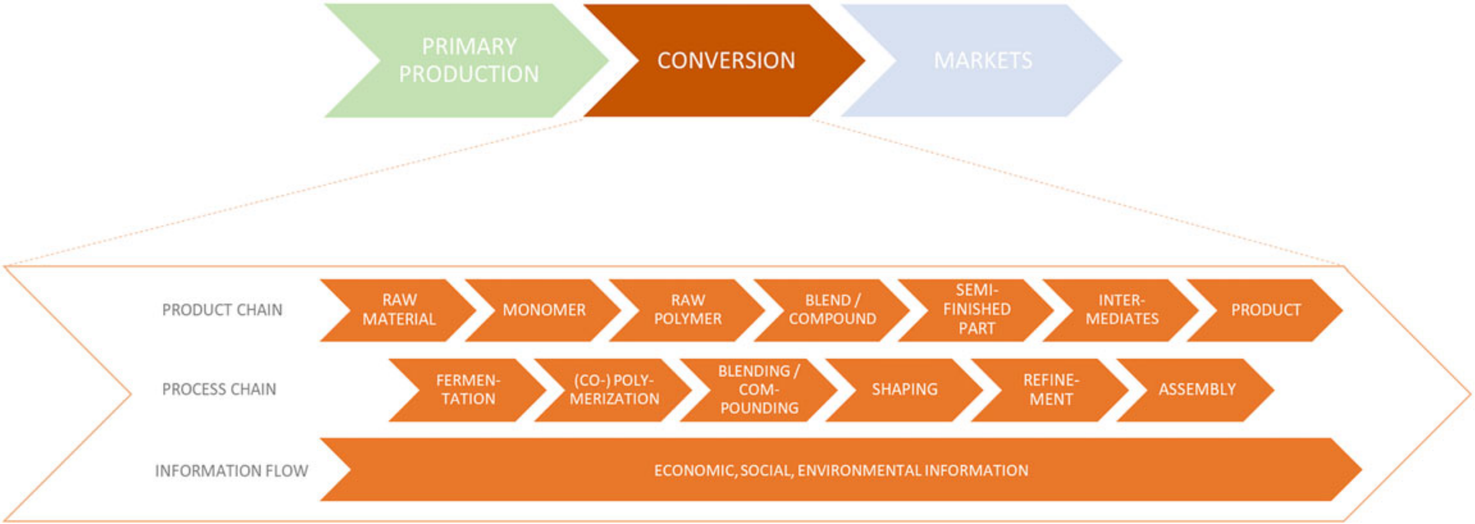

Fig. 5.9 Simplified value chain of the production of biobased plastics, showing the product and process chain, and information flow

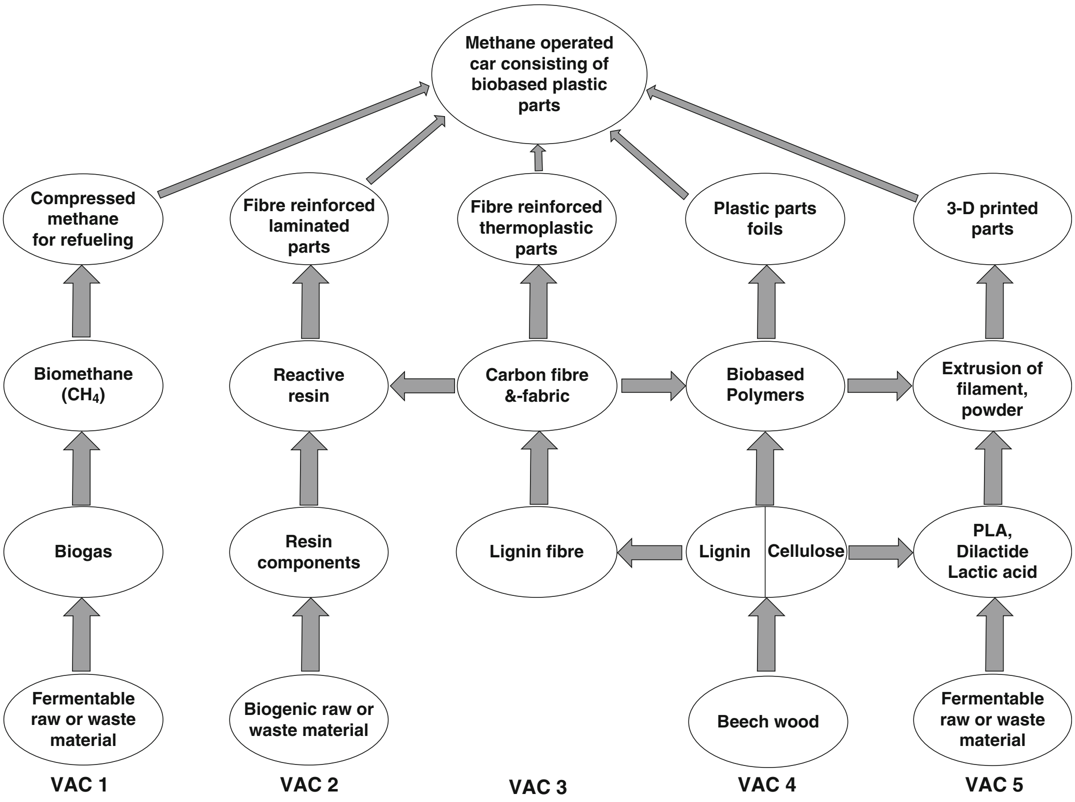

Fig. 5.10 Value network consisting of five value-added chains (VAC) for the manufacture of car parts from biobased plastic and biomethane as fuel (BIOPRO, shown at ACHEMA 2015)

is first used in the food sector to ensure food security or for production of pharmaceuticals in the healthcare industry. Sequentially, residual matter is used for feed and/or material, before by-products are finally exploited for energy generation (see Fig. 5.11).

In addition, also biorefining is seen as an application of the cascading approach. In biorefineries biomass serves as a source for several valuable products or functional components through different conversion processes and is thereby used as efficiently as possible. Although it is not a new concept, it has gained attention in recent years. Biorefinery systems differ according to the (1) flexibility to process various types of feedstock, (2) characteristics of the conversion processes and (3) product diversification (Sadhukhan et al. 2014). Some examples are lignocellulosic feedstock biorefinery, whole crop biorefinery and green biorefineries (which use nature-wet biomass), among others (Kamm et al. 2012). In grass refineries, wet grass is converted in a range of products such as plastics, insulation materials, fertilizers and energy (see Box 5.1).

Box 5.1 Grass Refinery

A grass refinery is an example of green biorefining. In this concept, ideally regionally produced meadow grasses are refined to a range of products including composites, insulation materials, fertilizers and electricity. Following a cradle-to-cradle approach, products can be fully recycled without

(continued)

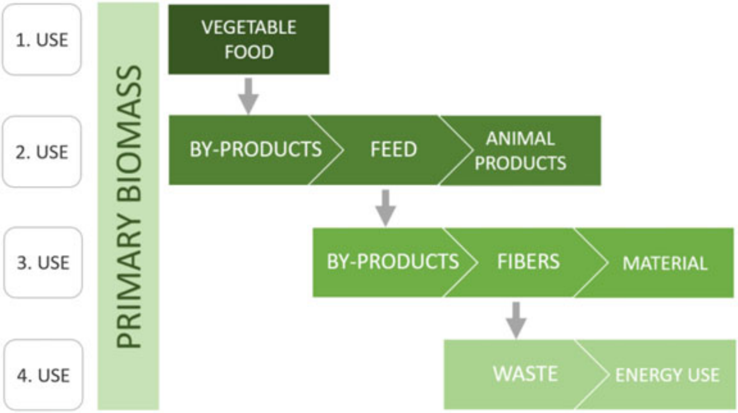

Fig. 5.11 Cascading use of primary biomass

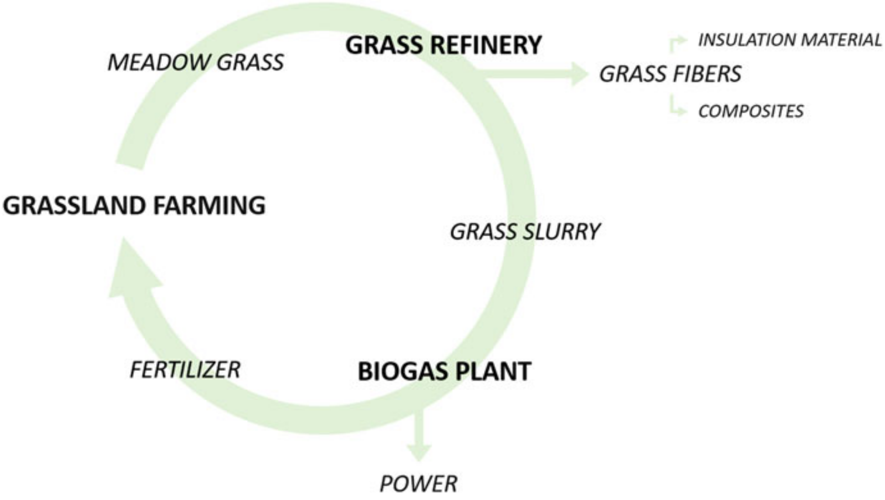

Fig. 5.12 Grass refinery

Box 5.1 (continued)

generation of waste. Within the production process, materials are used as efficiently as possible and in closed loops. For instance, process biogas and heat are used for heating or drying within the refinery (Fig. 5.12).

Obviously, the introduced interpretations of cascading use are not mutually exclusive and should be perceived complementary in order to ensure the most efficient use of biomass.

Furthermore, the concept of cascading is often seen to be complemented by the principle of circularity (Kovacs 2015). In biobased value chains, it addresses the closing of material and energy flows, transforming linear production processes into circular or closed ones, accordingly reducing the generation of waste.

To establish cascading of biological resources on an economy-wide scale, entire biobased value chains have to be formed and eventually integrated in value networks. The development of new biobased value chains requires cooperation between previously unconnected sectors in order to handle the specific characteristics of bioeconomic value chains.

Most of these characteristics are derived from the involvement of primary production of biological resources in the value chains. Especially in forestry or agriculture, production processes are characterized by seasonal patterns, occur decentralized and underlie quality variations due to environmental conditions. In addition, the transportability of biomass is often limited due to its low density and susceptibility to decaying. Accordingly, primary biomass processing has to take place on a regional scale and is characterized by various and divergent players. For instance, in future, so far rarely interacting industrial sectors such as established chemical companies and small-scale farmers will have to cooperate intensively, in order to produce biobased chemicals for an emergent bioeconomy (Berg et al. 2017).

Considering these features, biobased value chains form a strong contrast with continuous fossil-based production processes, and a substantial mind shift will be required in conventional business logics and approaches.

5.2.3 Examples of Value Chains in the Bioeconomy

In the following section, three examples of biobased value chains are given, for food, fuel and fibre production. These simplified value chains consist of components aggregating various process and product steps (see Fig. 5.9).

Before milk is distributed to the final customer (Fig. 5.13), multiple processes and product steps are required. For instance, the value chain component "feed production" includes all steps, such as feed crop production, harvest and storage, needed to supply dairy cows with feed. Similar to rearing of cows (dairy cattle farming) and the milk production itself, these processes can follow a large variety of different methods and techniques. The wide variety of approaches in agricultural production systems depends on various factors described in Sect. 6.1.

The value chain of biogas in Fig. 5.14 comprises four components. The feedstock mix depends on the biogas plant and management. Here, energy crops (e.g. corn or miscanthus) are cultivated, including all process steps from soil preparation to harvest. In the biogas plant, biomass is digested by methane-producing anaerobic microorganism. The following component contains all upgrading processes (e.g. purification), preparing the biogas for the market. The distribution component comprises chains visualising logistic, marketing and service.

The value chain of different paper-based materials is shown in Fig. 5.15. This includes forest management to produce wood and the following wood processing steps, such as fibre separation

Fig. 5.13 Dairy products value chain

Fig. 5.14 Biogas value chain

Fig. 5.15 Paper value chain

(pulping), which is possible by means of different processes. Finally, the separated fibres (pulp) undergo pressing and drying processes in order to remove water from the final paper product.

5.2.4 Using Value Chains and Value Networks in Technology Transfer and Innovation Support Activities

Technology transfer activities typically consist of efforts to commercialize research results in cooperation with individual companies. However, the technology transfer officer in charge of the commercialization of a particular product may be unaware of the complete value chain and the exact position of the company concerned along the chain. In a biobased economy, technology transfer and innovation support professionals need to interconnect all parties involved in a particular value network and learn about their individual needs and motivation to shift from fossil to biobased resources. Interactions between members of a value network are typically based on a vendor/purchaser relationship. This slows down the innovation process and often means that biobased components and products enter the market only if they are price competitive.

If economic developers succeed in addressing the needs of all parties in the value chain, highly innovative research and development projects become feasible. Following this approach, individual requirements (e.g. material quantities and qualities) can be addressed. The authors' experience has shown that the integration of all participants of a value chain into R&D projects can decrease development cycles of biobased products by half.

References

Berg S, Kirchner M, Preschitschek N et al (2017) Die Bioökonomie als Kreislauf- und Verbundsystem. In: Pietzsch J (ed) Bioökonomie für Einsteiger. Springer, Berlin

BMBF (2011) National research strategy bioeconomy 2030. Federal Ministry of Education and Research (BMBF), Berlin

Demoll (1927) Betrachtungen über Produktionsberechnungen. Arch Hydrobiol 18:462

European Commission (2012) A bioeconomy strategy for Europe. Working with nature for a more sustainable way of living. European Commission, Brussels

FAOSTAT (2014) Food and agriculture organization of the United States – Statistics Division. http://faostat.fao.org/

GBS (2015) Communiqué of the global bioeconomy Summit. Making bioeconomy work for sustainable development. http://go.nature.com/293zhq2. Accessed 25 Jun 2017

Haberl H, Geissler S (2000) Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecol Eng 16:111–121. https://doi.org/10.1016/S0925-8574(00)00059-8

Kaminski N (2000) Bioinformatics: a user's perspective. Am J Respir Cell Mol Biol. https://doi.org/10.1165/ajrcmb.23.6.4291

Kamm B, Gruber PR, Kamm M (2012) Biorefineries – industrial processes and products. Ullmann's encyclopedia of industrial chemistry. Wiley-VCH, Weinheim, pp 659–683

Kaplinsky R, Morris M (2002) A handbook for value chain research. Institute of Development Studies, University of Sussex

Kircher M, Bott M, Marienhagen J (2017) Die Bedeutung der Biotechnologie für die Bioökonomie. In: Pietzsch J (ed) Biökonomie für Einsteiger. Springer, Berlin, pp 105–128

Kovacs B (ed) (2015) Sustainable agriculture, forestry and fisheries in the bioeconomy – a challenge for Europe. Standing Committee on Agricultural Research – 4th Foresight Exercise. European Commission, Brussels

Lewandowski I, Wilhelm C (2016) Biomasseentstehung. In: Kaltschmitt M, Hartmann H, Hofbauer H (eds) Energie aus Biomasse: Grundlagen, Techniken und Verfahren. Springer, Berlin, pp 77–123

M4P (2008) Making value chains work better for the poor: a toolbook for practitioners of value chain analysis, Version 3. Making Markets Work Better for the Poor (M4P) Project, UK Department for International Development (DFID). Agricultural Development International, Phnom Penh

Ma JKC, Chikwamba R, Sparrow P et al (2005) Plant-derived pharmaceuticals-the road forward. Trends Plant Sci. https://doi.org/10.1016/j.tplants.2005.10.009

Nang'ole E, Mithöfer D, Franzel S (2011) Review of guidelines and manuals for value chain analysis for agricultural and forest products. Occasional Paper 17. World Agroforestry Centre, Nairobi

Odegard I, Croeze H, Bergsma G (2012) Cascading of biomass: 13 solutions for a sustainable bio-based economy. CE Delft, Delft

Porter ME (1985) Competitive advantage. Creating and sustaining superior performance. The Free Press, New York

Radmer RJ, Kok B (1977) Light conversion efficiency in photosynthesis. In: Trebst A, Avron M (eds) Photosynthesis I: photosynthetic electron transport and photophosphorylation. Springer, Berlin, pp 125–135

Raschke A, Carus M (2012) Industrial material use of biomass basic data for Germany, Europe and the world. Nova-Institute, Hürth

Sadhukhan J, Ng KS, Martinez E (2014) Biorefineries and chemical processes: design, integration and sustainability analysis. Wiley, Chichester. https://doi.org/10.1002/9781118698129

Taiz L, Zeiger E, Moller IM et al (2015) Plant physiology and development, 6th edn. Sinauer Associates, Sunderland

Wilhelm C, Selmar D (2011) Energy dissipation is an essential mechanism to sustain the viability of plants: the physiological limits of improved photosynthesis. J Plant Physiol. https://doi.org/10.1016/j.jplph.2010.07.012

Primary Production

6

Primary production is the synthesis of organic substances by autotrophic organisms from atmospheric or aqueous carbon dioxide (CO_2) (see Sect. 5.1). Primary productivity, which is the rate at which energy is converted into organic substances, depends on internal (genetic) and external (ecophysiological) factors. Figure 6.1 shows that the net primary production of biomass is highest in regions where high temperatures are combined with a good water supply and is totally absent in desert regions without a natural water supply.

Apart from light and water, there are other factors that determine primary productivity, including the availability of plant nutrients, mainly nitrogen (N), potassium (K) and phosphorus (P) (Fig. 5.3). The lack of any one of these factors can hinder biomass growth. Unfavourable site conditions, such as soil contamination or compaction, can also impair biomass growth. Because the process of photosynthesis consumes CO_2, potential biomass productivity increases with increasing atmospheric CO_2 concentrations. However, this additional stimulus cannot be transformed into higher productivity if water supply is limited by drought. That means the highest biomass growth is achieved when all factors affecting growth are at their relative optimum.

Primary productivity also differs depending on the type of plant or organism and its genetics. An example of this can be seen in the productivity of 'C3' and 'C4' plants. Most crops cultivated in temperate climates possess the C3 photosynthetic mechanism, so called because the first product of carbon fixation contains three carbon atoms. Wheat, sugar beet and trees are examples of C3 crops. Carbon fixation in the photosynthesis pathway of C4 crops results in a first product containing four carbon atoms. Sugar cane and other subtropical and tropical crops belong to this group. Under favourable environmental conditions, especially high temperatures, C4 crops are more productive than C3 crops because they possess a more effective biochemical mechanism of fixing CO_2. The genetic component of productivity can be exemplified by the breeding progress achieved in recent decades. It is presumed that the major proportion of yield increases seen in the agricultural crops wheat, rice and maize are the result of intensive breeding. Improved crop management, especially fertilization and crop protection, is the second most important factor driving yield increases.

Actual biomass production very much depends on the kind of land use (see Fig. 6.2). The highest productivity is generally achieved on intensively managed cropland with natural vegetation generally having the lowest.

It is anticipated that a growing bioeconomy will require an increasing supply of biomass. However, not all of the biomass produced can be made available for use. For example, in the

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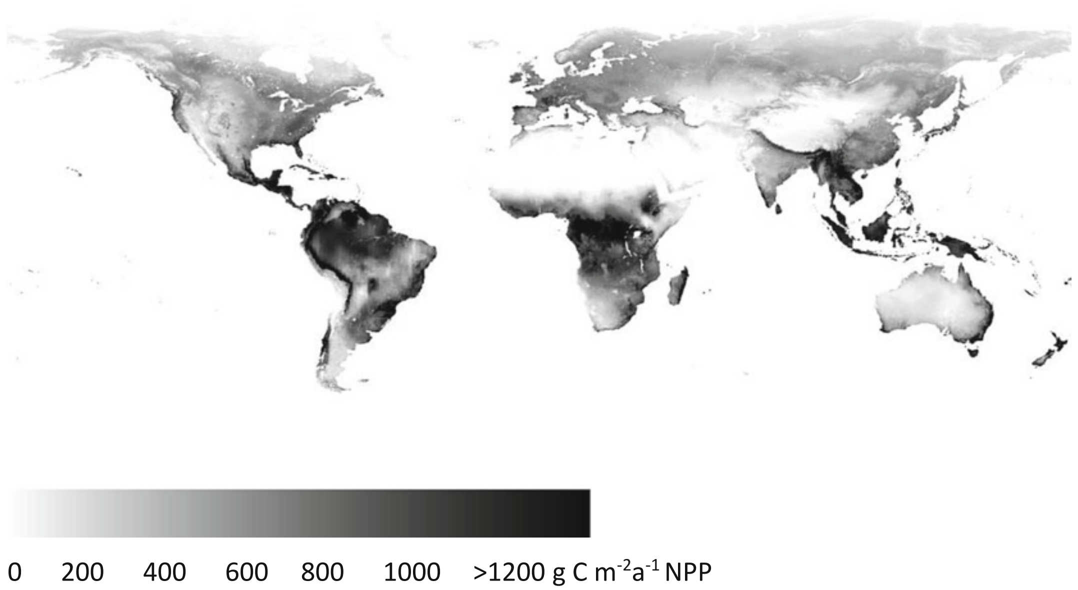


Fig. 6.1 Net primary production (NPP) of biomass, in gram increments of carbon (C) per m^2 and year (from Imhoff et al. 2004)

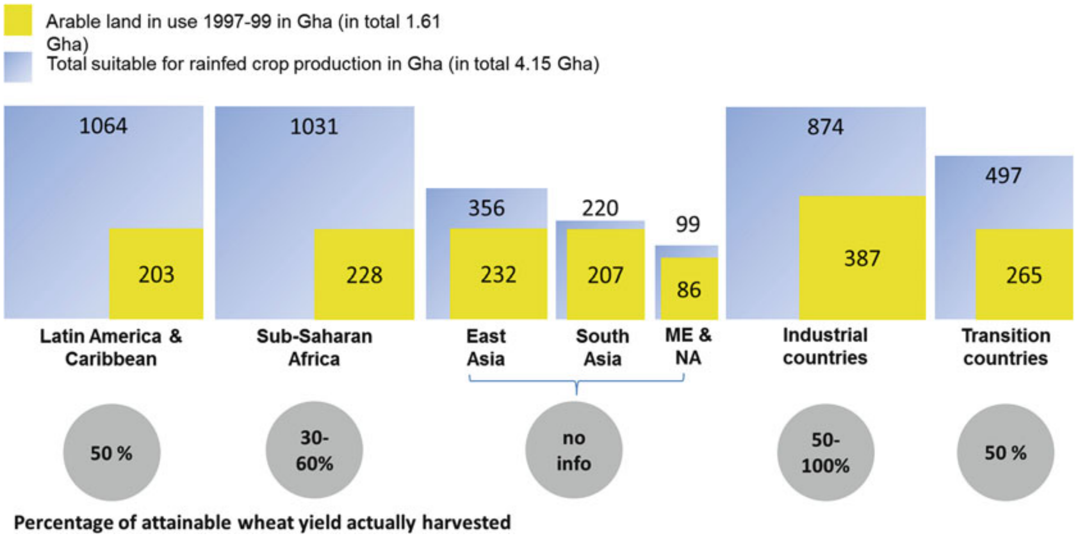


Fig. 6.2 Arable land in use and suitable for rainfed agriculture in different regions of the world. Also shown are the percentages of maximal attainable wheat yield in these regions (based on FAO 2002)

context of bioenergy development, there is an ongoing debate about biomass availability and whether the energetic and material use of biomass is in conflict with food supply.

The question of how much biomass can be sustainably used for human consumption, especially for bioenergy, has led to various biomass potential analyses being performed. Several global biomass potential assessments indicate that an additional biomass potential exists for material or energetic application that could be used without jeopardizing food supply (Dornburg et al. 2010; Piotrowski et al. 2015; Smeets et al. 2007). The methods applied in these studies are generally supply-driven, which means they assess biomass potentials on the basis of resources available for biomass production. These resources are either additional land or land that can be more efficiently used to increase biomass productivity. Other supply-driven studies assess and quantify potential biomass supply from untapped or underutilized resources, such as agricultural and forestry residues, landscape and grassland biomass and other organic wastes.

Today, it is generally agreed upon that biomass potential assessment studies should follow the following rules (see also Dornburg et al. 2010):

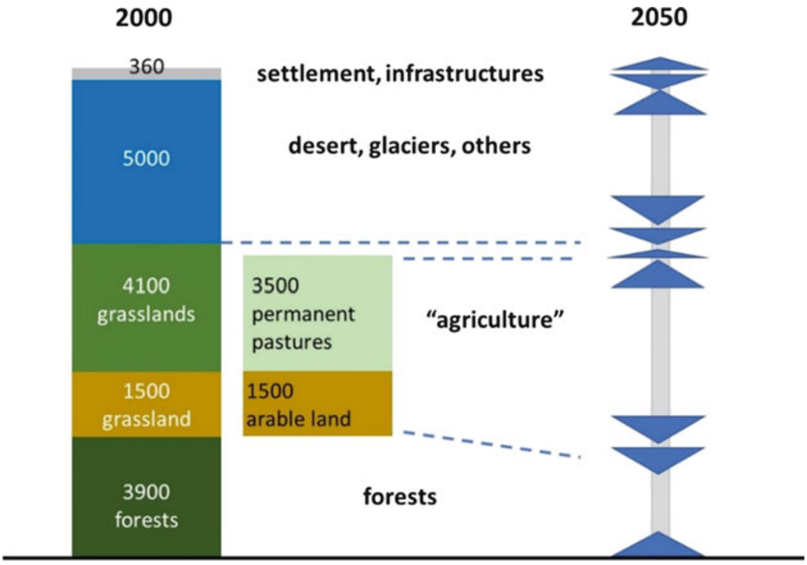
- They should only consider biomass that is not required now or in future for the purpose of food production. A biomass potential should only be indicated as such if it can be generated in addition to products from primary production needed for food or feed purposes.
- Biomass should not be produced in any areas of high conservation value (HCV). The Roundtable on Sustainable Palm Oil (RSPO) defines HCVs as '… biological, ecological, social or cultural values which are considered outstandingly significant or critically important, at the national, regional or global level. All natural habitats possess inherent conservation values, including the presence of rare or endemic species, provision of ecosystem services, sacred sites, or resources harvested by local residents. An HCV is a biological, ecological, social or cultural value of outstanding significance or critical importance' (RSPO 2016).

  Biomass should not be produced where it would lead to the destruction of high-carbon land-use systems, such as peat, natural forest or permanent grasslands.
- Biomass should be generated from the more efficient use of existing agricultural land and sustainable extraction from natural forests or other land-use forms. In addition, more efficient use should be made of existing biomass resources, for example, through more efficient biomass conversion techniques, and of residue streams to increase the biomass potential.

Recent studies have resulted in global biomass potentials ranging from 0 to more than 1100 GJ (Dornburg et al. 2010). The background assumptions applied in the modelling approach form the major determinant of the size of the biomass potential given. There are many factors that determine the sustainably usable biomass potential (Smeets et al. 2007; Dornburg et al. 2010) including:

- The local diet, mainly the kind and amount of meat and dairy products consumed. The biomass potential decreases with an increase in the amount of meat consumed because meat production requires 3–100 times more land than crop production (Smeets et al. 2007).
- The type and efficiency of meat production. The efficiency of meat production, expressed in terms of kg meat produced per kg feed, differs between animals, regions, feeding systems and others (see Sect. 6.1.10, Table 6.5).
- The efficiency of agricultural land use. The actual exploitation of agricultural land, indicated by the proportion of potential yield that is actually harvested, varies widely between countries. It can be close to full exploitation in industrial countries but as low as 30% in African countries (Fig. 6.2). Because biomass potentials are generally assessed by multiplying the respective yield by the amount of land available, the yield assumed is also a major determinant of biomass potentials.
- The amount and quality of land considered available for biomass production. The amount of land that is additionally available for biomass production is currently a topic of ongoing debate. The FAO (2002) estimated an untapped potential of 25 billion ha of agricultural land for rainfed biomass production (see also Fig. 6.2). However, large parts of these

Fig. 6.3 Major types of global land-use cover in Mha and future trends (from UNEP 2014)



areas may be characterized as 'marginal land'. Marginal production conditions can be defined in economic and biophysical terms (Dauber et al. 2012). Biophysical constraints to agricultural production include degradation though erosion, contamination, stoniness, and shallow soils and soils of low fertility. If marginal land is defined as land that does not support economically viable agricultural production, the status of marginality will depend on land-use and biomass prices. A caveat to the use of economically marginal land is the fact that the production of whatever biomasses, be it for food or energetic and material uses, on this land will result in low profit.

- The kind of biomass being considered. Lignocellulosic crops, such as trees and grasses, deliver the highest biomass and energy yields per hectare. Many potential studies (Hoogwijk et al. 2005; Smeets et al. 2007) are based on the assumption that short rotation coppice is grown on land available for biomass production. However, a number of material applications and liquid biofuel production require vegetable oils, sugar or starch. These can only be produced at lower yield levels.

These bio-based resources are produced on a land area of 14,900 million ha (Mha) globally, of which 1500 Mha are arable land, 4100 Mha are permanent grassland and pastures and 3900 Mha are forest (Fig. 6.3).

Agriculture and forestry are the largest primary production sectors, followed by fishery, aquaculture and production of algae and microorganisms. Each of these primary sectors forms an important part of the bioeconomy. They are described in the following sections.

6.1 Agricultural Production

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Abstract Agriculture is the cultivation of crops or the husbandry of livestock in pure or integrated crop/animal production systems for the main purpose of food production, but also for the provision of biomass for material and energetic use. Together with forestry, agricultural production represents the main activity of resource production and supply in the bioeconomy and the major activity delivering food as well as starch, sugar and vegetable oil resources. Today, 33% (about 4900 Mha) of the Earth's land surface is used for agricultural production, providing a living for 2.5 billion people. Agriculture shapes cultural landscapes but, at the same time, is associated with degradation of land and water resources and deterioration of related ecosystem goods and services, is made responsible for biodiversity losses and accounts for 13.5% of global greenhouse gas emissions (IPCC 2006).

In the future bioeconomy, agriculture needs to be performed sustainably. 'Sustainable intensification' aims at shaping agricultural production in such a way that sufficient food and biomass can be produced for a growing population while, at the same time, maintaining ecosystem functions and biodiversity. Sustainable intensification can

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partly be achieved by the development and implementation of innovative production technologies, which allow a more efficient use of natural resources, including land and agricultural inputs. Its implementation requires a knowledge-based approach, in which farmers are made aware of the requirements of sustainable production and trained in the implementation of sustainable agricultural production systems.

The planning of bio-based value chains and sustainable bioeconomic development demands an understanding of the mechanisms of biomass production and supply (as described in this chapter) for the entire global agricultural sector.

Keywords Farming systems; Agricultural production systems; Crop production; Livestock production; Sustainable agriculture

Learning Objectives

After studying this chapter, you will:

- Have gained an overview of global agricultural production
- Be able to explain why different agricultural production systems are adopted in different regions
- Have become acquainted with the technological and logistical preconditions for agricultural production
- Understand the mechanisms of options for sustainable agriculture and intensification

Agriculture is the cultivation of crops and rearing of livestock in pure or integrated crop/livestock systems for the main purpose of food production, but also for the provision of biomass for material and energetic use. Agricultural production systems are determined by the following factors: the production activity (crop, animal or integrated crop/animal production), the organizational form (e.g. small-scale family or large-scale industrial farm), the climatic (e.g. tropical, temperate) and other environmental conditions (e.g. soil properties) and socio-economic factors (e.g. population density, land availability, agrarian policy, farm and market structures). Agricultural production is performed by farming entities within an agroecosystem.

The terms ‘farm’ and ‘agroecosystem’ are defined below. This chapter describes how agricultural production systems are embedded in and determined by climatic, physical, environmental and societal conditions and the interactions (and interconnections) between them (Fig. 6.4). Furthermore, the principles of crop and animal production, their input and management requirements as well as their outputs, mainly in terms of yields, are described.

6.1.1 Farm Types

Farms are the entities that perform agricultural production by either cultivating crops or rearing livestock, or by a mixture of both. Farms are in general characterized according to size; available resources; local options for crop and animal production; organizational model and natural limitations of the surrounding agroecosystem, as a function of climate or soil types; and interaction with other floral and faunal species (Ruthenberg 1980; Seré and Steinfeld 1996; Dixon et al. 2001).

On a global scale, conservative approximations estimate that currently about 570 million farms exist, ranging from small-scale family farms to large-scale agro-industrial managed entities (Lowder et al. 2016). Family farms are still the most common farm type to date, where family members serve as the major work force. About 84% of all farms worldwide are classified as small-scale family or smallholder farms, cultivating on average about 0.5–2 ha of land, with 72% cultivating less than 1 ha and 12% cultivating about 1–2 ha only. These farms provide about 70–80% of agricultural products in Asia and Sub-Saharan Africa (IFAD 2013). Agro-industrial farming is characterized by larger-scale farming types based on production approaches known from industry, i.e. the use of mechanical-technical methods, large capital inputs and high productivity. These farms can be organized as family farms as well as by company-based organizational structures.

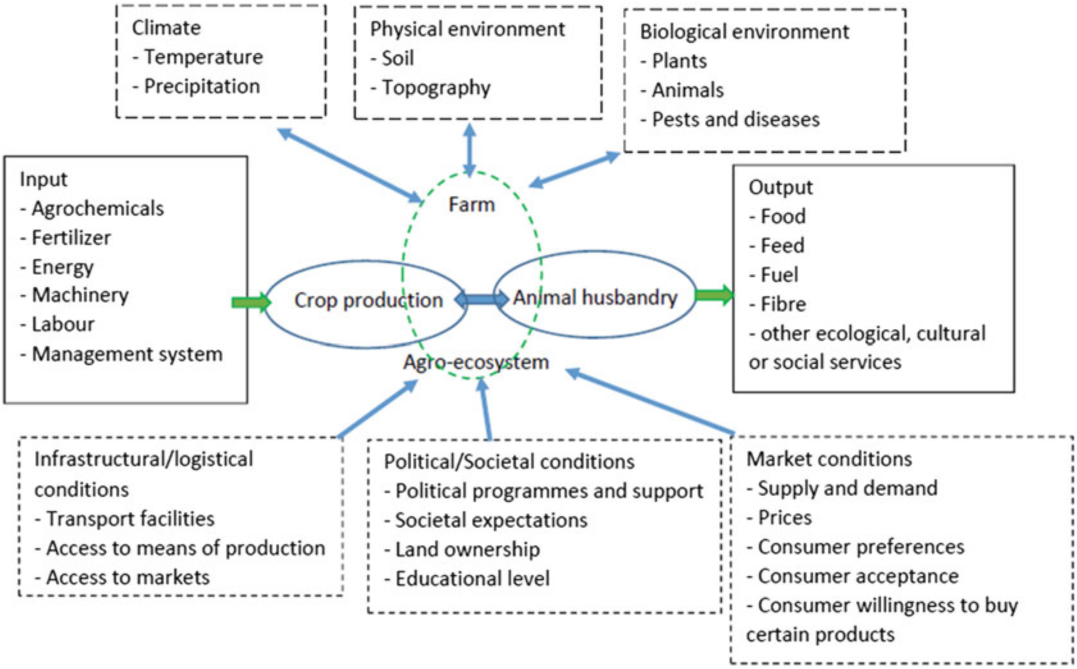

Fig. 6.4 Agricultural production systems and their determinants

Farming Systems

Farming systems can be classified according to the following criteria (Dixon et al. 2001):

- Available natural resource base, including water, land, grazing areas and forest
- Climate, of which altitude is one important determinant
- Landscape composition and topography
- Farm size, tenure and organizational form
- Dominant pattern of farm activities and household livelihoods, including field crops, livestock, trees, aquaculture, hunting and gathering, processing and off-farm activities
- Type of technologies used, determining the intensity of production and integration of crops, livestock and other activities
- Type of crop rotation: natural fallow, ley system, field system, system with perennial crops
- Type of water supply: irrigated or rainfed
- Level of annual and/or perennial crops used
- Cropping pattern: integrated, mixed or separated cropping and animal husbandry
- Degree of commercialization: subsistence, partly commercialized farming (if >50% of the value of produce is used for home consumption) and fully commercialized farming (if >50% of produce is used for sale)

Notably, fruit trees are often defined as perennial crops from an agricultural perspective and are not considered as forestry-based systems. However, exceptions are ‘agroforestry’ types that combine annual cropping with trees and pasture systems (referred to as ‘agrosilvopastoral’) or the combination of tree species and annual crops (referred to as ‘agrosilvicultural’).

Figure 6.5 provides an overview of the global distribution of the most important farming and land-use systems. Given the wide mixture of locally possible farm type systems, only broadly defined farm and land-use types are distinguished. Further information on regional farm-type composition can be found in the online databases and map portals listed at the end of this chapter.

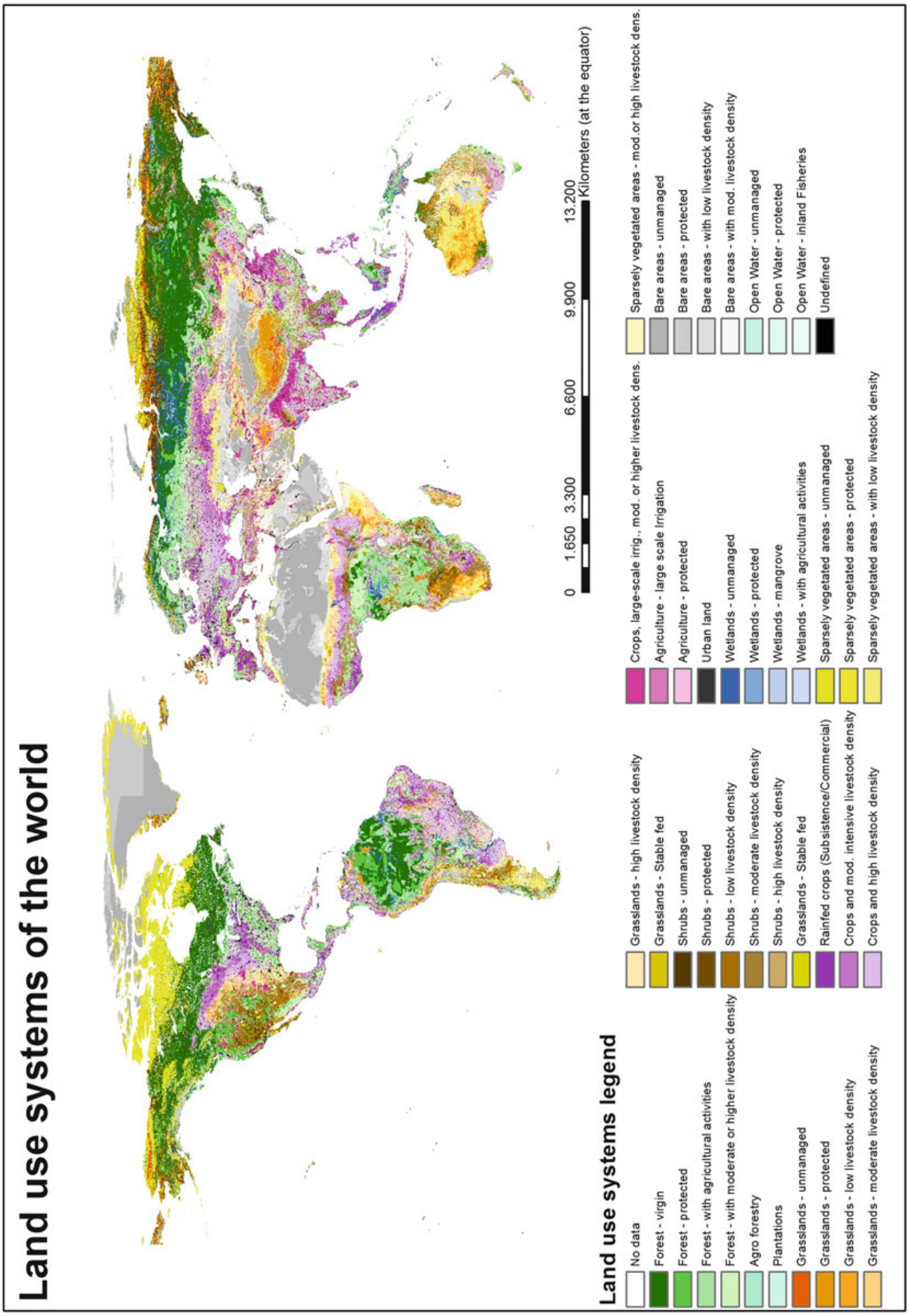

Fig. 6.5 Land use systems of the world (based on Nachtergaele and Petri 2008)

6.1.2 Agroecosystems

An agroecosystem can be defined as the spatial and functional unit of agricultural activities, including the living (=biotic) and nonliving components (=abiotic) involved in that unit as well as their interactions (Martin and Sauerborn 2013). It can also be described as the biological and ecophysiological environment in which agricultural production takes place. In this case, the environment consists of all factors affecting the living conditions of organisms. The different physical and chemical effects that originate from the nonliving environments represent the *abiotic factors*. In terrestrial habitats, they essentially include the properties of the soil (e.g. pH value, texture, carbon content), specific geographic factors (e.g. topography and altitude) and climatic conditions (e.g. precipitation, light and thermal energy, water balance). The effects of the *biotic* factors originate from the organisms and can be exerted on other individuals of the same species (intraspecific), on individuals of a different species (interspecific) or on the abiotic environment (e.g. on specific soil properties). From a species perspective, the biotic environment essentially consists of other species, to which it can have different forms of relationship. These include feeding relationships, competition and mutualism (Gliessman 2015; Martin and Sauerborn 2013).

6.1.3 Climate and Agricultural Production

As described above, the type of crops that can grow on a site mainly depends on the availability of water, the temperature and the light intensity. Agricultural production can therefore be characterized according to the climatic zone, classified according to temperate, subtropical, or tropical conditions. Deserts also sustain some extensive agricultural use through grazing. Climatic zones can also be distinguished according to the original vegetation, e.g. forests. Table 6.1 gives an overview of the main climatic/vegetation zones, their characterization and selected major food and energy crops cultivated.

6.1.4 Physical Environment and Agricultural Production

The physical environment mainly determines options for agricultural production through the topography of the landscape and soil properties.

The topography defines if or how well the land can be accessed and managed mechanically. Soil cultivation, such as ploughing, is difficult on steep slopes, and there is the danger of erosion.

The soil characteristics most relevant for crop production are:

- Organic matter, mainly occurring in the upper A soil horizon (see Fig. 6.6). Organic matter determines the soil's water-holding capacity and can supply plant nutrients.
- Soil texture or grain size distribution (clay: <0.002 mm; silt: 0.002–0.05 mm; sand: 0.05–2 mm), which determines the water-holding capacity and workability of the soil as well as its susceptibility to degradation processes.
- The pH, which is a numeric scale used to specify the acidity ($pH < 7$) or basicity ($pH > 7$) of the soil.
- Soil depth, bulk density and stoniness. These determine the water-holding capacity of the soil, how well it can be treated mechanically, how well plant roots can penetrate it and how much space is available to plant roots for the acquisition of water and nutrients.

Crop production requires the natural resource soil. However, it is directly or indirectly responsible for the largest part of soil degradation processes, such as erosion and compaction. Soil degradation occurs when (a) forests are cleared to make room for agriculture, (b) conversion of land to intensive soil cultivation subjects the organic matter and upper horizons of soil to

Table 6.1 Major agricultural production systems in different climatic regions of the world (based on Davis et al. 2014)

Biome and type of agriculture	Rainfall mm a^{-1}	Temp. °C[a]	Growing days[b]	Potential crops[c]
Subtropical/temperate humid forest Large commercial and smallholder: intensive mixed agriculture, cereals and livestock, tree crops	1000–2500	10–30	270–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, coffee, tea, sugar crops, fruit, vegetables
Temperate broad-leaved forest Large commercial and smallholder: tree crops, forest-based livestock, large-scale cereal and vegetables, cereal/livestock	250–1500	−10–30	90–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, coffee, tea, fruit, vegetables
Temperate coniferous forest Forestry, large commercial and smallholder: cereals/roots, forest-based livestock	100–1500	−30–5	30–180	Cereals[d], roots, tubers
Temperate grassland Large commercial and smallholder: irrigated mixed agriculture, small-scale cereal/livestock, livestock	50–1000	−10–30	0–320	Cereals[d], fibres, oil crops, roots/tubers, sugar crops, fruit, vegetables
Tropical dry forest Large commercial and smallholder: tree crops, rice, cereals/roots	700–2500	15–30	30–300	Cereals[d], fibres, oil crops, tea, roots/tubers, coffee, sugar crops, fruit, vegetables
Tropical grassland Large commercial and smallholder: extensive, commercial ranching or mobile pastoralist systems, livestock	500–2500	15–30	30–300	Cereals[d], fibres, oil crops, tea, roots/tubers, coffee, sugar crops, fruit, vegetables
Tropical humid rainforest Large commercial and smallholder: subsistence agriculture, livestock, tree crop, root crop, partly protected land	1500–5000	25–30	300–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, tea, coffee, sugar crops, fruit, vegetables
Temperate and tropical desert Pastoralism	0–350	10–40	0–30	Succulents

[a] Average annual temperature, based on FAO GeoNetwork (2017a, b)

[b] In general, growth is limited by rainfall (or water availability) in tropical climates and by temperature in temperate climates; species might have evolved locally in order to survive the extremes of climate, some crops may not, leading to zero growing days. Crop selection and management can potentially extend the growing season in other cases

[c] Within a biome, the suitability of a site for a particular crop depends on a range of factors, including altitude, aspect, rainfall and soil type. Crops listed here are examples and are not intended to be a comprehensive list

[d] Cereals crops are generally of the gramineous family and are cultivated to harvest dry grain only (as food or feed) or the total plants (as feed or bioenergy source), e.g. wheat, rice, barley, maize, rye, oat, millet, sorghum, buckwheat, quinoa, fonio, triticale and canary seed

decomposition and runoff and (c) inappropriate soil cultivation methods lead to compaction and erosion.

Degradation of agricultural soils can be prevented or even reversed by appropriate management methods, but in some cases it requires time spans of decades or centuries for full restoration. Conservation and low-tillage farming, where the tilling of soil is kept to a minimum or avoided altogether, strive to preserve soil fertility. There are a range of measures through which the farmer can maintain soil fertility, including (a) maximizing soil coverage by intercropping, crop rotation optimization and mulching, (b) enhancing soil organic matter supply through intercropping and applying crop residues; (c) reducing soil

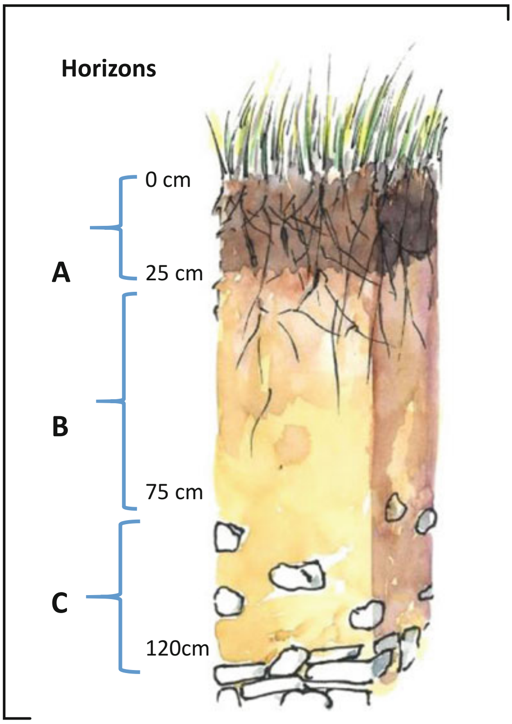

Fig. 6.6 Typical soil profile with different horizons © Ulrich Schmidt

cultivation intensity and growing perennial crops and (d) avoiding erosion by contour farming, i.e. soil cultivation parallel to slopes.

Soil Erosion
Soil erosion is the physical loss of soil caused by water and wind. Rainfall leads to surface runoff, especially when soil has been cultivated, is not covered by vegetation or is on a steep slope. Wind erosion mainly occurs in semiarid and arid regions. In this process, wind picks up solid particles and carries them away. Erosion is a major process in soil degradation.

6.1.5 Biological Environment and Agricultural Production

The biological environment (=biotic factors) refers to the natural occurrence of organisms, such as animals, plants, microorganisms, bacteria and viruses, at a specific site. These can all become constraints in crop production and livestock husbandry, for example, through animals eating the crops; weeds competing with crops for nutrients and water; crops becoming infected with fungal, viral or bacterial diseases; or the competition for and lack of fodder of moderate-to-high quality for animal feeding.

At the same time, agricultural production has a strong impact on biodiversity through the use of pesticides, herbicides and fertilizers, increased landscape homogeneity associated with regional and farm-level specialization and habitat losses when natural vegetation is converted to agricultural land (Hilger and Lewandowski 2015; Lambin et al. 2001).

Mixed cropping systems may lead to higher overall product yields than monocultures. However, if the target is the maximization of the yield of one specific crop, the highest area yield is achieved by monoculture, i.e. the cultivation of a single crop or variety in a field at a time. This is because the management system (i.e. crop protection, fertilization, harvesting time) can be best optimized for a homogenous plant community. Any other plants in the field compete with the crop for growth-promoting factors (water, light and nutrients) and are therefore considered weeds that need to be controlled or eradicated in order to avoid a reduction in crop yield. Animals that feed on the crops are also in conflict with agricultural production, except for natural predators of pests (e.g. birds of prey that catch mice) and beneficial insects (e.g. ladybirds than eat aphids), which help to increase agricultural crop productivity.

There are two concepts which are often discussed in the context of agriculture and maintenance of biodiversity: land sharing and sparing. ‘Sharing’ refers to the attempt to integrate as much biodiversity as possible into the agricultural area, generally at the expense of productivity. ‘Sparing’ aims to divide the land into areas used intensively for agriculture and others left natural and uncultivated. There is scientific evidence that the principle of sparing may be more successful in supporting biodiversity than that of sharing.

6.1.6 Infrastructure and Logistics

Mechanization has greatly enhanced land-use and labour productivity. In modern agricultural production, all processes of soil cultivation, crop establishment, fertilization, crop protection and harvesting are performed mechanically by agricultural machinery specifically optimized for the crop at hand. For this reason, modern agriculture is capital-intensive. In order to secure a reliable and efficient supply chain with low losses, infrastructure and logistics are required for the agricultural production system and storage and transport of the products to the markets. The better the infrastructure and logistic conditions, the lower the supply chain losses. These can reach up to 70% in areas where agricultural infrastructure is poorly developed. The lack of infrastructure (roads, storage facilities) is seen as a major barrier to increasing biomass supply in developing countries. Huge investments would be required to overcome these bottlenecks.

Digitalization is becoming increasingly relevant in contemporary agricultural infrastructure. Modern tractors are equipped with electronic devices, such as GPS (Global Positioning System). In precision farming (see Box 6.4), for example, GPS, electronic sensors and computer programs steer the spatially specific and resource-use-efficient application of agrochemicals.

6.1.7 Political and Societal Conditions

Agricultural, environmental and market policies have a significant impact on agricultural production in terms of what is produced and how. Examples of market policy impacts are described in Sect. 8.1. Agricultural policy programmes are made by many nations, and so-called common agricultural policies (CAP) determine agricultural policies at EU level. They mainly steer the subsidies provided to farmers and the production volumes of certain agricultural commodities. In the 1990s, European agriculture produced more than the markets could take up without detrimental price effects. Therefore, farmers were obliged to set land aside and and compensated. At that time, 15% of land had to be set aside. Today this land is required for the production of energy and industrial crops, and no more set aside obligations exist. Currently CAP rules determine how agricultural subsidies are coupled to environmental beneficial management measures under the so-called ‘cross-compliance (CC)’, and farmers are obliged to integrate ‘greening areas’ to support biodiversity.

Societal expectations determine how agricultural and environmental policy programmes are framed. For example, in Europe there is little acceptance of genetically modified organisms (GMO; see Sect. 5.1), and the production of GM crops is strictly forbidden.

As has been described above (Sect. 6.1.1), the evolution of farming systems very much depends on social structures, especially how land access is granted and who owns how much land. Also, the educational level of farmers not only determines the success or income of farms, but also whether farmers have the knowledge and willingness to manage their farm sustainably. Finally, the empowerment of farmers is an important condition for shaping a sustainable agriculture for the future.

6.1.8 Market Conditions

The most important animal-based products globally are cow milk and cattle, pig and chicken meat (see Table 6.2). Rice, wheat and maize are the most important crop-based commodities and are traded globally. Section 8.1 describes how supply and demand steer the agricultural commodity markets and determine market prices.

There are local, regional and global markets. But it is the demand of those markets that are accessible to farmers that determines what and how much they produce.

Consumer preferences and the consumer’s willingness to buy certain products and to pay a certain price are important market determinants.

Table 6.2 Top agricultural products in terms of production value and production quantities, world 2012 (FAOSTAT 2014)

Commodity	Production in $1000	Production in MT
Milk, whole fresh cow	187,277,186	625,753,801
Rice, paddy	185,579,591	738,187,642
Meat, indigenous, cattle	169,476,916	62,737,255
Meat, indigenous, pig	166,801,086	108,506,790
Meat, indigenous, chicken	132,085,858	92,730,419
Wheat	79,285,036	671,496,872
Soybeans	60,692,327	241,142,197
Tomatoes	59,108,521	161,793,834
Sugar cane	57,858,551	1,842,266,284
Eggs, hen, in shell	54,987,685	66,372,549
Maize	53,604,464	872,791,597
Potatoes	48,770,419	365,365,367

The willingness of consumers to pay a certain price is especially important for sustainably or ‘better’-produced products. One of the challenges in a bioeconomy is that ecologically more sound production is accompanied by higher production costs. Therefore, bio-based or sustainably produced products are often more expensive than conventional ones. Markets for bio-based products can only develop if consumers are well informed and willing to make a conscious choice for the ‘better’ product.

6.1.9 Principles of Crop Production

Every crop performs best in specific climatic conditions and can best be grown in either a temperate, subtropical or tropical climate (see also Table 6.1). The climatic profile of a crop is usually determined by the region of its origin (see Fig. 6.7 and also: http://blog.ciat.cgiar.org/origin-of-crops/). Breeding (see Sect. 5.1.2) can produce crop varieties that are adapted to specific climatic conditions. A prominent example is maize, whose cultivation area in Europe was extended north by breeding for cold tolerance.

The most important prerequisite for successful crop production is the choice of an appropriate crop and variety for a specific site. This does not only refer to climatic parameters. Crops also have specific demands with regard to soil conditions and biotic (e.g. pests and diseases) and abiotic (e.g. drought, contamination, salinity) stresses. In addition, the appropriate management measures need to be chosen according to the crop and site conditions (see Fig. 6.8). Whereas site conditions are given naturally, crop management is the anthropogenic influence on crop production.

Crop rotation is the temporal sequence of crops on a field. If annual crops (seeding and harvesting in the course of 1 year) are grown, the farmer can choose a new crop every year. Perennial crops are grown on the same field for 3–25 years, depending on the optimal production period of the crop. Intercropping is the integration of a catch crop in between two major crops. Catch crops are often grown to prevent soil runoff (erosion) or nutrient leaching or to provide organic matter to the soil. Crop rotations are generally optimized from an economic viewpoint, i.e. those crops with the highest market value are grown. However, there are biological and physical limits to crop rotation planning. It has to allow enough time for field preparation between the harvesting of one crop and the sowing of the next. Generally, it is not recommended to cultivate the same crop in a field for two or more consecutive years because pests, diseases and weeds often remain in crop residues and soils and can attack the follow-on crop. A change of crop is also necessary due to the depletion of soil nutrients. For this reason, it is recommended to avoid growing the same crop, or crops with similar demands and susceptibility to pests and diseases, in succession.

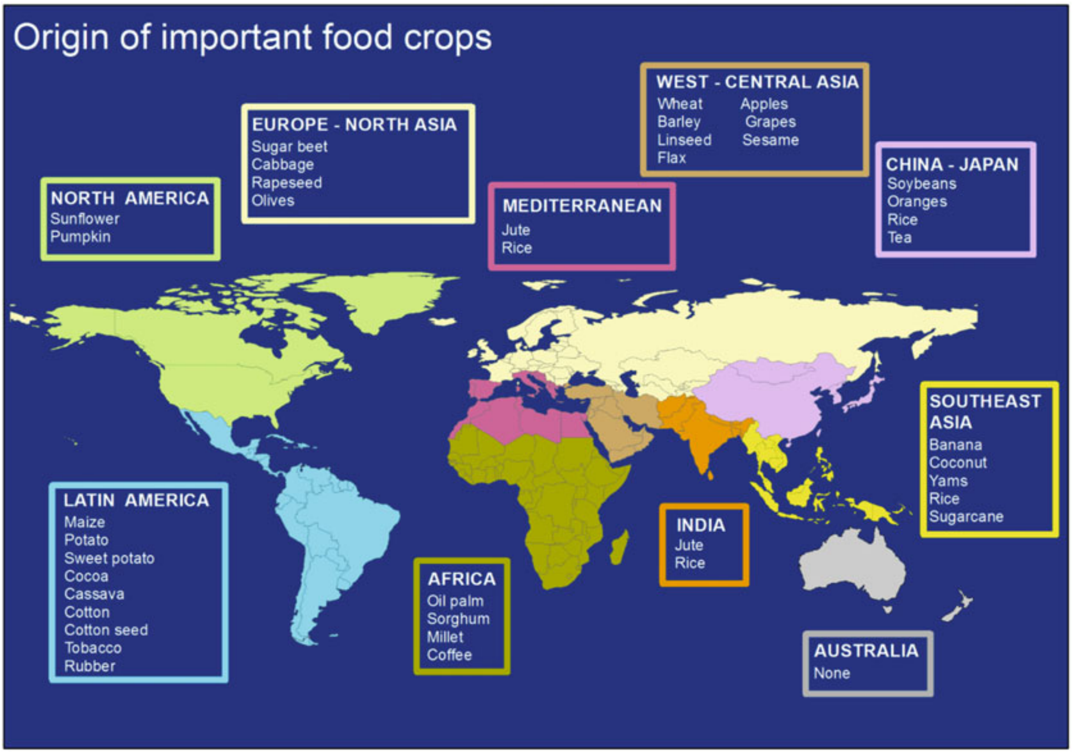

Fig. 6.7 Origin of important food crops (based on Khoury et al. 2016)

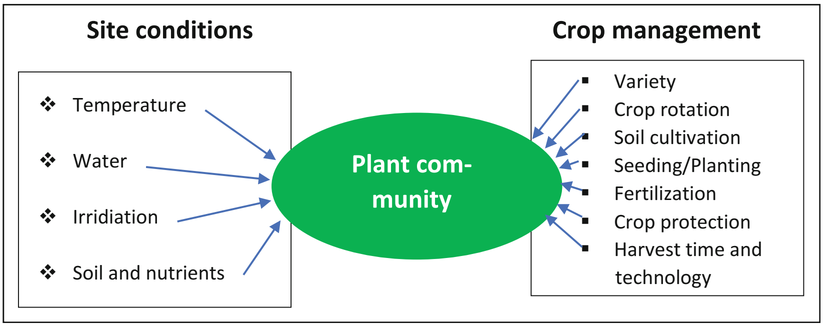

Fig. 6.8 Factors determining success of crop production

Soil cultivation is performed to loosen the soil, to incorporate residues, organic and mineral fertilizer, to control weeds and to prepare the soil for sowing or planting. The timing of and technology used for soil cultivation have to be adapted to the demands of the crop and soil conditions. Treating a wet soil and using heavy machinery can have negative impacts on the soil structure (compaction). Ploughing is the most effective soil treatment in terms of soil loosening and weed control. However, to protect soil organic matter and to avoid erosion, less intensive soil cultivation technologies are to be preferred. These, however, can lead to increased weed pressure and weed control demand.

Crops are established via *sowing* or *planting*. Sowing is cheaper and easier to mechanize and is the method used for most major crops, such as

Table 6.3 List of selected crops with information on water, fertilizer and pesticide demand, parts harvested and constituents utilized

	Sugar cane	Corn	Soy	Oil palm	*Miscanthus*
Crop type	Perennial	Annual	Annual	Perennial	Perennial
Photosynthetic pathway	C_4	C_4	C_3	C_3	C_4
Water demand (mm a^{-1})	High: 1500–2500	Moderate: 670–800	Moderate: 600	High: 2000–2500	Low: >450
Fertilizer demand (kg ha^{-1} a^{-1})	N: 45–300 P: 15–50 K: on demand	N: 145–200 P: 26–110 K: 25–130	N: 0–70 P: 32–155 K: 30–320	N: 114 P: 14 K 159	N: 0–92 P: 0–13 K: 0–202
Pesticide needed?	Yes	Yes	Yes	Yes	No
Main parts harvested	Stems, leaves	Grain	Grain	Grain	Stems
Constituents utilized	Sugar	Starch	Oil	Oil	Lignocellulose
Uses	Food, biochemicals/fuels, (feed)	Food, feed, biochemicals/fuel	Feed, biodiesel	Food, biochemicals a.o.[a]	Bioenergy, building materials, biocomposites, second-generation biochemicals

[a] Oil derivatives are used in the cosmetic and other industries (from Davis et al. 2014)

cereals, maize, sugar, oilseed rape, etc. Some crops have to be planted. Examples are sugar cane, which is established via stem cuttings, and oil palm, established via plantlets. In each case, the soil has to be prepared for planting by loosening it and removing weeds that would hamper crop establishment (soil cultivation).

Fertilization refers to all measures aimed at supplying nutrients to the crop (e.g. application of mineral or organic fertilizer) or improving soil conditions relevant for nutrient uptake (e.g. liming or application of organic substances). The optimal amount of fertilizer is determined according to the expected nutrient demand and withdrawal by the crop. Nitrogen (N) is the nutrient with the strongest yield effect. It is supplied to the soil via mineral or organic fertilizer, N-fixing legumes or atmospheric deposition. In ecological agriculture, N is only supplied via organic fertilizer and biological N fixation (see Box 6.1). In addition, potassium (K), phosphorus (P) and calcium (Ca) are required for optimal crop growth and are generally applied when in shortage. As well as being a plant nutrient, Ca has an influence on soil structure and pH. The so-called crop macronutrients also include magnesium and sulphur (S). These are often combined with PK fertilizer and are only applied when there is an obvious shortage. This also applies to the so-called micronutrients, such as iron (Fe), chloride (Cl), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), cobalt (Co) and nickel (Ni), which are only required in small quantities. Typical fertilizer requirements of major crops, including biomass crops, of temperate regions are shown in Table 6.3.

Crop protection refers to measures for the suppression or control of weeds, diseases and pests. Weeds compete with crops for all factors affecting growth and reduce crop yield and/or quality. So do pests and diseases, which feed on plant parts or their products of photosynthesis and often reduce the photosynthetically active surface area of plants. Every crop has a range of pests and diseases to which it is susceptible. Diseases can be caused by fungi, bacteria or viruses. If weeds, pests and diseases are not controlled, they can lead to large or total crop losses. There are a number of crop protection measures including mechanical (e.g. weeding) and chemical (herbicides, pesticides (Box 6.2)) methods. In organic agriculture (Box 6.4), no chemical/synthetic crop protection measures are allowed. Instead, biological methods (e.g. natural predators, pheromone traps) are used together with biological pesticides (e.g. extracts from neem tree) and mechanical weed control.

Harvest technology and timing are relevant for the harvest index (proportion of harvested product versus residues) and the quality of the product. Appropriate harvest time and technology avoid pre- and postharvest losses.

Box 6.1: Biological Nitrogen Fixation

Nitrogen (N) is one of the most abundant elements on Earth and occurs predominately in the form of nitrogen gas (N_2) in the atmosphere. There is a specialized group of prokaryotes that can perform biological nitrogen fixation (BNF) using the enzyme nitrogenase to catalyse the conversion of atmospheric nitrogen (N_2) to ammonia (NH_3). Plants can readily use NH_3 as a source of N. These prokaryotes include aquatic organisms (such as cyanobacteria), free-living soil bacteria (such as *Azotobacter*), bacteria that form associative relationships with plants (such as *Azospirillum*) and, most importantly, bacteria (such as Rhizobium and *Bradyrhizobium*) that form symbioses with legumes and other plants (Postgate 1982).

In organic agriculture, BNF is the major N source, and leguminous crops are grown for this purpose. There have been many attempts to associate N-fixing bacteria with crops other than legumes, with the objective of making them independent of external N supply. It is anticipated that BFN will play a major role in the sustainable intensification of agricultural production.

Box 6.2: Pesticides

Pesticide means any substance, or mixture of substances of chemical or biological ingredients, intended for repelling, destroying or controlling any pest or regulating plant growth (FAO and WHO 2014).

Pesticides can have different chemical structures (organic, inorganic, synthetic, biological) and target organisms.

Crop Yields

Crop yields depend on the climatic and management factors depicted in Fig. 6.9. Thus, yield potentials have a climatic/site-specific and a management component. They usually increase with the educational level of farmers and their access to means of production, in particular fertilizer and pesticides. The potential yield on a specific site, which is mainly determined by crop genetics and growth-promoting factors, is generally much higher than the achievable yield (Fig. 6.9). The achievable yield is limited by the availability of nutrients and water and can be improved by yield-increasing measures, such as fertilization and irrigation. The actually harvested yield, however, is normally lower than the achievable yield, because it is reduced by pests and diseases and/or harvest losses. These can partly be overcome through improved crop management and agricultural technology, such as efficient harvesting technology.

The ratio of actual to achievable yield is highest in industrial and lowest in developing countries where farmers have less access to means of agricultural production and are less educated (see Fig. 6.2). For this reason, and also due to climatic differences, it is not possible to provide yield figures for the performance of a crop on every site and for all circumstances. Table 6.4 provides typical, average yields for selected major crops per hectare (ha = 10,000 m^2).

6.1.10 Principles of Livestock Production

Global Livestock Population Trends

Global livestock production has a value of at least US$1.4 trillion and employs about 1.3 billion people (Thornton 2010). Livestock has a great significance in the livelihoods of people in the developing world, providing support for 600 million poor smallholder farmers (Thornton 2010).

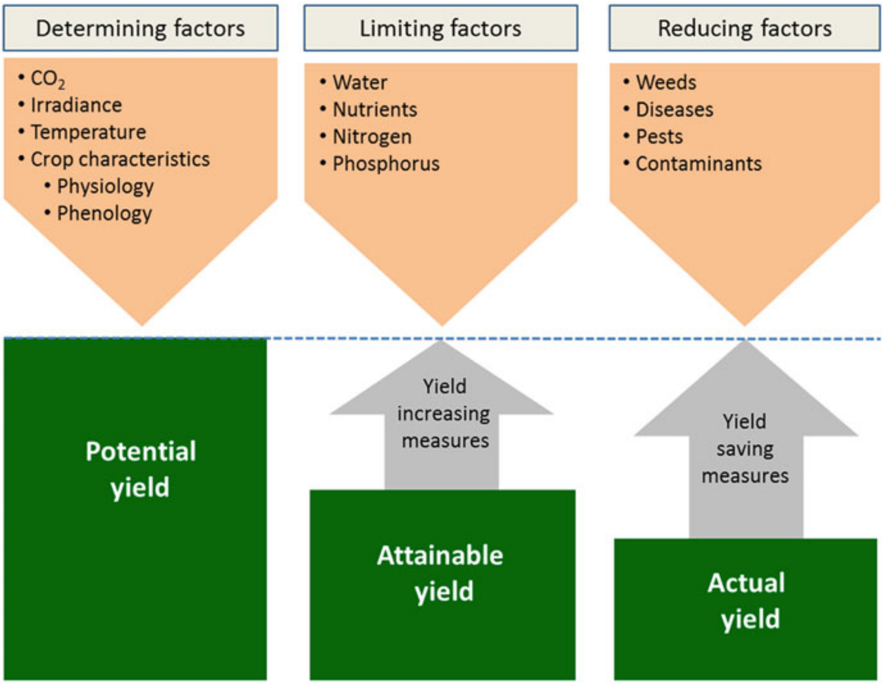

Fig. 6.9 Determination of crop yields (adapted from Rabbinge 1993)

Between 1961 and 2014, the number of animals in the least-developed countries (LDC) increased 2.4-, 7.1- and 6.9-fold for cattle, chicken and pigs, respectively, with major increases in the last two decades. By contrast, in the European Union (EU), livestock populations increased about 1.5-fold between 1961 and the beginning of the 1980s and, since then, have remained more or less stagnant with slight decreases in cattle and slight increases in chicken populations (author's own calculations; FAOSTAT 2017).

Primary production from livestock has increased in both developing and industrialized countries. In developing regions, this is a result of increasing livestock populations and performance levels (e.g. kg milk or meat/animal), whereas in industrialized countries the growth has almost exclusively been achieved by improving animal performance. There is still a large yield gap between industrialized and developing countries. In 1961, yields of chicken and pig meat per animal were 52% and 92% higher, respectively, in the EU than in the LDC. In 2014, these yields were still 40% and 49% higher, respectively, in the EU than in the LDC. For cattle, the productivity gap between industrialized and developing countries has even increased in the last 50 years. In 1961, milk yields were 9.8-fold higher and meat yields 1.5-fold higher in the EU than in the LDC. In 2014, they were 20- and 2.3-fold higher, respectively (author's own calculations; FAOSTAT 2017).

Classification of Livestock Production Systems Livestock production systems vary greatly between different regions of the world, and their development is determined by a combination of socio-economic and environmental factors. Many of these systems are thus the result of a long evolution process and have traditionally been in sustainable equilibrium with their surrounding environments (Steinfeld et al. 2006). Livestock production systems are generally classified based on the following criteria (Seré and Steinfeld 1996; Steinfeld et al. 2006):

- Integration with crops
- Relation to land

Table 6.4 Average yields of selected crops (in dry matter DM) (from KTBL 2015; FNR 2008; FAOSTAT 2014)

Crop	Harvested product (main ingredient)	Yields (t DM ha^{-1} a^{-1}) of harvested products			Typical uses	Major producing country
		Low	Average	High		
Temperate						
Wheat	Grain (starch)				Food, feed, biofuel	Europe, Ukraine, USA
Summer		3.4	5.4	7.1		
Winter		5.4	7.4	9.5		
Corn/maize	Grain (starch)	6.2	9.5	12	Food, feed, biofuel	USA, Europe
	Whole crop	12	18	25	Feed, biogas	
Potato					Food, feed, biofuel, bioplastics	Europe
Rape seed	Seed (Oil)	2.2	3.7	4.7	Food, feed, biofuel, biochemicals	Europe
Sun flower	Seed (Oil)	1.3	2.5	4.3	Food, feed, biofuel, biochemicals	USA
Sugar beet	Beet (Sugar)	45	67	85	Food, feed, biofuel	Europe
Hennep	Fibre		0.77		Textiles	China, Europe
Flax	Fibre		0.66		Textiles	Europe, China
Subtropical						
Rice	Grain (starch)				Food, feed	Thailand, Vietnam, China, India
Corn/maize	Grain (starch)				Food, feed, biofuel	USA, Europe
Sugar cane	Stems (Sugar)		71 (fresh)		Bioethanol, food, feed	Brazil, India, China
Soy bean	Grain (protein, oil)	2.9			Food, feed, biodiesel	USA, China, Brazil
Cotton	Fibre	2.0			Textiles	Australia, India, USA
Tropical						
Cassava	Tuber (starch)				Food, feed	
Oil palm	Fruits (oil)		2.9		Food, cosmetics, biochemicals, biodiesel	Indonesia, Malaysia, Nigeria
Abaca	Fibre		1.46		Yarn, ropes	Philippines, Abaca

- Agroecological zone
- Intensity of production
- Type of product

In this regard, most livestock production systems are classified into three categories:

- *Grazing-based systems*. In these livestock systems, more than 90% of feed dry mass stems from grassland. Of all the production systems, they cover the largest area: about 26% of the Earth's ice-free land surface (Steinfeld et al. 2006). This category mainly includes the keeping of ruminants in mobile or sedentary systems. Nomadic and transhumant systems have developed in regions of the world with high inter- or intra-annual variability in precipitation and/or ambient temperatures and thus plant biomass yields of grasslands. Examples include the steppes of Central and East Asia, the semiarid to arid savannahs of Africa and the highlands of Europe, the Middle East, Northern Africa and South America. Sedentary, grazing-based ruminant systems are normally found in regions with higher precipitation, lower climatic variability and higher primary production of grasslands. These include, for instance, ranching systems of North and South America and Australia characterized by large pasture and herd sizes as well as extensive, grazing-based cattle, sheep and goat systems in Europe.

- *Mixed systems*. These are the most important production system worldwide. They typically refer to mixed crop-animal systems, in which livestock by-products such as manure and draught power and crop residues are used as reciprocal inputs and where farmers commonly grow multipurpose crops (e.g. to produce grain for human consumption and stover for animal feed) (Thornton 2010). Two-thirds of the global human population live and within these systems (Thornton 2010). Mixed systems are particularly relevant in developing regions, where they produce about three-quarters each of ruminant milk and meat, 50% of pork and 35% of poultry meat (World Bank 2009).
- *Landless systems*. These systems represent livestock production units in which less than 10% of feed dry mass stems from the unit's own production (Seré and Steinfeld 1996). They are mainly pig and poultry systems. Globally, 55% of pig meat, 72% of poultry meat and 61% of eggs are produced in these systems (authors' own calculations; Steinfeld et al. 2006). A minor proportion of beef cattle stocks that are raised in so-called feedlots also belong to this category. Such landless systems are increasingly under pressure due to growing public awareness of environmental and animal welfare issues. In addition, (peri-) urban production units are commonly landless systems. Raising livestock within or in the vicinity of large human settlements provides fresh products to the markets, but also imposes health risks for humans due to the accumulation of animal wastes.

The livestock production systems described above are interrelated, and very often modifications in one system will result in concomitant modifications in another. For example, landless milk production in Kenya depends on grazing-based systems for the replacement of the milking herd (Bebe et al. 2003). Therefore, the size and number of each type of production unit influences the other. Furthermore, human population growth and societal changes put each system under pressure to adjust to evolving market demands, growing urbanization, diminishing availability of traditionally used resources and even increasing public scrutiny. Decreasing access to land and improving access to markets drive the conversion of extensive and mixed systems into more intensive production units, making these systems more efficient in the utilization of inputs to the livestock system. However, some of the systems will not be able to adapt to the new conditions and will collapse (imploding systems) (Fig. 6.10).

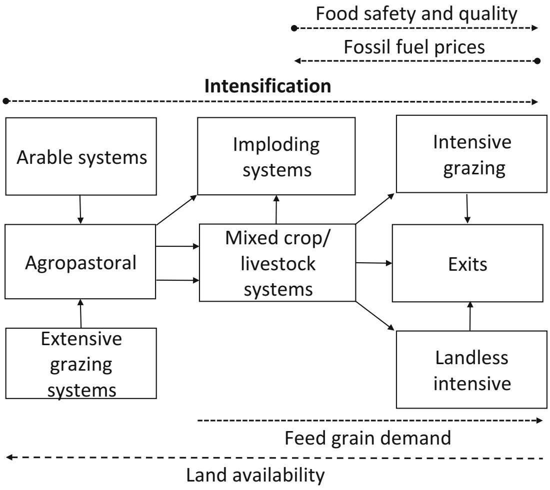

Fig. 6.10 Schematic presentation of development pathways of main livestock production systems and selected main drivers (from World Bank 2009)

Feed Resource Use in Livestock Production Systems

The feed conversion ratio (FCR) is a measure of the amount of feed (e.g. kg dry mass) needed by an animal to produce a unit (e.g. 1 kg) of meat, milk or eggs. It is the inverse of feed conversion efficiency (i.e. the ratio between the product yield and the feed input). Hence, the lower the FCR, the more efficient the conversion of feed energy or nutrients into animal products. The FCR is higher if evaluated at herd level than at the level of an individual producing animal, because the demand for feed biomass of nonproducing animals in the herd is also taken into account. The FCR varies greatly between different livestock products, production systems and regions of the world (Table 6.5). For instance, the FCRs for sheep and goat meat are more than nine times higher than for pig or poultry meat and much higher than for milk. Furthermore, the FCR is higher in grazing-based than mixed and industrial ruminant livestock systems (Herrero et al. 2013) and higher in Sub-Saharan Africa, the Caribbean, Latin America and South Asia than in North America and Europe.

This variation in FCR is mainly determined by the genetic potential of the animals and the intake, digestibility and nutrient concentrations of the available feed, with breeding and health management also playing a role. At low-feed intake level, a major proportion of the energy (and nutrients) ingested by an animal is used for maintenance purposes or is lost via urine and faeces and emission of methane, and only a minor proportion is converted into, for instance, milk or meat. However, with increasing feed intake, the proportion of feed energy (and nutrients) converted into meat, milk or eggs increases (Fig. 6.11; highlighted in green; van Soest 1994). Hence, improving energy and nutrient intakes and thus animal performance will greatly enhance the efficiency of feed resource use in livestock systems.

In line with this, the majority of monogastric livestock worldwide is kept in industrial systems, even in the less-developed countries of South and East Asia, Latin America and Sub-Saharan Africa (see above). Concentrated feeds (i.e. feeds rich in energy and/or protein and generally low in fibre, such as cereal grains and their by-products) as well as soybean and fish meal as high-quality protein sources commonly account for more than 80% of their diet (on a dry matter basis; Seré and Steinfeld 1996; Herrero et al. 2013). The high digestibility of these feeds promotes intake and animal growth rates. Consequently, the FCR in pig and poultry systems are much lower than in ruminant livestock (except dairy production) and are very similar across the various regions of the world.

Table 6.5 Feed conversion ratio for the production of milk, meat and eggs by different livestock species (in kg dry feed per kg animal product, evaluated for producing animals) (modified from Smeets et al. 2007; based on Bouwman et al. 2005; Bruinsma 2003)

Region	Milk	Bovine meat	Sheep and goat meat	Pig meat	Poultry meat and eggs
North America	1.0	26	58	6.2	3.1
Oceania	1.2	36	106	6.2	3.1
Japan	1.3	15	221	6.2	3.1
West Europe	1.1	24	71	6.2	3.1
East Europe	1.2	19	86	7.0	3.9
CIS/Baltic States	1.5	21	69	7.4	3.9
Sub-Saharan Africa	3.7	99	108	6.6	4.1
Caribbean and Latin America	2.6	62	148	6.6	4.2
Middle East and North Africa	1.7	28	62	7.5	4.1
East Asia	2.4	62	66	6.9	3.6
South Asia	1.9	72	64	6.6	4.1

CIS Commonwealth of Independent States

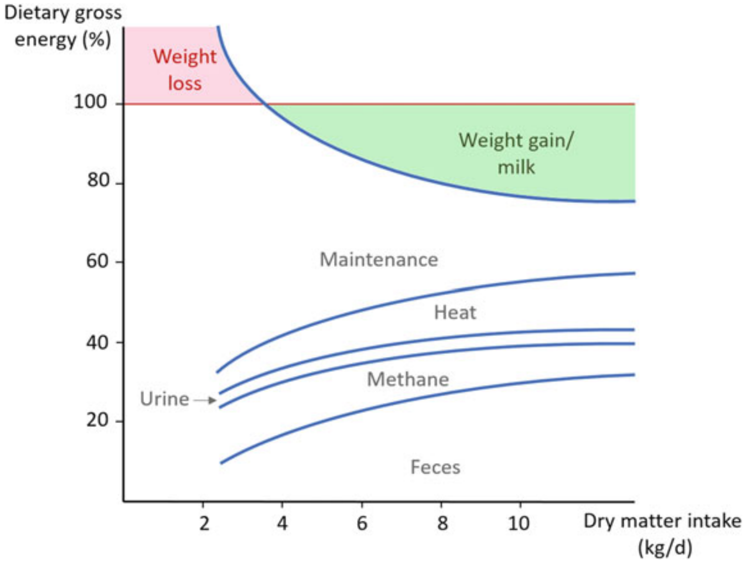

Fig. 6.11 Changes in the proportion of energy lost in faeces, urine, heat production and methane and in the proportion of energy used for maintenance and weight gain/milk production with increasing feed intake in ruminants (From van Soest 1994; based on Mitchell et al. 1932)

By contrast, ruminant feeding is much more diverse, and their diets comprise (on a dry matter basis) at least 50% roughage (i.e. bulky feeds with generally higher fibre concentrations and lower digestibility than concentrate feeds) with a few exceptions such as beef cattle finishing in feedlots. Moreover, the slower maturation and longer reproductive cycles of ruminants, as compared to pigs and poultry, result in higher proportions of nonproducing animals within the herds. Consequently, the FCR at both the animal and system level is higher in ruminant than in monogastric livestock. The FCR in milk production is lowest. Because milk contains about 85% water, its nutrient and energy density is very low compared to other animal-derived food products. While most ruminant livestock in industrialized countries is kept in mixed systems (Seré and Steinfeld 1996) where feeding is based on cultivated forage and concentrate feeds, animals in other regions of the world commonly graze on (semi-)natural grasslands or are fed crop residues, and use of concentrate feeds is lower. These differences in diet composition and hence performance of animals are responsible for the differences in the FCR of ruminant products between the various production systems and regions of the world.

Box 6.3: Feed Conversion Ratio (FCR)

Common approaches to evaluating the FCR and ecological footprints of livestock systems do not differentiate between the types of plant biomass used as feed. For instance, the use of feed resources inedible for humans, such as roughage and crop residues, may reduce competition with plant biomass as food or feed. When expressed as the amount of energy and protein from human-edible feeds per unit of animal product, differences in FCR between livestock products become much smaller, because ruminant diets typically contain lower proportions of feeds suitable for human consumption. In some cases, the FCR is even lower for the production of beef than for pork, poultry meat and eggs (Wilkinson 2011). Similarly, these approaches only focus on either milk, meat or eggs as primary products and do

(continued)

Box 6.3 (continued)

not (adequately) account for other outputs or services provided by livestock. For instance, animal manure is an important source of nutrients for the maintenance of soil fertility in crop production, in particular in mixed farming systems of Sub-Saharan Africa, Latin America and South and East Asia. Neglecting this additional output overestimates the actual FCR in mixed systems. Also, calves born in dairy cattle systems are also raised to produce meat. Correcting for the greenhouse gases emitted during the production of the same amount of meat in specialized beef cattle systems considerably reduces the carbon footprint of cow milk (Flysjo et al. 2012) and diminishes the differences between various production systems.

As the vast majority of expenses in livestock husbandry comes from the provision of animal feed, the FCR greatly determines the profitability of livestock farming. Moreover, the FCR is a key determinant of the demand for natural resources and the emissions of environmental pollutants in livestock systems. For instance, about 98% of the water needed to produce animal products (i.e. water footprint) is related to the production, processing, transport and storage of feed for livestock, whereas only 1% each is needed as drinking or service water (Mekonnen and Hoekstra 2010). Accordingly, the water footprints of beef, mutton and goat meat are higher than of pig and poultry meat and are even higher in grazing-based than in mixed or industrial ruminant systems, in particular those of Europe and North America characterized by a lower FCR. There are similar differences in the carbon footprint of animal products (Herrero et al. 2013). Hence, any improvements in the FCR will greatly contribute to increasing profitability and reducing environmental emissions and (natural) resource use in livestock farming.

6.1.11 Towards Sustainable (Intensification of) Agriculture

In the bioeconomy, agriculture needs to be performed sustainably. This requires a definition and characterization of sustainable agriculture. One approach is to categorize farming systems according to their management concepts (see Fig. 6.12). Industrial farming aims to maximize economic benefit through a high level of mechanization and the application of synthetic pesticides and fertilizers for crop production and through the utilization of specialized breeds and intense feeding, health and reproductive management for animal production. Integrated farming uses both synthetic and biological means of nutrient supply and pest control, but applies input and management measures at levels considered economically justified and that reduce or minimize ecological and health risks. Additionally, integrated farming makes use of naturally occurring strengths in plants and animals used for production purposes, like resistance to drought in certain crops or tolerance to diseases and parasites in certain animal breeds. The conservation of natural resources, including genetic resources, is at the focus of both organic farming and conservation farming. In organic farming, no synthetic fertilizers, pesticides or feed supplements are allowed. Conservation farming mainly focuses on agronomical practices that enhance soil conservation via, e.g. cover crops or incorporation of crop residues into the soil; here there might be a conflict with livestock in mixed production systems because livestock will compete for crop residues as feed and may compromise the objectives of conservation agriculture. Finally, precision farming strives to minimize agricultural inputs by applying spatially specific management to crops and accurate and timely feeding to animals using modern agricultural technologies including digitalization (see Box 6.4). All these farming concepts apply management rules to define and operationalize sustainable agricultural management.

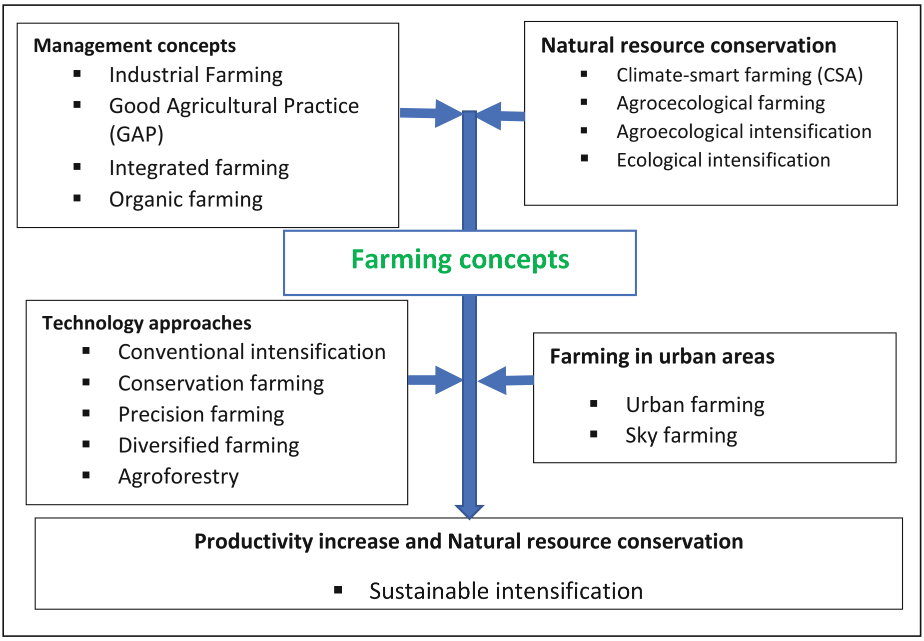

Fig. 6.12 Farming concepts

Box 6.4: Farming Concepts with a Clear Definition (Rather Than a Conceptual Approach)

Good Agricultural Practice (GAP)

'Good Agricultural Practice (GAP), for instance in the use of pesticides, includes the officially recommended or nationally authorized uses of pesticides under actual conditions necessary for effective and reliable pest control. It encompasses a range of levels of pesticide applications up to the highest authorized use, applied in a manner which leaves a residue which is the smallest amount practicable' (FAO and WHO 2014). With respect to, for instance, health management in livestock farming, GAP includes the prevention of entry of diseases onto the farm, an effective health management (e.g. record keeping, animal identification and monitoring) and the use of chemicals and medicines as described (IDF and FAO 2004).

In the EU, 'good farming practice' (GFP) is used synonymously with GAP. National codes of GFP constitute minimum standards for farm management and serve as a precondition for payments to farmers in the context of 'cross-compliance'. Cross-compliance is the attachment of environmental conditions to agricultural support payments (Baldock and Mitchell 1995) and is an obligatory element of the Common Agricultural Policy (CAP). In the EU, cross-compliance as well as GAP rules are generally laid down in laws or legal guidelines.

Integrated Farming

Integrated farming seeks to optimize the management and inputs of agricultural production in a responsible way, through the holistic consideration of economic, ecological and social aspects. This approach aims at minimizing the input of agrochemicals and medicines to an economical optimum and includes ecologically sound management practices as much as possible. As one example, 'Integrated Pest Management (IPM) means the careful consideration of

(continued)

Box 6.4 (continued)

all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human and animal health and/or the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms' (FAO and WHO 2014). Moreover, the close linkage of crop and livestock components in agroecosystems allows for efficient recycling of agricultural by-products or wastes, thereby reducing the reliance on external inputs such as fertilizers or animal feeds.

Organic Farming

'Organic Agriculture is a production system that sustains the health of *soils, ecosystems* and *people*. It *relies on ecological processes, biodiversity and cycles adapted to local conditions*, rather than the use of inputs with adverse effects. Organic Agriculture combines *tradition, innovation* and *science* to benefit the shared environment and promote *fair relationships* and a good *quality of life* for all involved' (IFOAM 2005). There are several variants of organic agriculture, including livestock organic production. All of them forbid the use of synthetic pesticides and fertilizers in crop production. Crop nutrient demands and crop health are managed through biological methods of N fixation, crop rotation and the application of organic fertilizer, especially animal manure. Regarding livestock, organic production fosters the welfare of animals, and it restricts the use of synthetic feed supplements to those conditions where the welfare of the animal might be compromised by a serious deficiency. Similarly, organic livestock production focuses on disease prevention, and it prohibits the use of antibiotics, unless any other option is available to stop the animal from suffering.

Precision Farming

Precision farming is a management approach based on the spatially specific and targeted management of agricultural land and fields. It makes use of modern agricultural production technology and is often computer-aided. In crop farming, the objective of precision farming is to take account of small-scale differences in management demand within fields. Sensors that assess the nutritional status and health of crops support their spatially differentiated management. Similarly, precision farming in livestock production aims at (continuous) monitoring of, for instance, the nutrition, performance, health and reproductive status of (individual or small groups of) animals in real-time. Such information helps farmers to make appropriate decisions in animal, feed or grazing management to optimize production, health and welfare of animals but also to increase efficiency of natural resource use in and reduce environmental impact of livestock farming.

Conservation Farming

'Conservation Agriculture (CA) is an approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely:

Continuous minimum mechanical soil disturbance.

Permanent organic soil cover.

Diversification of crop species grown in sequences and/or associations' (FAO 2017a).

In a future bioeconomy, agriculture will need to make combined use of all available knowledge and technology that can help increase productivity while, at the same time, reducing the negative environmental impacts of agricultural production. This vision is also described as 'sustainable intensification' (see Box 6.4).

Box 6.5: Sustainable Agricultural Intensification

The Royal Society (2009) defined sustainable intensification as a form of agricultural production (both crop and livestock farming) whereby 'yields are increased without adverse environmental impact and without the cultivation of more land'. More recently, Pretty et al. (2011) extended this definition of sustainable agricultural intensification to 'producing more output from the same area of land while reducing the negative environmental impacts and at the same time, increasing contributions to natural capital and the flow of environmental services'.

Box 6.6: Sustainable Intensification of Livestock Production

Examples of India and Kenya show that small changes in feeding practices like balancing diet with the same feed ingredients, feeding small additional amounts of concentrate and introducing cooling systems can greatly increase yields and total animal production and the sustainability of the production systems (Garg et al. 2013; Upton 2000).

There is evidence that the nutrient-use efficiency increases, while the intensity of methane emissions (g/kg milk) decreases by feeding nutritionally balanced rations designed from locally available resources in smallholders of cattle and buffaloes (Garg et al. 2013).

Even though challenging, larger improvements can be made in those production systems where the animal is still far from reaching its genetic potential for production, like those typically found in tropical and in developing regions.

Other intensification option is the more systematic use of agricultural or industrial by-products. However, one main problem of these materials is the unknown content of nutrients, therefore, a characterization of the available resources per region and their feeding value for each species may help to introduce them as ingredients in animals' diets. In this regard, even at the production units with high levels of intensification, advances towards sustainability can be made. In recent years the inclusion of citrus by-product from the juice industry has been regularly practised in dairy cattle diets.

Moreover, later examples have shown that small proportions of crop residues like wheat straw and corn stover—as source of physically effective fibre—can be included in diets of high-yielding dairy cows without negative impacts on yields (Eastridge et al. 2017). Such by-products have been traditionally assumed not to be suitable for diets of high-yielding animals and have been rather associated in mixed systems with less productive animals.

The use of local forages as source of protein can also aid to the sustainable intensification of production systems. However, for a farmer to adopt any management practice, this has to fit into the farmer's daily routine or only minimally alter it; additionally, it should allow the farmer to afford it.

In order to define and describe the goals of sustainable agriculture, relevant criteria need to be established. Discussions in various international, multi-stakeholder roundtables have led

Table 6.6 Summary of criteria for sustainable agricultural production and biomass supply, compiled from the sustainability studies of the Roundtable on Sustainable Palm Oil (RSPO), the Round Table on Responsible Soy (RTRS), Bonsucro and the Roundtable on Sustainable Biomaterials (RSB) (from Lewandowski 2015)

Social criteria
Respect of human and labour rights
– No child labour
– Consultation/stakeholder involvement
– Payment/fair salary
– No discrimination (sex, race)
– Freedom of association
– Health and safety plans
– Respect of customary rights and indigenous people
Smallholders' rights
Responsible community relations
Socio-economic development
Well-being
Ecological criteria
Protection of biodiversity/wildlife/HCV areas
Environmental responsibility
– Minimization of waste
– Reduction of GHG
– Efficient use of energy
– Responsible use of fire
Soil degradation
Water resources/quality
Air pollution
Use of best practice/responsible agricultural practices
– Responsible use of agrochemicals
– Training of employees
Responsible development of infrastructure and new areas of cultivation/plantations
– Impact assessment prior to establishment
– No replacement of HCV areas after year X
– No establishment on fragile soils
– Restoration of degraded land
– Compensation of local people, informed consent
– Maintenance of sites with high-carbon soil content
General and economic criteria
Commitment to continuous improvement
Wise use of biotechnology
Climate change and GHG mitigation
Food security
Use of by-products
Traceability
Transparency
Legality
Responsible business practices
Respect for land-use rights

to a set of internationally accepted criteria being compiled. The general criteria of the sustainability standards elaborated by these roundtables are shown in Table 6.6.

However, even if we manage to set the criteria for sustainable agriculture, the aspiration of 'absolute' sustainability appears inoperable. This is because the manifold trade-offs between sustainability goals and conflicting stakeholder perceptions of sustainability render the simultaneous fulfilment of all sustainability criteria shown in Table 6.6 impossible. Therefore, the concept of sustainable agricultural intensification will need to strive for the best possible compromise between productivity increase and natural resource conservation.

There are many options for increasing agricultural productivity. Figure 6.13 shows the numerous technical approaches that can contribute to this goal. These include breeding of efficient crop varieties and animal breeds; development of efficient, site-specific crop and livestock management and land-use systems; development of specific feeding strategies for an animal type and region (see Box 6.6); logistic optimization; and exploration of new biomass resource options, such as algae and biomass from permanent grasslands.

The largest potential for maximizing yields through improved cropping and livestock systems is seen in approaches targeted at closing the yield gap between achievable and actually harvested yields. In many regions of Africa, Latin America and Eastern Europe, this gap averages up to 55% (FAO 2002). The problem is often not the biophysical suitability of the site, 'site x crop combination' or production potential of livestock animals but insufficient agronomical practices and policy support (Yengoh and Ardo 2014). However, to avoid the intensification of agricultural production necessary to exploit the yield gap becoming, or being perceived as, ecologically 'unsustainable', concepts for 'sustainable intensification' need to be elaborated. In addition, advanced agricultural technologies, such as precision farming (Box 6.4), that can improve productivity without negative ecological impacts, need to be further developed.

Crop and animal breeding

- Improved crops and varieties
    - Higher yield and optimized quality
    - Improved efficiency (use of water, nutrients)
    - Stress tolerance (biotic and abiotic stress)
    - Efficient photosynthesis, C4 pathway
    - Improved plant architecture
    - Higher yields of by-products and residues
    - Perennial crops
- Animal breeds with high feed-use efficiency
- Development of new biogenic resources, such as algae

Crop management and farming systems

- Development of site-specific crop management systems with optimal combinations of: crop choice, variety choice, soil cultivation, crop establishment, fertilization, irrigation, and crop protection regimes
- Development of efficient, low-input, low-emission, soil-conserving cropping systems (sustainable intensification, precision farming, low-intensity soil tillage or no-till, integrated crop protection and production systems)
- Soil improvement and reclamation (e.g. phytoremediation, biochar)
- Participation and training of farmers in development and implementation of improved management systems
- Access for farmers to modern varieties, fertilizer, and crop protection
- Access for farmers to local and regional markets
- Strengthening the rights of smallholder farmers
- Integrated "Food-Feed-Fuel-Fibre" and "animal-crop-bioenergy" production systems and multi-product use of crops
- Urban farming

Land-use systems

- Multiple land-use systems
- Perennial land-use systems
- Maintenance and use of grassland systems
- Amelioration and use of marginal and degraded land
- Bottom-up, participatory approaches to land-use planning

Harvest, transport, pre-treatment, storage

- Improved supply chain logistic
- Availability of transport, pretreatment and storage infrastructure, infrastructural investments
- Reduction of harvest, transport, treatment, and storage losses

Conversion

- Exploitation of residue and by-product streams, closing nutrient cycle
- Efficient biomass use
- Reduction of food wastes
- Allocation of biomass to most sustainable uses

Biomass and product use

- Efficient biomass conversion systems
- Efficient bioenergy technologies
- Biorefineries, different uses of biomass components
- Cascading: material followed by or combined with energetic use

Fig. 6.13 Technical and socio-economic options for mobilizing the sustainable biomass potential, allocated to different production scales in the bio-based value chain (from Lewandowski 2015)

The provision of technical solutions for the improvement of cropping and livestock systems alone will, however, not be sufficient to mobilize the sustainable biomass supply. Farmers must also be willing to adopt these solutions and see an advantage in their application (Nhamo et al. 2014). Also, farmers must be able to afford the agricultural inputs required and be in a position to apply them. This calls for support through credit programmes and access for farmers to markets and training programmes (Nhamo et al. 2014).

Agriculture and Greenhouse Gas (GHG) Emissions

Agriculture also needs to contribute to climate change mitigation via a reduction of greenhouse gas (GHG) emissions. The main GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Presently, global agriculture emits about 5.1–6.1 Gt $CO_{2\text{equivalents}}$ of GHG a year (Smith et al. 2007). CO_2 is mainly released from microbial decay or burning of plant litter and soil organic matter and also comes from the use of fossil resources in agricultural production. CH_4 is mainly produced from fermentative digestion by ruminant livestock, from the storing of manure and from rice grown in flooded conditions (Mosier et al. 1998). N_2O comes from nitrification and denitrification of N in soils and manures, or from N volatilization, leaching and runoff, and its emission is enhanced with higher levels of N fertilization (for soils) or high levels of N feeding (for animals) (IPCC 2006).

The global technical potential for GHG mitigation in agriculture is estimated to be in the range of 4.5–6.0 Gt $CO_{2\text{equivalents}}$/year if no economic or other barriers are considered (Smith et al. 2007). In general, GHG emissions can be reduced by increasing plant and animal productivity (i.e. unit of final product per unit of area or per animal) and by more efficiently managing inputs into the system (e.g. applying the appropriate amount of fertilizer needed for a particular crop under the soil/climatic conditions, closed nutrient cycling). Other options include land management that increases soil carbon sequestration (e.g. agroforestry), improving diet quality to reduce enteric CH_4 formation, soil management that enhances the oxidation of CH_4 in paddy fields and manure management that minimizes N_2O formation. Finally, also the use of bioenergy is a mitigation option (see Fig. 6.14; for details

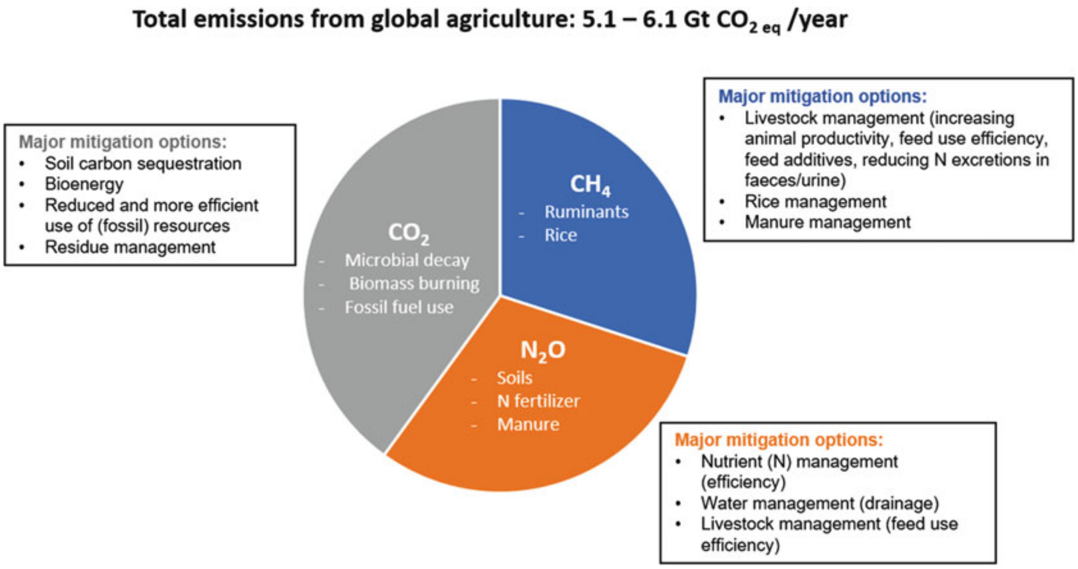

Fig. 6.14 Greenhouse gas emissions from global agriculture in Gt $CO_{2\text{equivalents}}$/year together with major emission sources. Boxes indicate major GHG mitigation options in agricultural management (data from Smith et al. 2007)

on agricultural GHG mitigation options, see Smith et al. 2007).

Review Questions

- What are the main determinants for the kind of agricultural production performed?
- What are the management options for improving productivity in crop and animal production?
- What is sustainable agriculture and sustainable intensification?
- How can negative environmental impacts of agricultural production be minimized?

Further Reading

For statistics of agricultural production, see FAOSTAT (http://www.fao.org/faostat/en/#home) and USDA (https://www.usda.gov/topics/data)

FAO (Food and Agricultural Organization of the United Nations) (2011) The state of the world's land and water resources for food and agriculture. Earthscan, Milton Park, Abingdon, OX14 4RN

van den Born GJ, van Minnen, JG, Olivier JGJ, Ros JPM (2014) Integrated analysis of global biomass flows in search of the sustainable potential for bioenergy production, PBLY report 1509, PBL Netherlands Environmental Assessment Agency

6.2 Forestry

Gerhard Langenberger and Melvin Lippe

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Abstract Forests cover about 30% of the Earth's total land area, harbouring most of the world's terrestrial biodiversity and containing almost as much carbon as the atmosphere. They have many functions, providing livelihoods for more than a billion people, and are of high relevance for biodiversity conservation, soil and water protection, supply of wood for energy, construction and other applications, as well as other bio-based resources and materials such as food and feed. The forestry sector was the first to adopt a sustainability concept (cf. Carlowitz), and sustainable use and management of forests remains an important issue to this day. Forestry is a multifunctional bioeconomic system and has an important function in securing the sustainable resource base for the present and future bioeconomy.

Keywords Forest distribution; Forest types; Natural forests; Planted forests; Forest products; Forest management

Learning Objectives

After studying this chapter, you should:

- Have gained an understanding of forests as distinct ecosystems
- Be aware of the multiplicity of functions and services which forests provide or safeguard
- Be able to explain why forests are an important multifunctional eco- and production system and how they contribute to the maintenance

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of ecosystem services, such as biodiversity protection and climate change mitigation

- Have gained an overview of the major forest types and their distinctive features
- Be aware of the characteristics and specifics of forest management
- Understand the relevance of forests for the bioeconomy

6.2.1 Forestry and Forests

Forestry is the practice and science of managing forests. This comprises the exploitation of both natural and near-natural forests. Near-natural forests are those where the original tree species composition is still apparent and the original ecosystem dynamics have been maintained, at least to some extent. The artificial establishment of forests following either recent or historical removal of the original forest cover ('reforestation' or 'afforestation') is also becoming increasingly important. This can be done with native tree species, which were part of the original forest cover, or with so-called exotic species—species from other ecosystems and often even continents. Forestry thus comprises the utilization, management, protection and regeneration of forests.

It is common understanding that forests are composed of trees. But when can an aggregation of trees be called a forest? Are trees along a road—an avenue—already a forest? Are Mediterranean olive groves or *Eucalyptus* plantations forests? Can recreational parks with scattered trees, e.g. 'Central Park' in New York and the 'English Garden' in Munich, be defined as forests? At first glance, this might not be of relevance since the purpose of such areas is obvious—they are not used, e.g. for timber production. Nevertheless, other areas covered by trees may not be defined as parks, but still fulfil similar important protection tasks or recreational purposes, such as Frankfurt's city forest (Frankfurt a.M. 2017). Therefore, a general definition of a forest could include the following criteria:

- Forests are an accumulation of trees, which are lignified, erect, perennial plants.
- They develop a 'forest climate', which differs considerably from the open land and is characterized by much more balanced temperature fluctuations and extremes, reduced wind speeds and a higher relative humidity.
- This results in characteristic soil properties with usually high-soil organic matter contents.
- The different forest types with their characteristic vertical structures provide a multitude of habitats and ecological niches supporting diverse plant and animal communities.

Since forests play an important role in the bioeconomy, for carbon storage and thus for climate change mitigation measures, a more technical definition is required, which can be used for analyses and statistics. For this reason, the FAO lay down criteria to define forests, which can be found in Box 6.7:

Box 6.7: Forest Definition According to FAO (2000) (Shortened and Simplified)

- Covers natural forests and forest plantations, including rubber wood plantations and cork oak stands.
- Land with a *tree canopy* cover of more than *10%* and an *area* of more than *0.5 ha*.
- Determined both by the presence of trees and the absence of other predominant land uses (cf. agriculture).
- Trees should be able to reach a *minimum height of 5 m*.
- Young stands that have not yet but are expected to reach a crown density of 10% and tree height of 5 m are included under forest, as are temporarily unstocked areas.

(continued)

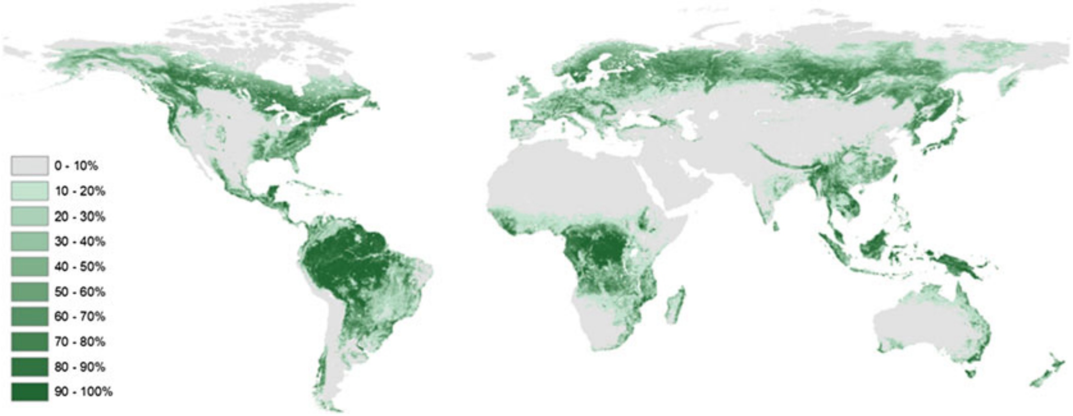

Fig. 6.15 Global extent of forest areas (based on FAO 2010)

Box 6.7 (continued)

Excludes:

– Stands of trees established primarily for agricultural production, for example, fruit tree plantations, and also agroforestry systems or short rotation coppice plantations.

6.2.2 Forest Distribution, Floristic Regions and Forest Types

6.2.2.1 Global Forest Distribution

Most regions of the Earth with a suitable climate (sufficient water availability and minimum length of growing season) were originally covered by forest. Since humans began to colonize the planet, forests have been exploited for resources and cleared, especially for agricultural production (cf. Albion 1926). Figure 6.15 provides an overview of the global distribution of forests, and Table 6.7 shows the forest cover by region. In Fig. 6.16, the countries with the largest forest areas are listed.

Table 6.7 Global forest area and regional distribution (based on FAO 2015a)

	Forest area	
Region/subregion	1000 ha	% total forest area
Eastern and Southern Africa	267,517	7
Northern Africa	78,814	2
Western and Central Africa	328,088	8
Total Africa	674,419	17
East Asia	254,626	6
South and Southeast Asia	294,373	8
Western and Central Asia	43,513	1
Total Asia	592,512	15
Russian Federation (RUF)	809,090	20
Europe excl. RUF	195,911	5
Total Europe	1005,001	25
Caribbean	6933	0
Central America	19,499	0
North America	678,961	17
Total North and Central America	705,393	17
Total Oceania	191,384	5
Total South America	864,351	21
World	4033,060	100

6.2.2.2 Floristic Kingdoms and Forest Types

There are several approaches to distinguish and classify the natural vegetation of the Earth. A key criterion of all approaches is the floristic distinctiveness of an area. A major classification of the Earth's vegetation based on the endemicity and the presence or absence of taxa is the formulation of floral kingdoms, a concept first suggested by Good (1947) and later elaborated by Takhtajan (1986). This concept distinguishes

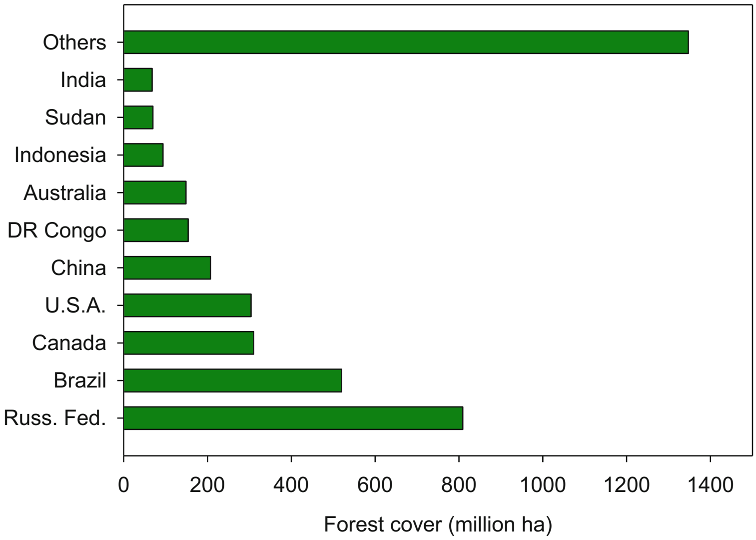

Fig. 6.16 The most important countries in terms of forest area (based on FAO 2015a, b)

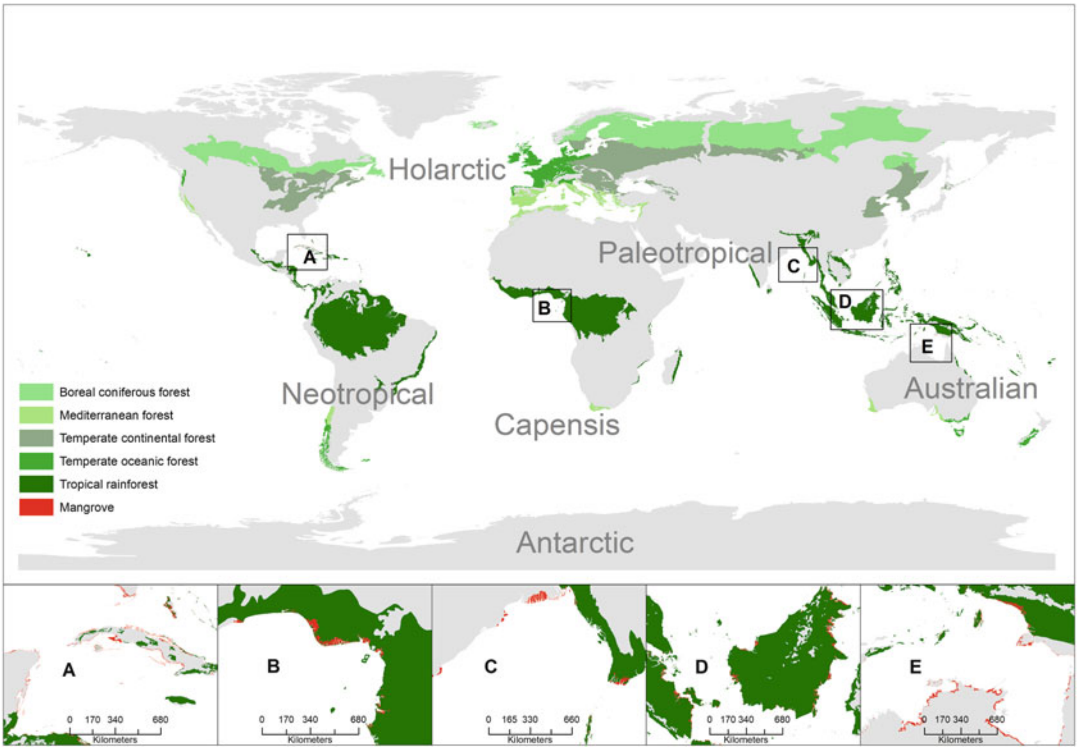

Fig. 6.17 Floristic kingdoms and global extent of important forest types (based on FAO 2010; Giri et al. 2010)

six floral kingdoms—the Holarctic, Neotropical, Paleotropical, Australian, Capensis and Antarctic kingdoms (see Fig. 6.17)—which are further subdivided into floristic regions and provinces. Since the floral kingdoms represent major species groups, they also give an indication of the general usability of the associated forests and thus reflect the bioeconomical potential.

The following overview of the floristic kingdoms lists plant groups of major economic importance together with their common use:

Holarctic

The Holarctic comprises the vegetation in the Northern Hemisphere beyond the tropics and subtropics. The forest types included are the boreal and temperate forests (see below). This huge area is characterized by representatives of important timber-tree families, such as the pine family (Pinaceae) with, e.g. firs (*Abies* spp.), spruces (*Picea* spp.), larches (*Larix* spp.) and pines (*Pinus* spp.), and several broad-leaved tree families such as the beech family (Fagaceae) with beech (*Fagus* spp.), oak (*Quercus* spp.) and chestnut (*Castanea* spp.). Other important timber families are the birch family (Betulaceae) with birch (*Betula* spp.), alder (*Alnus* spp.) and hornbeam (*Carpinus* spp.) and the willow family (Salicaceae) with poplar (*Populus* spp.) and willow (*Salix* spp.). The Holarctic is also a centre of diversity of the rose family (Rosaceae) with its cherries (*Prunus* spp.), apples (*Malus* spp.) and peaches (*Pyrus* spp.). The *Prunus* spp. in particular play an important role in a forest bioeconomy as source of valuable hardwood.

Neotropical

The Neotropical kingdom mainly covers Central and South America. It is of crucial importance as source of food plants such as tomato and pineapple (cf. Vavilov Centers) (Hummer and Hancock 2015). Nevertheless, it is also home to a range of highly valued hardwoods, e.g. true mahogany (*Swietenia mahagoni*) (cf. Anderson 2012), as well as the major provider of natural rubber, the Pará rubber tree (*Hevea brasiliensis*).

Paleotropical

The Paleotropical kingdom covers the huge and very diverse, mainly tropical area from Africa to Southeast Asia. It is particularly important as the origin of the Dipterocarpaceae family, a timber-tree family with several hundred species. This family is the source of important tropical timbers such as meranti, kapur, balau, etc. (Wagenführ 1996). The Combretaceae are another plant family with important timber trees including, for example, *Terminalia* spp. (framiré, limba). The Paleotropical kingdom is also the centre of diversity of the figs (Moraceae).

Australian

The Australian kingdom is the origin of important plantation-tree species, especially *Eucalyptus* spp. (Myrtaceae family). These are a crucial source of pulpwood. In addition, it is a centre of diversity of *Acacia* spp. (Fabaceae family), which also play an important role in tropical tree plantations.

Capensis

The Capensis is of more importance as source of ornamentals than for forestry. It is a centre of diversity of the heath family (Ericaceae).

Antarctic

The Antarctic kingdom includes one tree group of mainly regional importance to a forest bioeconomy, the southern beeches (*Nothofagus* spp.).

The Major Forest Types

While plant kingdoms refer to taxonomic distinctiveness and thus reflect evolutionary processes rather than habitat homogeneity, forest types reflect environmental conditions and are therefore an important classification for ecology, productivity and management options (Table 6.8).

Boreal Forests

Boreal forests cover about 13% of the Earth's land surface. They are found in the Northern Hemisphere, mainly between 50° and 70° north, and comprise the huge conifer-dominated forests of northern Europe, northern Russia, Canada and Alaska, also known as taiga. In the south, they merge with the temperate-mixed and broad-leaved forests. Climatically, they are cold-humid with annual precipitation between 250 and 500 (750) mm, mainly occurring during summer. Despite the regionally very low precipitation, the hydrological balance is usually positive due to

Table 6.8 Total biomass dry matter stock per hectare and net primary production of different forest types (cited in Richter 2001; Busing and Fujimori 2005[a])

Forest type	Dry matter stock per hectare/tonnes	Net primary production/g m^{-2} $year^{-1}$
Boreal forest	60–400	363–870 (1050?)
Temperate forest	150–500	1090–1775
Temperate pine forest, Oregon, USA	850	1890
Temperate redwood rainforest, California, USA[a]	3300–5800	600–1400 (only aboveground NPP)
Tropical rainforest	200–800 (1100)	3500
Mangroves	-	1700

Fig. 6.18 Large, homogenous tracts of pine forests interspersed with e.g. aspen are a typical feature of the boreal forest (left); fire plays a considerable role in nutrient cycling and forest regeneration (right) (Photos: G. Langenberger)

low evapotranspiration. The area is characterized by extreme temperature fluctuations, with permafrost soils where the average annual temperature drops below 0 °C. The vegetation period is on average 3–5 months, with a maximum of 6 months. The resulting forests are more or less single-layered with a maximum tree height of up to 20 m. It is comparatively poor on species and dominated by pine trees (*Pinus* spp., *Picea* spp., *Larix* spp., *Abies* spp.) and wind-pollinated broad-leaved trees (*Betula* spp., *Populus* spp.). The undergrowth is dominated by dwarf shrubs (e.g. *Vaccinium*), mosses and lichens. Ectomycorrhiza plays a crucial role in this type of ecosystem. Since these forests usually cover old landmasses, such as the Canadian shield, the soils are rather poor (e.g. podzols), and considerable surface humus layers (cf. the occurrence of mosses and *Vaccinium*) can be found. Fire plays a considerable role in these forests. It transforms the accumulated biomass into nutrient-rich ashes and thus initiates the natural regeneration of the forests (Fig. 6.18). Due to their homogeneity and species composition, these forests are an important resource for pulp and paper production.

Temperate Forests

Temperate forests cover about 8% of the Earth's land surface. As with boreal forest, they mainly occur in the Northern Hemisphere. They can be found between 35° and 55°, depending on macroclimatic conditions. The mountain forests of Patagonia and New Zealand can be named as examples of temperate forests in the Southern Hemisphere. Temperate forests are characterized by more balanced climatic conditions than boreal forests. They are humid with precipitation between 500 and 1000 mm/year and rainfall maximum in summer. They experience frost periods, but with much less pronounced extremes. The average annual temperature ranges between 5 and 15 °C, and the vegetation period lasts between 5 and 8 months. They show a pronounced seasonality, often with gorgeous autumn colours, e.g. during the 'Indian summer' in north-eastern USA and Canada.

Temperate forests display a high diversity of, in particular, deciduous broadleaf trees, but also evergreen trees, which can attain considerable dimensions. Tree heights of 50 m have been documented for firs, Douglas firs, oaks and beeches, even in Germany. Economically important species include oaks, beeches, maples, basswood, poplars, cherries, hickories, tulip trees, etc. Conifers such as spruce, fir and pine play an important economic role locally as planted forests. Ecologically, these forests are not only rich in tree species, but are also often characterized by a distinct shrub and herb flora. Geophytes are a typical feature of temperate forests. Two structural layers can often be distinguished. Temperate forests are not homogenous but display a high diversity of tree types depending on local site and microclimatic conditions (Arbeitsgemeinschaft Forsteinrichtung 1985). Another important difference between boreal and temperate forests is the prevailing soil types. Temperate forests mainly grow on young, post-glacial soils, often brown soils. Economically, temperate forests are still important providers of pulp wood, and especially construction timber. The production of maple syrup in eastern North America and of honey in fir forests ('Tannenhonig') can also be mentioned as specialized uses of temperate forests.

The coastal temperate rainforests of the North American West Coast represent a special case of temperate forest. They occur from Alaska down to California along the Pacific coast and its mountain ranges and are characterized by mild winters and moderate summers accompanied by high precipitation. They are dominated by conifers, comprising some of the most impressive tree species in the world including redwood (*Sequoia sempervirens*) (Fig. 6.19), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) and Douglas fir (*Pseudotsuga menziesii*). These forests are of considerable economic importance for the timber industry and are intensively exploited. Most of these species have been tested as exotics in Germany, but only Douglas fir has been established as a common component of German forests. Today it plays a considerable economic role.

Mediterranean Forests

Mediterranean forests are defined by a set of climatic conditions rather than the locality. As such, they not only occur around the Mediterranean

Fig. 6.19 Redwood (*Sequoia sempervirens*) in a Californian national park (note the relative height of the human) and the common clear-cutting practice of West Coast forests in Oregon (Photos: G. Langenberger)

Sea but also in South Africa, California, central Chile and Southern Australia. The respective climate is characterized by mild, rainy winters and very hot, dry summers. The vegetation is sclerophyllous; the trees are evergreen. Although the forests around the Mediterranean Sea were degraded hundreds of years ago, some economically important forest products still play a role to date. The olive tree (*Olea europaea*) provides fruits and oil and is also regarded as a popular timber source. The cork oak (*Quercus suber*) not only produces cork for corking wine bottles but also for use as a very good flooring material. Cork oak stands are formally classified as forests by FAO (2000). The pine *Pinus pinea* produces the pine nuts (pignoli nuts), which are actually pine seeds, used in modern cuisine, for example, in pestos. The argan tree (*Argania spinosa*) of Morocco has recently attracted attention through its oil, which is traded as Argan oil and used in cosmetics but also as a food oil. Historically, the Lebanon cedar (*Cedrus libani*), which was already mentioned in the Old Testament, played an important role as valuable timber source in the Middle East. One of the most important plantation trees, the Monterey pine (*Pinus radiata*), actually originates from California, where it did not play a considerable role. But it proved to be a high-potential plantation species outside its natural habitat.

Tropical Rainforests

Tropical rainforests are the world's most diverse forests. While the climatic conditions in these forests are more or less similar around the world, structure, species composition and usability display distinct differences. Tropical rainforests are characterized by average temperatures between 24 and 30 °C and a minimum average annual temperature of 18 °C. Rainfall exceeds 1800 mm per year. The vegetation is dominated by a high diversity of woody plants, which can attain considerable heights of 30–50 m, sometimes even 70 m. Due to the high diversity, the density of individual species are usually very low, the exception being the dipterocarp forests of Southeast Asia. The high species diversity is also reflected in the structural diversity and associated ecological niches. A common misunderstanding is that tropical rainforests are impenetrable jungles. The opposite is the case, at least in undisturbed forests. Due to the shade created by the high and dense canopy, only little undergrowth develops, and it is easy to walk through the stands.

Three major tropical rainforests are usually distinguished: the American rainforest, mainly comprising the Amazon and Orinoco basins, the Indo-Malayan and Australian rainforest and the African rainforest. All of them are considered important timber sources.

Mangroves

Mangroves (Fig. 6.20) are forests growing in the intertidal zone of tropical and subtropical coastlines, estuaries and deltas (cf. 'Sundarbans' in Bangladesh; see also Fig. 6.17 A–E). Their adaption to regular inundation by saltwater is unique and requires tolerance to salt as well as oxygen shortage (cf. stilt roots, pneumatophores). They are found throughout the tropics and subtropics. Depending on the coastline and tidal dynamics, there can be a distinct zonation of species. Mangroves have been and, in some regions, still are a considerable source of timber, firewood and charcoal as well as tannins. They are of importance as a food source for fish and shells. With their zonation of different tree species, which often stretch a considerable distance into the sea, mangroves can protect shorelines and play an important role in coastal nutrient cycling and as spawning grounds for fish, which find protection in the shallow water and between the often impenetrable stilt roots of, for example, the *Rhizophora* trees. Due to the past heavy exploitation, these functions and services are often obsolete nowadays. Mangroves continue to be threatened by transformation into fishponds, rice fields, resorts and so on.

6.2.2.3 Natural and Planted Forests

Forests regenerate themselves naturally either through succession (cf. pioneer species) following a major disturbance (fire, storm, etc.) or less

Fig. 6.20 Mangroves are an impressive feature of many tropical coastlines (Island of Leyte, Philippines) (Photo: G. Langenberger)

obviously by the replacement of single trees or tree groups in gaps (cf. Box 6.8) after natural mortality or smaller disturbances (lightning, local storm damage, etc.). The same processes more or less apply to human-caused disturbances, such as clear-cutting and selective logging. But since the time and direction of these processes are difficult to steer and manage, they are often replaced by human intervention, and trees are replanted immediately after the harvest. This is called 'reforestation'. When a forest is re-established after a long period of other land uses, such as crop production or cattle ranching, it is called 'afforestation'.

Box 6.8: Pioneer and Climax Tree Species
Two major strategies of tree regeneration can be distinguished: pioneer species, e.g. birches (*Betula* spp.), are adapted to establish on open, often disturbed sites. They require full sun and are generally fast growing and thus especially suitable for the establishment of plantations. They produce huge quantities of volatile seeds (wind dispersal) that establish particularly well on mineral soils. Climax tree species are adapted to regenerate in the microclimate conditions of already existing forests. They are shade-tolerant in their youth, but rather slow growing and much more sensitive to climate extremes (drought, frost). They usually produce far less but larger seeds. They can regenerate under old pioneer species or in gaps in old forests. Typical examples are beech (*Fagus* spp.) and firs (*Abies* spp.).

Artificial regeneration can be practised either with 'native' or 'exotic' species. Exotic species are those that are not native to the region or country. Thus, a native species in one country can become an exotic species in a neighbouring country and vice versa (cf. teak originating from Indo-Burma and nowadays being also planted in Central America, Eucalyptus from Australia planted in Spain, Monterey pine from California planted in New Zealand). The use of exotic species in forestry is often controversially and highly emotionally discussed, in contrast to agriculture, where it is not challenged that actually all commercial crops are exotics. In Germany, there is the interesting case of the Douglas fir (*Pseudotsuga menziesii*), a tree species of high economic value, that originates from western North America. Douglas fir was native to Central Europe before the ice ages, which caused the extinction of many tree taxa in Europe which can nowadays still be found in North America. Douglas fir was successfully reintroduced to Germany at the beginning of the nineteenth century and became an important source of construction timber. It established well in the forest community and can now be classified as naturalized. It is often used to replace Scots pine (*Pinus sylvestris*), which was planted to restore degraded soils in the past, since it is much more productive. Thus, Scots pine is 'native' to Germany but never occurred naturally at the majority of sites it can be found today. Originally, these sites were occupied by broadleaf trees (especially oaks). Therefore, neither Douglas fir nor Scots pine is autochthonous (native) to these sites, and it is debatable whether, ecologically, Douglas fir is worse than Scots pine.

6.2.3 Forest Services and Functions

Forests have accompanied human development from time immemorial. They provided shelter, wood for fire, tools and construction purposes, as well as fruits, mushrooms and meat. And this has not really changed to the present day. But what has changed is the intensity of usage, the sophistication of products manufacture and the improved understanding and greater importance of forests for human wellbeing. Forests have played a special role in the development of mankind due to a complex set of societal perceptions and expectations (cf. Harrison 1992). Nowadays, in addition to the sustainable production of physical goods, forests are expected to provide a multitude of services. This has resulted in restrictions in management practices that far exceed those of agricultural production, including tree species selection, mode of management, forest protection, application of agrochemicals and even mode of harvesting. This section gives an introduction into the modern usage of forests, distinguishing between their traditional function as physical resource provider and the contemporary function of non-physical service provider.

6.2.3.1 Products from Forests

The Tree as Major Source of Forest Products
A tree is defined as an erect, lignified plant composed of three major functional units, namely, root system, trunk and crown (Fig. 6.21). Thus, it comprises a below-ground and an above-ground component, which is of importance when calculating biomass and carbon sequestration potentials. The main tree parts that are used for economic purposes are the stem and major branches. Stump and roots, minor branches and leaves usually remain in the forest to maintain organic matter and nutrient cycling, since the majority of forests are not fertilized, in contrary to forest plantations.

The root system anchors and stabilizes the tree in the soil. It ensures the provision of water and nutrients, usually supported by a symbiosis

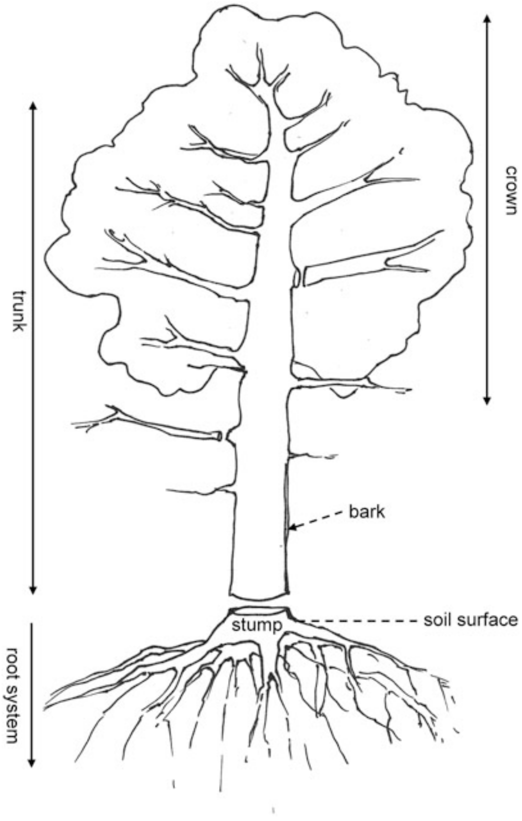

Fig. 6.21 The major components of a tree (from Young et al. 1964, simplified)

between the tree and fungi referred to as 'mycorrhiza', which is specific to the tree species. The trunk merges via branches into the crown and connects the root system with the leaves, which serve as photosynthetic units. It transports the water and nutrients absorbed by the root system in its central, woody part, the xylem, via the branches to the leaves. In return, the assimilates produced by the leaves are transported downwards in the phloem, which is located in the inner side of the bark. These assimilates are used for tree growth, including root growth and regeneration, and to provide food for the mycorrhiza. The tree crown usually begins where the trunk starts to divide into a hierarchy of branches, at the ends of which the leaves are found. This is however strongly dependent on the age and position of the tree in the population. While the crown of young trees reaches down to the soil, old trees often have a long straight bole without any branches, especially in dense forests. Solitary trees can retain their low branches throughout their entire lifespan. The tree root system needs to be flexible in order to adapt to different site conditions. Three major types of root system can be distinguished: the taproot system, heart-root system and sinker root system (Fig. 6.22).

The taproot system is based on a central, dominant root supplemented by side roots. This system provides very stable anchorage and is typical for oaks, firs and pines, but also the Neotropical rubber tree *Hevea brasiliensis*. The heart-root system does not have a clear root hierarchy, but rather spreads homogenously in the soil. It is fairly typical for a wide variety of species, such as birches and beeches. The sinker root system is characterized by a dominant horizontal root system near the soil surface from which vertical sinker roots develop that can reach considerable depths. Since the sinker roots are sensitive to waterlogged and compacted soils, they are often not well developed, erroneously leading to the perception that the root system is generally flat. Spruce trees display a typical sinker root system.

Wood

The major physical resource provided by a tree is its wood. The ability to make fire altered the course of human evolution and the energy source involved was wood. This did not change for hundreds of thousands of years, until 'recently' coal and then oil replaced wood. In the wake of the recent renewable energy boom, wood is currently experiencing a renaissance as an energy

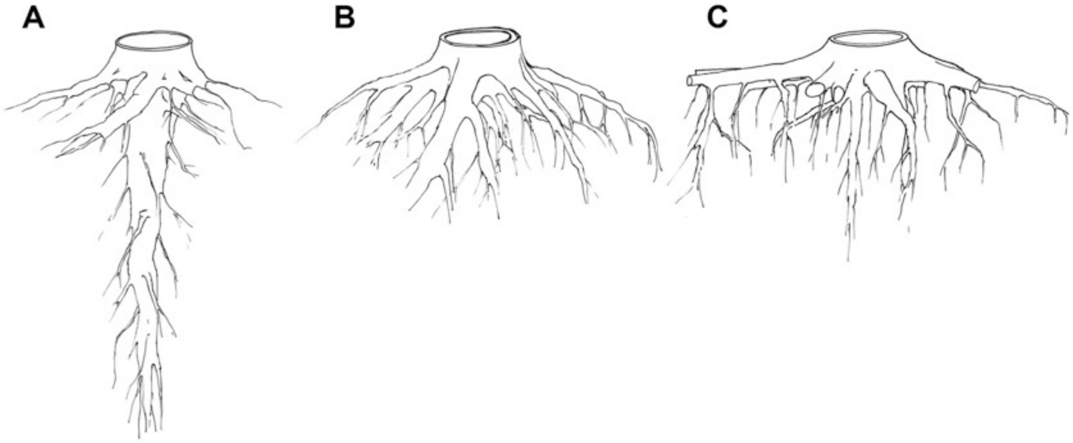

Fig. 6.22 The major root systems of trees: taproot system (left), heart-root system (middle), sinker root system (right). The actual development and structure depend strongly on site and soil conditions. Soils with a high water table can lead to a very shallow and flat root system (even in pines) © Ulrich Schmidt

source, either as raw wood or wood chips or pellets. Additionally, wood serves as raw material for tools, furniture, a wide variety of construction purposes and paper production.

Box 6.9: Chemical Composition of Wood

Carbon (50%)
Oxygen (43%)
Hydrogen (6%)
Nitrogen (1%, incl. minerals)

To understand the relevance of wood in a bioeconomy, it is crucial to be aware of its composition and features. The major components of wood are cellulose, hemicelluloses and lignin. Wood is often compared to a concrete construction, with the cellulose fibres representing the steel reinforcement which give the construction elasticity and the lignin representing the concrete which provides stability. Additionally, wood contains fat, starch and sugars as minor components, as well as resins, tannin agents, colour agents, etc. From a chemical point of view, wood is composed of carbon (C), oxygen (O), hydrogen (H), nitrogen (N) and minerals (see Box 6.9).

Since the molecular weight relation of carbon dioxide to carbon is 3.7 to 1, it is easy to calculate the carbon sequestration potential of wood from its species-specific dry weight. It should be mentioned that there is a traditional distinction between so-called hard woods (broad-leaved trees) and soft woods (conifers). Hard woods are usually heavier and have a shorter fibre length than soft woods. The latter is of importance, e.g. in paper production. Table 6.9 shows the average dry weight and bulk density of common timber species. Bulk density is the mass of dry matter in relation to the volume of the freshly harvested wood. It is an important parameter for the calculation of, among others, the carbon dioxide equivalents stored in trees. For example, a balsa tree with a volume of 1 m^3 has a dry matter wood content of about 120 kg. As the proportion of carbon is 50% (Box 6.9), this gives 60 kg carbon. The molecular weight of carbon dioxide is 3.7 times that of carbon. Thus 1 m^3 of balsa wood stores 60 kg × 3.7 = 222 kg of carbon dioxide (CO_2). The same calculation for a beech tree with a bulk density of 554 kg m^{-3} results in a figure of 1025 kg and for a pockwood tree 1935 kg.

Table 6.9 Density figures of some common tree species (all data from Knigge and Schulz 1966)

Tree species	Average dry density in g cm^{-3a}	Boundary values of dry density in g cm^{-3a}	Bulk density in kg m^{-3a}
Balsa	0.13	0.07–0.23	120.8
Spruce	0.43	0.37–0.54	377.1
Poplar	0.37	0.27–0.65	376.8
Pine	0.49	0.30–0.86	430.7
Maple	0.59	0.48–0.75	522.2
Oak	0.64	0.38–0.90	561.1
Beech	0.66	0.54–0.84	554.3
Pockwood	1.23	1.20–1.32	1045.5

[a] There is a small but relevant difference between the dry density, usually measured in g cm^{-3}, and bulk density, measured in kg m^{-3}. This is due to the fact that wood shrinks during the drying process. The bulk density relates the fresh volume of a wood sample or tree to the respective wood content. The dry density relates the volume of an oven-dried, shrunken wood sample to its weight. The latter figure is therefore higher, since the reference volume is smaller

Dry wood has a calorific value of 5–5.2 kWH kg^{-1}, and, depending on the species and its wood density, one m^3 of piled hardwood can replace around 200 l of fuel oil given a wood moisture of about 15% (air dry).

Due to its chemical and physical composition, wood has some unique features which distinguish it from other materials, resulting in a wide spectrum of applications. It is comparatively light, flexible, easy to work and often even very ornamental. It is thus used for construction purposes such as houses and boats; for flooring, furniture, carvings and tools; as well as for the production of paper and semi-natural fibres including viscose and modal. Wood also serves food industry applications, e.g. as artificial vanillin produced from lignin and as xylose, a sugar produced from wood.

Globally traded forest products are recorded in a standardized form. Table 6.10 shows the major trade categories with associated volumes for the year 2015.

Table 6.10 Global production of forest products in 2015 (FAO 2017a)

Product[a]	Unit	Production in 2015
Roundwood	million m^3	**3.714**
Wood fuel	million m^3	1.866
Industrial round wood	million m^3	1.848
Wood pellets	million tonnes	**28**
Sawnwood	million m^3	**452**
Wood-based pannels	million m^3	**399**
Veneer and plywood	million m^3	171
Particleboard and fibreboard	million m^3	228
Wood pulp	million tonnes	**176**
Other fibre pulp	million tonnes	**12**
Recovered paper	million tonnes	**225**
Paper and paperboard	million tonnes	**406**

[a] For definitions see FAO (1982, 2017b)

Table 6.11 Bushmeat provision of forests and agricultural land together[a] in Germany, hunting year 2015/2016 (only hoofed game) (DJV 2017)

	Amount in tonnes[b]	Value in mio €[c]
Red deer	4865.51	21.9
Fallow deer	2157.33	10.8
Wild boar	23,908.82	95.6
Roe deer	12,330.29	61.7
Total	43,261.95	190.0[d]

[a] Hunting districts are not delimited along land-use boarders but are based on ownership. The overall hunting area in Germany amounts to 32 mio. hectares

[b] Animal with skin

[c] Price for whole animal with skin and bones ('primary value')

[d] The monetary value given in the table does not take into account the associated value chain and added values due to processing

Other physical goods that can be obtained from forests (e.g. fruits, mushrooms) are referred to either as 'non-wood' or 'non-timber forest products' (NWFP, NTFP). Depending on the region of the globe, these may provide important contributions to the population's livelihood or be used for recreational activities. Since Mediterranean cork oak stands are classified as forests, the cork produced can also be classified as a non-wood forest product, as can the natural rubber produced in the millions of hectares of rubber tree plantations in Southeast Asia.

A special case with considerable regional importance is the meat provisioning service. So-called bushmeat is a source of protein in many African regions. In some Southeast Asian countries, e.g. Vietnam, forest species are being hunted to extinction to feed the insatiable hunger for exotic meat of the region's new rich. Bushmeat hunting and trade is usually illegal and uncontrolled and has considerable negative impacts on the affected species' populations. However, hunting practices in North America and Europe, for example, show that it is also possible to use forests as a sustainable source of considerable amounts of meat. Table 6.11 shows the case of Germany, where about 380,000 persons currently own a hunting licence.

In addition to the monetary value of the meat, annual hunting fees can also constitute a considerable source of income for forest owners and often exceed the annual income from wood production. Expenditure on hunting equipment is another economically relevant factor.

6.2.3.2 The Protective Role of Forests

Forests fulfil important protective functions. In mountainous regions, they protect settlements, farms and infrastructure from avalanches and rockfalls. Due to the specific forest climate, which maintains soil humidity and thus enhances water infiltration rates, forests usually reduce surface runoff and erosion. The root network stabilizes the soil and acts as a buffer against landslides.

Along streams, forests stabilize river banks and often serve as water (and sediment) retention areas during periods of flooding. In the tropics, mangroves have a protective role on shorelines, serving as wave breaks and also as spawning ground for fish, safeguarding the livelihood of fishermen.

Forests are also crucial for the hydrological cycle and as water protection areas. In urban centres, forests play a considerable role as air filters and oxygen providers. On a global scale, forests are crucial for carbon sequestration and serve as long-term carbon sinks.

6.2.3.3 Forests for Recreational Activities

Forests are important for recreational activities. In Germany in particular, it is said that people have a very close affinity to their forests. For this reason, forests are open access, and generally people are allowed to enter without permission. Hiking, jogging, biking and mushroom collection are common recreational activities. But hunting, which is practised nationwide, should also be mentioned.

6.2.3.4 The Socio-economic Importance of Forests in a Bioeconomy: A Case Study—Germany

Germany is a highly industrialized country with a land surface of nearly 360,000 km^2, of which 32% are classified as forest. Centuries of intensive use, degradation, reforestation and afforestation mean that today the forests are mainly production forests and only parts can be defined as near-natural. Despite this intensive use and exploitation in the past, the forests have largely maintained their original level of biodiversity, with the exception of large carnivores and predators, which historically competed with humans and have been hunted to extinction. These include bear, wolf, lynx and large birds of prey, such as eagles and vultures.

Without human interference, German forests would be characterized by broadleaf trees, mainly beech. Beech-dominated forests would cover around 74% of the total forest area, followed by oak forests with 18%. Through historical developments, however, German forests are nowadays dominated more by conifers, which cover 60% of forest area, with broadleaf forests only covering 40%. One main reason for this development is that conifers are easier to propagate and establish than broadleaf trees, especially on open lands, and in the past were often the only viable option to ensure the re-establishment of forests. As a result, the currently dominant tree species are as follows: 28% spruce (*Picea abies*), 23% pine (*Pinus sylvestris*), 15% beech (*Fagus sylvatica*) and 10% oaks (*Quercus robur*/*petraea*).

Table 6.12 Forest ownership structure in Germany (from BMEL 2017)

Forest ownership	Share of forest/%
Private[a]	48
Federal states	29
Corporations	19
Federal government[b]	4
	100

[a] About 50% of private forests are smaller than 20 ha
[b] Especially military training grounds

In recent years, there has been a trend towards the return to the original site-adapted species composition, mixed stands and abandonment of clear-cuts. This has been mainly triggered or accelerated by devastating storm damage, especially—but not only—in spruce monocultures (e.g. hurricanes Vivian and Wiebke in 1990 and Lothar in 1999). To date, around 73% of German forests are classified as mixed forests, composed of different tree species.

Forest distribution and ownership within Germany varies greatly between the federal states. Rhineland-Palatinate and Hesse have the highest forest cover at 42% each, while Schleswig-Holstein has only 10%. The ownership structure is quite heterogeneous (Table 6.12) and dominated by private owners. The private sector, that is, private and corporate forests together, accounts for 67% of the total forest area and around two million owners.

Forests and their associated value chains are of considerable socio-economic importance. On average, each hectare of forest has a timber stock of 336 m^3 and an annual timber growth of around 11 m^3, resulting in an annual timber production of more than 120 million m^3. The forest sector as a whole has an annual turnover of 170 billion euros, providing nearly 1.3 million jobs (BMEL 2017).

6.2.4 Forest Management

The management of forests has some peculiarities which need to be understood to properly assess their potentials and restrictions in a bioeconomy. One major difference compared to all other biological production systems is the time horizon. In forestry, we are dealing with decades or even centuries—in contrast to the short rotation time of modern agriculture. This requires much more foresight. In agriculture, a wrong decision might result in the loss of an annual crop. In forestry, a wrong decision with regard to tree species may reveal its disastrous consequences only after some decades. For example, a single exceptional summer or winter season can ruin the entire long-term investment in one blow, which is particularly bitter in times of high interest rates. This long-term perspective together with the necessity of food production is the main reason that, in the majority of developed countries, forests have been pushed back into less productive or difficult-to-manage sites and replaced by agriculture on good soils.

As a consequence, forest investments focus on short rotation plantations, while the management of natural or near-natural forests is practised in state-owned or traditionally privately owned forests.

6.2.4.1 The Exploitation and Use of Forests

The first use of forests was exploitative—the desired products (meat, wood, other non-wood products) were harvested without considering their regeneration. Soon, people discovered that an overuse can result in a shortage of supply. For this reason, the majority of rural tribes around the world have use restrictions, even though these may not be written down or documented as they would in a modern society.

However, forests were often cleared to create open space for crop production. This form of agriculture can still be found in the tropics, where it is called ‘shifting cultivation’ or ‘swidden agriculture’. The use of fire is a key element in this practice, and, in the course of time, vast areas can be deforested, even with very primitive tools. The forest is cut down during the dry season and the dry matter burned at the beginning of the rainy season. The open land is used for crop production for 2–3 years. After that time, it is abandoned, and the forest can re-establish and regenerate into a secondary forest.

The great onslaught on tropical forests in particular, but also boreal forests, stems from technical developments, especially the chain saw and related heavy machinery such as bulldozers, skidders and nowadays harvesters. With these tools, it was and still is possible to extract timber at an unprecedented speed. Although usually only the most valuable trees are harvested, the damage to the remaining forest can be tremendous, due to the heavy machinery and the lack of technical (felling) skills. In addition, lack of regulations and non-implementation of existing rules and corruption have led to the degradation and disappearance of large tracts of tropical forests.

In sustainable forestry, two major approaches can be distinguished: *clear felling* and *selective logging*, i.e. the targeted removal of single trees.

Clear felling is the most simple and straightforward practice. All trees on a given area are harvested. This has considerable advantages from a production point of view. First, harvesting can be conducted very efficiently, and a huge amount of biomass can be made available. Clear felling allows site modifications such as stump extraction and ploughing which requires large machinery, but also facilitates artificial regeneration. This type of forest usage and regeneration is typical in plantation forestry (cf. *Eucalyptus*, *Acacia*, *Pinus* spp.), where the fast production of a single commodity is the main objective.

Selective logging targets individual trees of high value, with the intention of maintaining forest structure and functions. It is often practised in mixed, near-natural forests. One selection criterion is a preset minimum diameter. This management practice is highly demanding and involves all aspects of management. First of all, the identification of the right trees requires the forest manager to know his forests very well. Harvesting logistics need to be worked out before logging begins to reduce the impact on the remaining forest stand. This requires the establishment of a skidding infrastructure and related felling schemes (cf. directed felling).

Fig. 6.23 Clear-felling system in conifer forests of the western USA (Photo: G. Langenberger)

Good logging skills are necessary to implement the felling scheme and minimize felling damages. The concept as a whole aims at the production of single but high-value trees. This kind of logging is usually accompanied by natural regeneration.

However, in practice, the situation is much more complex and diverse than described above, and the two approaches are often mixed, depending on local circumstances. Thus, small clear-cuts can be used to promote light-demanding species, and the natural regeneration is sometimes assisted by artificial planting either to support stagnant regeneration or to change species composition. Figure 6.23 shows the common clear-felling practice of conifer forests in the western USA. Large tracts of forests are clear-cut, but blocks of forest are maintained in between as a source of seeds.

6.2.4.2 Management Cycles

Generally, five natural development phases can be distinguished in the lifetime of a tree:

- Establishment phase: This comprises the establishment of a tree seed at a given site.
- Youth phase: The time between the establishment and maturity (seed production) of a tree.
- Optimal phase: Adult stage with regeneration.
- Stagnation phase: Decreasing vitality.
- Natural decay: die-off and replacement.

The length of each stage is species-specific and, as a result, different species are used in different management schemes. For all production forests, the stagnation phase and natural decay are eliminated by prior harvest.

Two major tree types can be distinguished based on their life strategy: the *pioneer species* and the *late-successional* and *climax forest* species (see Box 6.8). Typical *pioneer species*, e.g. birch and pine, all share a similar strategy. They produce large quantities of wind-dispersed seeds, prefer mineral soils for regeneration and require full sunlight to establish and grow. Plantation forestry uses species from this group, as they show tremendous growth in their youth but soon reach a culmination in increment, allowing for short rotations. Their natural lifespan is comparatively low (Table 6.13).

The majority of *late-successional and climax forest species* are adapted to regeneration inside the forest, in shady conditions or small light gaps. The seeds are usually larger (e.g. beech) than those of pioneers, and the seedlings can often not tolerate full sunlight exposure or temperature

Table 6.13 Life expectancy of selected tree species and production figures[a]

Tree species	Potential max. age in years	Rotation period in years	Average annual increment[b] in m^3/ha
Broadleaf trees			
Alder (*Alnus glutinosa*)	150	90	4.5–8
Ash (*Fraxinus excelsior*)	200	120	4.5–6.1
Beech (*Fagus sylvatica*)	300	150	4.2–8.6
Birch (*Betula pendula*)	120	80	3.6–4.9
Eucalyptus (*E. camaldulensis*) (plantation)	1000	7–15	2–30
Oaks (*Quercus petraea*, robur)	800	200	3.6–6.4
Teak (*Tectona grandis*)	>200	80	0.6–14.8
Conifers			
Douglas fir (*Pseudotsuga menziesii*)	1000	100	9.4–17.1
Fir (*Abies alba*)	500	150	7–12.8
Larch (*Larix decidua*)	500	140	4.1–7.2
Pine (*Pinus sylvestris*)	600	140	1.2–7.0
Spruce (*Picea abies*)	600	120	5.6–11.9

[a] Different sources: Schütt et al. (1992), Schober (1987), Lamprecht (1989), Jacobs (1955)

[b] The annual increment strongly depends on site quality and thinning concept; the values given for temperate-zone species refer to the highest rotation length given in yield tables. If rotation length is reduced, average annual increments can be higher

extremes. The establishment of these species in open spaces poses considerable problems. Therefore, such species are more often used in permanent mixed forests. They usually have slower growth in their youth than pioneer species, but maintain a considerable level of increment up to a high age and can grow quite old (Table 6.13).

Once trees have been established, either as a monoculture or within the framework of a natural regeneration concept, they need to be tended. Fertilization is common practice in forest plantations. The risk of fire should be taken into consideration in plantation schemes, but also competition from grass, which can make weeding necessary. Lianas are often reported as a serious problem hampering natural regeneration in selectively logged forests (especially in the tropics). Here, growth regulation and competition control is necessary after the establishment of the young trees, for example, misshapen and damaged trees, and trees of low vitality are removed. As the trees grow taller and start to differentiate, thinning is required, that is, the promotion of trees which fulfil quality and growth expectations by the removal of competitors. This is the first management step which can lead to positive economic returns through the marketing of wood. Depending on the management scheme, several thinning rounds need to take place before final harvest.

6.2.4.3 Forest Certification and Sustainability Initiatives

Sustainability has recently become a buzzword with as many meanings as it has advocates. The ‘invention’ of the term by Carlowitz in 1713 originally aimed at the provision of a permanent timber source for industry. Since then, the meaning of the term has evolved, based on scientific progress and ecological understanding, and has now taken on an ecosystem-oriented connotation, comprising the protection of species diversity and ecosystem functions. While forest management regulations in the temperate-zone and industrialized countries are usually well developed and implemented, forest use in the tropics has been and often still is pure exploitation, leading to forest degradation and finally transformation, sometimes intentionally to expand agricultural land. As a reaction to the tremendous forest losses in the tropics in the second half of the last century, environmentalists and other civil society organizations came together to consider options to change this development using market pressure. As a result, forest certification schemes were developed, probably the most prominent being the 'Forest Stewardship Council', better known as FSC (https://ic.fsc.org/en). As FSC was initiated by environmental and human rights organizations (in particular WWF, Greenpeace, etc.), forest owners and the forest industry reacted by creating their own, more user-friendly certification scheme, the 'Programme for the Endorsement of Forest Certification' (PEFC: https://pefc.org/). There are other certification schemes, each with somewhat different criteria and focus, e.g. that of the organic farming label 'Naturland' (http://www.naturland.de/en/).

Review Questions

- What are the specific features of forests?
- Distinguish between the different forest types.
- How do they contribute to mankind's needs and to the bioeconomy?
- What is the relevance of forests in meeting global challenges such as the mitigation of climate change?
- What is sustainable forest management?

6.3 Aquatic Animal Production

Johannes Pucher

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Abstract Aquatic animals are fundamental to a well-balanced, healthy human diet due to their profile and content of essential amino acids, polyunsaturated fatty acids, vitamins and minerals. Since the 1990s, the growing demand for aquatic food cannot be satisfied by capture fisheries alone and has therefore caused a steady increase in aquaculture production of on average 8.8% annually. Today aquaculture is the fastest-growing agricultural sector globally, especially in Asia. There are 18.7 million fish farmers globally, and annual aquaculture production is worth around 150 billion euros. It is expected that aquaculture will increasingly contribute to protein supply and healthy nutrition of the growing world population.

Fish production can be performed at different intensity levels, from production systems based on natural feed resources to closed systems in ponds or tanks which fully rely on external feed. New integrated aquaculture systems are increasingly being developed and applied, which follow a more direct implementation of a circular bioeconomy and focus on a more efficient use of nutrients and water. The best choice of production method largely depends on local conditions.

Keywords Aquaculture production; Aquaculture systems; Integrated aquaculture

Learning Objectives

After studying this chapter, you should:

- Have gained an overview of the global supply with aquatic animal biomass by fisheries and aquaculture

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- Be able to explain why different aquaculture production systems and intensities are adopted in different regions and environmental surroundings
- Understand the interdisciplinary dimension of aquaculture production
- Have become acquainted with challenges for future development of sustainable aquaculture production

Aquatic animals like fish, crustaceans, molluscs and echinoderms are fundamental to a well-balanced, healthy diet due to their profile and content of essential amino acids, polyunsaturated fatty acids (e.g. eicosapentaenoic acid and docosahexaenoic acid), vitamins, and minerals (FAO 2014). On one hand, aquatic food products are increasingly consumed as healthy and easily digestible food by richer consumers. On the other hand, aquatic animal-based protein resources are highly important for the food and nutrition security of the poor in developing countries and emerging economies.

In 2012, the global production of aquatic animal-based biomass reached 158 million tons, of which 136.2 million tons were used for human consumption and 21.7 million tons for other uses like fishmeal and fish oil production (FAO 2014). The growth in world population, rising per capita consumption, and better access to global and local markets have led to an increasing global demand for aquatic food and feed resources (FAO 2014). The World Bank (2013) expects the demand to increase aquatic food production up to 152 million tons by 2030.

Of the 2012 total annual production, 91.3 million tons were harvested by capture fisheries, and 66.6 million tons were produced in aquaculture (Fig. 6.24). For human food production, capture fisheries mainly supply the markets with organisms of higher trophic levels, like piscivorous or carnivorous fish, mollusc species and crustaceans (Neori and Nobre 2012; Tacon et al. 2010). Species of lower trophic level (esp. pelagic fish species) are also used for non-food purposes including the production of fishmeal and fish oil, which are dominantly used as feed sources in aquaculture (Shepherd and Jackson 2013). Capture landings for food and non-food purposes are dominantly harvested in seas and oceans (79.7 million tons in 2012), whereas 11.6 million tons were landed from freshwater systems.

Over the past decade, the amount of aquatic animal biomass landed globally by capture fisheries has been maintained at a relatively constant level through the utilization of ever more effective fishing gear and landing technologies and by the overexploitation of several natural stocks (Pauly 2009). Since the 1990s, the growing demand for aquatic food cannot be satisfied by capture fisheries alone and has caused a steady increase in aquaculture production of on average 8.8% annually, making aquaculture the fastest-

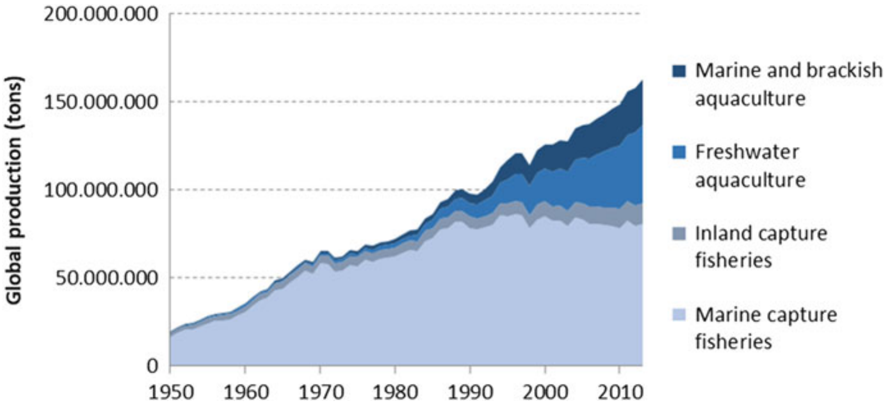


Fig. 6.24 World capture fisheries and aquaculture production (data from FAO 2015a, b)

Table 6.14 Aquaculture production by region in 2012 (FAO 2015a, b)

	Production of aquatic animals (million tons)
Africa	1.49
Americas	3.19
Asia (excl. China)	17.79
China	41.11
Europe	2.88
Oceania	0.18
Total	66.63

growing agricultural sector globally (FAO 2014), especially in Asia (Table 6.14). According to the FAO (2016), there are now 18.7 million fish farmers worldwide, and aquaculture production is worth around 139 billion euro (83 billion euro from finfish, 16 billion euro from molluscs, 30 billion euro from crustaceans, 3 billion euro from other aquatic animals and 5 billion euro from seaweeds). Aquacultural production is growing in developing and emerging economies in particular, leading to a strong global imbalance in geographical supply and demand in seafood, as 37% of seafood produced globally is exported (data 2012, FAO 2014). In 2012, 49% of the seafood import value of developed countries originated from developing countries (FAO 2014). Consequently, seafood products consumed in industrialized countries are often produced in developing or emerging economies. This makes harmonized and internationally accepted standards and regulations for production, processing and trading of aquatic foods essential to ensure an adequate level of protection for the consumer.

Aquaculture is defined by the FAO as having '. . .some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, . . .' (FAO 1997, p. 6). Today, about 520 single species or groups of species (excluding plants and mammals) are cultured in marine, brackish, or freshwater aquaculture systems. As there is a large variation in the nutritional requirements and feeding behaviour (planktivorous, herbivorous, detritivorous, omnivorous, piscivorous/carnivorous) of cultured species, a wide range of aquaculture production systems exist to accommodate the specific needs of the species and integrate aquaculture into the local/regional conditions. Aquaculture production systems differ greatly with regard to their intensity of production, which can be classified (Fig. 6.24) according to the yield, stocking density, level of external feed/fertilizer inputs, dependency on natural food resources, management/technical requirements, capital, labour and risks (Edwards et al. 1988; Tacon 1988; Prein 2002). In general, aquaculture production systems are classified into three intensities (extensive, semi-intensive and intensive aquaculture) and are integrated differently into the spatial bioeconomies and biomass flows.

Feed Conversion Ratio (FCR)
The FCR indicates how much feed (dry matter) is needed to produce one unit of fresh fish. This unit highly depends on the feed quality, culture condition, production intensity and trophic level of the species.

In *extensive aquaculture*, aquatic organisms from mainly lower trophic levels are grown solely on natural feed resources (e.g. bacteria, phytoplankton, zooplankton, zoobenthos, detritus, prey fish) without substantial inputs of external feed or fertilizer. The systems are most often run as *polycultures* (combination of several species with different feeding niches in the same pond) for local and regional markets. The stocking densities per area and the annual yields are low due to the limited productivity of the natural feed resources. Extensive aquacultures require only low levels of technical equipment, management schemes and financial investment, but large areas of water per yield, as the internal production of feed resources is entirely based on natural primary (algae) production within the ponds. Extensive aquaculture systems are only applicable in areas where suitable surface waters are abundant and are not polluted. These natural aquaculture systems are often highly important for the preservation of biological biodiversity as they provide suitable habitats for a wide range of

Fig. 6.25 Semi-intensive carp polyculture in a pond in Vietnam (Photo: J. Pucher)

flora and fauna. As no external feed and fertilizers are used, extensive aquaculture systems act as a nutrient sink and counteract eutrophication. In developing countries in particular, extensive aquaculture plays an important role for the food security of poorer communities, as minimal management and inputs are required to produce highly nutritious food resources. The future expansion of extensive freshwater aquaculture systems is very limited due to the limited availability of suitable water resources. It would require the more efficient use (intensification) and recycling/multiple use of freshwater in integrated systems without increasing the risk of contamination with undesired substances that reduce the safety of food products. A special form of extensive aquaculture is *extractive aquaculture* in which filter-feeding aquatic species are cultured in more eutrophic waters. The most predominant example is the production of bivalves (e.g. mussels, oysters) which are grown in coastal waters and feed on plankton and detritus. Similarly, seaweeds are grown in coastal waters and take up dissolved nutrients. These extractive aquacultures have high potential as they counteract eutrophication especially in coastal zones, but care should be taken regarding potential contamination with marine toxins, pathogens and undesired substances that are harmful for human health.

In *semi-intensive aquaculture*, aquatic organisms are grown in natural or constructed ponds (Fig. 6.25) on a combination of external supplemental feed and natural feed resources supported by organic or inorganic fertilizer inputs in combination with a suitable water management. Again, these systems are most often run as *polycultures* of several species of lower trophic levels for regional or national markets. To effectively utilize the protein-rich natural feed resources, external feeds often contain high levels of carbohydrates/energy to supply the cultured species with the required nutrients in a balanced and effective way (De Silva 1995). In developing countries, by-products of lower quality (e.g. press cakes, brans and manure) are often used as feed and fertilizer resources. Semi-intensive aquaculture is characterized by medium stocking densities, moderate use of technical equipment (e.g. aeration) and medium management requirements. As with extensive aquaculture, semi-intensive aquaculture offers a range of habitats for flora and fauna and stabilizes biodiversity. On a global scale, semi-intensive aquaculture is extremely important for the supply of highly nutritional food and is most often highly integrated into spatial bioeconomies and biomass flows (e.g. water, feed and fertilizers). In the developing countries and emerging economies of Asia and Africa, semi-intensive aquaculture in integrated agriculture aquaculture (IAA) systems is very important. These systems integrate agricultural production with livestock husbandry and pond aquaculture. By-products from each farming activity are used as feed or fertilizer for another farming activity, leading to a circular bioeconomy at farm or regional level. However, in such IAAs, an intensification of one farming activity (e.g. application of pesticides or inorganic fertilizers) has a direct impact on the efficiency of the entire system and may also affect the safety of their products (Pucher et al. 2014; Schlechtriem et al. 2016). A sustainable and safe expansion of this type of aquaculture needs to be well integrated into the regional situation. But the largest part of an increased future production necessary to supply the rising demand can only be achieved by an intensification of aquaculture (Tacon et al. 2010).

Intensive aquaculture is the production of aquatic species, mostly piscivorous/carnivorous species, in monocultures for large national/international markets. It enables the highest control over the culture conditions including water quality, feed utilization, hygienic conditions and health management. In intensive aquaculture, the cultured species are grown solely on external feeds, which are specifically formulated and produced to supply them with all required nutrients and energy, thus enabling an efficient and maximized utilization of resources such as water and feeds. These systems are specifically designed to adjust and stabilize the culture conditions to the needs and requirements of the cultured species (e.g. oxygen supply, temperature, currents, salinity, pH). The use of technical equipment (aerators, water quality monitoring, filters, nitrification and denitrification units, pumps, disinfection units, temperature controls, automatic feeders, etc.) permits the highest stocking densities. This high-intensity aquaculture allows the greatest yields, space efficiency, monetary return and standardization of products, but necessitates a high level of monetary investment, management and skilled staff (Fig. 6.26). Potential risks are insufficient quality and safety of feeds and water resources, environmental pollution and eutrophication by effluents, genetic mixing of aquaculture escapees and wild stocks, inadequate utilization of veterinary medicines (e.g. antibiotics) and production technologies, as well as outbreaks of diseases, technical failure and price competition on national/international trading.

Intensive aquaculture is conducted either in net cages (Fig. 6.27) or in land-based flow-through systems or closed recirculation aquaculture systems (RAS). Net cages are installed in rivers, lakes or marine waters and enable direct contact of the cultured species with the surrounding environment via the water, which supplies them with oxygen and flushes out faeces and dissolved metabolites. This type of aquaculture is affected by the surrounding environment through diseases and parasites, which may attack the cultured species, and also directly affects the environment through the effluent water, which makes the site selection of such production highly important.

Flow-through systems and closed recirculation aquaculture systems (RAS) are constructed indoor or outdoor tanks and ponds (Figs. 6.28 and 6.29). In so-called land-based systems, the water flow can be better controlled, allowing higher protection of cultured species from external influences (e.g. parasites, contaminated waters) and also higher protection of the environment, as effluents can be filtered and treated before release. Flow-through systems direct water through the culture raceways, supplying oxygen to the organisms and flushing out metabolites and faeces. By contrast, RAS recycle the water by filtering solid wastes out and oxidizing the highly toxic ammonium (main metabolite of the culture species' protein metabolism) to less toxic nitrate. The reaction allows multiple recirculation of the water and thus a higher water-use efficiency. Inclusion of denitrification units can even increase this multiple water use, allowing highly

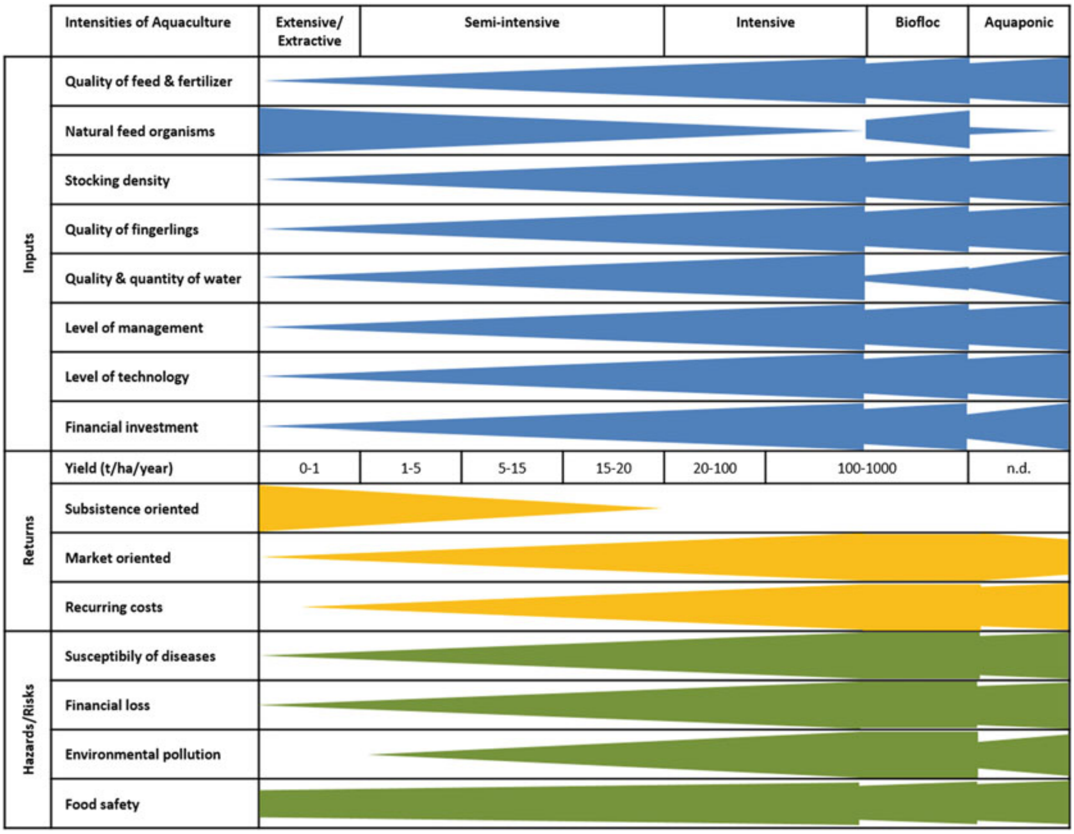


Fig. 6.26 Classification of different aquaculture production systems according to their intensities of inputs, returns and hazards/risks (redrawn and expanded from Edwards et al. 1988 in cooperation with U. Focken)

Fig. 6.27 Intensive net cage culture of salmon in Norway (Photo: J. Pucher)

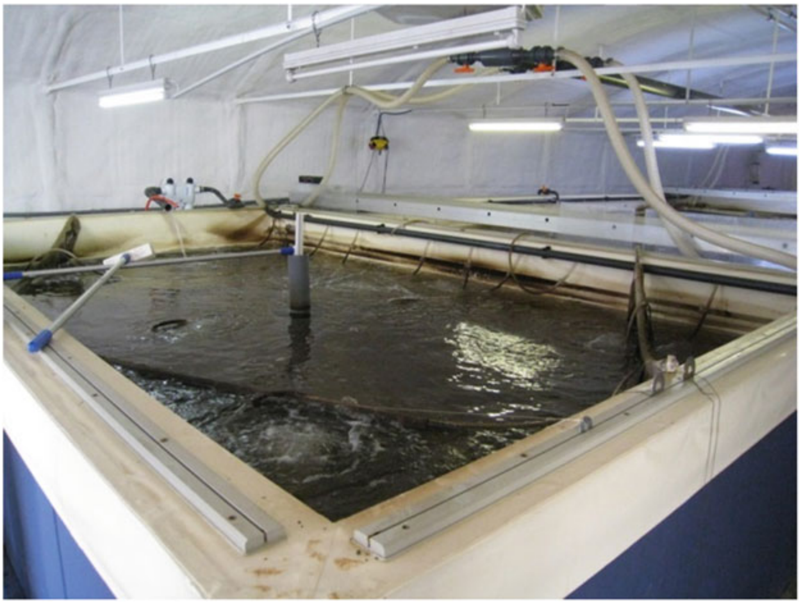


Fig. 6.28 Intensive indoor shrimp production in a recirculating aquaculture system in Germany (Photo: J. Pucher)

Fig. 6.29 Intensive outdoor shrimp production in a pond system in Vietnam (Photo: J. Pucher)

controlled production with minimal use of water resources (Fig. 6.30).

Fish-In-Fish-Out (FIFO) Ratio

Measure to compare the dependency of different aquaculture species on marine feed resources (fishmeal and fish oil) from wild non-food-producing fish. This concept of indexing is highly discussed (Kaushik and Troell 2010; Byelashov and Griffin 2014).

Intensive aquaculture offers great potential for future production due to its high productivity, efficiency and controllability. But an increase in intensive aquaculture production is creating a higher demand for classical feed resources (e.g. fishmeal and fish oil) and land/water to

Fig. 6.30 Intensive outdoor pangasius production in a pond system with feed supply in Vietnam (Photo: J. Pucher)

produce plant-based feed resources (Tacon and Metian 2008). The limited availability and increasing price of fishmeal and fish oil for the intensive production of piscivorous species and increasing consumer awareness are pushing the sector to minimize the use of fishmeal/fish oil and replace them with alternative, plant-based resources. Nowadays, soybean protein in particular is often used in aquafeeds for piscivorous species. However, globally other plant-based as well as animal-based by-products from other branches of the bioeconomy are also used (Hardy 2010; Hernández et al. 2010), including press cakes and protein extracts from plant oil production, protein extracts from single-cell technology, blood and bone meal, insect meal and unsaturated fatty acids from vegetable and algae oils.

Other novel methods of integrated aquaculture systems are increasingly being developed and applied, which follow a more direct implementation of a circular bioeconomy and focus on a more efficient use of nutrients and water. Integrated multi-trophic aquaculture (IMTA) is a combination of several aquatic species of different trophic levels which are co-produced in order to utilize the applied nutrients more effectively and reduce environmental impacts. A prominent example is the combination of intensively fed carnivorous fish with filtering species such as mussels or seaweed. This might be realized in open waters, or shellfish is farmed in fish farm drainage canals, while the effluents from the fish are directed over mussel and/or seaweed beds. These filtering species filter out solid particles and algae that take up dissolved nutrients from aquaculture effluents. This concept allows the partial binding of emitted nutrients from intensive aquaculture to supply additional products (e.g. mussels, seaweed).

Another form of modern integrated aquaculture is the combination of intensive aquaculture (of fish) and hydroponic production of plants like herbs and vegetables. These so-called aquaponic systems are designed to utilize the excreted dissolved nutrients from aquaculture production as fertilizer for plants. Some systems even recycle water from evapotranspiration. This increases both nutrient and water-use efficiency. These systems are currently being promoted for (peri-) urban regions to supply urban niche markets with locally produced food products. Additionally, waste heat from industrial activities can be utilized to increase their competitiveness. However, the competitiveness and efficiency of aquaponic production systems is presently the subject of scientific discussion.

Biofloc systems are increasingly applied and are a mixed form of semi-intensive and intensive aquaculture. Here, fish or shrimps are kept in intensively managed aquaculture tanks or ponds with minimized water exchange. In addition to the feed for the cultured species, low-value, carbohydrate-rich by-products (e.g. molasses, vinasses) are applied as an energy source for a microbial community of heterotrophic and chemotrophic bacteria. These bacteria organically bind the nutrients excreted by the culture species (e.g. nitrogen and phosphorus) to form so-called bioflocs, which are eaten by the culture species. High water aeration is necessary to supply the culture species and bacterial community with sufficient oxygen and keep the bioflocs suspended in the water so that dissolved nutrients are efficiently captured and serve as an internally recycled feed resource. Such systems promise a higher-nutrient efficiency and productivity of used water sources, but potential risks include the accumulation of undesirable substances in the system.

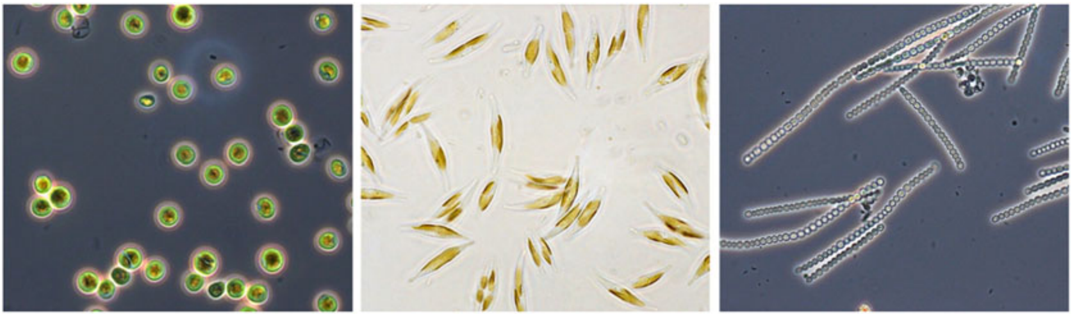
As described above, aquaculture can take a number of different forms and operate at various scales, while it can vary from subsistence-oriented small-scale fish farming in the family pond to the industrial-scale production for international markets. Aquaculture is part of complex value chains and is influenced by a range of environmental, societal and governmental factors. For future aquaculture production of healthy and safe food products, it is important to focus on environmental, social and economic sustainability and integrate aquaculture into the regional surrounding circumstances. These surrounding circumstances include the availability and quality of water resources, feed resources, know-how of workers and public, availability of technology, acceptance within the society for the production systems and products, permitting regulatory framework on environmental performance, production licences, water use, animal welfare, market demand and prizes, production costs, seasonality, risks of food safety and biosecurity, availability and quality of stocking material, climate change and post-harvesting/processing. Risk assessments, value chain analysis and market surveys might be needed to mitigate potential risks. In general, it is more resource efficient to culture species of lower trophic level and increase the utilization of by-products by establishing production chains with alternative feed resources. The choice of production method is highly dependent on local conditions, and therefore, it might be suitable to establish polycultures/multi-trophic systems in one location but more suitable to establish intensive recirculating aquaculture systems (Fig. 6.28) in another location. Improving animal welfare and sustainability of aquaculture as well as implementing eco/welfare-labelling and quality assurance/certification is targeted to increase the consumer acceptance.

Review Questions

- Which of the various aquaculture production systems show a higher productivity and economic performance?
- Which of the various aquaculture production systems are more sustainable in terms of the use of water, feed resources and energy in a site-specific context?
- What risks might arise from circular production concepts for the cultured animals and the consumers?

6.4 Microalgae

Ursula Schließmann, Felix Derwenskus, and
Ulrike Schmid-Staiger



Light-microscope images of different microalgae species. © Fraunhofer IGB, Stuttgart

Abstract Microalgae are one of the most important global biomass producers and can be used commercially to produce specific food, feed and biochemical compounds. The cultivation process differs completely from that of land-based plants because they are grown under more or less controlled conditions in different types of bioreactor systems in salt, brackish or fresh water. Special processing requirements apply to the extraction of valuable compounds from algae biomass and further use of the residual biomass, especially in cascade utilization. In general, the chemical characteristics and market specifications, for example the required degree of product purity, determine the downstream processing technique. Additional requirements are the avoidance of an energy-intensive drying step wherever possible and the ensuring of gentle extraction processes that both maintain the functionality of biochemical compounds and permit the extraction of further cell components.

The vast number of microalgae strains differ fundamentally in cell size, cell wall formation and biomass composition. By applying successive extraction procedures, both the principal fractions (e.g. proteins, polar membrane lipids with omega-3 fatty acids, non-polar triacylglycerides) as well as high-value components such as carotenoids can be obtained sequentially from the microalgae biomass.

Keywords Microalgae cultivation; Reactor systems; Algal composition; Algae-based products; Microalgae biorefinery

Learning Objectives
After reading this chapter, you will:

- Have gained an overview of the definition, metabolism and capability of microalgae
- Know about the most important parameters for the cultivation of microalgae in different photobioreactor systems
- Be aware of the huge diversity of valuable constituents in microalgae biomass and know about their areas of application

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- Understand the main difficulties in downstream processing of microalgae biomass in terms of a biorefinery concept

6.4.1 Microalgae Cultivation, Composition and Products

Microalgae are one of the most important global biomass producers. Not only do they provide a large contribution to global oxygen production, but they are also able to produce several high-value compounds such as proteins, omega-3 fatty acids or antioxidant colourants. Microalgae represent a diverse group of plant-like, unicellular organisms, of which there are an estimated 300,000 different species on earth today. So far, about 40,000 species have been described, and a few have been analysed in detail (Batista et al. 2013; Mata et al. 2010). The term 'microalgae' includes prokaryotic cyanobacteria as well as eukaryotic microalgae species capable of growing in the presence of sea water (e.g. oceans), fresh water (e.g. lakes, rivers) and on several kinds of ground surfaces (e.g. soil) (Richmond 2004).

Microalgae
The term microalgae includes prokaryotic cyanobacteria and eukaryotic microalgae species. According to recent estimations, about 300,000 different species exist on Earth today.

Depending on the species, microalgae are able to grow under heterotrophic, mixotrophic or photoautotrophic conditions (Morales-Sánchez et al. 2014; Perez-Garcia et al. 2011; Cerón-García et al. 2013) (Table 6.15). When cultivated in photoautotrophic conditions, they capture light and use its energy to convert carbon dioxide (CO_2)—a relevant greenhouse gas—via photosynthesis into chemical energy in the form of carbon-rich biomass. It is estimated that about 50% of global oxygen is produced by microalgae. Like terrestrial plants, microalgae require nitrogen and phosphorus for optimal growth. However, compared to higher plants, their cultivation has a considerable number of advantages (Schmid-Staiger et al. 2009). These include a five-to-ten times higher biomass productivity per area unit than terrestrial plants and the possibility of cultivation in controlled reactor systems on land not suitable for conventional agricultural purposes (Meiser et al. 2004). Closed reactor systems lead to a substantial reduction in water consumption compared to the cultivation of land plants, as no water is lost through evaporation or infiltration. Since several microalgae species can be cultivated in brackish or coastal seawater, the consumption of fresh water is reduced as well.

Reactor Systems

Cultivation in reactor systems enables the constituents of microalgae biomass to be influenced by regulating various process parameters, in particular nutrient supply and light intensity (Münkel et al. 2013). One major challenge in the cultivation of phototrophic organisms is the provision of sufficient light for the culture. For this reason, many different open and closed bioreactor systems have been developed for algae cultivation, each with its own advantages and disadvantages (Singh and Sharma 2012). The system used is determined by the desired product and the algae species. The most common systems are open ponds, tubular reactors and flat-panel reactors (see Fig. 6.31).

Open ponds are natural or artificial lakes with a culture depth of about 20–30 cm. In general, these reactors reflect the natural algae environment. The first open ponds were built in the

Table 6.15 Potential growth conditions of different microalgae

	Heterotrophic	Mixotrophic	Photoautotrophic
Light		x	x
CO_2		x	x
Organic carbon source	x	x	

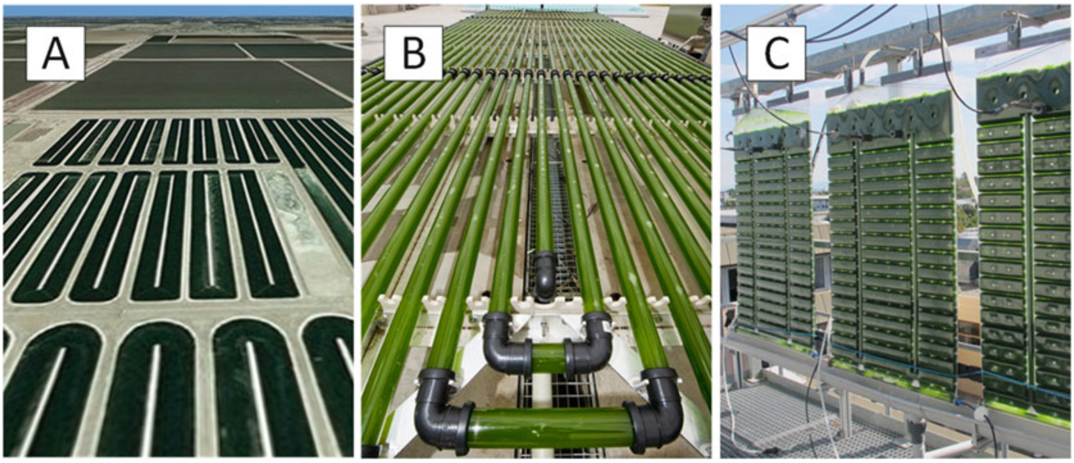

Fig. 6.31 Different bioreactor systems used for microalgae cultivation: (**A**) race-way ponds in southern California (White 2011, AlgaeIndustryMagazine.com), (**B**) tubular reactors (AlgaePARC, Wageningen University, Netherlands) and (**C**) flat-panel-airlift bioreactors (Fraunhofer IGB, Stuttgart, Germany)

1950s, and research in this field is still continuing today (Das et al. 2015). Raceway ponds are an improvement on simple ponds and are usually equipped with a paddle wheel to generate a higher flow velocity (see Fig. 6.31A). The cultivation of algae in open ponds is an established technology with low investment costs. Furthermore, ponds are simple to operate. Disadvantages are low process control (e.g. lack of cooling, difficult CO_2 supply, high water evaporation rate), low biomass productivity and low algae concentration (approx. 1 g_{DW} L^{-1}) due to insufficient light supply as a result of inadequate mixing conditions. The open system also carries a high risk of contamination with other algae, bacteria and predators. Open ponds are particularly used for the commercial cultivation of extremophile algae such as *Spirulina*, which tolerates high pH values, and *Dunaliella salina*, which can survive in high salt concentrations.

In *tubular reactors*, the biomass is pumped through transparent tubes with a diameter of several centimetres and a length of up to 100 m. CO_2 is usually supplied in a closed mixing tank. The CO_2 consumption and oxygen production of the microalgae can lead to pH and oxygen gradients in the culture, as the flow in the tubes is usually nonturbulent. The closed system enables high process control and low contamination risk. Examples of microalgae species grown in tubular reactors on a large scale are *Chlorella vulgaris* for food supplements and *Haematococcus pluvialis* for the production of astaxanthin, a red colourant (Pulz 2001).

As light is the most important parameter in algae cultivation, reactors with a high surface-to-volume ratio have been developed. *Flat-panel reactors* are vertical systems with a culture depth of only a few centimetres and are mixed by bubbling gas at the bottom. This gas flow prevents oxygen accumulation and the high light availability leads to an increased biomass productivity and concentration compared to other bioreactor systems. The concentration can be more than ten times higher than in open ponds. However, in conventional flat-panel reactors, there is little horizontal mixing, as the gas bubbles only move directly upwards in an unimpeded manner. For this reason, a modified flat-panel-airlift (FPA) reactor has been developed (see Fig. 6.31C). It consists of static mixers that produce a circular current in each chamber of the reactor (Bergmann et al. 2013). The flow pattern constantly entrains the algae cells from the dark to the light side of the reactor (see Fig. 6.32). Thus, an optimal light distribution is ensured, which results in very

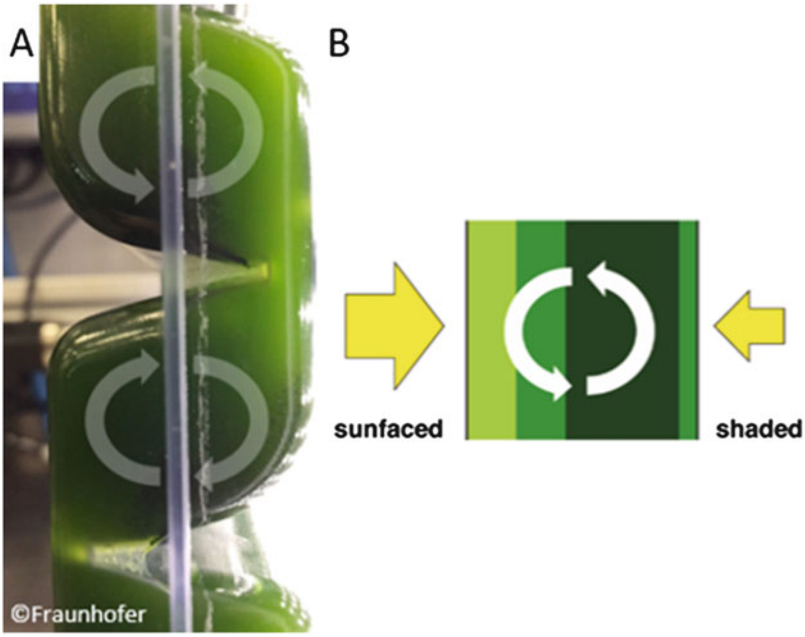

Fig. 6.32 (**A**) Side view of a flat-panel-airlift bioreactor and (**B**) schematic image of the flow pattern within each compartment. The cyclic flow pattern provides a transport from microalgae cells from the sun-faced to the shaded side of the bioreactor

Fig. 6.33 Flat-panel-airlift bioreactor (FPA) with artificial illumination, pH- as well as temperature control and automated feeding system ©Fraunhofer IGB

high productivities (up to 2 g_{DW} L^{-1} d^{-1}) and leads to a high biomass concentration of up to 20 g_{DW} L^{-1}.

These reactors can be equipped with automation systems, which provide full control of CO_2, temperature, pH value and nutrient concentration in the culture (Münkel et al. 2013). The reactors can be used indoors illuminated by LEDs (see Fig. 6.33) or outdoors operating on natural sunlight (see Fig. 6.31C).

Algal Composition and Products
Microalgae can produce a large number of substances that are of interest to various sectors

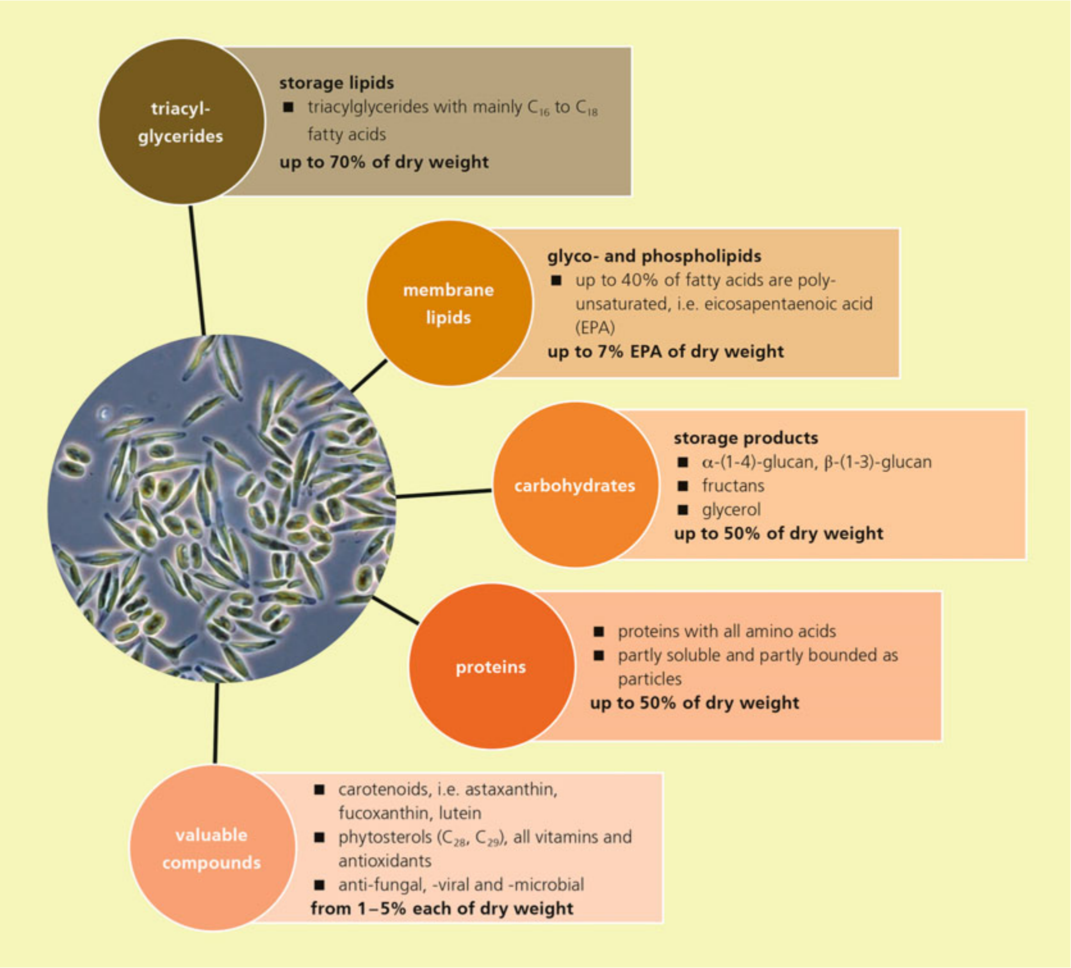

Fig. 6.34 Biochemical components of microalgae biomass. The amount of each component depends on the species as well as the cultivation conditions

including, in particular, the food, feed, cosmetics and pharmaceutical industry. Depending on the species used and the cultivation conditions, they are able to produce large quantities of fatty acids in the form of triacylglycerides (up to 70% of dry weight), proteins (up to 50% of dry weight) or polar membrane lipids with omega-3 fatty acids (up to 7% of dry weight), as well as a broad variety of carotenoids and phytosterols. The aim is to use these compounds in food production without changing their techno-functional, nutritional and physiological properties (see Fig. 6.34).

Due to the great diversity of constituents and different cell wall characteristics of various microalgae species, it is necessary to carry out selective processing of the biomass in order to effectively extract high-quality components. The composition of microalgae ingredients depends on the selected strain and the process conditions (Pal et al. 2011; Mulders et al. 2014). Given sufficient nitrogen and phosphorous supply, microalgae tend to produce large amounts of proteins. These can constitute up to 60% of the total dry cell mass and appear very suitable for food and feed purposes, since the amino acid

Table 6.16 Microalgae ingredients and their areas of application

Microalgae ingredients	Area of application
Carbohydrates	Use as renewable energy source (e.g. bioethanol, biodiesel, palm oil substitute)
Triacylglycerides	
Proteins	Supplements for food and feed applications (e.g. animal feed in aquacultures, fish oil replacement, nonanimal protein source)
Membrane lipids	
Pigments and phytosterols	High-value products for nutrition, chemical and pharma industry

profile is in balance with WHO/FAO recommendations (Becker 2007). However, the only commercial products on the market so far are dietary supplements. As chlorella is rich in chlorophyll and lutein, it is thought to have beneficial health properties and is used in supplements for the reduction of oxidative stress and treatment of several diseases including age-related macular degeneration (ARMD) (Granado et al. 2003). In addition, some microalgae species (e.g. *Phaeodactylum tricornutum*, *Pavlova lutheri*, *Nannochloropsis oceanica*) have phospho- and galactolipids in their chloroplast membranes that contain polyunsaturated omega-3 fatty acids, especially eicosapentaenoic acid (EPA, C20:5, ω3) and docosahexaenoic acid (DHA, C22:6, ω3) (Chini Zittelli et al. 1999; Krienitz and Wirth 2006; Pieber et al. 2012). EPA (typically contained in the human diet in fish oils) can act as a precursor of prostaglandin-3, which can inhibit platelet aggregation. It is also thought that a specific EPA intake can help to reduce inflammation and the symptoms of depression (Martins 2009).

When microalgae cells are cultivated under nitrogen or phosphor starvation, some species (e.g. *Chlorella vulgaris*) are able to accumulate huge amounts of triacylglycerides consisting of glycerol and saturated and mono-unsaturated lipids (mainly C16-C18 fatty acids). Under appropriate conditions, these fatty acids constitute more than 60% of the total dry mass (Münkel et al. 2013). Other species (e.g. *Chlorella sorokiniana*) are able to accumulate large amounts of carbohydrates in the form of starch. Extraction of unsaturated fatty acids and carbohydrates is simple. These products are of interest to the energy sector, since they can be converted to biodiesel (from fatty acids) or bioethanol (from carbohydrates) or used as platform chemicals for further synthesis (Harun 2010). Until now, all studies and estimations have confirmed that the production of biodiesel from microalgae is still too expensive and not yet competitive with fossil fuels (Rodolfi et al. 2009; Norsker et al. 2011). However, in addition to the main products, microalgae biomass can include several high-value by-products such as carotenoids (e.g. astaxanthin, β-carotene, fucoxanthin, lutein) and phytosterols, which are of interest considering their antioxidant and anti-inflammatory properties (Ahmed et al. 2014; Macías-Sánchez et al. 2007; Ahmed et al. 2015; Francavilla et al. 2010). Some carotenoids can be used as natural and healthy food colourants (see Table 6.16).

6.4.2 Microalgae Biorefinery: Adding Value by Fractionation

In the context of the bioeconomy, algae biomass needs to be utilized as holistically and efficiently as possible. Although microalgae can be used as whole cells for nutritional purposes, it is often worth fractionating the different constituents to add value to the biomass and thereby vindicate comparatively high production costs. However, developing appropriate downstream processes is a huge challenge, since microalgae biomass usually contains more than one main constituent of interest, e.g. saturated fatty acids as biodiesel feedstock, and proteins, omega-3 fatty acids and carotenoids for food and feed applications. Furthermore, the quality and amount of valuable components can vary greatly according to the origin of each species and cultivation conditions, e.g. light availability and nutrient supply (Münkel et al. 2013; Pal et al. 2011). Hence, cell disruption and extraction parameters have to be adjusted carefully depending on the composition of constituents and also individually for each specific microalgae strain.

Well-known downstream processes used, for example, for terrestrial plants or bacteria, cannot be easily transferred to microalgae, since these are cultivated in aqueous media and the solid matter content is far below the values achieved in classical fermentation processes (Posten and Feng Chen 2016). Thus, microalgae biomass requires a solid-liquid separation (e.g. by flotation, filtration or centrifugation) to harvest and concentrate microalgae cells produced in open ponds or closed bioreactors. Subsequently, an additional drying step (e.g. spray drying or lyophilization) can be necessary to remove residual water, since water may interfere with solvent extraction or disturb the hydrolysis process for biofuel production.

In most cases, harvesting is followed by a cell disruption step. For many microalgae species, this step is mandatory since multilayered microalgae cell walls can be very robust and might impede direct contact between the solvent and compounds to be extracted (Brennan and Owende 2010). Cell disruption can also improve the bio-accessibility of antioxidant compounds used in food and feed applications (Gille et al. 2016). For this purpose, mechanical cell disruption, e.g. by bead milling, high-pressure homogenization or sonication, tends to be more effective than chemical or enzyme-based treatments (Safi et al. 2014).

Cascaded Extraction
Combination of multiple extraction steps in order to extract multiple products while avoiding the degeneration of molecules and organic compounds within each fraction.

Nowadays, one of the most common approaches in the extraction of products from algae is to separate lipids (e.g. fatty acids and carotenoids) from proteins. This can be realized by cascaded extraction using high-pressure extraction methods. These methods have a relatively low environmental impact compared to conventional solvent extraction. Unit operations such as subcritical pressurized liquid extraction (PLE) using organic solvents (e.g. ethanol, ethyl acetate) or supercritical fluid extraction (SFE) using carbon dioxide can be applied sequentially to separate products according to their polarity. Both extraction methods operate at high pressure and moderate temperature and can thus preserve the nutritional value and techno-functionality of the recovered compounds (Liau et al. 2010; Mendes et al. 2003; Pieber et al. 2012). Furthermore, there are several suitable solvents that meet the requirements and regulations of the food and feed sectors. Other extraction techniques, which have already been described for the extraction of plant biomass, including ultrasound-assisted extraction (UAE), pulsed electric field extraction (PEF) and microwave-assisted extraction (MAE), are also at the focus of current research in order to adapt them for microalgae treatment (Parniakov et al. 2015; Pasquet et al. 2011; Plaza et al. 2012).

Review Questions

- What are the differences between heterotrophic, mixotrophic and photoautotrophic growth, and what are main advantages and disadvantages of each growth type?
- What makes microalgae so interesting concerning their composition of ingredients in comparison to terrestrial plants?
- Which criteria have to be met for a microalgae reactor system to achieve high biomass productivity as well as energy efficiency?
- What are the main challenges concerning cascaded utilization of microalgae biomass?

6.5 Economics of Primary Production

Christian Lippert

Tea plantation *Seeyok* in Darjeeling (India) July 2016 © Christian Lippert

Abstract When developing new bio-based products and assessing their market opportunities, the correct calculation of all expected unit costs is indispensable. The provision of natural resources from primary agricultural or forest production is an important cost component in this calculation. All renewable natural resources require a certain time to grow. For this reason, in order to correctly account for all external and internal net benefits of natural resources, it is important to calculate the related capital costs and model the biological growth over time. For permanent crops and woodland resources, it is particularly important to derive optimized single and infinite rotations for different kinds of plantations. For this purpose, the corresponding biological growth expectations need to be combined with an investment appraisal. This chapter introduces basic concepts dealing with interest calculation based on the existence of (economic) capital growth and biological growth.

Keywords Biological growth function; Investment appraisal; Capital budgeting; CostingDiscounting; Forest economics

Learning Objectives
After studying this chapter, you should be able to:

- Apply an investment appraisal with special regard to farm and forestry economics
- Model biological growth by means of the Euler method

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- Combine simple biological growth models and investment appraisal to optimize single and infinite rotations for different kinds of plantations
- Identify optimal replacement times for long-lasting assets in agriculture and horticulture

In this chapter, Sect. 6.5.1 outlines basic concepts of compound interest calculation (i.e. capital growth) and illustrates reasons for and methods of discounting. Section 6.5.2 deals with simple ways to mathematically describe and simulate biological growth. Combining both approaches enables us to plan optimum resource use over time: in this context, we will identify optimum harvest (or rotation) times in forestry (Sect. 6.5.3) and determine the optimum replacement time for permanent crop plantations that continuously yield yearly benefits (Sect. 6.5.4). Our analysis will focus on private wood- and crop-related benefits. However, in Sect. 6.5.3 we will also briefly discuss how the inclusion of forest-related positive externalities (for a definition of externalities, see Sect. 10.4) from regulating or cultural ecosystem services affects harvest decisions and optimum forest use over time. As the important concepts are presented quite concisely here, the reader should refer to Perman et al. (2011) for more detailed explanations. An interesting application of the approach presented in Sects. 6.5.3 and 6.5.4 can be found in Guo et al. (2006).

6.5.1 Investment Appraisal (Capital Budgeting)

In real life, every resource use results in an intertemporal sequence of benefits (B_t) and costs (C_t). In this context, a net benefit of a given amount of money is usually considered less valuable the farther in the future it is expected to occur. Thus, future benefits (B_t) and costs (C_t) have to be compared with present ones (B_0 and C_0). The standard approach to making future net benefits equivalent to present net benefits is to *discount* the former by multiplying them with a so-called discount factor. Diminishing an expected future amount of money by means of discounting involves accounting for possible capital growth, because the present value of the future amount is the money that one would need right now (as initial principal sum) in order to obtain the given future value as the initial principal sum plus the accrued compound interest. Discounting can be performed either assuming a discrete process (illustrated in Sect. 6.5.1.1) or a continuous process (illustrated in Sect. 6.5.1.2) in time. Section 6.5.1.3 uses the example of electricity production to briefly illustrate the correct calculation of per unit costs (in this case costs per kilowatt-hour of electricity) when the relevant cost components are unevenly distributed over time.

6.5.1.1 Basic Concepts of Discrete Discounting

Assuming a discrete process with time steps of 1 year corresponds to the common approach taken in banking. Future net benefits or cash flows ($B_t - C_t$) are transformed into present values by multiplying $B_t - C_t$ by a *discount factor* $(1 + r)^{-t}$, where r is an interest rate that reflects the opportunity cost of capital. Opportunity costs are the benefits foregone from a hypothetical alternative use of the capital invested in the project under consideration. If the money had not been invested in this project, it could have been alternatively placed at an interest rate r. Future cash flows can only be compared to present cash flows ($B_0 - C_0$) by discounting. The discounted present value B_0 of a benefit B_t arising at the end of year t is given by

$$B_0 = \frac{B_t}{(1+r)^t} = B_t(1+r)^{-t}. \qquad (6.1)$$

Usually the so-called discount rate r to be chosen by the decision maker is the interest rate at which loans could be raised or the rate at which his own capital (equity) could be placed or a weighted average of these two interest rates (the weights corresponding to the shares of loans and equity used when investing). For example, assuming a discount rate of $r = 2\%$, the present value of an expected benefit of 100 € in $t = 5$ years is $B_0 = B_t(1 + r)^{-t} = 100 \text{ €} (1 + 0.02)^{-5}$

= 100 € × 0.90573 = 90.57 €. In this case, 100 euros available in 5 years have the same value as 90.57 € today. In other words: one would have to place 90.57 € today at a rate of return r of 2% in order to obtain a benefit of 100 € in 5 years.

For simplicity, assuming in investment appraisal that all yearly benefits $B_1, B_2, \ldots, B_T$ and all yearly costs $C_1, C_2, \ldots, C_T$ related to a certain project are *payments in arrears*, which means that in each case, they occur exactly *after t years* ($t = 1, 2, \ldots, T$), whereas the benefit B_0 and the cost C_0 are to be obtained or to be paid right now, one obtains the *Net Present Value (NPV)* of the project:

$$\mathrm{NPV} = \sum_{t=0}^{T} (B_t - C_t)(1+r)^{-t} \tag{6.2}$$

As a general rule, a project is only worthwhile as long as its NPV is positive. If the NPV is negative, this means the project is unprofitable. Of course, the NPV strongly depends on the assumptions made regarding the discount rate r and when calculating the net benefits $B_t - C_t$. Therefore, careful sensitivity analyses should be performed when calculating NPVs. For instance, one should always analyse how the NPV is affected by a ceteris paribus change of the discount rate applied. The NPV declines sharply with increasing discount rate, especially for projects like forest plantations that yield main net benefits particularly late in the future.

The *discounted payback period* [year k in Eq. (6.3)] is the first period at which the summed up discounted net benefits of an investment are greater than or equal to zero, so that

$$\begin{aligned}\mathrm{NPV}_k &= \sum_{t=0}^{k} (B_t - C_t)(1+r)^{-t} \\ &\geq 0 \quad \text{and} \quad \mathrm{NPV}_{k-1} \\ &= \sum_{t=0}^{k-1} (B_t - C_t)(1+r)^{-t} < 0. \end{aligned} \tag{6.3}$$

As long as future prices and costs contained in net benefits $\mathrm{NB}_t = B_t - C_t$ have been calculated at today's prices (i.e. not accounting for inflation), a real interest rate r (i.e. an interest rate adjusted for inflation) should be used when calculating the NPV. Where future net benefits already account for price increases due to inflation, the discount rate applied should be a nominal interest rate (i.e. the interest rate actually paid or received). For a given nominal interest rate rn and a given inflation rate in, the real interest rate r is

$$r = \frac{\mathrm{rn} - \mathrm{in}}{1 + \mathrm{in}} \tag{6.4}$$

For instance, a nominal interest rate $\mathrm{rn} = 4\%$ and an inflation rate $\mathrm{in} = 2\%$ yields a real interest rate $r = (0.04 - 0.02)/(1 + 0.02) = 0.0196 = 1.96\ \%$. Hence, for a relatively low inflation rate in, one can say that the real interest rate r approximately corresponds to the nominal interest rate rn minus the inflation rate in.

If an NPV is greater than zero, in principle, the corresponding project is worthwhile. If there are two alternative projects with identical capital needs (or in the case of plantations, with identical land requirements), the project yielding the higher NPV is to be preferred. However, as the NPV depends on the amount of capital invested, in the case of projects that require different amounts of capital, one should also examine the internal rates of return for the different investment alternatives. The *internal rate of return IRR* is the *discount rate that*—for given net benefits $(B_t - C_t)$—*leads to an NPV of zero*:

$$\mathrm{NPV} = 0 = \sum_{t=0}^{T} (B_t - C_t)(1 + \mathrm{IRR})^{-t}. \tag{6.5}$$

When calculating the IRR in this way, the implicit assumption is made that all positive net benefits (cash flows) obtained at the end of the different time periods $t < T$ can be reinvested at the corresponding IRR. For huge IRRs, however, this assumption is unrealistic. In such cases, a *modified IRR (MIRR)* is to be determined:

$$\mathrm{MIRR} = \sqrt[T]{\frac{\sum_0^T \mathrm{NB}_t^{\mathrm{pos}}(1+\mathrm{rr})^{T-t}}{\sum_0^T \mathrm{NB}_t^{\mathrm{neg}}(1+\mathrm{rf})^{-t}}} - 1. \tag{6.6}$$

where $\mathrm{NB}_t^{\mathrm{pos}}$ are all cash flows $B_t - C_t$ that are positive and can be reinvested at a rate of return rr and $\mathrm{NB}_t^{\mathrm{neg}}$ are the absolute values of all cash flows $B_t - C_t$ yielding negative amounts of money that need to be financed at an interest rate *rf*.

Constant annual cash flows in arrears (i.e. a constant yearly rent or an annuity $\mathrm{NB}_t = B_t - C_t = \text{constant} = \mathrm{NB}$ for all $t = 1, \ldots, T$) can be transformed into one single present value applying the *Present Value Annuity Factor (PVAF)*:

$$\mathrm{NPV} = \sum_1^T \mathrm{NB}(1+r)^{-t} = \mathrm{NB}\sum_1^T (1+r)^{-t} = \mathrm{NB}\frac{(1+r)^T - 1}{r(1+r)^T} = \mathrm{NB}\cdot\mathrm{PVAF}. \quad (6.7)$$

Thus, the PVAF transforms a *constant(!)* yearly payment *NB* (to be obtained for the next *T* years) into one single present value. Note that $t = 1, \ldots, T$ and that formula (6.7) applies for payments in arrears. In the case of a *perpetuity* (i.e. an 'eternal' annuity $\mathrm{NB}_t = \mathrm{NB}$ with $t = 1, \ldots, \infty$), the PVAF in formula (6.7) can be simplified:

$$\mathrm{NPV}_\infty = \sum_1^\infty \mathrm{NB}(1+r)^{-t} = \mathrm{NB}\sum_1^\infty (1+r)^{-t} = \mathrm{NB}\frac{1}{r} = \mathrm{NB}\cdot\mathrm{PVAF}_\infty. \quad (6.7a)$$

NPV_∞ is the amount of money that one would have to place today at an interest rate r in order to obtain a rent $\mathrm{NB} = r\,\mathrm{NPV}_\infty$ every year again and again (and for the first time at the end of year 1) without ever depleting the calculated necessary capital stock NPV_∞.

The reciprocal value of the *PVAF* is the *capital recovery factor (CRF)*, which transforms a single present value or payment into *T* constant yearly payments *NB* in arrears (to be obtained after each year t; $t = 1, \ldots, T$):

$$\mathrm{CRF} = \frac{1}{\mathrm{PVAF}} = \frac{r(1+r)^T}{(1+r)^T - 1}. \quad (6.8)$$

The capital recovery factor may also be used to convert the NPV of a project or investment into an average yearly profit (or loss) resulting from the corresponding project. For farmers, the notion of a yearly profit is easier to comprehend than the idea of an NPV that corresponds to the amount of money theoretically obtained when converting all project-related cash flows into present values and adding them up.

6.5.1.2 Basic Concepts of Continuous Discounting

Discrete discounting as introduced in the previous section is common business practice. However, continuous discounting by means of an interest rate ϱ that is applied continuously (at infinitely small time steps) to a capital stock K_t in order to add compound interest is easier to handle in mathematics than discrete discounting. Continuous capital growth K_t is described by means of Euler's number e (=2.71828…):

$$K_t = K_0 e^{\rho t} \Rightarrow \frac{dK_t}{dt} = \rho K_0 e^{\rho t} \Rightarrow \frac{dK_t}{dt} = \rho K_t \Rightarrow \frac{\frac{dK_t}{K_t}}{dt} = \frac{\dot{K}}{K_t} = \rho. \quad (6.9)$$

The unit of the capital growth rate ϱ is *% divided by the time unit* for which the capital growth function has been calibrated, e.g. *%/year*. Applying the formula for continuous compounding, one can again ask for the present value B_0 of a benefit B_t that will be available in t years:

$$B_t = B_0 e^{\rho t} \Rightarrow B_0 = B_t e^{-\rho t}. \quad (6.10)$$

Thus, the term $e^{-\varrho \cdot t}$ is the *discount factor for continuous discounting*. Hence, given a discount rate of $\varrho = 2\%$, the present value of an expected benefit of 100 € in $t = 5$ years gives a present value $B_0 = 100$ € $e^{-0.02 \times 5} = 90.48$ €. So, according to this calculation, in 5 years, 100 € have the same value as 90.48 € today. This is less than the 90.57 € found in the case of discrete discounting above using Eq. (6.1) at a discount rate of 2%. The reason for this discrepancy is that one needs slightly less money today in order to have 100 € in 5 years when compound interest (i.e. the interest on interest) is calculated and added continuously. Every discount rate r (for discrete discounting) can be transformed into an equivalent discount rate ϱ (for continuous discounting):

$$B_0 = B_T(1+r)^{-T} = B_T \mathrm{e}^{-\rho T} \Rightarrow \\ \rho = \ln(1+r). \qquad (6.11)$$

So, if $r = 2\%$, the equivalent rate $\varrho = \ln(1 + 0.02) = 0.01980 = 1.98\%$ and, for the example, $B_0 = 100\ € \ \mathrm{e}^{-0.0198 \times 5} = 90.57$ €. In the case of continuous discounting, the real interest rate (ϱ) corresponds exactly to the difference between the nominal interest rate and the inflation rate (ϱn − in). If all cash flows $B_t - C_t$ always occur in arrears at the end of year t ($t = 1, \ldots, T$), we can write

$$\mathrm{NPV} = \sum_{t=0}^{T} (B_t - C_t)\mathrm{e}^{-\rho t}. \qquad (6.12)$$

For constant net benefits in arrears $\mathrm{NB}_t = B_t - C_t = \mathrm{NB}(t = 1, \ldots, T)$, we obtain

$$\begin{aligned} \mathrm{NPV} &= \mathrm{NB}_0 + \sum_{t=1}^{T} \mathrm{NBe}^{-\rho t} \\ &= \mathrm{NB}_0 + \mathrm{NB}\sum_{t=1}^{T} \mathrm{e}^{-\rho t} \\ &= \mathrm{NB}_0 + \mathrm{NB}\frac{\mathrm{e}^{\rho T} - 1}{(\mathrm{e}^{\rho} - 1)\mathrm{e}^{\rho T}} \\ &= \mathrm{NB}_0 + \mathrm{NB} \cdot \mathrm{PVAF} \qquad (6.13) \end{aligned}$$

In the case of a *perpetuity* (i.e. an 'eternal' annuity $\mathrm{NB}_t = \mathrm{NB}$ with $t = 1, \ldots, \infty$), the *continuous discounting Present Value Annuity Factor (PVAF)* simplifies to $\mathrm{PVAF} = 1/(\mathrm{e}^{\varrho} - 1)$. Again, the capital recovery factor (*CRF*) transforming a single present payment into T yearly payments (always to be obtained at the end of year t; $t = 1, \ldots, T$) is given by the reciprocal value of the *PVAF*:

$$\mathrm{CRF} = \frac{1}{\mathrm{PVAF}} = \frac{(\mathrm{e}^{\rho} - 1)\mathrm{e}^{\rho T}}{\mathrm{e}^{\rho T} - 1}. \qquad (6.14)$$

In the special case of a *constant flow of money throughout the whole year* NB_{fl} (i.e. a constant yearly amount $\mathrm{NB}_{\mathrm{fl}}$ is equally distributed over the year t, $t = 1, \ldots, T$), the money obtained at every time span Δt amounts to $\mathrm{NB}_{\mathrm{fl}} \cdot \Delta t$. Assuming infinitely small time steps $\Delta t = \mathrm{d}t$, discounting and summing up these payments yields

$$\begin{aligned} \mathrm{NPV} &= \int_0^T \mathrm{NB}_{\mathrm{fl}}\mathrm{e}^{-\rho t}\mathrm{d}t = \mathrm{NB}_{\mathrm{fl}} \int_0^T \mathrm{e}^{-\rho t}\mathrm{d}t \\ &= \frac{1 - \mathrm{e}^{-\rho T}}{\rho}\mathrm{NB}_{\mathrm{fl}} = \mathrm{PVAF} \cdot \mathrm{NB}_{\mathrm{fl}}. \qquad (6.15) \end{aligned}$$

where T approaches infinity—analogous to the case of discrete discounting [see Eq. (6.7a)]; the PVAF collapses to $1/\varrho$.

6.5.1.3 Calculating Average Cost-Covering Prices for (Bio-)energy

When comparing different ways of producing energy, the average cost per unit (e.g. of electricity expressed in Euro per kWh) needs to be correctly calculated. In principle, this average cost corresponds to a hypothetical *cost-covering electricity price* ($P_t = P$) in Euro per kilowatt-hour (€/kWh) that is assumed to be constant over the years t. The International Energy Agency (IEA) calls this cost-covering electricity price *Levelized Costs of Electricity* (*LCOE*). To fully cover all costs, the present value of all benefits needs to be equivalent to the present value of all costs (general representation):

$$
\sum_{t=0}^{T} P \cdot E_t (1+r)^{-t} + \sum_{t=0}^{T} H_t (1+r)^{-t} = \sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t)(1+r)^{-t} \Rightarrow
$$

$$
\mathrm{LCOE} = P = \frac{\sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t - H_t)(1+r)^{-t}}{E_0 + \sum_{t=1}^{T} E_t (1+r)^{-t}} \tag{6.16}
$$

where I_t = Investment expenditures in year t; M_t = Operations and maintenance expenditures in year t; F_t = Fuel expenditures (if relevant) in year t; C_t = Carbon costs in year t (if relevant); D_t = Decommissioning costs in year t; H_t = Value of heat produced in year t (if relevant); r = real discount rate (here: discrete discounting, for continuous discounting, the discount factors $(1 + r)^{-t}$ are to be replaced by $e^{-\rho \cdot t}$); E_t = Electricity generation in kWh in year t; and $P = LCOE$ = Cost-Covering Electricity Price (Levelized Costs of Electricity) in €/kWh. Assuming that $E_0 = 0$ (i.e. no electricity can be produced during the initial year when the power plant is built) and that for $t = 1$ through T the yearly energy production $E_t = E$ is constant, we can write

$$
P = \frac{\sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t - H_t)(1+r)^{-t}}{E \sum_{t=1}^{T} (1+r)^{-t}} = \frac{\sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t - H_t)(1+r)^{-t}}{E \cdot \mathrm{PVAF}}. \tag{6.16a}
$$

Given that expenditures I_t occur at the beginning and costs D_t at the end of corresponding projects, it should be considered how an increasing discount rate r applied by decision makers affects the average cost calculation according to Eq. (6.16) with respect to the cost components I_t and D_t. An interesting application and comparison of LCOE for different renewable energy technologies is given in Kost et al. (2013).

6.5.1.4 Cost-Benefit Analysis and Environmental Externalities

Externalities related to natural and environmental resources use result mainly from regulating and cultural ecosystem services. Social losses from resource degradation associated with certain production activities need to be accounted for when carrying out thorough bioeconomic cost-benefit analyses or cost calculations. The monetary valuation of corresponding externalities is beyond the scope of this chapter. Here, in the context of investment appraisal, we concentrate on how to find an adequate discount rate to apply when dealing with environmental benefits (or possible benefits foregone) that occur partly far in the future. Many resource-use decisions have a long-term impact, especially when they lead to resource depletion or ecosystem degradation. Hence, when discounting future environmental benefits, two questions arise: (1) Should common economic net benefits be discounted in the same way as the value of ecosystem services linked to nature preservation? (2) Which discount rate should be chosen when dealing with very long time horizons exceeding our own lifetime?

1. To answer the first question, the ideas put forward by Krutilla and Fisher (1975) may be useful: Let $B(D)_t$ be the annual benefit (e.g. farm produce) valued at today's market prices arising in year t from the development of some pristine land (e.g. forestland or moor) that is converted to farmland in year $t = 0$. $C(D)_t$ is the corresponding annual cost incurred when purchasing all inputs necessary to maintain production. These costs are also valued at present market prices. In contrast, $B(P)_t$ is the social benefit resulting from the ecosystem services provided by the pristine land. These annual environmental benefits will be forgone once the land is converted. They may be referred to as benefits of 'wilderness' preservation. Also, these yearly benefits, which are

benefits foregone once the land is converted, are assessed based on today's price and income conditions. ϱ is a real discount rate for continuous discounting. (N.B.: inflation does not matter in this context, as it is simply a general price increase.) Then the NPV of the development project is

$$\mathrm{NPV} = \int_0^T \{B(D)_t - C(D)_t\} \mathrm{e}^{-\rho t} \mathrm{d}t - \int_0^T B(P)_t \mathrm{e}^{-\rho t} \mathrm{d}t, \tag{6.17}$$

the second integral being the overall environmental cost of the development project in terms of 'wilderness' benefits foregone. The interesting question now is how the values $B(D)_t$, $C(D)_t$ and $B(P)_t$ will evolve over time relative to each other. In this context, Krutilla and Fisher (1975) believe that the relative value of benefits from 'wilderness' preservation $B(P)_t$ is likely to increase over time when compared to the prices contained in $B(D)_t$ and $C(D)_t$. The reasons for this are (1) the prospects of ongoing economic growth and technical progress that will reduce the relative value of the net benefits $B(D)_t - C(D)_t$ resulting from the development of the pristine land, (2) supposed high-income elasticities of demand for certain ecosystem services from 'wilderness' in contrast to stagnating (or even decreasing) supply of such services and (3) lack of substitution possibilities for these ecosystem services. Assuming the value of benefits from 'wilderness' preservation is given by $B(P)_t = BP_0 \, \mathrm{e}^{\alpha t}$ with BP_0 being its present value and α the rate at which this value grows over time, we can write

$$\mathrm{NPV} = \int_0^T \{B(D)_t - C(D)_t\} \mathrm{e}^{-\rho t} \mathrm{d}t - \int_0^T BP_0 e^{\alpha t} \mathrm{e}^{-\rho t} \mathrm{d}t \tag{6.18}$$

Further assuming that the annual benefit BP_0 is equally distributed over the year and that the 'wilderness' benefits could be enjoyed for an infinite number of years ($T \rightarrow \infty$) if pristine land was preserved, applying Eq. (6.15) yields

$$\begin{aligned} \mathrm{NPV} &= \int_0^T \{B(D)_t - C(D)_t\} \mathrm{e}^{-\rho t} \mathrm{d}t - BP_0 \int_0^\infty \mathrm{e}^{-(\rho - \alpha)t} \mathrm{d}t \\ &= \int_0^T \{B(D)_t - C(D)_t\} \mathrm{e}^{-\rho t} \mathrm{d}t - \frac{BP_0}{\rho - \alpha}. \end{aligned} \tag{6.19}$$

Hence, the larger the assumed growth rate α (i.e. the future relative value increase of ecosystem services emanating from pristine land), the less likely it is that the project should go ahead. When the rate α is close to or even equals the discount rate ϱ, the development project should not be implemented (as then $BP_0/(\varrho - \alpha) \rightarrow \infty$). One should be aware that in practice, no matter what the assumed values of $B(D)_t$, $C(D)_t$ and $B(P)_t$ are, the project decision finally made by policy-makers strongly depends on their individual discount rates as well as on their assumptions of how the scarcity of 'wilderness'-related ecosystem services will increase in the future.

2. Applying a high discount rate in cost-benefit analysis when future environmental benefits are at stake means that these benefits receive a particularly low weight (the lower the farther in the future they occur). When increasing the discount rate applied, the NPV of a development project that contains environmental costs as future benefits forgone is then more prone to become positive. This is the case at least as long as the initial investment cost is relatively small and especially when the useful life of the project is much shorter than the expected time span during which the corresponding environmental impacts are relevant. One may think about nuclear energy and its very long-lasting environmental impact in this context.

Discounting future generations' benefits foregone entailed by today's resource use means systematically diminishing the opportunity costs inflicted on people living in the future. It is an ethical issue whether this is acceptable or not. It is frequently argued that the *social discount rate*, applied by a benevolent government explicitly accounting for the welfare of future generations, should be lower than common *private discount rates*, applied by private decision makers who are planning for their own business and usually deal with time horizons covered by their expected lifetimes. However, there may also be reasons for using relatively high social discount rates in project appraisal: firstly, this is not always unfavourable for the environment, as a high discount rate means not only attributing low weight to environmental damages in the far future but also lower weight to project benefits in the medium term (this aspect is more relevant the higher the initial investment cost). Secondly, applying relatively high discount rates is justified when believing that through economic growth, future generations will be wealthier than the current generation and able to substitute the lost environmental benefits in question. Thus, the answer to the question which discount rate to use then partly depends on how optimistic we are about future technical progress and resource substitution possibilities. When no substitute for an essential ecosystem service is in sight, a low discount rate is to be chosen, as suggested by *Krutilla* and *Fisher*. Following ideas expressed by Weitzman (1998), the discount rate applied may also depend on the time horizon t itself:

$$\mathrm{NPV} = \int_{0}^{T} \{B(D)_t - C(D)_t - B(P)_t\} \mathrm{e}^{-\rho_t t} \mathrm{d}t \text{ with } \rho_t = \rho(t) \text{ and } \frac{\mathrm{d}\rho}{\mathrm{d}t} \leq 0. \tag{6.20}$$

This involves using higher discount rates (derived from common market interest rates) for the relatively near future or for time periods within the decision makers' own expected lifetime. For the remote future, lower discount rates should be applied. This last point is all the more relevant as one does not believe in ongoing future growth of wealth.

6.5.2 Biological Growth Functions

When trying to optimize the use of a renewable resource, one needs to describe the development of the corresponding resource stock over time. Often it is adequate to describe biological growth as a function of current stock volume S_t. Defining

$$\frac{\mathrm{d}S_t}{\mathrm{d}t} = S'(t) = \dot{S} = \text{rate of change}, g(S_t) = \frac{\frac{\mathrm{d}S_t}{\mathrm{d}t}}{S_t} = \frac{\dot{S}}{S_t} = \text{growth rate of the stock},$$

then $G(S_t) = g(S_t) \cdot S_t$ is the biological growth function or regeneration function giving the related net biological growth $G(S_t)$ for every stock size S_t. In the simplest case when the rate of change ($\mathrm{d}S_t/\mathrm{d}t$) is proportionate to the current stock (meaning that $g(S_t) = g$ is a constant), we have exponential growth (see the dotted graph and the corresponding differential equation in Fig. 6.35).

However, an undisturbed evolution of the wood volume of a plantation is more likely to correspond to the simple logistic growth displayed in Fig. 6.35. For small stock sizes S_t, the value of the bracket in the differential equation for logistic growth is close to 1. Thus, at the beginning, there will be exponential growth; then, the growth rate of the stock will continuously decline until the stock volume asymptotically approaches an upper limit. The quadratic growth function or regeneration function $G(S_t)$ leading to logistic growth is said to be density dependent (the growth depending on plant or population density). $G(S_t)$ is a differential equation as the derivative of S_t is a function of S_t itself:

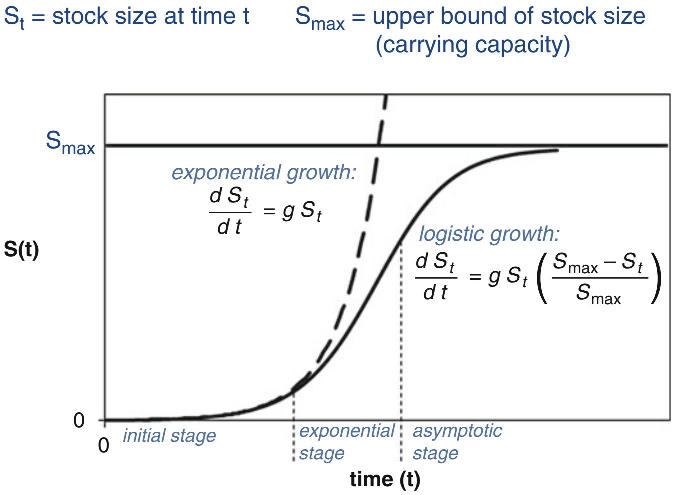

Fig. 6.35 Stock size over time for exponential growth and for logistic growth

$$G(S_t) = \frac{\mathrm{d}S_t}{\mathrm{d}t} = gS_t\left(\frac{S_{\max} - S_t}{S_{\max}}\right) = gS_t - \frac{g{S_t}^2}{S_{\max}}. \tag{6.21}$$

Solving Eq. (6.21) for S_t yields the development of the stock volume over time for an initial stock size S_0:

$$S_t = \frac{S_{\max}}{1 - \left(\frac{S_0 - S_{\max}}{S_0}\right)\mathrm{e}^{-gt}}. \tag{6.22}$$

For convenience, when modelling the growth of a plantation for a certain codomain of time, function (6.22) may be approximated relying upon a cubic function $S_t = a^*t + b^*t^2 + c^*t^3$ (a and b being positive parameters, c being a negative parameter).

However, there may be additional (e.g. harvest-related) factors influencing $\mathrm{d}S_t/\mathrm{d}t$ in every time period that further complicate the growth function and the resulting equation describing the stock volume over time S_t. In such cases and when there is a clear functional relationship between $\mathrm{d}S_t/\mathrm{d}t = S'(t)$ and S_t, we may rely on the *Euler method* (according to *Leonhard Euler*, 1707–1783) to model stock development over time. This method is a numerical procedure to approximately solve differential equations for which an initial value is known. Its basic principle is to calculate stock size $S(t_{k+1})$ at point in time $t_{k+1}(=t_k + \Delta t)$ by simply adding the change [derived from the known function $G(S_t)$] taking place during time period Δt to the stock size $S(t_k)$ at point in time t_k:

$$S(t_{k+1}) = S(t_k + \Delta t) \approx S(t_k) + S'(t_k)\Delta t. \tag{6.23}$$

If this procedure is repeated again and again, one obtains an approximation for the development of the stock volume $S(t_k)$ at consecutive points in time t_k with $k = 0, \ldots, T - 1$). The resulting time path $S(t)$ will be the more accurate the smaller the chosen time step Δt.

6.5.3 Forest Economics and Bioeconomic Modelling of Plantations

From an institutional economics point of view and accounting for different possible institutional settings, natural forests yield different kinds of resources. Forests provide renewable resources as *private goods*: resource units can be allocated on the margin (i.e. consumed in small units), and property rights are usually enforceable (e.g. timber in German forests). Other forest-related renewable resources are *common pool resources*: resource units can be allocated on the margin; there is rivalry in consumption, but excludability is only obtained at prohibitively high cost (e.g. mushrooms in German forests). Thus, whether a resource is a private good or a common pool resource depends on the specific distribution of property rights along with local institutions and transaction costs for the enforcement of property rights. In addition, forests yield several *environmental resources as public goods (or forest use-related positive externalities)* that cannot be allocated on the margin and whose beneficiaries usually cannot be excluded and do not affect each other's utility (i.e. non-excludability and non-rivalry in consumption) (e.g. many forest-related ecosystem services). Further examples of forest-related private or common pool resources are fuelwood, charcoal, pulpwood, timber, fruits, nuts, mushrooms, medicinal plants, honey, wild game, drinking and irrigation water. Examples of positive externalities are protection against landslides, recreational and aesthetic amenities, cultural ecosystem services and regulating ecosystem services including the provision of plant and animal habitats, soil formation and nutrient cycling, water and air quality regulation, waste decomposition, climate regulation and CO_2 storage. Hence, forests are multi-attribute assets, and this should be kept in mind when analysing optimum harvesting strategies. In the following sections, however, we will focus on wood production as in traditional forest management. Forest land or a forest plantation can be seen as a capital asset with intrinsic growth and often an opportunity cost as the land could be used otherwise. The objective is to maximize the NPV of a forest plantation. First, a single rotation will be considered (i.e. trees are planted and logged at age T, then the land is used for a non-forest purpose, e.g. for agriculture). Second, optimization will be performed for an infinite rotation (i.e. the same tree species are replanted after every clear-cutting). Third, we will briefly discuss how positive forest externalities affect optimum harvest strategies (for further information, see Perman et al. 2011).

6.5.3.1 Optimum Resource Use in a Single-Rotation Forest Model

Let kpl be the initial planting costs (at time $t = 0$); P today's price per unit of harvested timber; c the marginal harvest cost—so that $p = P - c$ is the so-called stumpage price (value of a timber unit free of harvest cost); R the opportunity cost of the forest land (e.g. agricultural land rent foregone); ϱ the real discount rate (continuous discounting); T the harvest age of the stock (i.e. the time when the plantation is to be clear-cut); and S_T the volume of the stock reached at time T. Thus, the harvest age T is to be chosen in a way that maximizes the following NPV:

$$\mathrm{NPV}(T) = -kpl - \int_{t=0}^{T} R\,\mathrm{e}^{-\rho t}\mathrm{d}t + pS_T\mathrm{e}^{-\rho T}. \tag{6.24}$$

As the land's opportunity cost is constant over time and applying Eq. (6.15), we get

$$\mathrm{NPV}(T) = -kpl - R\frac{1-\mathrm{e}^{-\rho T}}{\rho} + pS_T\mathrm{e}^{-\rho T}. \tag{6.25}$$

Calculating the first derivative of NPV(T) and rearranging the first-order condition $\mathrm{NPV}'(T) = 0$, necessary to achieve an optimum, we find

$$p\frac{\mathrm{d}S_T}{\mathrm{d}t} = \rho p S_T + R. \tag{6.26}$$

Consequently, the optimum harvest time T is reached when in the last year of forest use (in period T), the stumpage value of the last period's stock increase ($p\ S_T/\mathrm{d}t$ = additional income when waiting one more period) is equal to the interest to be earned when harvesting the whole stock ($\varrho\ p\ S_T$ = additional income when converting attained forest capital into cash) plus the opportunity cost of the land (R = additional income when using the land alternatively, e.g. for crop production). If the value increment from forest growth on the left-hand side of Eq. (6.26) is still greater than the opportunity cost of bound capital and land displayed on the right-hand side, it is still better to wait with the harvest and let the forest grow instead of capitalizing on the harvested wood. One could also say that we are comparing possible biological growth with economic growth possibilities (a truly 'bioeconomic' consideration). Rearranging the optimum condition slightly (6.27) yields

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{R}{pS_T}. \tag{6.27}$$

implying that, at optimum harvest time T, the growth rate of the stock should be equal to the real interest rate plus the relative capital increase from alternative land use, or the growth rate of the stock should equal the possible rate of return of the capital bound (incl. land). The latter is the possible capital growth rate when converting the forest (the natural capital) into cash.

6.5.3.2 Optimum Resource Use in an Infinite-Rotation Forest Model

Where there are no alternative land-use possibilities (i.e. $R = 0$), it does not really make sense to assume that the forest land will be left fallow after T years. If the forest plantation turned out to be profitable ($\mathrm{NPV}(T) > 0$), the plantation should be replaced after clear-cutting in year T, which means that at time T, the NPV (T) can be obtained again. But then, as long as all assumed price and cost parameters do not change, reforestation should be done again and again at points in time T, $2T$, $3T$, …, nT with n approaching infinity. This is the case for an *infinite* (sequence of) *rotation*(s) with T being the *rotation length*. As the NPV of an infinite rotation is the NPV of the first rotation plus the discounted (residual) value of the land after clear-cutting in year T, we can write

$$\mathrm{NPV} = -kpl + pS_T\mathrm{e}^{-\rho T} + \mathrm{NPV}\,\mathrm{e}^{-\rho T}. \tag{6.28}$$

Hence, the NPV of an infinite rotation is the NPV due to the land use of the first T periods plus the discounted NPV of the same infinite rotation. This second term accounts for the still infinite sequence of rotations from period T onwards. Solving Eq. (6.28) for NPV gives

$$\mathrm{NPV}(T) = \frac{pS_T\mathrm{e}^{-\rho T} - kpl}{1 - \mathrm{e}^{-\rho T}}. \tag{6.29}$$

A similar expression could be deduced for the case of discrete discounting. Again, we can use the first-order condition $\mathrm{NPV}'(T) = 0$ to derive an optimum condition that needs to be fulfilled at harvest time T (and at times $2T$, $3T$, …, nT as well). This way, we obtain the so-called Faustmann rule (in honour of *Martin Faustmann*, 1822–1876):

$$\frac{p\,\frac{\mathrm{d}S_T}{\mathrm{d}t}}{pS_T - kpl} = \frac{\rho}{1 - \mathrm{e}^{-\rho T}}. \tag{6.30}$$

Solving Eq. (6.29) for kpl and entering the corresponding term for kpl into (6.30) yields, after rearranging a condition that is quite similar to condition (6.27) above:

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{\rho\mathrm{NPV}}{pS_T}. \tag{6.31}$$

The rotation length T is to be chosen so that when harvesting, the growth rate of the stock just equals the interest rate plus the relative capital increase due to the average land rent from future forest use. Again, the possible growth rate of the stock should be equal to the possible rate of return of the capital bound (incl. land). ϱNPV is the perpetuity (the 'eternal' annuity) from continuous forest use. In this context, the NPV is also referred to as 'site value' of the forest land (i.e. the maximized NPV from an infinite number of rotations).

6.5.3.3 Forest Model with Positive Externalities

Finally, it should be discussed how the forest externalities mentioned above affect wood-harvesting strategies. For simplicity, let us assume that these external benefits *FE* (e.g. from habitat support or landscape amenities) occur after a certain time once the forest has been planted and remain constant until clear-cutting at time T. From a social point of view, and according to the same reasoning that led to condition (6.27) for the single-rotation forest model, the optimum condition to determine harvest time now is

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{R - \mathrm{FE}}{pS_T}. \tag{6.32}$$

The opportunity cost of the land (R) is diminished by the welfare gains due to forest externalities (FE). As the right-hand side of this optimum condition is smaller now than in the case of $\mathrm{FE} = 0$, and considering the growth rate of the stock is declining because of logistic growth, the optimum harvest age T will occur later than when merely considering wood benefits. Not surprisingly, positive forest externalities will delay clear-cutting and forest replacement by an alternative land use.

The optimum conditions for traditional forest management derived in this chapter should be applied when dealing with certain types of plantations. However, one should be aware that, given the multiple beneficial ecosystem services related to the existence of natural forests, clear-cutting of forests should be avoided. According to § 5 (3) of the *German Federal Nature Conservation Act*, forests should be managed sustainably without clear-cutting. *Selective forestry* to obtain near-natural forests is to be implemented instead. This allows for continuous wood harvest and natural regeneration. The issue of optimum forest use over time then turns out to be a question of realizing *maximum sustainable yield*. In principle, this means the forest manager needs to find the stock volume at which the forest regeneration function $G(S)$ [see Eq. (6.21) as an example] is at its maximum.

6.5.4 Determining the Optimal Replacement Time in Agriculture and Horticulture

The reasoning applied in Sect. 6.5.3 can be easily extended to assets or projects that also involve benefits and costs between time periods 0 and T (e.g. hop gardens, rubber plantations, greenhouses). In addition to the symbols already introduced, let ka be the initial investment cost for the asset considered (at time $t = 0$) and Ra_T the residual value (salvage value) of the asset that is received at time T. The NPV of such an investment is

$$\begin{aligned}\mathrm{NPV}(T) = &-ka \\ &+ \sum_{t=1}^{T} (B_t - C_t - R)\mathrm{e}^{-\rho t} \\ &+ Ra_T \mathrm{e}^{-\rho T}.\end{aligned} \tag{6.33}$$

The ex ante *optimum useful lifetime T* is again obtained by considering $\mathrm{NPV}'(T) = 0$ leading to

$$B_T = C_T + R - \frac{\mathrm{d}Ra_T}{\mathrm{d}t} + \rho Ra_T. \tag{6.34}$$

This means the optimum lifetime of the investment is reached once the marginal benefit when using the asset one more period (B_T) is equal to the marginal cost of using it one more period. This marginal cost consists of additional operating costs (C_T) plus the opportunity cost of the land needed (R) plus the amount of the loss due to a reduced residual value ($\mathrm{d}Ra_T/\mathrm{d}t$ is negative and corresponds to depreciation of the asset) plus the interest forgone because the residual value is cashed one time period later (ϱRa_T).

In the case of identical replacement of the asset, analogous to Eq. (6.29), the NPV of an infinite sequence of the corresponding investment is

$$\mathrm{NPV}(T)=\frac{-ka+\sum_{t=1}^{T}(B_t-C_t)\mathrm{e}^{-\rho t}+Ra_T\mathrm{e}^{-\rho T}}{(1-\mathrm{e}^{-\rho T})}=\frac{\mathrm{NPV}(T)^*}{(1-\mathrm{e}^{-\rho T})}. \tag{6.35}$$

$\mathrm{NPV}(T)^*$ being the NPV of a single investment. For discrete discounting, the NPV of an infinite identical replacement is

$$\mathrm{NPV}(T)=\frac{-ka+\sum_{t=1}^{T}(B_t-C_t)(1+r)^{-t}+Ra_T(1+r)^{-T}}{1-(1+r)^{-T}}=\frac{\mathrm{NPV}(T)^*}{1-(1+r)^{-T}}. \tag{6.36}$$

Calculating $\mathrm{NPV}(T)$ using Eqs. (6.35) or (6.36) for different possible replacement times T and thus searching for the highest NPV lead to the optimum ex ante *replacement time* of the asset. Ex ante *decision situation* here means that the corresponding asset is not yet purchased or the plantation not yet implemented, and one wants to determine the optimum useful life given expected prices and costs before starting the project.

In contrast, in an ex post *decision situation*, the asset or the plantation is already being used, and one wants to know when to replace it by an alternative or identical land use. Very important when making ex post decisions on how long to continue the use of an asset, a plantation or a forest stand, the initial investment costs of the *present* use (*kpl* or *ka*) do not matter! Once an investment has been implemented, these initial costs are so-called sunk costs already paid for in the past. Such sunk costs cannot be recovered. In ex post decision situations, marginal net benefits of the current land use have to be compared to average net benefits (ANB) of the considered possible future land use:

$$B_T-C_T+\frac{\mathrm{d}Ra_T}{\mathrm{d}t}-\rho Ra_T=\mathrm{ANB}. \tag{6.37}$$

As long as the marginal net benefit when continuing to use the old asset [i.e. the left-hand side of Eq. (6.37)] is still greater than the ANB of the future use, the current use should be continued. ANB is to be calculated for the new replacing investment using Eqs. (6.33) or (6.35). Note that in Eq. (6.37), $\mathrm{d}Ra_T/\mathrm{d}t$ (i.e. the depreciation in period T) is usually negative.

Review Questions

- Explain the basic difference between discrete and continuous discounting.
- In which cases can one make use of a *Present Value Annuity Factor* (*PVAF*) when calculating a *Net Present Value* (*NPV*), and under which conditions does this factor collapse to ‘one divided by the discount rate’?
- Explain and illustrate by means of a formula containing the main cost components how to calculate cost-covering electricity prices for a biogas plant.
- Following the ideas of *Krutilla* and *Fisher*, what are the reasons the future value of certain ecosystem services (i.e. benefits related to ‘wilderness’ preservation) should be discounted at relatively low discount rates in a cost-benefit analysis?
- Explain the basic concept of the *Euler method*.
- Write down and explain the *Net Present Value* (*NPV*) of (a) *a single-rotation forest model* and (b) *an infinite-rotation forest model*—with reference to the growth rate of the stock. For both cases, give an optimum condition that is to be met when maximizing the NPV.
- Explain how to identify the ex ante *optimum useful lifetime* of an agricultural asset (e.g. a rubber plantation) (a) in the case of an alternative land-use opportunity and (b) in the case of identical replacement.
- Give a rule for the optimum replacement time in an ex post *decision situation*, and explain why so-called sunk costs do not matter in this context.

References

Ahmed F, Fanning K, Netzel M et al (2014) Profiling of carotenoids and antioxidant capacity of microalgae from subtropical coastal and brackish waters. Food Chem 165:300–306. https://doi.org/10.1016/j.foodchem.2014.05.107

Ahmed F, Zhou W, Schenk PM (2015) Profiling of carotenoids and antioxidant capacity of microalgae from subtropical coastal and brackish waters. Algal Res 10:210–217. https://doi.org/10.1016/j.algal.2015.05.013

Albion RG (1926) Forests and sea power: the timber problem of the royal navy, 1652–1862. Revised edition (December 1999) edn. US Naval Institute Press

Anderson JL (2012) Mahogany – the costs of luxury in early America. Harvard University Press, Cambridge

Arbeitsgemeinschaft Forsteinrichtung/Arbeitskreis für Standortskartierung (1985) Forstliche Wuchsgebiete und Wuchsbezirke in der Bundesrepublik Deutschland. Landwirtschaftsverlag, Münster-Hiltrup

Baldock D, Mitchell K (1995) Cross-compliance within the common agricultural policy: a review of options for landscape and nature conservation. Institute of European Environmental Policy, Brussels

Batista AP, Gouveia L, Bandarra NM et al (2013) Comparison of microalgal biomass profiles as novel functional ingredient for food products. Algal Res 2: 164–173. https://doi.org/10.1016/j.algal.2013.01.004

Bebe BO, Udo HMJ et al (2003) Smallholder dairy systems in the Kenya highlands: cattle population dynamics under increasing intensification. Livest Prod Sci 82(2-3):211–221. https://doi.org/10.1016/S0301-6226(03)00013-7

Becker EW (2007) Micro-algae as a source of protein. Biotechnol Adv 25:207–210. https://doi.org/10.1016/j.biotechadv.2006.11.002

Bergmann P et al (2013) Disposable flat panel airlift photobioreactors. Chem Ing Tech. 85:202–205. https://doi.org/10.1002/cite.201200132

BMEL (2017) Bundesministerium für Ernährung und Landwirtschaft. http://www.bmel-statistik.de/

Bouwman AF, Van Der Hoek KW et al (2005) Exploring changes in world ruminant production systems. Agric Syst 84(2):121–153. https://doi.org/10.1016/j.agsy.2004.05.006

Brennan L, Owende P (2010) Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sustain Energy Rev 14:557–577. https://doi.org/10.1016/j.rser.2009.10.009

Bruinsma J (2003) World agriculture: towards 2015/2030. An FAO perspective. Food and Agriculture Organization (FAO). https://doi.org/10.1016/S0264-8377(03)00047-4

Busing RT, Fujimori T (2005) Biomass, production and woody detritus in an old coast redwood (Sequoia sempervirens) forest. Plant Ecol 177(2):177–188

Byelashov OA, Griffin ME (2014) Fish in: fish out: perception of sustainability and contribution to public health. Fisheries 39(11):531–535. https://doi.org/10.1080/03632415.2014.967765

Cerón-García MC, Fernández-Sevilla JM, Sánchez-Mirón A et al (2013) Mixotrophic growth of Phaeodactylum tricornutum on fructose and glycerol in fed-batch and semi-continuous modes. Bioresour Technol 147:569–576. https://doi.org/10.1016/j.biortech.2013.08.092

Chini Zittelli G, Lavista F, Bastianini A et al (1999) Production of eicosapentaenoic acid by Nannochloropsis sp. cultures in outdoor tubular photobioreactors. J Biotechnol 70:299–312. https://doi.org/10.1016/s0168-1656(99)00082-6

Das P, Thaher MI, Hakim MAQM et al (2015) Sustainable production of toxin free marine microalgae biomass as fish feed in large scale open system in the Qatari desert. Bioresour Technol 192:97–104. https://doi.org/10.1016/j.biortech.2015.05.019

Dauber J, Brown C et al (2012) Bioenergy from "surplus" land: environmental and socio-economic implications. BioRisk. https://doi.org/10.3897/biorisk.7.3036

Davis SC, Hay W, Pierce J (2014) Biomass in the energy industry: an introduction. Published by BP p.l.c.

De Silva SS (1995) Supplementary feeding in semi-intensive aquaculture systems. In: New MB, Tacon AGJ, Csavas I (eds) Farm-made aquafeeds. FAO Fisheries Technical Paper 343. FAO, Rome, pp 24–60

Dixon J, Gulliver A, Gibbon D (2001) Farming systems and poverty: improving farmers' livelihoods in a changing world. FAO/World Bank, Rome/Washington, DC. https://doi.org/10.1017/S0014479702211059

DJV (2017) DJV-Handbuch Jagd. DJV-Service GmbH, Bonn

Dornburg V, van Vuuren D et al (2010) Bioenergy revisited: key factors in global potentials of bioenergy. Energy Environ Sci. https://doi.org/10.1039/b922422j

Eastridge ML, Starkey RA et al (2017) Dairy cows fed equivalent concentrations of forage neutral detergent fiber from corn silage, alfalfa hay, wheat straw, and corn stover had similar milk yield and total tract digestibility. Anim Feed Sci Technol 225:81–86

Edwards P, Pullin RSV, Gartner JA (1988) Research and education for the development of integrated crop-livestock-fish farming systems in the tropics. International Center for Living Aquatic Resources Management, Manila

FAO (1982) Classification and definitions of forest products. Food and Agriculture Organization of the United Nations, Rome, p 250

FAO (1997) Aquaculture development. FAO Technical Guidelines for Responsible Fisheries 5. FAO, Rome

FAO (2000) On the definition of forest and forest change. Food and Agriculture Organization of the United Nations, Rome, p 15

FAO (2002) World agriculture: towards 2015/2030. An FAO perspective, Food Agricultural Organisation. Earthscan Publications Ltd, London, p 106

FAO (2010) Global forest resources assessment 2010. Food and Agriculture Organization of the United Nations, Rome

FAO (2014) The state of world fisheries and aquaculture 2014. Opportunities and Challenges. Rome

FAO (2015a) Global forest resources assessment 2015. Food and Agriculture Organization of the United Nations, Rome

FAO (2015b) Fisheries and Aquaculture Department, Statistics and Information Service FishStatJ: Universal software for fishery statistical time series

FAO (2016) The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all. Rome

FAO (2017a) What is conservation agriculture? http://www.fao.org/ag/ca/1a.html. Accessed 8 Jan 2017

FAO (2017b) FAOSTAT-forestry database. Food and Agriculture Organization of the United Nations, Rome

FAO (Food and Agricultural Organization of the United Nations) and WHO (World Health Organization) (2014) The international code of conduct on pesticide management. Rome, Italy. E-ISBN: 978-92-5-108549-3. http://www.fao.org/fileadmin/templates/agphome/documents/Pests_Pesticides/Code/CODE_2014Sep_EN. Accessed 8 Jan 2017

FAO GeoNetwork (2017a) http://www.fao.org/geonetwork/srv/en/main.home. Accessed 23 Feb 2017

FAO GeoNetwork (2017b) FAO GeoNetwork. http://www.fao.org/geonetwork/srv/en/main.home. Accessed 23 Feb 2017

FAOSTAT (2014) Food and agriculture organization of the United States – Statistics Division. http://faostat.fao.org/

FAOSTAT (2017) Statistical Database. Rome. www.fao.org/faostat/en/#data/QA

Flysjo A, Cederberg C et al (2012) The interaction between milk and beef production and emissions from land use change – critical considerations in life cycle assessment and carbon footprint studies of milk. J Clean Prod. https://doi.org/10.1016/j.jclepro.2011.11.046

FNR (2008) Studie zur Markt- und Konkurrenzsituation bei Naturfasern und Naturfaserwerkstoffen (Deutschland und EU). In: Gülzower Fachgespräche 26, Fachagentur Nachwachsende Rohstoffe e.V., Gülzow

Francavilla M, Trotta P, Luque R (2010) Phytosterols from Dunaliella tertiolecta and Dunaliella salina: a potentially novel industrial application. Bioresour Technol 101:4144–4150. https://doi.org/10.1016/j.biortech.2009.12.139

Frankfurt a.M. (2017) Stadtwald. Stadt Frankfurt am Main. https://www.frankfurt.de/sixcms/detail.php?id=2800&_ffmpar%5b_id_inhalt%5d=101676. Accessed 10 Jul 2017

Garg MR, Sherasia PL et al (2013) Effects of feeding nutritionally balanced rations on animal productivity, feed conversion efficiency, feed nitrogen use efficiency, rumen microbial protein supply, parasitic load, immunity and enteric methane emissions of milking animals under field conditions. Anim Feed Sci Technol 179(1):24–35

Gille A, Trautmann A, Posten C et al (2016) Bioaccessibility of carotenoids from Chlorella vulgaris and Chlamydomonas reinhardtii. Int J Food Sci Nutr 67:507–513. https://doi.org/10.1080/09637486.2016.1181158

Giri C, Ochieng E, Tieszen LL et al (2010) Status and distribution of mangrove forests of the world using earth observation satellite data. Glob Ecol Biogeogr: J Macroecol 20(1):154–159

Gliessman SR (2015) Agroecology: the ecology of sustainable food systems. CRC Press, Boca Raton

Good R (1947) The geography of the flowering plants. Longmans, Green, London

Granado F, Olmedilla B, Blanco I (2003) Nutritional and clinical relevance of lutein in human health. Br J Nutr 90(3):487–502. https://doi.org/10.1079/BJN2003927

Guo Z, Zhang Y, Deegen P et al (2006) Economic analyses of rubber and tea plantations and rubber-tea intercropping in Hainan, China. Agrofor Syst 66(2): 117–127. https://doi.org/10.1007/s10457-005-4676-2

Hardy RW (2010) Utilization of plant proteins in fish diets: effects of global demand and supplies of fishmeal. Aquacult Res 41(5):770–776. https://doi.org/10.1111/j.1365-2109.2009.02349.x

Harrison RP (1992) Forests – the shadow of civilization. The University of Chicago Press, Chicago

Harun R (2010) Bioprocess engineering of microalgae to produce a variety of consumer products. Renew Sustain Energy Rev 14:1037–1047. https://doi.org/10.1016/j.rser.2009.11.004

Hernández C, Olvera-Novoa MA, Hardy RW et al (2010) Complete replacement of fish meal by porcine and poultry by-product meals in practical diets for fingerling Nile tilapia Oreochromis niloticus: digestibility and growth performance. Aquacult Nutr 16(1):44–53. https://doi.org/10.1111/j.1365-2095.2008.00639.x

Herrero M, Havlik P et al (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc Natl Acad Sci. https://doi.org/10.1073/pnas.1308149110

Hilger T, Lewandowski I (2015) Seeds of change—plant genetic resources and people's livelihoods. In: Pilipavičius V (ed) Agroecology. IN TECH, Rijeka

Hoogwijk M, Faaij A, Eickhout B et al (2005) Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass Bioenergy. https://doi.org/10.1016/j.biombioe.2005.05.002

Hummer KE, Hancock JF (2015) Vavilovian centers of plant diversity: implications and impacts. HortScience 50:780–783

IFAD (2013) Smallholders, food security and the environment. Human behavior and environment

IFOAM (International Federation of Organic Agriculture Movement) (2005) http://www.ifoam.bio/en/organic-landmarks/definition-organic-agriculture. Accessed 8 Jan 2017

Imhoff ML, Bounoua L, Ricketts T et al (2004) Global patterns in human consumption of net primary production. Nature. https://doi.org/10.1038/nature02619

International Dairy Federation (IDF) and Food and Agriculture Organization (FAO) (2004) Guide to good dairy farming practice. Rome. ISBN: 92-5-105094-5

IPCC (2006) 2006 Guidelines for national greenhouse gas inventories. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) Prepared by the national greenhouse gas inventories programme. IGES, Japan

Jacobs MR (1955) Growth habits of the eucalypts. Forestry and Timber Bureau, Canberra

Kaushik S, Troell M (2010) Taking the fish-in fish-out ratio: a step further…. Aquacult Eur 35:15–17

Khoury CK, Achicanoy HA et al (2016) Origins of food crops connect countries worldwide. Proc R Soc B: Biol Sci. https://doi.org/10.1098/rspb.2016.0792

Knigge W, Schulz H (1966) Grundriss der Forstbenutzung. Paul Parey, Hamburg

Kost C, Mayer JN, Thomsen J et al (2013) Levelized Cost of Electricity Renewable Energy Technologies. Fraunhofer Institute for Solar Energy Systems ISE, Stuttgart

Krienitz L, Wirth M (2006) The high content of polyunsaturated fatty acids in Nannochloropsis limnetica (Eustigmatophyceae) and its implication for food web interactions, freshwater aquaculture and biotechnology. Limnologica 36:204–210. https://doi.org/10.1016/j.limno.2006.05.002

Krutilla, JV, Fisher AC (1975) The economics of natural environments; studies in the valuation of commodity and amenity resources. The Johns Hopkins University Press, Baltimore (quoted in Perman R, Yue M et al (2011) Natural Resource and Environmental Economics, 4th edn. Pearson, Harlow, p 395ff)

KTBL (2015) KTBL-Taschenbuch Landwirtschaft Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt

Lambin EF, Turner BL et al (2001) The causes of land use and land cover change: moving beyond the myths. Glob Environ Change 11(4):261–269

Lamprecht H (1989) Silviculture in the Tropics. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn

Lewandowski I (2015) Securing a sustainable biomass supply in a growing bioeconomy. Glob Food Sec. https://doi.org/10.1016/j.gfs.2015.10.001

Liau BC, Shen CT, Liang FP et al (2010) Supercritical fluids extraction and anti-solvent purification of carotenoids from microalgae and associated bioactivity. J Supercrit Fluids 55:169–175. https://doi.org/10.1016/j.supflu.2010.07.002

Lowder SK, Skoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev. https://doi.org/10.1016/j.worlddev.2015.10.041

Macías-Sánchez MD, Mantell C, Rodríguez et al (2007) Supercritical fluid extraction of carotenoids and chlorophyll a from Synechococcus sp. J Supercrit Fluids 39:323–329. https://doi.org/10.1016/j.supflu.2006.03.008

Martin K, Sauerborn J (2013) Agroecology. Springer, Amsterdam

Martins JG (2009) EPA but not DHA appears to be responsible for the efficacy of omega-3 long chain polyunsaturated fatty acid supplementation in depression: evidence from a meta-analysis of randomized controlled trials. J Am Coll Nutr 28 (5):525–542. https://doi.org/10.1080/07315724.2009.10719785

Mata TM, Martins AA, Caetano NS (2010) Microalgae for biodiesel production and other applications: a review. Renew Sustain Energy Rev 14:217–232. https://doi.org/10.1016/j.rser.2009.07.020

Meiser A, Schmid-Staiger U, Trösch W (2004) Optimization of eicosapentaenoic acid production by Phaeodactylum tricornutum in the flat panel airlift (FPA) reactor. J Appl Phycol 16:215–225. https://doi.org/10.1023/B:JAPH.0000048507.95878.b5

Mekonnen MM, Hoekstra AY (2010) The green, blue and grey water footprint of farm animals and animal products. UNESCO-IHE Institute for Water Education. https://doi.org/10.5194/hess-15-1577-2011

Mendes RL, Nobre BP, Cardoso MT et al (2003) Supercritical carbon dioxide extraction of compounds with pharmaceutical importance from microalgae. Inorg Chim Acta 356:328–334. https://doi.org/10.1016/S0020-1693(03)00363-3

Mitchell HH, Hamilton TS et al (1932) The effect of the amount of feed consumed by cattle on the utilization of its energy content. J Agric Res 45:163

Morales-Sánchez D, Tinoco-Valencia R, Caro-Bermúdez MA et al (2014) Culturing Neochloris oleoabundans microalga in a nitrogen-limited, heterotrophic fed-batch system to enhance lipid and carbohydrate accumulation. Algal Res 5:61–69. https://doi.org/10.1016/j.algal.2014.05.006

Mosier A, Kroeze C et al (1998) Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology. Nutr Cycl Agroecosyst 52:225

Mulders KJM, Janssen JH, Martens DE et al (2014) Effect of biomass concentration on secondary carotenoids and triacylglycerol (TAG) accumulation in nitrogen-depleted Chlorella zofingiensis. Algal Res 6:8–16. https://doi.org/10.1016/j.algal.2014.08.006

Münkel R, Schmid-Staiger U, Werner A et al (2013) Optimization of outdoor cultivation in flat panel airlift reactors for lipid production by Chlorella vulgaris. Biotechnol Bioeng 110:2882–2893

Nachtergaele F, Petri M (2008) Mapping land use systems at global and regional scales for land degradation assessment analysis. LADA Technical Report

Neori A, Nobre AM (2012) Relationship between trophic level and economics in aquaculture. Aquacult Econ Manage 16:40–67

Nhamo N, Rodenburg J et al (2014) Narrowing the rice yield gap in east and Southern Africa: using and adapting existing technologies. Agric Syst. https://doi.org/10.1016/j.agsy.2014.08.003

Norsker NH, Barbosa MJ, Vermuë MH et al (2011) Microalgal production—a close look at the economics. Biotechnol Adv 29:24–27. https://doi.org/10.1016/j.biotechadv.2010.08.005

Pal D, Khozin-Goldberg I, Cohen Z et al (2011) The effect of light, salinity, and nitrogen availability on lipid production by Nannochloropsis sp. Appl Microbiol Biotechnol 90:1429–1441. https://doi.org/10.1007/s00253-011-3170-1

Parniakov O, Barba FJ, Grimi N et al (2015) Pulsed electric field assisted extraction of nutritionally valuable compounds from microalgae Nannochloropsis spp. using the binary mixture of organic solvents and water. Innov Food Sci Emerg Technol 27:79–85. https://doi.org/10.1016/j.ifset.2014.11.002

Pasquet V, Chérouvrier JR, Farhat F et al (2011) Study on the microalgal pigments extraction process: Performance of microwave assisted extraction. Process Biochem 46:59–67. https://doi.org/10.1016/j.procbio.2010.07.009

Pauly D (2009) Beyond duplicity and ignorance in global fisheries. Sci Mar 73(2):215–224

Perez-Garcia O, Escalante FME, Bashan LE et al (2011) Heterotrophic cultures of microalgae: metabolism and potential products. Water Res 45:11–36. https://doi.org/10.1016/j.watres.2010.08.037

Perman R, Yue M, Common M et al (2011) Natural resource and environmental economics, 4th edn. Pearson, Harlow

Pieber S, Schober S, Mittelbach M (2012) Pressurized fluid extraction of polyunsaturated fatty acids from the microalga Nannochloropsis oculata. Biomass Bioenergy 47:474–482. https://doi.org/10.1016/j.biombioe.2012.10.019

Piotrowski S, Essel R et al (2015) Nachhaltig nutzbare Potenziale für Biokraftstoffe in Nutzungskonkurrenz zur Lebens-und Futtermittelproduktion, Bioenergie sowie zur stofflichen Nutzung in Deutschland, Europa und der Welt. http://bio-based.eu/downloads/nachhaltig-nutzbare-potenziale-fuer-biokraftstoffe-in-nutzungskonkurrenz-zur-lebens-und-futtermittelproduktion-bioenergie-sowie-zur-stofflichen-nutzung-in-deutschland-europa-und-der-welt/

Plaza M, Santoyo S, Jaime L (2012) Comprehensive characterization of the functional activities of pressurized liquid and ultrasound-assisted extracts from Chlorella vulgaris. LWT – Food Sci Technol 46:245–253. https://doi.org/10.1016/j.lwt.2011.09.024

Posten C, Feng Chen S (eds) (2016) Microalgae biotechnology, Advances in biochemical engineering/biotechnology. Springer International Publishing, Cham

Postgate JR (1982) The fundamentals of nitrogen fixation. Cambridge University Press, Cambridge

Prein M (2002) Integration of aquaculture into crop-animal systems in Asia. Agricult Syst 71:127–146

Pretty J, Toulmin C, Williams S (2011) Sustainable intensification in African agriculture. Int J Agric Sustain 9 (1):5–24

Pucher J, Gut T, Mayrhofer R et al (2014) Pesticide contaminated feeds in integrated grass carp aquaculture: toxicology and bioaccumulation. Dis Aquat Org 108: 137–147. https://doi.org/10.3354/dao02710

Pulz O (2001) Photobioreactors: production systems for phototrophic microorganisms. Appl. Microbiol Biotechnol 57:287–293. https://doi.org/10.1007/s002530100702

Rabbinge R (1993) The ecological background of food production. In: Derek J, Chadwick DJ, Marsh J (eds) Crop protection and sustainable agriculture, Ciba foundation symposium, vol 177. Wiley, Chichester, pp 2–29

Richmond A (ed) (2004) Handbook of microalgal culture: biotechnology and applied phycology. Wiley-Blackwell, Oxford

Richter M (2001) Vegetationszonen der Erde. Klett-Perthes, Gotha

Rodolfi L, Chini Zittelli G, Bassi N et al (2009) Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor. Biotechnol Bioeng 102: 100–112

Royal Society (2009) Reaping the benefit, Science and the sustainable intensification of global agriculture. The Royal Society. ISBN: 978-0-85403-784-1. https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/4294967719.pdf

RSPO (2016) Roundtable on sustainable palm oil. http://www.rspo.org/about/who-we-are/working-groups/biodiversity-high-conservation-values. Accessed 12 Dec 2016

Ruthenberg H (1980) Farming systems in the tropics, 3rd edn. Oxford University Press, Oxford

Safi C, Ursu AV, Laroche C et al (2014) Aqueous extraction of proteins from microalgae: effect of different cell disruption methods. Algal Res 3:61–65. https://doi.org/10.1016/j.algal.2013.12.004

Schlechtriem C, Pucher J, Michalski B (2016) Dietary burden calculations relating to fish metabolism studies. J Sci Food Agricult 96(5):1415–1419. https://doi.org/10.1002/jsfa.7607

Schmid-Staiger U, Preisner, Marek P et al (2009) Kultivierung von Mikroalgen im Photobioreaktor zur stofflichen und energetischen Nutzung. Chem Ing Tech 81: 1783–1789. (in German)

Schober R (1987) Ertragstafeln wichtiger Baumarten, 3rd edn. J.D. Sauerländer's, Frankfurt aM

Schütt P, Schuck HJ, Stimm B (eds) (1992) Lexikon der Forstbotanik – Morphologie, Pathologie. Ökologie und Systematik wichtiger Baum- und Straucharten. ecomed, Landsberg/Lech

Seré C, Steinfeld H (1996) World livestock production systems: current status, issues and trends. Animal Production and Health Paper. FAO, Rome

Shepherd CJ, Jackson AJ (2013) Global fishmeal and fish-oil supply: inputs, outputs and markets. J Fish Biol 83 (4):1046–1066. https://doi.org/10.1111/jfb.12224

Singh RN, Sharma S (2012) Development of suitable photobioreactor for algae production – a review. Renew Sustain Energy Rev 16:2347–2353

Smeets EMW, Faaij APC et al (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energy Combust Sci. https://doi.org/10.1016/j.pecs.2006.08.001

Smith P, Martino D et al (2007) Agriculture. In: Climate change 2007: mitigation, contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change

Steinfeld H, Wassenaar T, Jutzi S (2006) Livestock production systems in developing countries: status, drivers, trends. Rev Sci Tech 25(2):505–516

Tacon AGJ (1988) The nutrition and feeding of farmed fish and shrimp – a training manual. 3. Feeding methods. FAO Field Document, Project GCP/RLA/075/ITA. Field Document 7/E, FAO, p 208

Tacon AGJ, Metian M (2008) Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. Aquaculture 285(1–4):146–158

Tacon AGJ, Metian M, Turchini GM et al (2010) Responsible aquaculture and trophic level implications to global fish supply. Rev Fish Sci 18(1):94–105. https://doi.org/10.1080/10641260903325680

Takhtajan A (1986) Floristic regions of the world. University of California Press, Berkeley

Thornton PK (2010) Livestock production: recent trends, future prospects. Philos Trans R Soc Lond Ser B Biol Sci 365:2853–2867. https://doi.org/10.1098/rstb.2010.0134

UNEP (2014) Use AGL: Balancing consumption with sustainable supply. A report of the working group on land and soils of the international resource panel. Bringezu S, Schütz H, Pengue W, OBrien M, Garcia F, Sims R, Howarth R, Kauppi L, Swilling M, and Herrick J

Upton M (2000) The livestock revolution-implications for smallholder agriculture: a case study of milk and poultry production in Kenya. Food and Agriculture Organization Livestock Information and Policy Branch, AGAL

Van Soest PJ (1994) Nutritional ecology of the ruminant. Cornell University Press, Ithaca

Wagenführ R (1996) Holzatlas, 4th edn. Fachbuchverlag Leipzig, Leipzig

Wageningen UR. Cost-effective algae production within reach. www.wur.nl/en/Expertise-Services/Facilities/AlgaePARC/News/Show/Costeffective-algae-production-within-reach.htm. Accessed 18 Nov 2014

Weitzman ML (1998) Why the far-distant future should be discounted at its lowest possible rate. J Environ Econ Manage 36(3):201–208. https://doi.org/10.1006/jeem.1998.1052

White F (2011), PNNL studies algae petroleum replacement. www.AlgaeIndustryMagazine.com/pnnl-studies-algae-petroleum-replacement. Accessed 16 Jun 2017

Wilkinson JM (2011) Re-defining efficiency of feed use by livestock. Animal. https://doi.org/10.1017/S175173111100005X

World Bank (2009) Minding the stock: bringing public policy to bear on livestock sector development. Report No. 44010-GlB

World Bank (2013) FISH TO 2030: prospects for fisheries and aquaculture. World Bank Report Number 83177-GLB, Washington, DC

Yengoh GT, Ardo J (2014) Crop yield gaps in Cameroon. Ambio. https://doi.org/10.1007/s13280-013-0428-0

Young HE, Strand L, Altenberger R (1964) Primary dry and fresh weight tables for seven tree species in Maine. Tech. Bul. 12., Agr. Exp. Station, Maine

Online Sources

FAO GeoNetwork.: http://www.fao.org/geonetwork/srv/en/main.home

Global agroecological zones.: http://www.fao.org/nr/gaez/en/

Global assessment of land resources and land degradation.: http://www.fao.org/nr/land/use/en/

Global Forest watch.: http://www.globalforestwatch.org/

7 Processing of Biobased Resources

The fundamental idea behind the bioeconomy is processing of biobased resources into a wide range of products in the food, feed, energy, and material sectors. Due to the special characteristics of biobased resources (see Sect. 5.1), appropriate conversion approaches need to be selected with the desired application in mind.

Food supply is the most traditional and, of course, most essential function of biobased resources. Section 7.1 presents fundamental knowledge on food quality and food processing techniques.

For production of materials, our economic system is predominantly based on finite fossil carbon resources, such as natural gas, crude oil, and coal. Crude oil is the basis for most fuels and is refined into more useful products such as naphtha, gasoline, diesel, asphalt, heating oil, kerosene, and gas. These are further processed to intermediates and final products including plastics, fibers, vanishes, and adhesives. Petroleum (or naphtha) is a liquid raw material consisting of reduced hydrocarbons which are mostly oxidized to the desired product. In this process, inorganic, often metallic, catalysts are used and both high temperatures and pressures are applied. The conversion starts with pure and relatively concentrated educts, making product recovery comparatively simple.

Biorefinery concepts explore possible routes for the refining of renewable resources to fuels, energy, and materials, analogous to chemical refining processes. These generally make use of all biomass components, resulting in various educt streams which can be converted to basic products. In contrast to crude oil, naphtha, and other petrochemical fractions, biomass materials for biorefineries display lower energy densities, are solid rather than liquid, and are partially oxidized.

Lignocellulose is the most abundant biopolymer and is a solid raw material. It consists of three main components, namely the carbohydrates cellulose and hemicellulose (polyoses) and lignin. Cellulose and hemicellulose are polymers consisting of hexoses and pentoses; lignin is a cross-linked phenolic polymer built up from aromatic alcohols.

Fractionation and depolymerization are prerequisites for further bioconversion. Lignin is most often separated from the carbohydrates and combusted to supply the bioconversion process energy. The carbohydrates can be depolymerized by acid or enzymatic hydrolysis, to form aqueous sugar solutions with a sugar content of about 0.2–2%, which is then concentrated. In this approach, the structure of the resource is preserved, to give relatively defined sugar streams. These sugar streams may be used in biotechnological processes to supplement the substrates sucrose and glucose originating from sugarcane, sugar beet, and hydrolysis of starch (Sect. 7.2).

Another concept is the thermochemical conversion (Sect. 7.3) of the renewable feedstock,

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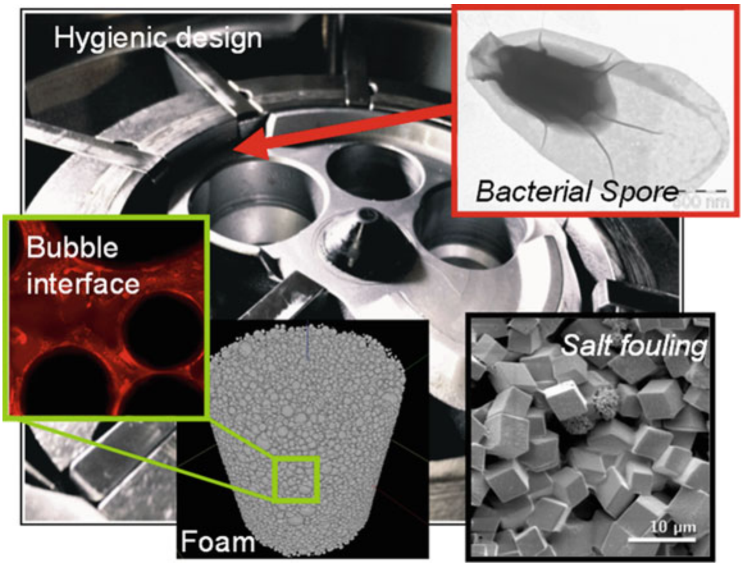
which is technologically less demanding. This method breaks down the biomass into a complex mixture of partly reduced substances.

The sugar and lignin fractions are partially oxidized and, in many cases, have to be reduced to gain valuable products. For this purpose, CO_2 has to be removed from the carbon skeleton. This implies that on a mass base product yields generally are lower than in petrochemical production. For these reactions, catalysts have to be employed which act highly specifically and stop at a certain oxidative step. Biocatalysts (whole cells or enzymes) possess these properties but, in contrast to inorganic catalysts, they require physiological conditions. The reactions are performed at moderate temperature (10–60 °C), under normal pressure. But as the educt stream is yet diluted, also the product stream is diluted, consisting of only 1–10% of the product, and 90–99% of water. This demands a quite intensive downstream processing.

In a biobased economy renewable feedstocks, thus mainly plants, form the basis for materials. Biorefineries provide concepts for thermochemical and biochemical conversion of biobased materials towards fuels, materials, and energy. However, for mobility and energy solutions solar, wind, or geothermal energy are promising, but for materials the use of renewable feedstocks is the most suitable solution so far. Carbon capture and utilization technologies potentially may be included in the biorefinery concepts.

7.1 Food Processing

Myriam Loeffler and Jörg Hinrichs



Abstract Food science and technology is the science that deals with the physical, biological, and chemical processes relevant for the processing of food and food ingredients. The goal is to research, develop, and optimize technical procedures based on natural and engineering sciences as well as socioeconomic factors in order to provide high-quality and safe food for human consumption. Food processing refers to the conversion/transformation of raw materials to a safe food product. This chapter introduces the physical, chemical, and biological unit operations typically used in food processing to ensure food safety and quality. The influence of intrinsic as well as extrinsic parameters on microbial growth behavior is highlighted and examples of important factors that need to be considered during food processing are introduced (water activity, enzyme activity, lipid oxidation). At the end of the chapter, strategies for new product developments are also presented.

Keywords Food quality; Food safety; Shelf life; Industrial processing; Food functionality; Water activity; Product development

Learning Objectives

After studying this chapter, you should

- Be familiar with food components and ingredients.
- Know basic processes used in food processing and drivers of technical food processing.
- Be aware of aspects, important for the development of new food products.

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7.1.1 Food and Food Ingredients

The word "food" refers to substances and products that are taken in by humans through the mouth for the purpose of nutrition and/or pleasure. For this reason, the term also includes products that one normally wouldn't think of as foods, such as:

- Alcoholic beverages
- Food ingredients such as salt and spices
- Food additives such as thickeners
- Food supplements such as minerals and vitamin preparations

Major food ingredients (the big five) are:

- Water
- Proteins (Fig. 7.1)
- Fat (Fig. 7.2)
- Carbohydrates (e.g., the monosaccharide glucose, disaccharide lactose, and polysaccharides cellulose and starch)
- Minerals (e.g., calcium, iron, magnesium, zinc)

Minor components/micronutrients are:

- Vitamins (fat- or water soluble)
- Other functional components

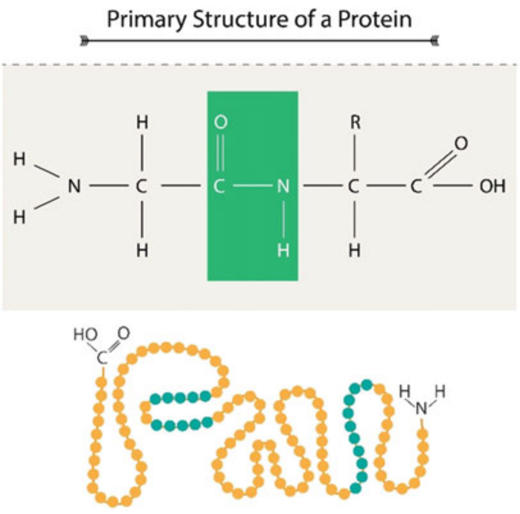

Fig. 7.1 Protein structure; green: peptide bond-linking amino acids

7.1.2 Unit Operations of Food Processing

For the consumer, food does not merely give the feeling of satiety (energy) and supply micronutrients, but it provides a pleasurable experience through aroma, taste, color, and texture. Moreover, ritual functions (e.g., the Eucharist) and prohibitions (e.g., Jewish food regulations) are linked to food and food consumption. Nowadays, quite a few of these prohibitions can be explained and understood by looking at former climatic and hygienic conditions and the related diseases. For instance, it is well known that beans should not be consumed without processing. Raw beans contain a toxic protein (phasin), which has to be denatured prior to consumption by heating or pickling to prevent intestinal colic. Thus, knowledge of the cultivation, storage, preservation, and processing of food was and still is of great importance. In this context, food processing describes the conversion/transformation of raw material to a safe food product.

Today, there is a variety of possibilities (e.g., unit operations) to convert and hence process plant and animal raw materials to semifinished goods (e.g., flour), ready-to-eat end products (e.g., bread), and convenience food including special diets.

A distinction has to be made between physical, biological, and chemical methods used for raw material and food processing. Depending on the requirements, these techniques may be applied individually, in a particular order or in combination. Table 7.1 gives an overview of unit operations used in food processing. Most of these techniques were developed a long time ago and then adapted to different food matrices. A few, such as irradiation, have been introduced much more recently.

With the beginning of industrialization in the second half of the eighteenth century, major technical advances were made in crop and plant cultivation, food processing, and packaging. For instance, research findings of Justus Liebig led to an increase in agricultural production of about 90% between 1873 and 1913. The

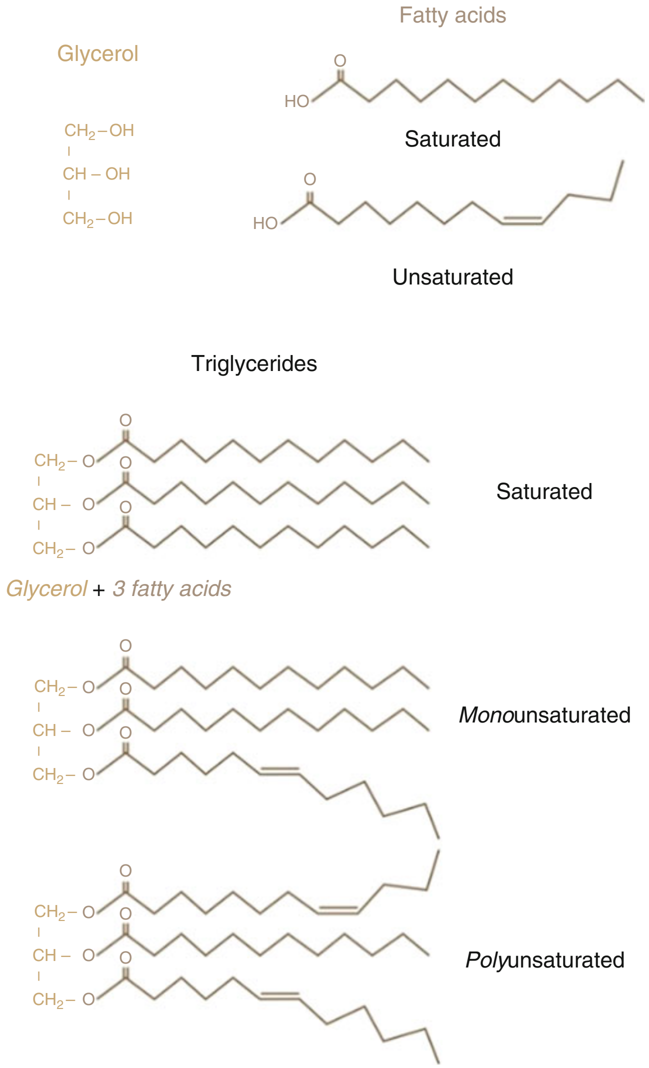

Fig. 7.2 Structure of glycerol, saturated and unsaturated fatty acids, and triglycerides

use of fertilizers, scientifically based animal breeding, and initial mechanization of agriculture allowed more and more people to be supplied with food. At the same time, new methods of preservation and packaging were developed (e.g., 1804, sterilization of milk) to extend storage time and improve food transportation, leading to a marked increase in small-scale and large-scale operating companies in Europe and North America.

7.1.3 Food Quality, Shelf Life, and Food Safety: Drivers of Technical Food Processing

An important requirement for the storage and trade of food and food ingredients is that they either retain their specific properties (best case) or undergo only minor physicochemical and/or microbial changes over a longer period of time, thus guaranteeing food quality and safety.

Table 7.1 Examples of food processing objectives classified by main principle and listing of unit operations applied

Main principle	Objective	Unit operation
Physical	Removal of dirt and unwanted components	Washing, sieving, peeling
	Crushing	Cutting, grinding, crushing
	Enrichment of certain components	Pressing, separating, filtering, distilling, extracting, evaporation, drying, crystallization
	Texture alteration	Kneading, dispersing, emulsifying, foaming
	Shelf life	Heating, cooling, freezing, drying, microwave heating, irradiation, high pressure
	Destroying interfering or toxic substances	Blanching, cooking
	Improved digestibility, formation of aromas, browning	Heating, frying, cooking, steaming
Biological	Raw material transformation → taste, smell, texture	Fermentation, fermentative acidification, enzymatic reactions
	Shelf life	Fermentation, acidification
Chemical/ biochemical	Taste and texture	Addition of salt or/and sugar
	Shelf life	Addition of salt, sugar, or acid, smoking, addition of preservatives
	Destroying/inactivation of interfering or toxic substances	Acidification, heating
	Optical appearance	Addition of colorants

"Safe" in this context means that neither pathogens nor toxins are present in the food product prior to consumption. Many of the physical, biological, and chemical methods listed in Table 7.1 are used to prolong shelf life, but they may vary depending on the product. In the past, food products were often preserved by reducing water activity (Sect. 7.1.5) or through fermentation. For instance, foods already traded in antiquity included dry products such as salt, sugar, cereals, dried meat, and spices, or fermented products such as wine or vinegar, as well as salt-conserved products including fish (e.g., salt cod), meat, and cheese. Therefore, salt became an important commodity a long time ago, since it was essential for food preservation and seasoning.

7.1.3.1 Factors Affecting Microbial Growth

As our foods are of animal and/or plant origin, it is important to consider the raw material and product characteristics that may influence microbial growth during harvesting, food processing, and (short/long-term) storage.

Intrinsic Parameters (Examples)

1. *pH*

   Microorganisms can be classified according to the minimum, optimum (best growth requirements), and maximum pH values, at which they can grow. For certain food products, knowing the pH is of vital importance. For instance, yoghurt (pH 4.3–4.7) and fruit juices (pH 3.5–3.8) have a very low pH and are therefore mainly spoiled by yeasts and molds, while emulsified sausages have higher pH values (~5.9–6.2) and are very prone to contamination with food spoilage—(e.g., pseudomonads) or food-poisoning bacteria (e.g., *Listeria monocytogenes*).
2. *Moisture content*
   The preservation of foods by drying is achieved by the removal or binding of moisture, without which microorganisms are not able to grow. See also water activity in Sect. 7.1.5.
3. *Oxidation-reduction potential (O/R, Eh)*
   Aerobic microorganisms such as *Bacillus* ssp., as well as most molds and yeasts, require positive Eh values (oxidized) for growth, whereas

anaerobes such as *Clostridium botulinum* require negative Eh values (reduced). However, it should be noted that a lot of bacteria are facultative anaerobes and are thus able to grow under either aerobic or anaerobic conditions.

4. *Nutrient content*
   Nutrient requirements for microbial growth include water, a source of energy (e.g., sugars), a source of nitrogen (e.g., proteins), vitamins and related growth factors, as well as minerals (Sect. 7.1.1). The requirements differ depending on the strain. Generally, Gram-positive bacteria are known to have the highest requirements.
5. *Antimicrobial constituents*
   Naturally occurring antimicrobials include for instance lysozyme (eggs, milk) and the lactoperoxidase system (bovine milk).

Extrinsic Parameters (Examples)

Extrinsic parameters also play a crucial role in microbial growth.

1. *Temperature*
   This includes processing temperature and storage temperature.
   Here it should be noted that microorganisms can also be classified according to their growth temperatures:

   - Psychrotrophs (optimum: 20–30 °C; grow well at or below 7 °C; e.g., *Pseudomonas* ssp.)
   - Mesophiles (optimum: 30–40 °C; grow well above 20 °C and below 45 °C, e.g., *Escherichia coli* O157:H7)
   - Thermophiles (optimum: 55–65 °C; grow well at and above 45 °C, e.g., *Streptococcus thermophilus*)

2. *Other parameters*
   Other extrinsic parameters that should be considered are relative humidity of the environment and the presence of gases (e.g., CO_2) and/or other microorganisms that produce, e.g., substances that are inhibitory or even lethal to other microorganisms (e.g., bacteriocins, organic acids).

7.1.4 Special Features of the Industrial Processing of Food

The general principles and requirements of industrial scale food processing do not differ from homemade, small-scale processing—they usually involve the raw materials, a recipe, and the necessary equipment. In all cases, the end product is expected to be safe and to have a high sensory quality with regard to flavor, taste, color, and texture. Some products may have further requirements such as health aspects. In the food industry, all these requirements are the responsibility of the manufacturer and once products are on the market they are subjected to state quality standard monitoring.

In general, industrial scale food production is characterized by a higher degree of automation. In addition, a “higher” safety level is required, since the semifinished or final products are often marketed over long distances, which in turn requires a longer shelf life and appropriate packaging. In cases where quality deficiency or damage is identified, the recall of industrial scale products is much more difficult than for locally marketed products.

7.1.4.1 Raw Materials

The following factors are of particular importance for technical food production:

- The bulk of raw materials used are of natural plant or animal origin. They have a great variability with respect to composition, autochthone microorganism flora, and processing properties.
- The availability of many raw materials (e.g., fruits, sugar beet, wine) is limited by seasonality.
- Plant raw materials (e.g., coffee, soy, hops) are often only cultivated in certain regions, leading to long transport distances.
- Raw materials are not always available in unlimited supply and their storage is only possible for a limited period of time.
- High price fluctuations are possible.

- Once processing has been started, it usually cannot be stopped.

Today, other socioeconomic aspects related to the selection of raw materials are taken into account. These are often described by terms such as "resource-conserving," "organic," "eco," "GMO-free," "climate-neutral," and "fair trade." However, as discussed below, these are of minor importance with respect to food processing.

7.1.4.2 Processing of Raw Materials

In the next step, the raw materials are converted into standardized (*quality attributes and/or functional properties*) products through various unit operations. For this reason, the chemical, biological, and physical properties of the raw materials and also their behavior during processing have to be taken into account. The technology-structure-function relationship behind the processing of raw materials (e.g., sugar beet, milk) into foodstuffs (sugar cubes, processed cheese) is illustrated in Fig. 7.3. In the figure, "technology" includes the substances and ingredients used, their concentration and composition, as well as the basic operation (s) applied (Table 7.1). The desired functionality of the product is achieved through the choice of process parameters (e.g., pressure, temperature, pH). The structure of the final product (e.g., sugar cubes: small crystals in the form of a cube of defined edge length, white, solid) is predominantly influenced by the technology used. In turn, the structure provides the basis for the functionality of certain food products (e.g., sugar cubes: dissolve rapidly in hot liquids; desired sweetness).

For the same raw material, even small changes in the process parameters of basic operations, the use of other machines/equipment, or a change in the order of the unit operations can influence the structure and thus also the functionality of the end product. This may or may not be advantageous for the application in question. The functionality includes subjectively and objectively measurable properties of the final product. Nowadays these properties are generally divided into techno-functionality (e.g., shelf life, texture, color, taste, smell, foam formation, emulsion formation) and bio-functionality (e.g., nutritional value, or health aspects).

7.1.5 Toolbox Used in Food Processing

Food science and technology deals with the physical, biological, and chemical processes relevant for the processing of food and food ingredients. The goal is to research, develop, and optimize technical procedures based on natural and engineering sciences as well as on socio-economic factors in order to provide high-quality and safe food for human nutrition. As it is not possible to give an in-depth account of all the factors that need to be taken into account, a few selected important examples are presented here.

Water Activity

As shown in Table 7.1, various unit operations can be used, for which a wide range of machines and equipment are available. The physical properties (e.g., liquid/solid), the chemical composition, and, in particular, the water content of the raw materials to be processed are of high importance. However, it is freely available water rather than the total water content that is crucial for appropriate processing. Figure 7.4 shows the intensity of various reactions depending on the water activity. The water

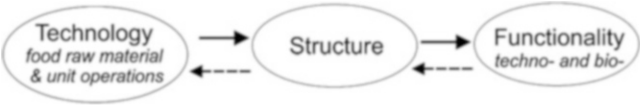

Fig. 7.3 Technology-structure-function relationship for the processing of food as well as the development of new food products

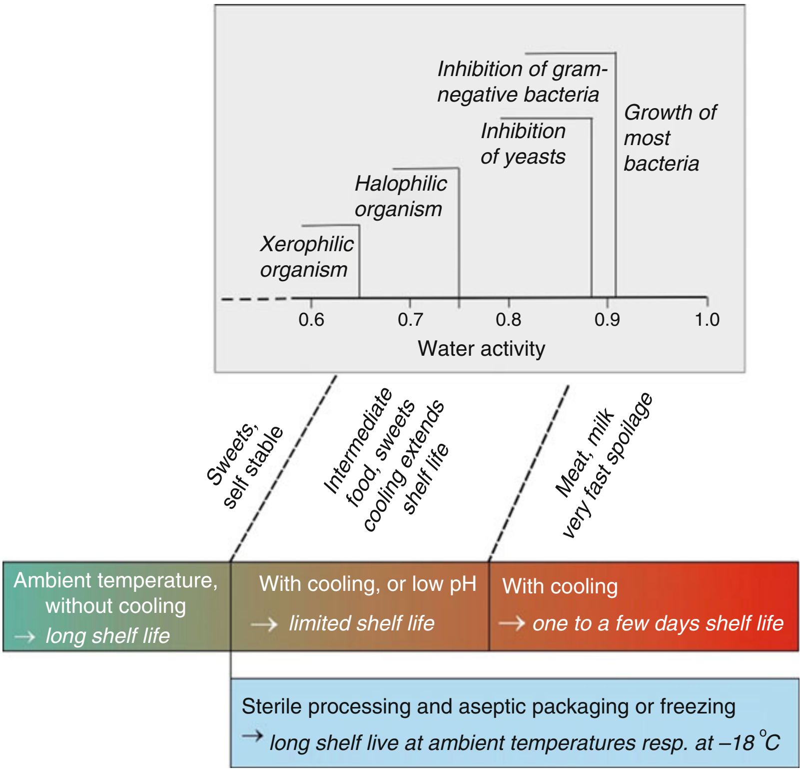

Fig. 7.4 Potential of microorganisms to grow on food depending on water activity (above). Potential shelf life of food and processed food under certain storage conditions (below)

Table 7.2 Water activity of various food raw materials and food products

Water activity	Food raw material, food products
≥0.98	Fish, meat, milk, egg, vegetables, juices, fruit, yoghurt, fresh cheese, soft cheese
0.95–0.97	Sausages, semihard and hard cheese
0.86–0.92	Raw sausage, raw ham, salami, parmesan
0.80–0.90	Jam, cakes, bread, syrup, sweetened condensed milk, flour, rice, ketchup
0.70–0.80	Soups, marzipan, dry fruit cakes, dried plums, jam of higher concentration
0.60–0.70	Honey, nougat, raisins, muesli, nuts, confectionery, dried fruit
0.5	Pasta, spices
0.4	Egg powder
0.3	Cookies
0.2	Milk powder

activity (a_w) value is calculated as the water vapor pressure of the raw material/foodstuff divided by the vapor pressure of pure water at the same temperature. Substances of low molecular mass, such as salts or sugars, are surrounded by water molecules and can thus reduce the water vapor pressure above the food and therefore also the a_w value.

If the water activity is very close to 1 (Table 7.2), the product is very prone to microbial spoilage, especially if cold storage is insufficient. Accordingly, all raw materials of animal origin must be processed quickly, unless they have their own protective mechanism (such as eggs). The unit operations, drying and salt addition (Table 7.1), can reduce the a_w value (Table 7.2, raw sausage). Freezing also reduces the mobility of water, preventing microorganisms from growing and reducing the rate of chemical reactions. Consequently, this

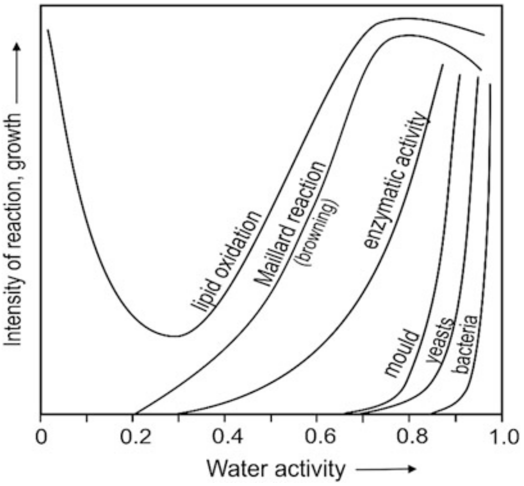

Fig. 7.5 Qualitative description of the intensity of chemical and biochemical reactions, as well as microbial growth, depending on water activity

process is now widely used to protect raw materials, semifinished products, and finished products from spoilage and to preserve vitamins, color, and texture. Many other reactions that also affect food quality, such as lipid oxidation, are directly related to water activity, as demonstrated in Fig. 7.5.

Enzyme Activity, Lipid Oxidation

As can be seen from Fig. 7.5, enzymatic reactions can be expected until a very low water activity of 0.4 is reached. Therefore, raw materials must be treated in such a way that existing enzyme activities do not lead to undesired changes in sensory properties, color, or texture. One way to prevent enzyme activity and kill microorganisms at the same time is through heating. However, heating can lead to nonenzymatic browning by the Maillard reaction. The reaction takes place between proteins and sugars and may cause desired (caramel, bread, malt beer) or undesired (juices, milk powder) effects depending on the characteristics of the food product.

It is interesting to note that the oxidation of lipids (fats) is lowest at a water activity of 0.2 (minimum) and more pronounced in products with either a lower ($a_w < 0.2$) or a higher water activity ($a_w > 0.2$). Thus, fat-containing egg powder and products with many unsaturated fatty acids can only be protected from lipid oxidation by appropriate packaging materials, a protective modified atmosphere without oxygen, or antioxidants. Figure 7.5 and Table 7.2 provide relevant information on some of the unit operations mentioned above necessary for the fulfilment of requirements regarding shelf life, safety, and preservation of the sensory properties of a food product.

Thermal Treatment

One of the most important unit operations is the thermal treatment of food (Table 7.1). Thermal treatments can improve food safety through killing pathogenic germs and viruses and prolong shelf life by killing spoilage organisms and inactivating enzymes already present in the product and microbial enzymes. However, it should be noted that (intensive) heat treatments may also destroy thermolabile vitamins and accelerate chemical reactions including the Maillard reaction mentioned above.

Example: Milk Production

Raw milk is an easily perishable foodstuff since it has a near-neutral pH and a water activity close to 1 (Table 7.2). It was recognized as early as the nineteenth century that raw milk can contain pathogenic microorganisms and is capable of transmitting diseases to humans.

It is therefore a legal requirement that raw milk obtained directly from the producer has to be boiled prior to consumption. However, boiling milk at 100 °C is not a very gentle treatment and can have a negative effect on its components.

Pasteurization

It is well known that *Mycobacterium tuberculosis* (discovered by Robert Koch in 1882, disease: tuberculosis) is one of the most thermostable pathogens in raw milk. For that reason, *M. tuberculosis* was used to define heating requirements for the pasteurization of milk. Figure 7.6 gives a summary of heat-based methods for the inactivation of pathogenic organisms. Short-

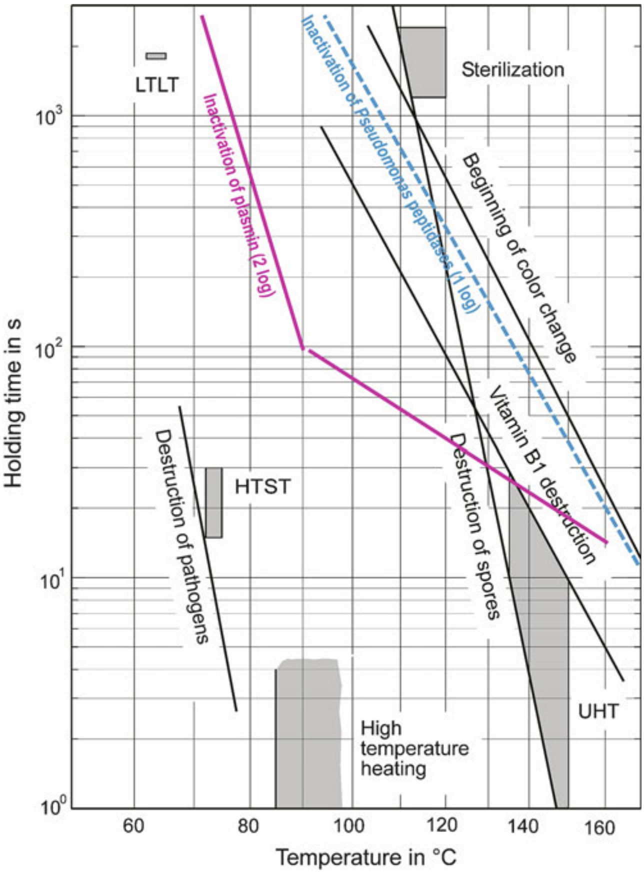

Fig. 7.6 Kinetics of some example reactions associated with milk heating (Stoeckel et al. 2016)

time pasteurization at 72–75 °C for 15–30 s provides a safe product with a shelf life of max. 10 days when stored at <8 °C. Longer is not possible because bacterial spores (extremely resistant, help bacteria to survive extreme conditions) are not sufficiently killed during pasteurization.

Sterilization

Sterilization is carried out following a traditional process developed by Apert in 1804. The milk is filled into cans or bottles, sealed, and then heated in an autoclave (Fig. 7.6). An autoclave is a pressure vessel in which temperatures of about 120 °C are reached using overpressure. If this temperature is maintained for about 20–30 min, mesophilic and thermophilic bacterial spores are inactivated. Sterilized milk has a shelf life of 1 year and can be stored at room temperature. However, the treatment is not very gentle. The heating area for sterile milk (Fig. 7.6) is above the line for visible browning (Maillard reaction) and above the line that marks lysine (an essential amino acid) and vitamin B1 (thiamine) losses.

UHT

It was not until 1952 that the process of ultrahigh-temperature heating (uperization) was developed by Alpura (Switzerland). In this process, the milk is heated to about 145 °C in just a few seconds, kept hot for a few seconds, and then rapidly cooled down again. The heating area used for UHT milk (Fig. 7.6) lies below the line for lysine and vitamin B1 losses but above the spore inactivation line. UHT milk is thus comparable to sterilized milk with regard to shelf life, but the method is more favorable with regard to the components.

7.1.6 Complexity of the Technologies Needed to Produce Different End Products from the Same Raw Material

Example: Products from Tomatoes

All final products mentioned in Fig. 7.7 are semi-finished products (e.g., ketchup, sauces, soup), which are used in households as products or as ingredients for food preparation.

The raw material "tomato" has to be selected and controlled in terms of variety, taste, color, texture, and maturity, with the functionality of the end product in mind.

Immediately after delivery, the tomatoes are washed, sorted, and then further processed using various operations and machines. For instance, after peeling, the tomatoes are filled directly into cans, to which tomato concentrate and, in some cases, also salt are added for better preservation of the tomatoes' structure for subsequent sterilization in the autoclave at 95 °C. Alternatively, peeled tomatoes are passed through sieves (pulp) or chopped (cubes) and then canned and sterilized.

Box 7.1 Process-Indicated Diagrams

Process-indicated diagrams are usually used in which the unit operations are named as process steps and delimited by a framework of substances (raw materials and additives, ingredients, intermediate products, and end products). Just as the process parameters, the chemical, physical, and (micro) biological properties of the substances that are important for the production process are given as "set points."

During processing, the substances are regularly analyzed and the process parameters then automatically logged ("actual value"). On the one hand, this is part of the quality assurance to meet requirements requested by law. On the other hand, this guarantees a final product with most widely standardized functional properties.

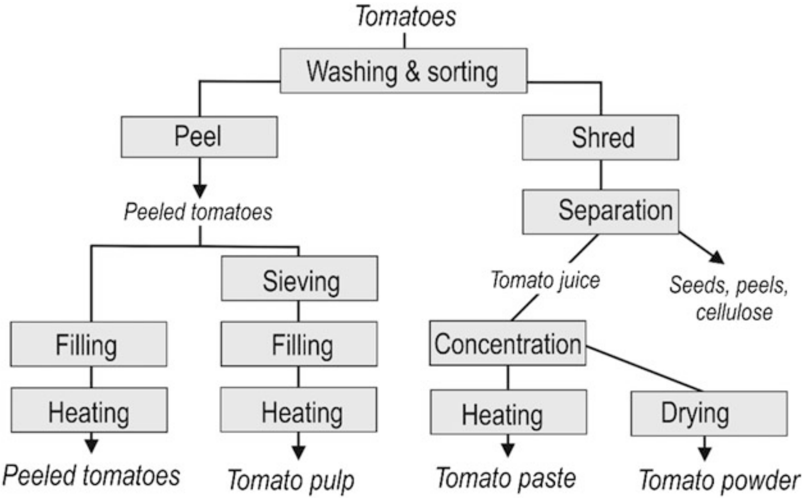

Fig. 7.7 Combination of process steps (boxes = unit operations) for the production of various tomato products for a range of applications (techno-functionality)

As the sterilization of larger containers (300–1500 kg) is not possible (heating and cooling would take hours and affect the quality of color, texture, taste, etc.), the products are continuously heated in heat exchangers, kept hot for a short, defined period of time, and then rapidly cooled. The products are then filled under aseptic conditions into previously sterilized containers. The production of tomato paste and powder requires further process steps including separation, concentration, and/or drying.

Energy and Water Consumption

Finally, a note on the energy and water consumption and the utilization/valorization of waste and side streams:

Technical developments not only allow the manufacture of products with a defined functionality and safety, but they also enable economical and responsible exploitation of water and energy resources. For example, the processing of foodstuffs requires an average of only 1–2 kg of water per kg of processed product, including the water required for cleaning procedures. In some cases, the water present in the product and removed during concentration is recycled. Energy consumption has also been markedly reduced. Food waste is composted and used either as fertilizer or in biogas plants for heat and electricity generation.

7.1.7 Strategies/Approaches for New Product Developments

Innovative companies generally launch a new product idea (Fig. 7.8) following existing trends or resetting trends by responding to changing consumer habits, social conditions (e.g., full-day child care), or trade demands. This also involves innovative technologies, such as membrane separation processes. Once the functional characteristics have been specified and the target consumer groups defined, a marketing concept is required that includes analysis of the market potential with respect to sales volume and price. The functionality of the final product needs to be specified as clearly as possible in order to be able to elaborate a detailed product concept.

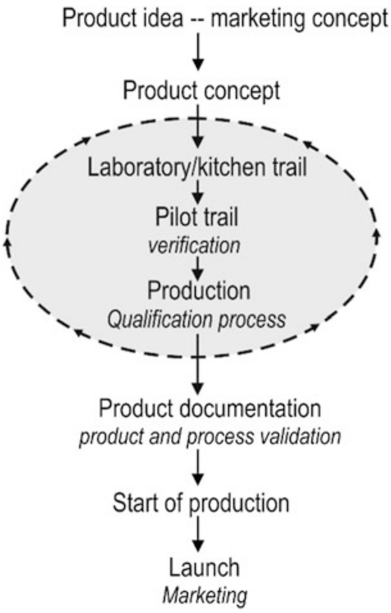

Fig. 7.8 From the idea to the new food product

Numerous aspects have to be taken into account during the product development process. The first step involves (preliminary) experiments in the laboratory, which consider the following aspects: selection of raw materials, additives, and other ingredients, a risk analysis (HACCP), specifications, appropriate test procedures for both the materials and functional properties, suppliers, shelf life, etc. The test procedures for the functional properties need to be defined and validated. The unit operations required to produce a product with certain functionalities as well as their sequence need to be defined. In addition, technical and legal requirements for the facilities have to be considered.

A pilot test then validates the technology used to produce a product with a certain structure and function and experiments are carried out to assess the shelf life. All these steps are repeated several times (Fig. 7.8) before the first production on a scaled-up level starts. At the same time, product declaration and packaging materials have to be adapted to the requirements of the product.

Once all these steps have been completed and the product documentation is available, the official production and supply to retailers can begin.

Once the new product is established on the market, it is important to constantly improve the recipe and to monitor market success. Only about 1 idea out of 100 will be successful in the long run.

7.1.8 Concluding Remarks

The technical processing of food should be seen as a continuous process of development that usually follows consumer demands. New technologies enable, for example, the decaffeination of coffee, the dealcoholization of beer, lactose reduction in dairy products, reduction of allergens, and production of fat-reduced foods that still taste good. Additionally, technical food production allows supply of a wide variety of high-quality food products at reasonable prices. Without technically processed products with a long shelf life, the supply of megacities could no longer be guaranteed, even in developing countries.

A new focus is the valorization of product waste and side streams, biorefinery, and use of "new" resources (depending on the country). Current research studies therefore have a strong focus on, for example, alternative protein resources (e.g., from microalgae and insects) but also on techniques that help to monitor the temperature history of food products during transportation and storage (e.g., time temperature indicators).

Review Questions

- What are the properties of proteins and fats in food? (use also other sources)
- What is meant by the term a_w-value/water activity?
- Describe and explain Fig. 7.6—assess pasteurization and sterilization of milk; consider aspects such as shelf life, storage conditions, nutrient value, and convenience.
- Assess/discuss traditional homemade and large-scale processing regarding present demands of growing cities and world population, food safety, and food security.
- Demonstrate the main steps to bring a new product idea (suggest your own one) to market. Discuss processing requirements needed to produce a certain product and also consider storage temperature as well as shelf life.

Further Reading

Kessler HG. Food and bio process engineering: dairy technology, 5th edn. Publishing House A. Kessler, Munich

Fellows PJ. Food processing technology – principles and practice, 4th edn. Elsevier Science/Woodhead Publishing, Kent

Belitz HD, Grosch W, Schieberle P. Food chemistry, 4th edn. Springer, Berlin

Jay JM, Loessner MJ, Golden DA. Modern food microbiology, 7th edn. Springer, New York

7.2 Biotechnological Conversion

Karin Moß, Marius Henkel, and
Rudolf Hausmann

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Abstract This chapter presents key terms and concepts in the field of industrial biotechnology. The inclusion of examples, such as ethanol fermentation, and production of polylactic acid (PLA) and propanediol (PDO), allows students to become acquainted with important concepts and their application. Industrial biotechnology, also known as “white biotechnology,” is devoted to the exploitation of living cells, such as yeasts, molds, bacteria, and enzymes. In the context of a bioeconomy, it may provide methods to replace and complement petroleum-based synthetics. Industrial biotechnology has been identified as a key enabling technology. Nowadays, industrial biochemicals are mainly produced from carbon sources based on sucrose and glucose. In a future bioeconomy, lignocellulosic plant biomass could become a key feedstock. However, for this purpose, technologies are required that can break down lignocellulosic biomass more easily, with less energy input, and creating less waste than is presently the case. The rapid development of genetic, synthetic biology and bioprocessing methods will lead to biotechnology increasingly complementing chemical industries.

Keywords Industrial biotechnology; Biological system; Bioprocess engineering; Strain development; Biocatalysts; Upstream and downstream processing; Biobased products

Learning Objectives

After reading this chapter, you should

- Understand the importance of industrial biotechnology for a biobased economy.

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- Know the key terms and concepts required to understand basic processes of bioprocess engineering.
- Know biotechnologically derived products of the present and the future.

7.2.1 Industrial Biotechnology

Industrial biotechnology uses microorganisms and enzymes for the production of biobased materials. These materials are utilized in the chemical, food and feed, healthcare, and biofuel sectors. Currently, biotechnology is a niche within the chemical industry, mostly providing products with demanding structure or stereochemistry requirements.

Historically, biotechnology dealt with uncontrolled food processing, such as in the production of wine, beer, vinegar, bread, cheese, and other fermented foods. In 1873, Louis Pasteur received a patent on isolated yeast, and since then the role of yeast in beer brewing and that of bacteria in vinegar fermentation has been exploited, and knowledge-based biotechnology began to evolve.

Contemporary industrial biotechnology, by contrast, uses controlled and induced production of various microbial products. This is achieved through the choice of and, in some cases, the genetic manipulation of the producing organisms and the development of bioprocess engineering. Bioprocess engineering provides both sterile conditions and control of several physiologically important parameters such as temperature (T), pH, dissolved oxygen (pO_2), and input of carbon and nitrogen sources as well as other components. Today, such methods enable reproducible processes to be performed, thus ensuring product quality.

There are three phases in bioprocess engineering: upstream processing, bioreaction, and downstream processing (Fig. 7.9). Upstream processing refers to all operations for the planning and preparation of the bioreaction. This includes the choice of the suitable biological system, the appropriate physiological parameters, as well as the strain development. The practical preparation of the bioreaction—i.e., preparation of media, sterilization of bioreactor, and preparation of pre-cultures—also belongs to this step. During the bioreaction, a given substrate is converted into the desired product by a biological system. Microorganisms (bacteria, yeast, fungi), mammalian cells, and enzymes may be utilized. As the resulting product typically comprises no more than 10–15% of the fermentation broth, downstream processing is needed in order to separate and purify the desired product.

7.2.2 Biological System

Bioprocess engineering employs biocatalysts, microorganisms, and cell lines, or parts thereof, for the generation of value-added products. The huge potential of the multitude of naturally occurring organisms that could be used has not yet been exploited. The phylogenetic tree in Fig. 7.10 shows biotechnologically important

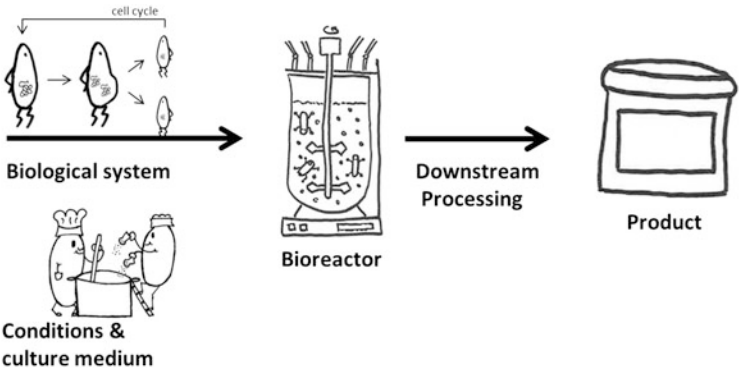


Fig. 7.9 Schematic overview of upstream, bioreaction, and downstream processing in biotechnology. The choice of the biologic system as well as conditions and culture medium belong to the upstream processing (by Johannes Kügler)

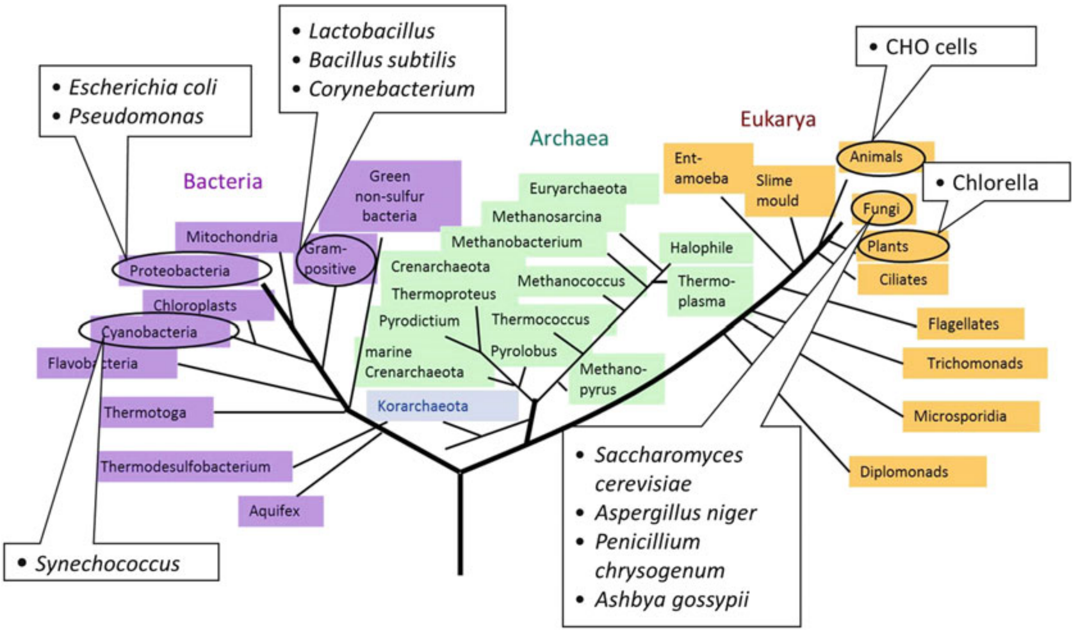


Fig. 7.10 Phylogenetic tree with important biotechnological used microorganisms

groups of organisms found within the prokaryotes (cyanobacteria, proteobacteria, Gram-positives) and the eukaryotes (fungi, animals, and plants). For the choice of a suitable biological system, it is important that the organism is able to produce the desired product efficiently. The process conditions, such as temperature, pH, and oxygen content, must be chosen according to the physiological requirements of biological system employed.

Important Groups of Organisms for Biotechnology

The most important microorganisms for biotechnology are bacteria, yeast, algae, and mammalian cells. Important *bacteria* used in industrial processes are, for example, *Escherichia coli* (for various processes, e.g., recombinant proteins), *Bacillus sp.* (detergent proteases, vitamin B2), *Clostridium acetobutylicum* (acetone, butanol), and *Corynebacterium glutamicum* (amino acids). They are easily genetically manipulated; robust against shear stress, pressure, and osmosis; show high productivity, cell densities, and growth rates; and are able to grow in comparatively inexpensive media. One disadvantage is that they are often deficient in secretion of proteins and are not able to perform important posttranslational modifications such as N-glycosylation. The bacteria may become infected by phages, possibly destroying the bacteria culture and resulting in the loss of production.

Industrially employed *yeast and fungi* include *Saccharomyces* (beer and wine yeasts, ethanol), *Penicillium (*many antibiotics, e.g., penicillin), and *Aspergillus* (some antibiotics, many organic acids, e.g., citric acid). Their advantages are the following: high productivity of homologous proteins, high cell densities, very good secretion, fast growth rates, good pH tolerance (very important for the production of acids), large cell size (simplifies downstream processing), and no problems with phages. Additionally, yeast and fungi can perform posttranslational modification. However, their glycosylation pattern is neither identical nor similar to that of humans, and this limits their use in pharmaceutical products.

The production of therapeutic glycoproteins for pharmaceutical use is performed by *mammalian cell* cultures. Various cell lines are employed industrially, the most relevant being Chinese hamster ovary cells (CHO), but also others to a lesser extent. Mammalian cell cultures are very sensitive in comparison to bacteria, yeast, and fungi. They grow very slowly, have only low cell densities, are sensitive to shear stress and osmosis, and require high investment and process costs. However, one advantage is that they perform posttranslational modification and glycosylation pattern identical to that of humans. These properties make them the standard solution for therapeutic protein production.

Homologous proteins: Proteins derived from the host strain's DNA.

Heterologous proteins: Proteins derived from the DNA of another organism than the host strain in which it is expressed.

Posttranslational modification: In protein synthesis, DNA sequences are first transcribed into RNA by RNA polymerase and then translated intro proteins by ribosomes. The protein's structure may then be modified, for example by the removal of biochemical groups or the addition of (in-)organic groups.

Glycosylation/glycosylation pattern: This is a specific posttranslational modification of the protein, in which sugar residues are attached to the protein. These sugar residues and their varying patterns are recognized by the immune system. It is thus mandatory that therapeutical proteins have the correct glycosylation and sugar residue pattern.

Strain Development: Genetic Improvement of Production Strains

Wild-type strains do not normally produce profitable quantities of the desired chemical substance. It may even be that the production strain does not naturally produce the desired substance at all. In order to enable the production or improve the productivity, strains are genetically modified. This is called strain development. Methods used include classic screening and mutagenesis, genetic engineering, metabolic engineering (directed mutagenesis), and synthetic biology.

In *classical mutagenesis* (example: penicillin), the microorganism known to produce the desired substance is mutagenized by chemicals or UV light, which introduces random changes in the genome. A screening is then carried out to select enhanced producers. Mutagenesis and screening are traditionally repeated iteratively for several generations of microorganisms. This approach is very time consuming. Another drawback is the introduction of several random mutations, which individually or collectively reduce the viability of the organism.

If the desired product is a direct gene product (i.e., a protein), *genetic engineering* is a suitable choice (example: insulin). Here, the gene encoding for the desired protein is additionally incorporated via a vector or chromosomal integration into the production strain, which then produces it either intra- or extracellularly.

In *metabolic engineering*, the metabolic pathways of a microorganism are improved by enhancement of desired pathways and deletion or attenuation of those that lead to by-products. Bottlenecks are identified through metabolic flux analysis (metabolomics and transcriptomics) and reduced by genetically enhancing biosynthesis routes. In this way, higher product titers (concentrations) with fewer by-products can be achieved (example: L-lysine and succinic acid).

The currently most modern approach is termed *synthetic biology*. In this approach, pathways are designed based on formerly gained knowledge (example: propane-1,3-diol, PDO) and the biosynthesis is reconstituted in the most suitable microorganism. Modified biosynthesis genes originating from various donors including plants may be exploited. Existing genome, metabolome, proteome, and transcriptome data can be used in computational modeling for further enhancement. In synthetic biology, these data are used to design nonnatural, novel pathways and circuits in production strains. These strains may than be used for industrial application. Databases such as National Center for Biotechnology Information (NCBI), BRaunschweig ENzyme DAtabase (BRENDA), Kyoto Encyclopedia of Genes and Genomes (KEGG), and many others are essential for the design of such microorganisms.

7.2.3 Basics of Bioprocess Engineering

Bioprocesses are characterized by the utilization of living cells or enzymes as catalysts, which are therefore termed biocatalysts. The production of the biocatalyst is thus the first step in the conversion of a given substrate to a desired product.

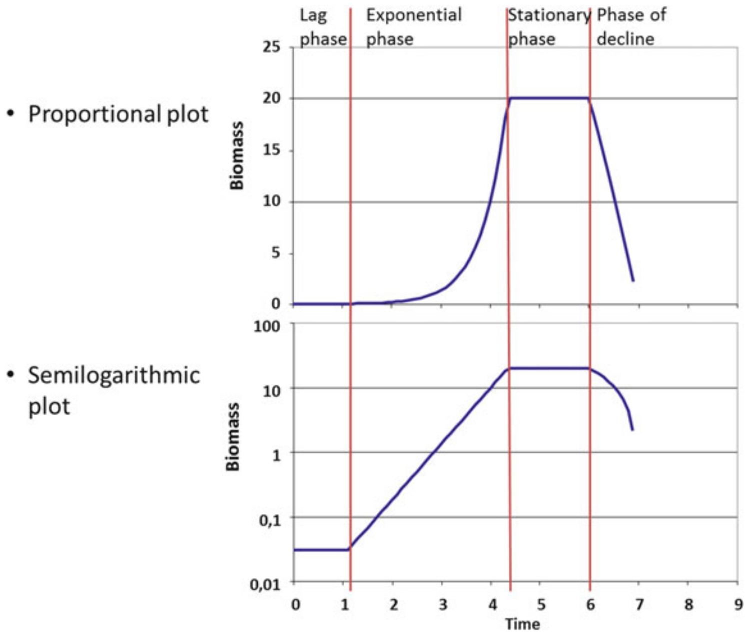
Biomass Growth

Bacteria and yeast multiply by binary fission. Bacteria grow by cell enlargement and subsequent fission in two identical bacteria cells. Yeasts grow by budding: they divide into a mother and a smaller daughter cell, leaving a scar on the mother cell. The daughter cell grows to the same size as the mother cell. Fungi are multicellular organisms and grow either by apical growth or ramification, where a new cell is added to an existing one. The rate of growth in the reactor is called the specific growth rate (μ). This may vary in a given bioprocess, depending on nutrient availability, substrate inhibition, accumulation of metabolites (acetate, alcohol, lactic acid), and population density. Typically, different growth phases can be distinguished (see Fig. 7.11): Initially microorganisms adapt to the new environment, which is apparent in the so-called lag phase, where the growth rate is zero. This is followed by an acceleration phase with an increased growth rate. A subsequent phase with constant growth rate, the exponential phase, is then observed. Population growth is finally limited by consumption of available nutrients and levels off. In bioreactor cultivations, the rates of growth and product formation are controlled by the setting of process conditions and feeding-in of nutrients.

Media Composition and Culture Conditions

In bioprocesses, the medium is the liquid in which the bioreaction is performed. It provides the microorganisms with an energy source and all necessary nutrients. Biomass is composed mainly of the elements carbon [C], oxygen [O], nitrogen [N], hydrogen [H], potassium [K],

Fig. 7.11 Formal classification of growth phases



phosphorus [P], and sulfur [S] and other microelements. In order to produce biomass, all these elements have to be present in the medium in a suitable concentration. Additionally, other growth factors such as vitamins and essential amino acids may be required. If any of these are missing or have been consumed, the cell growth will stop. However, as the cells are still alive, they still consume nutrients for cell maintenance. For most biotechnological processes, the carbon and energy source consists of carbohydrates such as glucose, sucrose, or starch, or carbohydrate residues such as molasses. They may also be provided by triglycerides such as vegetable oils. The nitrogen sources most often used are ammonia or ammonium salts, urea, corn steep liquor, yeast extract, soy flour, fish meal, or protein hydrolysates. Media can be differentiated into complex and defined media. Complex media contain at least one non-defined component, e.g., yeast extract or corn steep liquor. In a defined medium, the chemical composition of the carbon source, inorganic salts, as well as any other additions is precisely specified. A defined medium is used when strict control and reproducibility of the process are essential. Complex media are less expensive and can be used when strict control is not necessary.

Bioreactions have to be performed under physiological conditions, i.e., an environment that suits the microorganisms' preferences in terms of temperature, pH value, oxygen availability, ion concentrations, and water activity.

Bioreactors, Process Kinetics, and Process Control

Bioreactions are performed in a vessel called a bioreactor, which provides a sterile barrier, thus preventing contamination. A bioreactor can be understood as any defined space or apparatus, in which material conversions take place with the participation of biocatalysts. Functions of bioreactors include mixing (homogenization) of content, suspension of solids (microorganisms, pellets), emulsification of two non-intersoluble liquids, dispersal of gases (air or O_2) in the liquid, and ensuring that constant physical parameters (temperature, pH, pO_2) are in the optimal range. Therefore, devices for tempering, stirring, aeration, pH control, pO_2 control, foam control, and further addition of medium and acid or base are necessary. In this way, the processes can be controlled and reproduced. There are various types and shapes of bioreactors, including bubble column, fluidized bed reactor, tubular reactor (mainly for algae), and stirred-tank reactor. The last is the type most often used (Fig. 7.12).

Bioprocess kinetics describe the time-dependent courses of cell growth, product concentration, and substrate concentration during a bioprocess. Important parameters include the specific growth rate μ [1/h], the substrate consumption rate, the product formation rate, the productivity P_v (g/L h), and the product yield per substrate [$Y_{P/S}$ (g/g) or $Y'_{P/S}$(mole/mole)]. If investment and production costs are high, productivity is the most relevant parameter. If substrate costs are high, yield per substrate is most relevant.

Reactions can be performed in batch, fed-batch, or continuous mode. The easiest process mode is a batch culture, where the whole reaction is performed in the initial volume without further nutrient addition over time. The growth rate is not constant, as nutrients are consumed. Nutrients in excess may lead to metabolic overflow reactions. Fed-batch processes are started with a low volume and subsequent addition of nutrients. A constant or an exponential growth rate can be achieved and metabolic overflow prevented. Correspondingly, the volume increases over time. A continuous culture enables a steady flow of fresh medium into and of bioculture out of the reactor. The volume remains constant, but the microorganisms grow at the set growth rate. With this kind of bioprocess, a quasi-steady state of biomass and nutrient concentrations can be achieved. Batch and fed-batch cultivations are advantageous where defined charges are required, e.g., in the pharmaceutical industry. Most industrially relevant bioproduction processes are carried out in fed-batch mode.

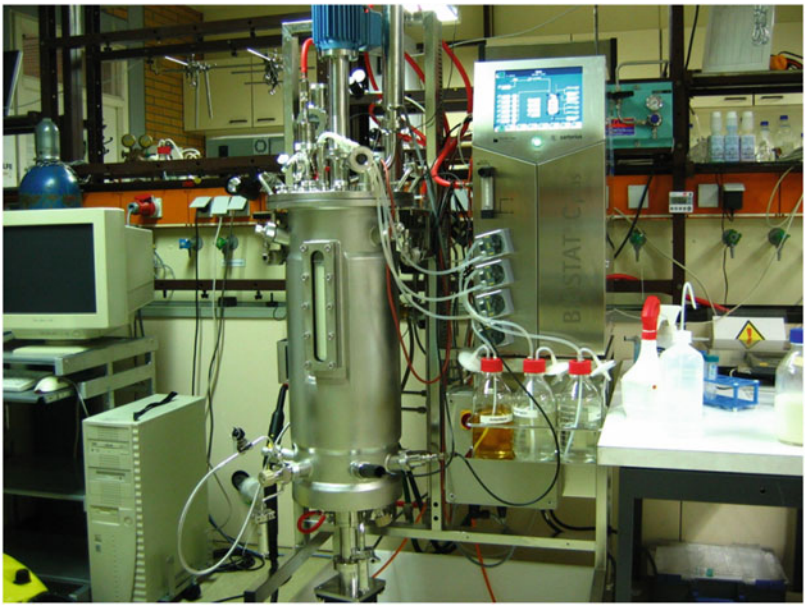
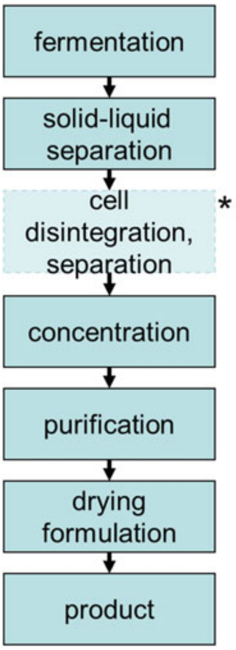


Fig. 7.12 A stirred-tank bioreactor for the controlled growth of microorganisms, with devices for stirring, O_2 and pH control, feeding-in of substrate, base, and antifoam

Downstream Processing

Downstream processing deals with the recovery of the desired product. This is often an extensive task, as the fermentation broth consists of 90–99% of water and hence the desired product is very diluted. In general, water has to be eliminated during downstream processing. Normally, further by-products are formed, which may be very similar to the target product. If, for example, an intracellularly produced heterologous protein is to be recovered, it has to be separated from numerous other proteins present in the cell, all consisting of chemically similar amino acid chains. For the recovery of the desired product, a generalized purification scheme can be followed, as shown in Fig. 7.13. The first step is nearly always a solid-liquid separation, where the solid biomass is separated from the surrounding liquid. If the target product is an extracellular compound, the biomass is discarded. If the target is an intracellular product, the supernatant is discarded. In the latter case, the cells are then disintegrated, and the solids are once again separated off and disposed of. In



* For intracellular products only

Fig. 7.13 General downstream processing scheme for a biotechnological product both cases, the remaining liquid is concentrated and then further purified in the next step. The degree of purification depends on the purity demands of the target product. For medical applications in particular, compliance with legislative regulations is cost intensive. In the last step, the product is dried, formulated, and packed, giving the final product, which is ready to be sold (Fig. 7.13).

Possible Products

For the biological conversion of renewable materials, microorganisms are used as catalysts. As a rule, only naturally occurring metabolites and products can be produced so far.

These products are formed by metabolization of a given substrate (mostly glucose from starch hydrolysis) to the desired product. In the process, the substrate passes through different metabolic pathways, which can be classified as primary or secondary metabolism. In the primary metabolic pathways, intermediates and products of low molecular weight are formed, which are then either used for the generation of macromolecules or broken down to supply the cell with energy. Examples of primary metabolic pathways are glycolysis and the citric acid cycle. With the exception of fermentation end products, all primary metabolites are normally only synthesized in the amount required by the cell. Overproduction of these products can be achieved by modification of the metabolic regulation. For some primary metabolites, e.g., citric acid, the appropriate choice of fermentation conditions, such as low pH and excess substrate supply, leads to overproduction. Secondary metabolic pathways generate substances that do not appear to be directly needed for the survival of the organism. Secondary metabolites are often complex in structure and can be biologically active. One example of a secondary metabolism pathway is the mevalonate pathway, which leads to the production of isoprenoids.

Some metabolic pathways require oxygen for the transfer of electrons. In this case, aerobic conditions, i.e., with aeration, need to be provided. Other metabolites are formed in anaerobic conditions, so here no aeration is required. Not all microorganisms exhibit all kinds of metabolic pathways. There are strictly aerobic, facultative anaerobic, microaerophilic, and strictly anaerobic microorganisms.

Possible products include *biomass*, as in baker's yeast and starter cultures; *primary metabolites* such as the end product ethanol and intermediates like organic acids and amino acids; *secondary metabolites* like antibiotics, alkaloids, toxins, and biosurfactants; *specialty products* like storage substances, exopolysaccharides (e.g., xanthan), and pigments; *enzymes* like amylases, proteases, and glucose isomerases; and *proteins* like recombinant proteins or monoclonal antibodies.

7.2.4 Application of Industrial Biotechnology

This section presents bioproducts that have already been established.

Antibiotics

An antibiotic is a substance, which either inhibits the growth of or kills a bacterium. There are several antibiotics on the market. The best known is penicillin, which inhibits cell membrane formation and thus bacterial growth. Antibiotics have revolutionized the cure of bacterial infections. However, the spread of multiresistance in pathogenic bacteria poses a global health threat, as the infections caused can no longer be treated with widely used antibiotics.

Penicillin was discovered by chance in 1927 by Sir Alexander Fleming. He noticed a fungal contamination growing on a bacterial culture. A halo with no bacterial growth had formed around the fungal (*Penicillium notatum*) colony. Fleming was able to produce an antibacterial extract with a titer of about 1.8 mg/L and named it penicillin. At first, penicillin was produced as surface cultures, making upscaling quite difficult. Nevertheless, as penicillin became important, especially for the cure of wounded soldiers, these surface cultures were performed industrially with high labor intensity in up to 100,000 milk bottles in parallel. With the development of bioprocess engineering and respective strains, it became possible to produce penicillin in submerged cultures, where the scaling up of the tank is comparatively easy. New and more potent penicillin-producing strains were screened for. With improved strains and bioprocess engineering technology, the penicillin titer was increased by a factor of 40,000 within the following 80 years. Today, about 10,000 different microbial antibiotics are known. However, only a fraction of these is exploited for medical purposes.

Organic Acids

Organic acids are basic chemicals and serve as building blocks for polymers or as acidifiers. Most of them are produced chemically (e.g., adipic acid), but citric, lactic, gluconic, itaconic, and succinic acid are almost exclusively produced biotechnologically. The four most important organic acids, each with a global production of more than one million tons per year, are acetic acid, acrylic acid, adipic acid, and citric acid. Of these, only citric acid is produced biotechnologically.

Acetic Acid

About 7,000,000 t of acetic acid are produced annually by chemical carbonylation of methanol. The conditions applied (150–200 °C and 3–6 MPa) are relatively mild for a chemical process. This reaction has a total carbon yield (Yc) of about 95%, i.e., 95% of the deployed carbon is converted to acetic acid. Biotechnological production by fermentation is modest in comparison: 200,000 t of acetic acid as a component of vinegar. Vinegar is produced by employing bacteria of the genus *Acetobacter* or *Gluconobacter* in an incomplete oxidation of ethanol to acetate. This reaction has to be performed under aerobic conditions, as an oxygen molecule is added to the ethanol. The fermentation takes place at 26–28 °C at normal pressure. Even though the yield ($Y_{(P/S)}$) is 85–90%, the final concentration is only 100–150 g/L and the total carbon yield (Y_c) starting with glucose is about 57%.

Acetic acid is used in the food industry as acidulants, preservatives (E 260), and vinegar. The main fraction of acetic acid is used for the preparation of polymers, such as polyvinyl acetate (PVAC) for paints and varnishes and ethylene vinyl acetate and cellulose acetate for cigarette filters, films, and other plastic products.

Succinic Acid

Succinic acid is one of the new substances which may pave the way to a biobased industry. It can be used as a platform chemical to be transformed into further products. These may then serve as building blocks, e.g., in polymers. It can also be used directly as a monomer for alkyd and polyester resins; plasticizers; flexibilizers; paint solvents; food additives (E 363); flavor enhancers; potassium, calcium, and magnesium succinate as a substitute for sodium chloride; and acidifier or acidity regulator. Succinic acid is a metabolite within the citric cycle and is gained under anaerobic conditions. Succinic acid can be produced by *E. coli* (company BioAmber), *Basfia succiniciproducens* (company Succinity, a joint venture between BASF and Corbion Purac), and *S. cerevisiae* (joint venture between DSM and Roquette). Whereas *E. coli* and *S. cerevisiae* had to be extensively genetically modified for high-titer succinic acid production, *B. succiniciproducens* secretes it naturally in relatively high quantities. In *E. coli* and *S. cerevisiae*, the by-product formation is deleted and the biosynthetic pathway enhanced. Under anaerobic conditions, the citric acid cycle is passed through in the reductive direction and succinic acid is formed and secreted into the medium as end product. Technically, this is realized in a two-phased bioprocess. For *E. coli* and *S. cerevisiae*, biomass is built up in the first phase under aerobic conditions. The second phase is the anaerobic production, where titers of about 100 g/L can be achieved.

Biopolymers

Nowadays, most plastics (300 Mt/a) are of petrochemical origin, and thus rely on a nonrenewable resource. The terms “bioplastic” and “biopolymer” incorporate several concepts. One is the biotechnological manufacture of monomers used to produce biobased synthetic materials such as lactic acid, propane-1,3-diol, succinic acid, isoprene, adipic acid, 1,5-diaminopentane, and others. Biobased synthetic materials may or may not be biodegradable. The term “biopolymer” also covers microbial polymers and in general polymers synthesized by living organisms such as polynucleotides (the nucleic acids DNA and RNA), polypeptides (proteins), and polysaccharides (polymeric carbohydrates). Biopolymers utilized as bioplastics are polyhydroxyalkanoates (PHA) such as polyhydroxybutyrate (PHB). However, the term “bioplastic” can also refer to a biodegradable plastic of petrochemical or mixed origin. In this chapter, we focus on biobased synthetic materials. From an economic point of view, polylactic acid (PLA) (global production ~370,000 t/a in 2011) and xanthan (global production ~110,000 t/a in 2012) are the most important biopolymers.

Bio-Nylon and Diamines, Cadaverine

Nylon (PA66) was the first 100% synthetic fiber to be produced. It is a polyamide that can be spun and is produced by the condensation of two chemically produced monomers: 1,6-hexanediamine and adipic acid. Similar biobased, or at least partly biobased, products can be made by replacing the 1,6-hexane diamine by 1,5-diaminopentane and the adipic acid by either sebacic or succinic acid, to give the products PA 5.10 or PA 5.4. These biobased polyamides can, for example, be used in textiles, carpets, and sportswear. 1,5-Diaminopentane (cadaverine) can be produced biotechnologically. For this, the lysine biosynthetic pathway of *C. glutamicum* was extended by one step, the lysine decarboxylase. This product has been manufactured by BASF at pilot scale and processed together with sebacic acid derived from castor oil.

Polylactic Acid

Polylactic acid (PLA) is a thermoplastic material with a rigidity and clarity similar to polystyrene (PS) or polyethylene terephthalate (PET). Its availability and attractive structure make it the front runner in the emerging bioplastics market. Its building block is lactic acid, produced by the fermentation of sugars. PLA is biodegradable and hence can be used for packaging material or single-use items, but also for household items. Lactide is formed by intermolecular dehydration of lactic acid. Polylactide (PLA) is prepared by catalytic ring opening polymerization of lactide. Only the pure enantiomers, generally L-lactic acid, can be polymerized. Even though *Lactobacilli* are wild-type strains able to generate lactic acid, they are no longer used for large-scale lactic acid production. This is due to the product inhibition, pH sensitivity, and susceptibility to phages. Today, genetically optimized *S. saccharomyces* strains are used, where an acetate dehydrogenase has been added to the genome. The advantages of this organism are its pH tolerance (>pH 2), no problems with phages, and the simple downstream processing. Disadvantages are lower productivities and that ethanol is formed as by-product.

Propane-1,3-Diol (PDO)

Propane-1,3-diol is a clear, colorless, odorless, biodegradable liquid with low toxicity. It is used in the manufacture of polyesters, for example polytrimethylene terephthalate (PTT) also known as 3GT. From these polyesters, clothing, fibers, automotive parts, carpets, solvents, and coatings are produced. Biotechnological production of PDO was the first industrial application of synthetic biology, as there is no organism known, which produces PDO directly from glucose. But it is known that *S. cerevisiae* converts glucose to glycerol and that the bacterium *Klebsiella pneumoniae* transforms glycerol to PDO. The cloning of the appropriate genes of both these microorganisms into *E. coli* gave a recombinant organism able to convert glucose to PDO. This is done in an aerobic process with a final concentration of 135 g/L propane-1,3-diol, a volumetric productivity (P_v) of 3.5 g/(L h), and a yield ($Y_{P/S}$) of 51% (m/m). PDO biotechnologically produced from corn glucose was introduced in 2006 and is considered the first basic chemical produced by a strain generated by synthetic biology methods.

Isoprene

Currently, synthetic rubber (20 million t/a) is derived entirely from petrochemical sources and comprises mainly styrene-butadiene rubbers (SBR). Natural rubbers are isoprene rubber (IR), gained from plants like the rubber tree (*Hevea brasiliensis*). Isoprene is a colorless liquid which is insoluble in water and volatile, as its boiling temperature is 34 °C. DuPont is working together with Goodyear on the development of a fermentation-based process for the production of bio-isoprene monomer (2-methyl-1,3 butadiene). The largest application area for bio-isoprene is the production of synthetic rubbers for "green" tires and elastomers. Two metabolic pathways exist, which lead to isoprene as secondary metabolite: the mevalonate (MVA) pathway and the methylerythritol-4-phosphate (MEP) pathway. For the fermentative production, an *E. coli* was chosen as production strain. The MEP pathway is endogenously present in *E. coli*, and the MVA pathway was additionally cloned into it. Later, an adapted isoprene synthetase was added to the genome. With this strain, an isoprene titer of 60 g/L and a volumetric productivity (P_V) of 2 g/(L h) were achieved. The yield ($Y_{P/S}$) was 11% isoprene per glucose. This is quite ineffective, given that the theoretical maximum is 24% for the MVA pathway and 29% for the MEP pathway. Isoprene is gaseous at 37 °C and therefore can be continuously removed from the exhaust gas of the bioreactor.

Polyhydroxyalkanoate

Polyhydroxyalkanoates (PHA) are microbial polymers (polyesters) produced by bacterial fermentation of sugars. Polyhydroxybutyric acid was discovered in 1926 in *Bacillus megaterium.* Numerous bacteria (>90) including *Cupriavidus necator* form PHAs as a reserve or storage materials. PHAs are therefore fully biologically degradable and have further useful properties such as thermoplasticity, biocompatibility, and nontoxicity. In 1990, the first biodegradable product (Biopl®) was launched in Germany. However, the plastic recycling system ("Gelber Sack") introduced here a year later inhibited the advance of this bioplastic. Today, PHA products are insignificant. Nevertheless, Metabolix has successfully commercialized PHA biopolymers for a range of applications. PHAs are considered a replacement for petrochemical polymers. Their potential applications include packaging material, hygiene products, and medical industry products.

Biofuels

Biofuels are renewable fuels derived from biomass through chemical or biochemical reactions. Depending on the feedstock used, three generations of biofuel can be differentiated. "First-generation" biofuels are based on food crops, such as sugarcane and corn, and are thus in direct competition with food. "Second-generation" or "advanced" biofuels are based on nonfood crops and lignocellulose with reduced or no food competition. "Third-generation" biofuels are based on algae, which avoids competition with food and lowers land requirements. The main biofuel used today is ethanol. Other biotechnologically producible biofuels are biobutanol, alkanes, biodiesel, and biogasoline. For biobutanol production, either *Clostridium acetobutylicum* or metabolically engineered *S. cerevisiae* can be used. As a proof of principle for microbial alkane production, the metabolic pathways of alkane production from cyanobacteria were functionally expressed in *E. coli,* which secretes the hydrocarbons. The company LS9 was heading towards commercialization of these microbial fuels, but the production was stopped as it proved uncompetitive with petroleum-based fuels.

7.2.5 Conclusion and Outlook

Currently, industrial biotechnology only accounts for a minor proportion of industrial chemical and material production. In comparison to petrochemical industries, biotechnology only holds a representative market share in a few niche areas. Thus, a major turnaround will be required to convert a major part of the current chemical industry towards a biobased one.

However, the potential exists for novel, environmentally friendly, knowledge-based products and this potential could generate new, high-level job opportunities for biotechnologists and bioeconomists in the future.

Review Questions

- Differentiate between “traditional biotechnology” and modern biotechnology by means of an example.
- Various microorganisms are applied in the industrial production of bioproducts. Assess advantages and disadvantages of the most important organisms.
- In few niche areas, biotechnologically derived products hold a representative market share. Compare and contrast an established product with a prospective bioproduct. Consider factors hindering or facilitating the introduction.

7.3 Thermochemical Conversion

Andrea Kruse

Abstract All thermochemical conversions help to overcome two main hurdles in the bioeconomy: the high oxygen content of biomass (low heating value if used as fuel) and the large variability in biomass composition and characteristics. In addition, all thermochemical conversions have in common that they can produce platform chemicals, materials, or fuels from a wide range of biomass types, and that the oxygen content is lower in the product than in the feedstock. The bioeconomy is not only a concept, but also requires technologies that are attractive enough for companies to put into practice, thus creating the technological base for a large-scale use of biomass.

For the substitution of fossil resources by biomass, new technologies are needed. In this chapter, students learn how biomass is converted by (thermo-)chemical conversion technologies to energy carriers or platform chemicals. One example is the conversion of chicory roots to the platform chemical hydroxymethylfurfural (HMF). After further chemical conversion, HMF can be used to produce a wide range of common objects from daily life, including bottles and stockings. Thermal conversion can also be

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applied to produce special carbon materials, e.g., supercapacitors, which will enable a more flexible use of e-cars.

Keywords Pyrolysis; Gasification; Carbonization; Torrefaction; Supercritical water; Hydrothermal processes; Platform chemical

Learning Objectives
After reading this chapter, you should

- Have an overview of thermochemical conversion technologies.
- Know the range of products which can be produced by thermochemical conversion.
- Be able to choose an appropriate process with respect to (a given) feedstock and desired product.

7.3.1 Introduction

When biomass is compared with fossil resources such as coal or oil, the main difference is its higher oxygen content. Cellulose, the main component of biomass, contains one oxygen atom per carbon atom. This reduces the heating value of biomass when used as fuel. The high oxygen content is also a disadvantage when biomass is used as chemical compounds to produce, for example, plastics. Figure 7.14 represents a small part of cellulose, using Lego® bricks to demonstrate its structure. Every red brick (which represents a carbon atom) has an OH group attached to it. In chemistry, this is called a functional group, which, put simply, means "a place to make chemical bonds." As can be seen, cellulose has a functional group at each carbon atom and is therefore considered "over-functionalized." For plastics, every basic chemical needs to have two functional groups, one at each end. This enables the formation of long chains, which are the basis of all polymers. In fact, this is what the word polymer means: a long chain of repeating units.

In principle, there are three possibilities to convert biomass into products: (1) biological or biochemical methods applied at low temperatures, (2) chemical conversion at medium temperatures, and (3) thermochemical processes at higher temperatures. This chapter focuses on thermochemical processes, which means chemical conversions that use heat as an important tool for the conversion. Thermochemical conversions are characterized by the desired product and the "agents" added to influence the reaction. The products are solids (char, coke, charcoal), a tarry liquid, and gases. Important agents include oxygen and air. The addition of these leads to a partial combustion of organic material, delivering the heat necessary for the conversion. This is then called an "autothermic process." Another important agent is water, added as a liquid or in the form of steam. Due to the large range of processes which are performed with or without water, the following sections distinguish between dry, steam-assisted, and hydrothermal biomass conversions. All conversion methods have one thing in common: the oxygen content is reduced, as illustrated in Fig. 7.14 for charcoal formation.

The characterization of fuels by the ratio of hydrogen to carbon and the ratio of oxygen to carbon can be displayed in so-called van

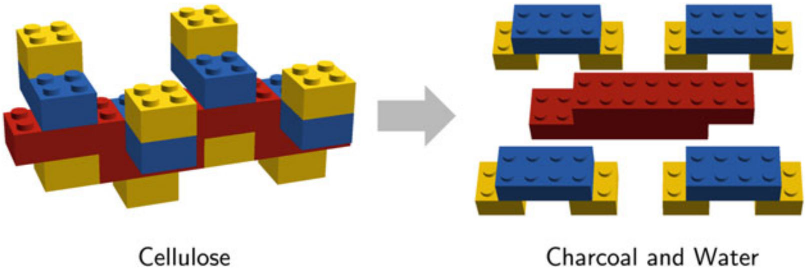

Fig. 7.14 Charcoal formation from biomass, illustrated using Lego® bricks. Red bricks represent carbon atoms, blue oxygen atoms, and yellow hydrogen atoms

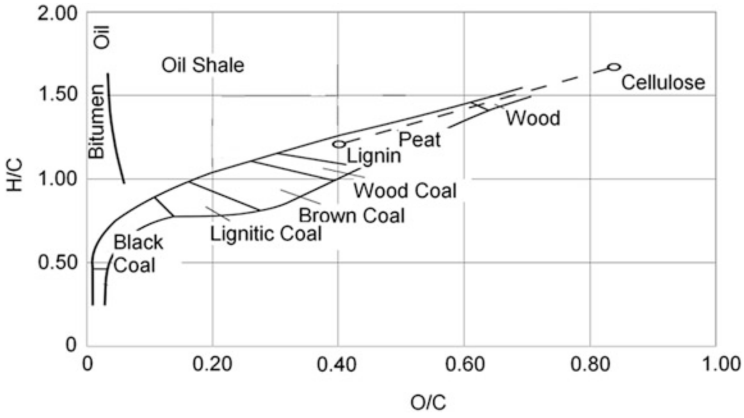

Fig. 7.15 Van-Krevelen diagram of fossil fuels and biomass

Table 7.3 Overview of dry processes (based on Hornung 2014)

	Conditions	Liquid (tar with water) (%)	Solid (char) (%)	Gas (%)
Fast pyrolysis	~500 °C, short hot vapor residence time < 2 s	60	20	20
Slow pyrolysis	~500 °C, ~1 h	30	50	20
Torrefaction	~300 °C, ~10–30 min		77	23
Slow—carbonization	~400 °C, ~hours/days	30	35	35
Gasification	~800 °C	5	10	85

Krevelen diagrams. Figure 7.15 shows different types of fossil coal and fossil oil, as well as wood as an example of biomass.

Biomass materials used for thermochemical conversions mainly consist of hemicellulose, cellulose, lignin, and ash. Cellulose and lignin have also been added to the van Krevelen diagram (Fig. 7.15). Lignin has a chemical composition similar to brown coal. As can be seen, fossil coal has both a lower oxygen and hydrogen content in relation to carbon. A line could be drawn from cellulose to coal in Fig. 7.15, corresponding to the elimination of water, as shown in Fig. 7.14. It should be pointed out here that the production of a liquid product similar to fossil oil can only be achieved by the addition of hydrogen, e.g., by coal hydrogenation. A conversion that eliminates oxygen only, instead of water, is not chemically possible. The only possibility of reducing the oxygen content without reducing the hydrogen content is through the elimination of carbon dioxide or carbon monoxide. Here methane or hydrogen is the other end product, not hydrocarbons.

7.3.2 “Dry” Processes

Dry processes are considered the more “traditional” conversion processes. In dry processes, the water content of the biomass needs to be below 10 wt%, which means the processes can only be applied to biomass with low water content, such as wood, straw, and crops which produce similar biomass, such as miscanthus. Other biomass feedstocks with higher water content have to be dried before being processed. As this requires a lot of energy, it is not usually done in practice. The dry processes are summarized in Table 7.3 (Fig. 7.16).

Dry biomass conversion generally leads to the formation of a mixture of solid, liquid, and gaseous products, the ratio of which changes with reaction conditions (Table 7.3). At the lowest temperatures of around 300 °C, the so-called torrefaction occurs. For this, continuous reactors like rotating tubes are often used. From a chemical point of view, the heating process first dries the biomass, and then leads to the formation of volatilized compounds from hemicellulose to

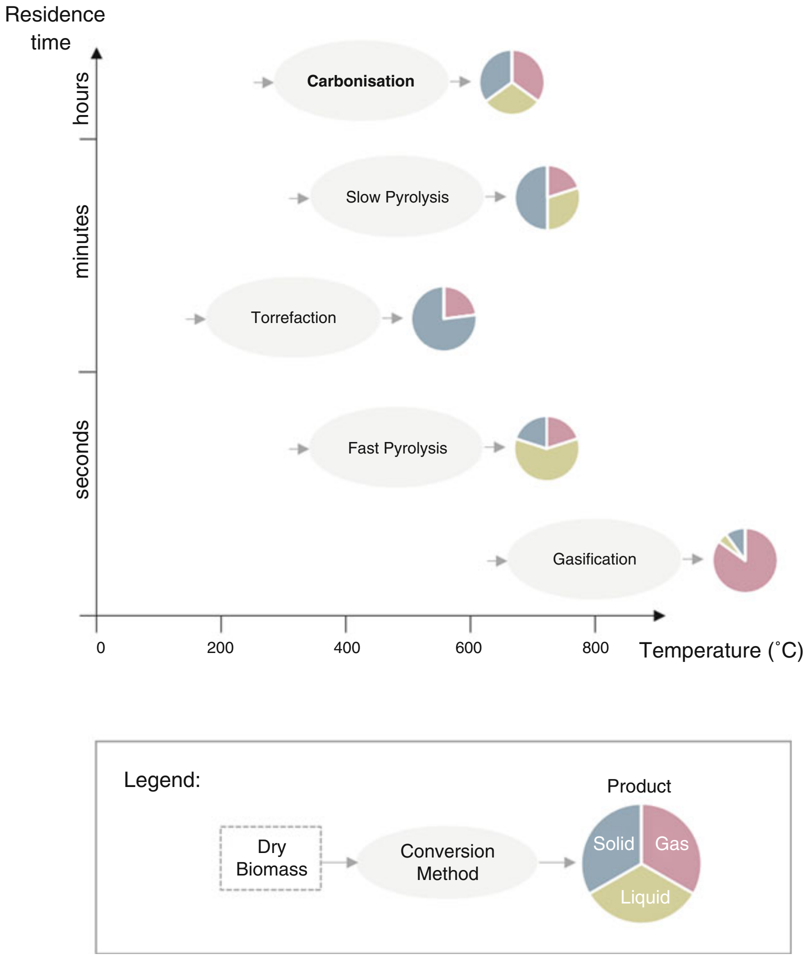

Fig. 7.16 Thermochemical conversion: dry processes

leave a solid, partially charred material. At higher temperatures, cellulose also forms volatiles and starts charring. The condensable gases are combusted outside the torrefaction plant to generate the heat required for the process. Torrefaction is usually regarded as a pretreatment process and is followed by another thermal treatment, e.g., gasification or combustion. The torrefied product has a slightly higher heating value than the original biomass as it has a lower oxygen content [e.g., 19 MJ/kg to 20–22 MJ/kg (Gucho et al. 2015)]. This reduces the relative transport costs and, in addition, the structural changes that occur during torrefaction mean that much less energy is required for milling.

Slow pyrolysis is applied to obtain a solid fluid and to reach complete conversion. Here, temperatures of 500–600 °C and longer reaction times lead to a complete charring of the biomass. Again, a rotating tube is often used and the combustible gases are used for heat generation. The classic process to produce charcoal is with kiln. In these, first a high amount of air is entered so that part of the volatiles formed by wood pyrolysis are burned. Once a high temperature has been reached, the air supply is reduced. Charring then occurs. The process takes several weeks. A large amount of tar compounds and particles leave the kiln with the gases, as no gas cleaning takes place. A more advanced version of the process uses a retort. Here, the reaction time is reduced to hours and no oxygen/air is added. The volatiles are combusted outside the retort in a burner and the off-gas is used for heating. There are virtually no emissions of tarry or hazardous compounds (see also "Biokohle—Herstellung, Eigenschaften und Verwendung von Biomassekarbonisaten" in further reading).

Pyrolysis
Conversion of biomass with heat and no or low amounts of oxygen to avoid combustion.

Many different types of slow pyrolysis reactors have been developed (Demirbas et al. 2016; Kan et al. 2016). Charcoal is used for the production of activated carbon, e.g., as a feed additive, in medicine, as a basis for catalysts, and for gas and water cleaning. It also forms the basis of black powder in fireworks and is used for metallurgic purposes, e.g., the production of copper. Today, the production of advanced carbon materials, such as supercapacitors and electrodes for fuel cells and hydrogen storage as well as modern battery parts, is of particular interest (see also "*Advanced Carbon Materials and Technology*" in further reading).

Carbonization
Reaction of biomass leading to a higher carbon content. Charring is a special case of carbonization, usually at around 500 °C and "dry."

In the case of complete conversion of biomass at around 500/600 °C, tar can be regarded as intermediate. The mixture containing hundreds of different compounds reacts further by polymerization processes to form coke and by further splitting to gases. Therefore, if this tar or the so-called pyrolysis oil is the desired product, fast heating up to 500–600 °C, a short reaction time of a few seconds, and quenching for fast cooling down are applied (Table 7.3). This is necessary to avoid the consecutive reactions to coke and gases. The formation of char and gases cannot be avoided completely, but the yields of pyrolysis oil can be maximized by a short and defined reaction time. From the point of heat transfer, fast heating up is only possible by solid-solid contact. There, in all types of reactors applied, biomass is heated up by direct contact with a hot surface, which might be metallic or sand particle. Usually burners, burning the gases coming out of the process, generate the heat necessary. At reaction condition, the pyrolysis oil is a condensate in one, two, or more steps, after separations of the char/coke particles usually by cyclones. If the water content is low, condensation of the pyrolysis oil is possible without phase separation in one step. Pyrolysis oil usually has a water content of 20–30% (g/g) (Bridgwater et al. 1999; Oasmaa et al. 2003). This water is partly a product of the reactions and originates from moisture in the biomass used. This is possible because of a lot of polar compounds like acids, sugars, aldehydes, and ketones are formed. Various types of phenols are also found in pyrolysis oil. If the water content is increased to above ~45%, phase separation occurs with the formation of an aqueous and organic phase. In addition, a lignin-like solid is precipitated. Therefore, in the case of relatively high water content it is useful to use a two-step condensation process. Here, an aqueous phase with high contents of acetic acid and an organic phase is produced (Dahmen et al. 2010). Pyrolysis products can be upgraded to car fuels, but this requires large amounts of hydrogen (Wildschut et al. 2009). Pyrolysis oil, or one fraction of it, is used as "liquid smoke" in the food industry and to attract wild pigs for hunting.

In the process called bioliq® (Dahmen et al. 2012), the first step of biomass conversion is fast pyrolysis and the second gasification. This addresses one of the principal challenges of biomass conversion process chains: the widespread, decentralized occurrence of biomass by splitting the biomass conversion into two steps, fast pyrolysis and gasification: The goal of the bioliq® process is to produce a fuel via syngas. To achieve economies of scale, the gasification and synthesis plant needs to have a high throughput, which means the biomass has to be supplied from a very large area. However, the amount of energy necessary to transport biomass—a material of relatively low heating value (16–19 MJ/kg, dry matter)—over long distances to supply a large gasification plant is very high. In the bioliq® concept, the biomass is first pyrolyzed in smaller, fast pyrolysis plants. Then the coke and the pyrolysis oil are mixed to a slurry. This slurry has an energy density ten times higher than that of straw, the biomass used as feedstock. The slurry is then transported to the gasification plant. In this case, a gasification temperature above 1000 °C is used to avoid tar formation.

The products resulting from gasification of biomass, for example in the bioliq® process, are very important in the bioeconomy for the substitution of fossil fuels by biomass. Gasification for the production of syngas and the following use of syngas to produce different products are common processes in industry today. Usually, coal or residues from fossil oil processing are gasified. Therefore, the resource can be changed to biomass to which the available processes for converting syngas can be applied without further need for adaptation. The processes are the production of ammonia, methanol production, Fischer-Tropsch synthesis to produce diesel fuel, oxosynthesis to produce aldehydes, ketones, and others. Besides air or oxygen, water or carbon dioxide is also added as a so-called gasification agent (Hofbauer 2009):

$$C_6H_{12}O_6 + 6H_2O \leftrightarrow 6CO_2 + 12H_2 \qquad (7.1)$$

The addition of water increases the yield of hydrogen following Eq. (7.1).

7.3.3 Steam-Assisted Processes

In conversion processes that use lower temperatures than gasification, for example pyrolysis, water is added. This alters the gas composition by increasing the hydrogen yield, as shown in Eq. (7.1). In addition, the heat transfer is improved. The heat transfer from gases to solids and throughout the solids is a limiting step for the conversion of biomass in slow pyrolysis and torrefaction. By adding water in the form of steam, a high carbonization conversion of biomass is achieved at lower reaction temperatures compared to the conversion without steam addition (Pütün et al. 2006).

7.3.4 Hydrothermal and Supercritical Water Processes

A special case of water being used as an agent in biomass conversion is the reaction in liquid or supercritical water as reaction medium. Biomass conversions in liquid water at increased temperatures are called “hydrothermal.” This expression originates from geology where it refers to reactions in liquid water at increased pressure and temperature. Depending on the temperature required, the pressure has to be adapted to avoid evaporation. An overview of hydrothermal processes is given in Fig. 7.17.

In addition to the different conversion processes, Fig. 7.17 includes the vapor pressure curve of water, ending in the critical point. All processes above this vapor curve are conducted in liquid phase. The higher the temperature, the higher the pressure needed to have liquid water as reaction medium. If the critical point is reached, the phase boundary between gaseous and liquid states no longer exists. This is called “supercritical” region.

Supercritical Water
Water at a temperature above 374 °C and a pressure above 22 MPa. It has the solvent behavior of a nonpolar solvent like pentane.

By adapting the pressure, a supercritical medium can be changed from liquid-like to gaseous-like density, without the appearance of a phase boundary.

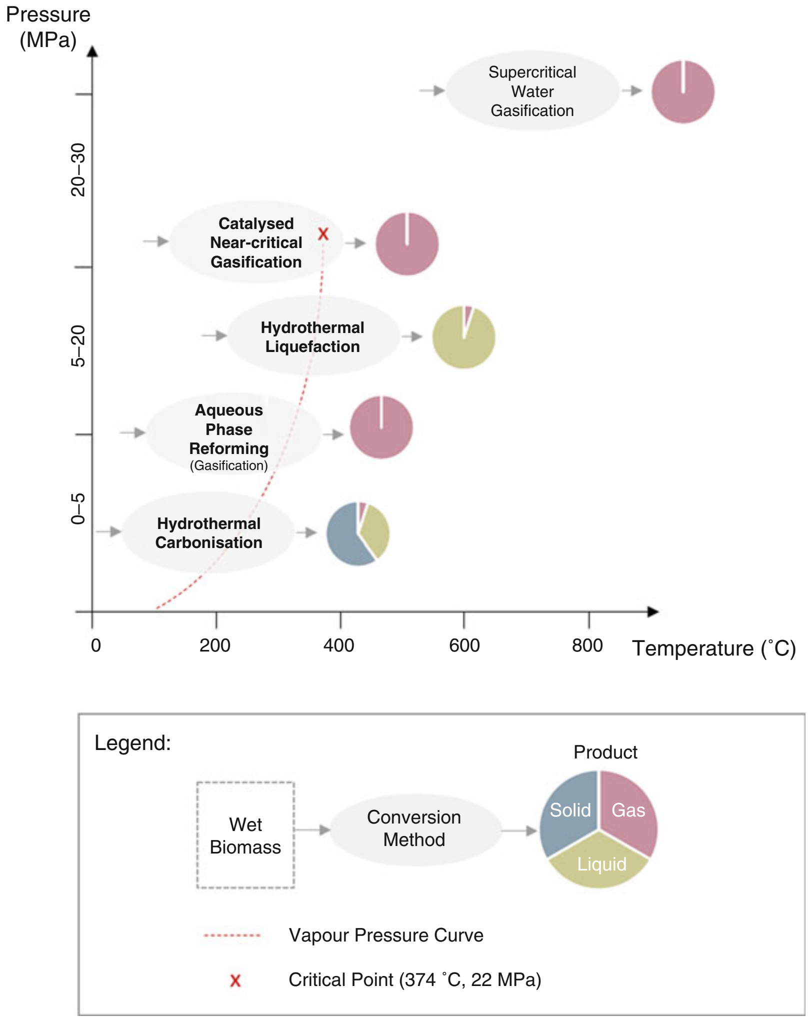

Fig. 7.17 Thermochemical conversion: hydrothermal and supercritical water processes

It may seem surprising that in Fig. 7.17 different processes with fairly similar reaction conditions are next to each other. In addition, the subcritical processes are all in the liquid region. This is due to the special properties of water, which change with temperature. Subcritical water has a higher ionic product, behaving like a mixture of a weak acid and a weak base. Therefore, reactions, which usually require the addition of acid or base, occur without these additions. In supercritical water—in contrast—the ionic product is very low. This means that, per definition, no Brønsted acids (compounds which produce H^+ ions in water) or bases can exist anymore. On the other hand, the solvent polarity of water decreases with temperature, although water remains as a polar and very reactive molecule. The reason for this is the lower interaction of the water molecules with each other and their faster thermal movement. As a consequence, the solubility of gases and nonpolar compounds increases and the solubility of salts decreases. At around 30 MPa, supercritical water behaves like pentane, with complete miscibility with gases, very good solubility of nonpolar compounds, and very low solubility of salts (Kruse and Dahmen 2015).

Hydrothermal and supercritical water processes are of special interest for the use and conversion of “wet biomass.” A living plant has a water content of 80–90%. Many biomass residues from agriculture and the food industry also have such high water contents. This kind of biomass can be converted by digestion. In this case, methane is the desired product, but the conversion is not complete because lignin and some type of fibers cannot be digested. The biomass could be dried if other products than methane are desired and a complete conversion is strived for, but this would cost a lot of energy. In hydrothermal processes, wet biomass is converted without drying and the water in the biomass becomes the reaction medium. Therefore, from a chemical point of view, hydrothermal processes are completely different from dry processes. In hydrothermal processes, the polar water molecules split the polar bonds of the biomass by hydrolysis. In contrast to dry processes, which are mainly solid–gas reactions, hydrothermal conversions usually occur in one phase, with fast degradation of the solid biomass by reaction with water. The fast splitting of biomass in water is the reason for the lower temperatures needed at hydrothermal conversions compared to dry processes. On the other hand, the high pressure is often regarded as a disadvantage of hydrothermal conversions of biomass (Kruse and Dinjus 2007).

Hydrothermal

Reaction conditions in liquid water at temperatures usually above 100 °C at increased pressure.

Hydrothermal carbonization occurs at temperatures typically in the range of 180–230 °C. Most of the carbohydrates, possibly even the complete biomass, are hydrolyzed and dissolved. The desired product, called HTC-coal or hydrochar, is formed via polymerization (Titirici et al. 2015a, b). This process has been further developed, e.g., to produce supercapacitors to store electricity from renewable resources or in electric cars (Titirici et al. 2015a, b).

Box 7.2 Nutrient Recovery

In high temperature, dry process nutrients like phosphates are part of a glass-like slag. They are not available for plants, directly. In low-temperature dry conversions, nutrients like phosphate leave the reactor with the char. They have to be leached by strong acids or used together with the char. In hydrothermal conversions, the situation is completely different: Hydrothermal carbonization offers the opportunity to recovery around 80% as pure fertilizer. In hydrothermal liquefaction, nutrients stay solved in water, and can be used, e.g., for algae growth (López Barreiro et al. 2015a). In supercritical waster salts, also nutrient precipitates and solids can be removed from the reactor.

Hydrothermal liquefaction occurs at around 300 °C in liquid water, often in the presence of basic catalysts. Here biomass is completely converted to smaller molecules like substituted phenols and different acids or other carbonyl compounds. This process was developed under the trade name “hydrothermal upgrading” by the company Shell (Goudriaan and Peferoen 1990). There are three differences between hydrothermal liquefaction and fast pyrolysis, also producing a liquid or “tarry” mixture from biomass. First, the process temperature of the hydrothermal method is very low. During flash pyrolysis, temperatures of around 500–600 °C and very short reaction times of a few seconds are applied. The short reaction times are necessary to avoid char/coke formation. Such limitations do not exist for hydrothermal liquefaction; this is the second difference between hydrothermal liquefaction and fast pyrolysis. A wide range of reaction times is applied. In dry flash pyrolysis, large amounts of solid and gaseous products are always formed. The third difference is that hydrothermal liquefaction leads to a low gas yield, mainly carbon dioxide and therefore with no energy content, and very low solid yields. The solids formed are often salts. In the reaction conditions, the tarry compounds are dissolved in water. After cooling down, the tarry liquid phase separates from the aqueous phase. Through this separation, the phenols formed from the biomass are concentrated in the tarry phase. Acid and other polar (i.e., oxygen-containing) compounds stay in the aqueous phase. Phase separation may take some time but leads to a tarry product with a high heating value. This heating value is higher than that of the tarry product of fast pyrolysis. In addition, the water content of hydrothermally produced oil is very low (<0.5% (g/g)) compared to fast pyrolysis oil (20–30%). The reason for this is simply that all polar compounds are in the water, not in the oil. A minor disadvantage of the low water content is the rather high viscosity of hydrothermally produced oil (López Barreiro et al. 2014; López Barreiro et al. 2015a). It usually flows above 80 °C. To decrease the viscosity and to obtain a more diesel-like fuel, this oil is hydrogenated. The product is called "HTU-Diesel" and in the Netherlands large efforts have been made to establish such a process. Due to the relatively low oxygen content, such a process is energetically and economically more interesting than for pyrolysis oil. Today, hydrothermal liquefaction is often used for the conversion of algae (Valdez et al. 2014; López Barreiro et al. 2015a, b, c). The reasons for this are the following:

1. Algae are very wet biomass and should be converted in water.
2. Fast-growing algae are usually rich in carbohydrates and the lipid content is too low for the production of biodiesel.
3. The aqueous phase contains various nutrients (minerals) which can be recycled (López Barreiro et al. 2015a).

The basic studies on hydrothermal liquefaction were done with wood. Wood is not a typical "wet" biomass. The use of relatively dry wood opens up the opportunity to recycle water, because wood has a relatively low water content. In the case of wet biomass, the water coming out of the process has to be "treated," maybe by digestion. Hydrothermal liquefaction with a throughput of 100 kg/h has been demonstrated in Apeldoorn, the Netherlands (Goudriaan and Peferoen 1990).

A special case of hydrothermal liquefaction is the hydrolysis of lignin to obtain phenols. Here, temperatures of around 400 °C are usually applied because of the lower reactivity of pure lignin than lignocellulose. In addition, hydrogenation, e.g., by hydrogen and catalyst addition, is conducted. Phenols are interesting platform chemicals for resin production.

Another special case of liquefaction is the production of hydroxymethylfurfural (HMF, Fig. 7.18) from sugars. HMF is one of or perhaps the most interesting platform chemical for the bioeconomy (Teong et al. 2014), mainly because of the two functional groups enabling the formation of many different consecutive products. These chemicals can replace fossil-based plastics, and potential end products include bottles for drinks and nylon stockings. HMF can be produced in hydrothermal conditions (Antal and Mok 1990; Yin et al. 2011) and is assumed to be an intermediate product of hydrothermal carbonization (Kruse et al. 2013).

Depending on the temperature and main product formed, three different hydrothermal gasification processes can be distinguished:

1. *Aqueous phase reforming*
   At relatively low temperatures of around 200 °C and in the presence of a noble metal catalyst, hydrogen is formed from compounds originating from biomass (Davda et al. 2005; Luo et al. 2008). Hydrogen formation as

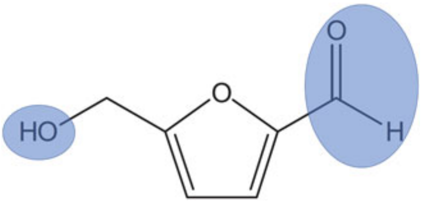

Fig. 7.18 Hydroxymethylfurfural with its two functional groups: an aldehyde and an alcohol

product is thermodynamically possible at this low temperature, but the concentration has to be very low at around 1% (Feng et al. 2004; Kruse 2008). A hydrogenation catalyst is necessary. This process can only be applied to biomass compounds, not to raw biomass. Therefore, it can be applied to aqueous effluent of other processes. The most important advantage of this process is that the catalyst uses the formed hydrogen to hydrogenate the feedstock. The extent to which this consecutive reaction occurs depends on which noble metal is used as catalyst (Davda et al. 2005; Huber et al. 2005). In a following step, aromatic compounds which can substitute terephthalic acid can be produced that can be used for PET bottles (Kumula 2011; Serrano-Ruiz et al. 2011).

2. *Near-critical catalyzed gasification*
   Near the critical point, methane is the thermodynamically preferred burnable product. Here, the (nearly) complete gasification and the hydrogenation of carbon monoxide to methane occur in the same reactor. In dry processes, this is not possible, because higher temperatures are needed for gasification, too high for methane formation. The formation of methane from hydrogen requires hydrogenation catalysts (Ni, Ru, Rd, PT, Pd) for sufficient yields. Only small amounts of methane can be formed via the decarboxylation of acetic acid, without a catalyst. In principle, two versions of near-critical gasification are conducted: Elliott et al. (2006, 2004) prefer subcritical conditions. The advantage is that salts are still soluble and the risk of plugging is low. In this concept, the biomass is first liquefied and then gasified in a solid-bed reactor filled with the catalyst. A mobile trailer version has also been constructed and is in use (Elliott 2008). F. Vogel and his group prefer supercritical conditions, which have the advantage of good solubility of organic compounds and gases. To handle the salt deposition, a special gravity separator is used (Brandenberger et al. 2013; Dreher et al. 2013). In near-critical catalyzed gasification, the stabilization of the catalyst is a special challenge. In particular, the support of the catalyst has to be stable in the highly aggressive aqueous medium. Pure carbon and Al_2O_3 have been found to be sufficiently stable as catalyst support. Elliott et al. (2006) found monoclinic zirconia, rutile titania, and carbon as the best choice for the support. Catalytically active metals are limited to nickel, ruthenium, and rhodium.
3. *Supercritical water gasification*
   Biomass with a dry mater content of at least 10% (g/g) and temperatures above 600 °C is required to produce hydrogen in reasonable concentrations, because of thermodynamic reasons. Challenges are finding suitable reactor materials and a method of handling salt deposition. The reactor material has to be a nickel-based alloy to withstand high temperatures and pressures. However, this material has varying corrosion stability and is usually expensive and difficult to obtain. As mentioned above, the solubility of salts is poor in supercritical conditions (Kruse 2008, 2009), but alkali salts are necessary to catalyze the water-gas shift reaction. Water-gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (7.2)$$

The equilibrium of the reaction lies to the right of Eq. (7.2), with hydrogen as the preferred product due to the high concentration of water, but alkali salts are necessary to reach the equilibrium. Gasification of glucose without alkali, in particular potassium, salts leads to a syngas with high carbon monoxide content. As biomass naturally contains alkali salts, its conversion usually does not require alkali salts to be added. A catalyst is not necessary, but, e.g., carbon is often used to avoid high temperature requirements or to increase the relative gas yield if the biomass has a high dry matter content.

Supercritical water gasification is a suitable method to convert agricultural residues, process water, sludges, and algae (Kruse 2008, 2009).

Larger scale gasification plants are operational in Karlsruhe/Germany and Hiroshima/Japan. The German plant converts various types of biomass including corn silage, spent grain, and grass on a scale of 100 kg/h slurry (Boukis et al. 2007). In the Japanese plant, the biomass proceeds through a liquefaction reactor before gasification. A special aspect of this plant is that a coal catalyst is fed into the gasification reactor, which can be reused. For details see also Kruse (2008, 2009). Such larger plants are important to assess the performance of the process, for example in terms of energy efficiency.

Review Questions

- What are the differences between "dry" and "wet" conversion technologies (feedstock, process conditions, and products)?
- What is the role of water in "wet" conversion processes?
- Name products and corresponding reaction conditions of hydrothermal gasification.

Further Reading

Dufour A. Thermochemical conversion of biomass for the production of energy and chemicals. Wiley, New York. ISBN: 978-1848218239

Hornung A (ed) Transformation of biomass: theory to practice. Wiley, Chichester. ISBN: 978-1119973270

Quicker P, Weber K (eds) Biokohle – Herstellung, Eigenschaften und Verwendung von Biomassekarbonisaten. Springer Vieweg, Wiesbaden. ISBN: 978-3658036881

Tiwari A, Shukla SK (eds) Advanced carbon materials and technology. Wiley, Hoboken. ISBN: 978-1118686232

7.4 Process and Product Cost Assessment

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Abstract When a new product or process is developed and introduced, market analyses and cost estimates are required to examine its marketability and manufacturing or production costs. Before a company takes the decision to construct a production plant and invest in the production and marketing of a certain product, it needs to make sure that the planned process is the most economical and thus the most profitable alternative. In order to make this decision in a sound manner, various tools are used to carry out an economic assessment, weighing up the different costs and revenues against each other. Profitability considerations are also used to develop business plans and assess the state and value of a company. When decisions to invest in chemical conversion plants are taken, a large number of factors have to be taken into account. Hard factors such as profitability and amortization time are important to outline the investment opportunity. However, they are not sufficient to fully characterize the process and thus correctly assess the investment potential. Soft factors also need to be considered in order to weight up further advantages and disadvantages of an investment. These include a number of criteria relating to the technical process, the location of the production plant, and the market situation. Production costs are strongly influenced by the technology applied along with its materials and energy balance. Therefore, process and product cost analysis takes place in early stages and during process engineering. The resulting economic data allow an economic analysis and the creation of a business plan, which help to determine whether a planned project is profitable or not.

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This chapter provides the fundamental knowledge for this process, together with an example of a cost estimation.

Keywords Costing; Investment costs; Manufacturing costs; Variable and fixed costs

Learning Objectives
After studying this chapter, you should

- Understand the principles of cost estimation in manufacturing.
- Be aware of the most important cost-determining factors.
- Be able to conduct your own simple estimates of process investment and manufacturing costs.
- Be able to understand cost assessments given in the literature.

7.4.1 Cost Assessment

In order to make sound investment decisions, the anticipated manufacturing costs of the product to be commercialized need to be known. Since the exact costs cannot be determined in advance, a cost estimate is performed.

The accuracy of a cost estimate increases as the process development progresses. In this period of time, conceptual and design work is carried out prior to building, expanding, or retrofitting a process plant. This includes the determination of all relevant process steps, the type and capacity of equipment, the resources to be used (energy, materials, work, time), and the consideration of all products, desired and undesired. The beginning of the process development is accompanied by a huge uncertainty—up to ±100%—while an accuracy of ±5% is not uncommon close to completion of the project. The *Association for the Advancement of Cost Engineering International* (AACE) proposes a subdivision of cost estimates into five classes (AACE International 2016). These are summarized in Table 7.4 and illustrated graphically in Fig. 7.19. The asymmetric distribution of the uncertainty is particularly apparent.

7.4.1.1 Investment Costs

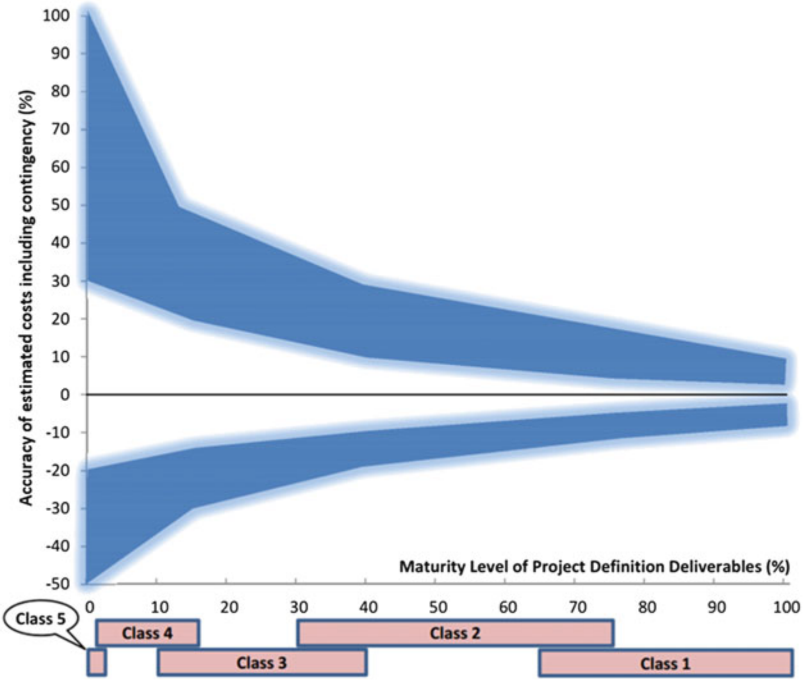
Investment costs [*capital expenditure, total capital cost (TCI)*] refer to expenditure that occurs before the plant is commissioned and operated. They consist of *plant costs*, or *ISBL costs* (*inside battery limits*), and off-site costs, or *OSBL costs* (*outside battery limits*). In this context, “battery limits” means the geographical location on which the plant is constructed. “Plant costs” refer to expenditure on apparatus, equipment, and other objects and activities directly required for the planning, construction, and operation of a plant, including:

- Main pieces of equipment: reactors, columns, heat exchangers, pumps, etc.

Table 7.4 Accuracy of cost estimates during process development (AACE International 2016)

Class	Project maturity (%)	Description	Accuracy lower limit (%)	Accuracy upper limit (%)
5	0–2	Estimate of order of magnitude, within screening and feasibility studies	20–50	30–100
4	1–15	Preliminary estimate, comparison of process alternatives based on conceptual designs	15–30	20–50
3	10–40	Definitive estimate, for acquisition of funding and investors, based on basic engineering	10–20	10–30
2	30–75	Detailed estimate, basis for contracting and project finance control	5–15	5–20
1	65–100	“Check” estimate, after successful negotiation with contracted companies based on detailed engineering	3–10	3–15%

Fig. 7.19 Schematic diagram showing the asymmetrical limits of cost estimate accuracy above and below baseline at different stages of process development (AACE International 2016)



- Pipelines and fittings: tubes, valves, insulation, paint, etc.
- Instrumentation and control: temperature, pressure, and level sensors, flow meters, process visualization software, etc.
- Electrical engineering: power supply, wiring, transducers, switches, etc.
- Construction work: scaffolding, fundament, buildings, etc.
- Plant assembly: staff and sub-contracting
- Miscellaneous: fire protection, interfaces (connection to power and media supply)
- Planning and execution: staff and sub-contracting
- Quality assurance
- Contingencies

“Off-site costs” refer to all costs associated with the plant, but not located inside the battery limits, most commonly items such as utilities or ancillaries.

Inside Battery Limits (ISBL) Costs

The main pieces of equipment account for a major share of the ISBL costs. For this reason, these are a good starting point for a first, rough estimate of the investment costs, even though, at the end of the day, they do not provide the largest contribution to ISBL costs.

To obtain a first estimate of the key apparatus costs, simple methods such as the capacitance method (Eq. 7.3) are applicable. They can be carried out without specific technological knowledge, purely on the basis of the desired capacity of the new apparatus (or even whole plants) relative to the capacity of comparable, already existing apparatus (or plant):

$$C_2 = C_1 \left(\frac{S_2}{S_1} \right)^n \tag{7.3}$$

C_2 denotes the cost of the new apparatus (or plant) with desired capacity S_2. C_1 denotes the already known cost of an existing reference apparatus with a given capacity S_1. Capacities may be given in mass and volume flows, electrical powers, volumes of reactors, and other vessels or the like. The degression or scale-up factor n indicates how strong the nonlinear relationship between capacity and cost is. Where

Table 7.5 Example of literature data for estimation of main equipment costs, FOB (Silla 2003)

Equipment	Capacity	Capacity units	FOB cost/303 US$ (Jan 1990)	Correlation range	Degression coefficient
Agitators					
Propeller	3.0	hp	2.8	1.0–7.0	0.5
Impeller	20.0	hp	12.0	3.0–100	0.3
Air cooler	1.0	ft^2	0.137	–	0.8
Blower, centrifugal	4000	ft^3/min	60	800–1.8 × 10^4	0.6
Compressor, centrifugal	600	hp	190	200–1.8 × 10^4	0.32
Electric motors					
Open drip proof	60	kW	3.0	0.2–5 × 10^3	1.1
Explosion proof	100	kW	9.5	0.3–8 × 10^3	1.1
Evaporator, vertical tube	1000	ft^2	180	100–8 × 10^3	0.53
Heat exchanger, shell and tube	1000	ft^2	14	100–5 × 10^3	0.65
Process furnace	20,000	kW	750	3 × 10^3–1.6 × 10^5	0.85
Pump, centrifugal					
High range	20	hp	9.0	2.68–335	0.42
Low range	0.29	hp	2.3	0.1–2	0.29
Reactors, CSTR					
Jacketed	600	gal	17	30–6 × 10^3	0.57
Glass lined	400	gal	33	30–4 × 10^3	0.54
Rotary vacuum filter	30	ft^2	60	4–600	0.67
Tanks, cone roof					
Low range	12 × 105	gal	170	2 × 10^5 – 1.2 × 10^6	0.32
High range	12 × 106	gal	170	1.2 × 10^6–1.1 × 10^7	0.32

$0 \leq n \leq 1$, a larger apparatus (plant) is, in relation, less expensive than a small device. Long-term experience has shown n to be 0.7 for petrochemical plants, between 0.4 and 0.5 for pharmaceutical and specialty chemicals, and between 0.8 and 0.9 for plants with a high consumption of mechanical work by, for example, compressors.

Apparatus costs, as purchased from the equipment suppliers, are called *free-on-board* (*FOB*). They are generally estimated via the capacity method (Eq. 7.3). Reference size and price are usually provided by the supplier. The degression coefficients for the main apparatuses can vary significantly (Seifert et al. 2012). Table 7.5 shows data, as typically found in the literature, compiled from Silla (2003), including the capacity of the reference device (always check the units given!), the FOB purchase costs, the correlation range for which the capacity rule is valid, and the degression coefficient.

However, in addition to the purchasing costs of an apparatus, further cost contributions are generated by its installation and integration into the plant. To estimate the total ISBL costs of the planned plant, a *structural method* such as the Lang method is used to determine these costs of connecting pipes, fittings, measuring and control devices, assembly, and the like. This method, which was developed by Lang in 1940 (Hirschberg 1999), can only be applied once the required main apparatuses have been determined and dimensioned and their prices are known. Instead of listing the individual prices of all other components (i.e., for each valve, tube) their costs are related to the main pieces of equipment based on empirical values; for example the cost of pipes lies between 30 and 100% of

Table 7.6 Lang factors for the calculation of ISBL costs

Cost type	Structural unit	Factor
Direct ISBL costs	Main apparatus (FOB)	1.00
	Tubing and fittings	0.40–1.00
	Instrumentation and control	0.20–1.20
	Electronics	0.20–0.50
	Construction (buildings)	0.30–1.00
	Plant assembly, installation	0.10–0.25
	Miscellaneous (insulation, etc.)	0.10–0.25
Indirect costs	Engineering	0.35–0.50
	Contingencies	0.15–0.30
	LF sum factor	2.70–6.00

the main apparatus costs. These empirical values are included in the calculation of the ISBL costs in the form of so-called Lang factors. These factors, which may be different for different types of plant, are added up and then multiplied by the sum of the costs of the main apparatus to give an estimate of total ISBL costs (Eq. 7.4):

$$\mathrm{ISBL} = \mathrm{LF} \cdot \sum_{k=1}^{N} \mathrm{FOB}_k \qquad (7.4)$$

The sum of the Lang factors (LF) usually ranges between 2.7 and 6.0. A typical value for chemical plants is, for example, 4.57. A list of the individual factors can be found in Table 7.6. In most cases, additional cost factors need to be taken into account. The tabulated prices often have to be adapted to the following factors:

- Specific technical requirements: corrosion resistance, high pressure and temperature, material compatibility. These need to be considered by separate material factors for each piece of equipment.
- Local factors: local infrastructure, availability and costs of trained staff, transportation costs, transport options.
- International factors: exchange rates, import fees.
- Annual factors: inflation, leading to price development for apparatuses and other equipment. Can be considered by a price index, e.g., according to Kölbel/Schulze, available from the VCI (Verband der Chemischen Industrie) at www.chemietechnik.de.

Outside Battery Limits (OSBL) Costs

The off-site costs of a chemical plant depend on the infrastructure available at the location of the planned plant. The OSBL stem from the infrastructure required to provide auxiliary materials (e.g., N_2, O_2, H_2) and energy (in the form of electricity, steam, or fuels) for the disposal of waste materials as well as for storage and overall on-site logistics. In general, make-or-buy decisions have to be made, meaning that it is necessary to consider whether it is more cost efficient to install the infrastructure on-site (within the battery limits) or to buy-in a service via an *over-the-fence contract* with external partners (Sinnot et al. 2009).

Example: Purchasing Costs of a Furnace

A pilot plant is to be constructed for the production of a bioenergy carrier by torrefaction of wood pellets. This would usually be fired by hot combustion gases, but the pilot plant is too small for such a design. Instead, the reactor is to be constructed as an electrically heated furnace with a max. capacity of 5 MW. We need to know the purchasing cost in Euro of a furnace with an electrical performance of 40,000 kW to be installed in Germany in 2016. The FOB reference data of a process furnace with a capacity of 20,000 kW, valid from January 1990, can be taken from Table 7.5. The purchase price is given as 750,000 US dollars and the degression coefficient is 0.85. First, the capacity method is applied using Eq. (7.5) to obtain the price for an oven of the desired capacity:

$$\begin{aligned} C_{\mathrm{USA},\$,1990} &= 750,000\ \$ \left(\frac{5000\ \mathrm{kW}}{20,000\ \mathrm{kW}}\right)^{0.85} \\ &= \mathrm{US}\$230,840 \end{aligned} \qquad (7.5)$$

Now the price has to be adjusted to the year 2016 by Eq. (7.6). It is assumed that the price of the furnace is similar to that of crude steel (since it is mostly made of steel). Thus the price increase is mainly given by the steel price development factor. Using European steel prices (IndexMundi) for comparison would also be permissible, since it can be assumed that the prices of globally traded steel have developed in nearly the same way around the world:

$$\begin{aligned} C_{\mathrm{USA},\$,2016} &= C_{\mathrm{USA},\$,1990}\left(\frac{C_{\mathrm{Steel},2016}}{C_{\mathrm{Steel},1990}}\right) \\ &= 230,840\ \$\left(\frac{54.85\,\frac{€}{t}}{14.05\,\frac{€}{t}}\right) \\ &= \mathrm{US}\$901,180 \end{aligned} \tag{7.6}$$

Then Eq. (7.7) is used to factor in the location change in the installation of the furnace with a location factor (taken from Sinnot et al. 2009):

$$\begin{aligned} C_{\mathrm{GER},\$,2016} &= C_{\mathrm{USA},\$,2016}\left(\frac{C_{\mathrm{GER}}}{C_{\mathrm{USA}}}\right) \\ &= 5.277.607,23\ \$\left(\frac{1.11}{1.00}\right) \\ &= \mathrm{US}\$1,000,310 \end{aligned} \tag{7.7}$$

Finally, using Eq. (7.8), the exchange rate is taken into account to give the purchase costs in Euro for the furnace with 5000 kW purchased in 2016 and installed in Germany:

$$\begin{aligned} C_{\mathrm{GER},€,2016} &= C_{\mathrm{GER},\$,2016}\cdot \text{Exchange rate} \\ &= 5,858,144.02\ \$ \times 0.90\,\frac{€}{\$} \\ &= 900,280\ € \end{aligned} \tag{7.8}$$

This results in a purchase price for the electrically heated torrefaction chamber of around 900,000 €. The calculation was based on the reference capacity and price taken from literature, and updated by the steel price development (as dominant cost factor) for the actual year of purchase, the change in location of the plant construction, and the US$/EUR exchange rate.

7.4.1.2 Manufacturing Costs

The manufacturing costs of a product can be divided into variable and fixed costs. For their calculation, it is important that the investment costs and the most important process parameters are already fixed or estimated reasonably accurately. *Variable costs of production* are all costs that occur during the operation of the plant and are dependent on its utilization. Variable production costs comprise the following:

- Material costs: Feedstocks, input and auxiliary materials (obtained from the mass balance of the process)
- Energy costs: steam, fuels (gas, heating oil), electrical power, cooling water, etc. (obtained from the energy balance of the process)
- Waste management: waste water disposal, off-gas treatment, solid residues, etc.
- Other costs: analytics, packaging, shipping, etc.

The *fixed costs of production* are all costs incurred during the operation of the plant which are not dependent on the degree of utilization of the plant. Fixed costs are, for example:

- Capital-related costs: depreciation of investment costs (fixed capital cost)
- Staff costs: wages, salaries, shift premiums, insurances, company bonuses
- General costs: transport, security, social services, plant management
- Repairs and maintenance
- Taxes and insurance

The capital fixed costs are calculated from the total investment costs, the depreciation time, and the production capacity:

$$\begin{aligned} &\text{Capital fix costs} \\ &= \frac{\text{ISBL} + \text{OSBL}}{\text{Depreciation time} \times \text{Product capacity}} \end{aligned} \tag{7.9}$$

The capital fix costs usually account for the largest proportion of the manufacturing costs. Therefore, they are the most relevant factor in the economic assessment of a production process. Additional costs to be considered for the production and sale of chemical products stem from marketing and selling activities (5–25% of revenues), research (2–5% of revenues, in larger companies), and for generalia such as financial, legal, and patent departments (3–5% of revenues) (Baerns 2013). A number of key performance indicators (KPI) are used to calculate the economic performance and profitability of an investment. The earnings (profit) are calculated from the revenues minus all costs within a certain time period. The profit depends on how much product can be sold to the market at the anticipated price. Thus, the earnings are directly related to the workload of a plant and primarily determined by the fixed (also incurred when the plant is not in operation) and variable costs of production.

7.4.2 Cost Estimation Example

Synthesis gas, a mixture of hydrogen and carbon monoxide, can be produced from lignocellulosic biomass, for example, in the bioliq® process at KIT (Dahmen et al. 2016). For this process, biomass is pretreated decentrally (close to the place of production) by fast pyrolysis to produce an energy-dense intermediate, which is collected from a number of these decentral plants to be further processed in industrial scale facilities. There, it is gasified to produce syngas, which, after cleaning, can in turn be used to produce various types of fuels and chemical products. Figure 7.20 shows a block flow diagram of the downstream production of gasoline in a hypothetical process. The mass and energy balance of a process is usually available from process simulation using software tools like ASPEN Plus or CHEMCAD. All the main pieces of equipment form blocks of unit operations (cooling, heating, pumping, filtration,

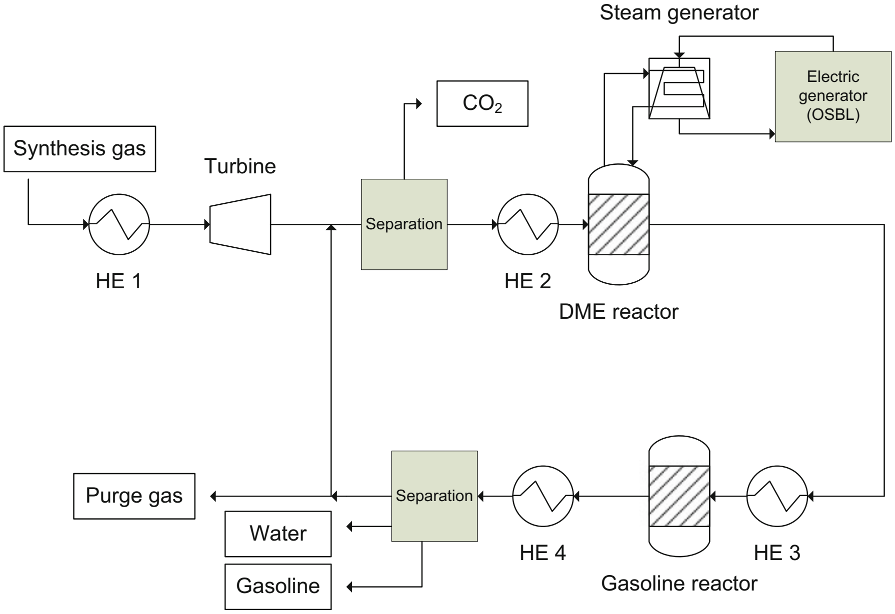


Fig. 7.20 Block flow diagram of gasoline production from synthesis gas

distillation, reaction, etc.) characterized by specific operating conditions combined with input and output streams of defined composition and conditions. Here, to reduce the complexity, we only consider the synthesis of the raw product for cost estimation. After an initial heat exchange (HE1), the high-pressure syngas (in the bioliq® process, a high-pressure gasifier is utilized) passes through a turbine producing electricity. Then, the CO_2 contained in the syngas (formed by partial oxidation in the previous gasification process) is separated at ambient temperature. In heat exchanger HE2, the temperature is adjusted for the first synthesis reactor. Here, the syngas is converted at 200 °C and 35 MPa into dimethylether (DME) in an exothermic reaction using a mixed catalyst that facilitates methanol synthesis, its dehydration, and the water-gas-shift reaction all at the same time (sum reaction equation: $3CO + 3H_2 \rightleftarrows CH_3OCH_3$). After reaction, a heat exchanger (HE3) is utilized to adjust the temperature to the optimum for gasoline synthesis over a zeolite catalyst at around 340 °C (sum reaction equation: $CH_3OCH_3 \rightleftarrows -(CH_2)- + H_2O$, where $–(CH_2)–$ stands for a formal hydrocarbon fuel unit in the resulting fuel mixture). The gas is then cooled down by heat exchanger HE4 prior to separation of raw gasoline, water formed during the reaction and non-reacted gas. Half of the remaining gas is recycled to the DME reactor.

A process simulation is carried out with some necessary assumptions to give a material and energy balance: the syngas composition is fixed (30 vol.% of H_2 and CO each, 20 vol.% CO_2, 15 vol.% N_2, and 5 vol.% H_2O), and the conversion of syngas to DME is 0.85 and that of DME to gasoline is 1.0. Side products are not considered. 20,000 kg of gasoline is produced per hour. Process simulation is extremely helpful when heat shifts are necessary: the heat of both exothermic reactions is to be used to preheat colder input streams and to produce steam for use in other parts of the plant. Therefore, efficiencies have to be considered: that of heat exchange is assumed to be 0.8 and that of steam generation 0.5. From the simulation, the desired capacities of the equipment can be derived for materials (kmol/s), power (MW), and heat exchangers (m^2) as given in Table 7.7.

In this example, the specific manufacturing costs are to be estimated for the year 2014 in EUR. It is assumed that the production plant is operated for 7000 h per year and a depreciation time of 10 years has been accepted.

The specific production costs (in €/kg) are calculated below according to the scheme shown in Fig. 7.21.

In Table 7.7, the main pieces of equipment are compiled together with the reference costs, reference and the desired capacity, and degression coefficients. These allow cost determination of the equipment in the desired size according to the capacity method. For CO_2 and product separation, additional costs of 18,750,000 € are assumed without further details.

Because reference costs can usually only be found for past years and are typically given in US$, conversion is required to obtain the actual costs (2014, with price development factor 1.35) in the appropriate currency (EUR, at 1 € = US$1.25). Since the date of the reference and currency are not necessarily the same for all pieces of equipment, it is recommended that this procedure is applied for each item. Material factors are also taken into account by using stainless steel instead of carbon steel for most pieces of equipment. The conversion of reference costs given in the literature to reference costs that take price development, exchange rate, and material factors into account is given in Table 7.8.

From these data, FOB costs are calculated according to Eq. (7.3). Then, Lang factors are applied to the FOB total, to give the ISBL costs. By adding OSBL costs, the total capital

Table 7.7 Calculation of TCI and capital fixed costs using the example of synthetic raw gasoline production from syngas

Total investment cost calculation						
ISBL calculation						
FOB calculation						
	Reference capacity	Capacity unit	Desired capacity	Reference costs/EUR[a]	Degression coefficient	FOB costs/ US$
HE1	609	m^2	609	224,536	0.6	224,536
Turbine	5.3	MWe	5.3	1,193,186	0.6	1,193,186
HE2	571	m^2	571	212,062	0.6	212,062
DME reactor	1	kmol/s	2.16	4,365,974	0.65	7,195,800
HE3	386	m^2	386	177,134	0.6	177,134
Gasoline reactor	1	kmol/s	1.36	4,365,974	0.65	5,340,334
Steam generator	1	MW	24.2	216,943	0.6	1,466,279
HE4	384	m^2	384	177,134	0.6	177,134
Separation unit						18,750,000
			FOB total/EUR			34,736,464
Application of Lang factors						
Piping and fitting	0.46				15,978,773	15,978,773
Instrumentation and control	0.24				8,336,751	8,336,751
Electronics	0.2				6,947,293	6,947,293
Construction	0.7				24,315,525	24,315,525
Plant assembly	0.28				9,726,210	9,726,210
Engineering	0.4				13,894,585	13,894,585
Contingencies	0.3				10,420,939	10,420,939
			ISBL total/EUR			124,356,540
OSBL calculation						
Power generators						17,500,000
			OSBL total/EUR			17,500,000
TCI calculation						
			Total investment cost/EUR			141,856,540
Fixed capital cost calculation						
Gasoline production capacity	20,000	kg				
Annual operation time	7000	h				
			Fixed capital cost/EUR a^{-1} kg^{-1}			0.101

[a]Derived from Table 7.8

investment costs, TCI, are obtained. Power generation is assumed to have an efficiency of 100%; losses have already been taken into account in the low steam generation efficiency.

Manufacturing costs are calculated from variable and fixed cost contributions in Table 7.9. Syngas is treated as a buy-in product, which is typical for large plant complexes, where the individual plants are considered as separated business units. Since the heat produced in the highly exothermic reactions is made use of, excess energy can be exported. As such, no energy costs are incurred; in contrast, revenues are gained from power export. Given the high

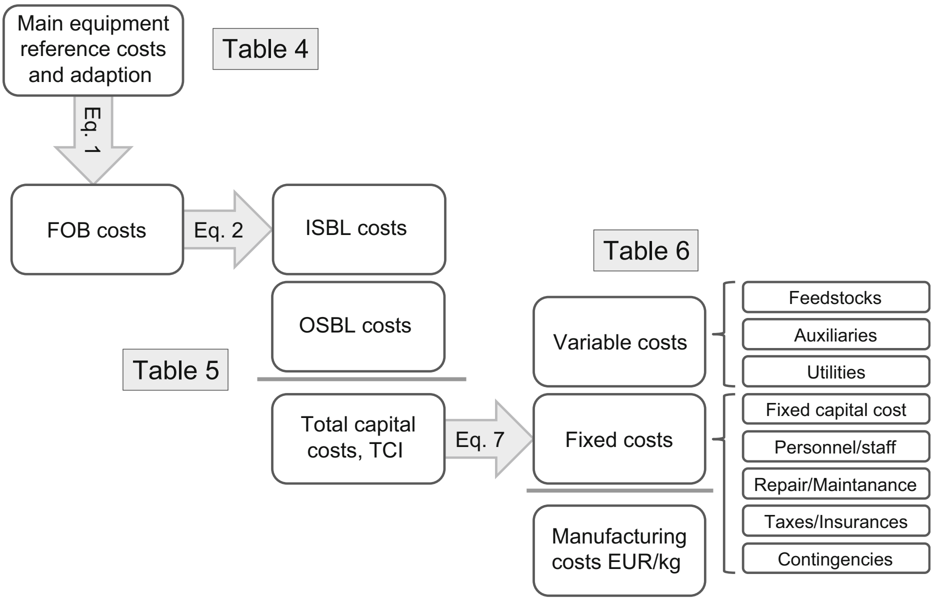


Fig. 7.21 Manufacturing cost calculation scheme

Table 7.8 Reference cost adaption for FOB calculation

	Reference costs US$, 2002	Reference costs EUR 2002 (factor 1/1.25)	Reference costs EUR 2014 (factor 1.35)	Material factor	Reference costs EUR, 2014 stainless steel[a]
HE1	90,000	72,000	97,624	2.3	224,536
Turbine	550,000	440,000	596,593	2	1,193,186
HE2	85,000	68,000	92,201	2.3	212,062
DME reactor	1,750,000	1,400,000	1,898,250	2.3	4,365,974
HE3	71,000	56,800	77,015	2.3	177,134
Gasoline reactor	1,750,000	1,400,000	1,898,250	2.3	4,365,974
Steam generator	200,000	160,000	216,943	1	216,943
HE4	71,000	56,800	77,015	2.3	177,134

Input data for Table 7.7

variable cost contributions of feedstock, those for auxiliaries can be neglected here.

To calculate the fixed costs, the fixed capital costs (as given in Table 7.7), and costs for personnel, repairs, and maintenance, as well as taxes and insurances are considered. The last two are usually expressed as a percentage of the total investment costs. Typical values for chemical plants are given in Table 7.9. Such plants usually require personnel for five shifts as well as a day shift. A typical team would be composed of a plant engineer, some administrative staff, shift

Table 7.9 Determination of manufacturing costs

Manufacturing costs		€/kg	€/a
Variable costs			
Syngas	0.214 €/kg	1.905	266,704,873
Energy (utilities)			
Revenues from power generation	0.05 €/kWh	−0.060	−8,456,432
Auxiliaries (catalyst/water)		negligible	negligible
	Total variable costs	1.845	258,248,441
Fixed costs			
Fixed capital costs		0.101	14,185,654
Personnel		0.004	590,000
Repairs/maintenance	5% of total capital costs	0.005	709,283
Taxes/insurance	1.5% of total capital costs	0.002	212,785
	Total fixed costs	0.112	15,697,722
	Total manufacturing costs	1.957	273,946,162

engineers and operators, and technicians for the repair of mechanical and electrical devices. Here, the equivalent of ten full-time staff is assumed.

7.4.3 Economic Considerations

The results of the cost calculation example given above reveal that, in total, 273,946,162 € per year or 1.957 € kg^{-1} need to be earned through the sale of the product to cover the investment costs before any profit can be made from it. There are a number of economic indicators that can give information on the financial state of a company, a process, or project operation These indicators also allow comparison of different process alternatives and sensitivity analyses, e.g., by changing feedstock, energy, selling prices, or other variables with time. Here are some of the most important measures for accounting and finance with practical, somewhat simplified definitions:

Revenue	Revenue is the amount of money that a company receives in a certain period of time. In the cost calculation example above, it is money earned by selling the gasoline product, calculated by multiplying the price (which is usually higher than the production costs!) by the amount of product sold in that period of time.
Costs	In this context, costs refer to the amount of money or monetary valuation expended in order to produce, market, sell, and deliver the product.
Profit	Profit is obtained when the amount of revenue gained from a business activity exceeds the costs, thus: profit = revenues − costs. It is worth mentioning that the profit is strongly dependent on the amount of marketed product or its selling price. Therefore, there is always pressure on process optimization to reduce fixed and variable cost contributions.
EBIT	*Earnings before interest and taxes* are a measure of the company's profit that includes all expenses except interest and income tax expenses. This indicator is usually

	applied to whole companies for the purpose of benchmarking and comparison, but can also be applied to individual parts of the business or processes operated.
EBITDA	In contrast to EBIT, the *earnings before interests, taxes, depreciation, and amortization* do not include depreciation and amortization in the calculation. It is closely related to cash flow as one of the most important key performance indicators.
Cash flow	The net amount of cash moving into and out of the business in a specified period of time. It is used to assess the quality of a company's income, that is, how liquid it is. It is calculated as the difference between revenues and expenses without considering interest, taxes, and amortization.
Profitability	Profitability is a measure of the efficiency of the employed capital investment by relating investment costs to achieved profit. It can be used to compare different business models and process alternatives.
ROCE	The *return on capital employed* relates revenues without interest and taxes (EBIT) to the capital employed. The reciprocal value is the time required to recoup the investments made (payout time).
NPV	The net present value is the difference between the present value of cash inflows and present value of cash outflows at a certain time. NPV is used to determine the profitability of a projected investment and includes the consideration of taxes. It is calculated by the following equation:

$$C(n) = \sum_{t=0}^{n} \frac{c_t}{(1+i)^t} \qquad (7.10)$$

where $C(n)$ is the NPV in year n, c_t is the cash flow, i is the tax, and t is the number of years.

Figure 7.22a shows the cash flow for a project to produce synthetic gasoline on the basis of the example given in Sect. 7.4.2. In this example, the investment is made to plan, design, and construct the production plant within 3 years. In this period of time, the investment costs expended result in negative cash flows. After this period and following commissioning, the plant produces a fixed amount of product at the same costs and profits (40,000,000 € per year). Figure 7.22b shows the NPV curve after interest has been paid. It can be seen that the payout time is achieved after 9 years. This and several other factors are most relevant for decision making in companies and, in particular, profitability of projected investments.

Review Questions

- Which simple method can be used for a first, rough cost estimate of a plant, when the technology is already state of the art?
- What are the main cost contributions in manufacturing costs?
- Why are capital fixed costs so relevant to manufacturing costs?
- What are the differences between ISBL and OSBL and between variable and fixed costs?
- What are the most relevant economic key indicators? How do they differ from each other?

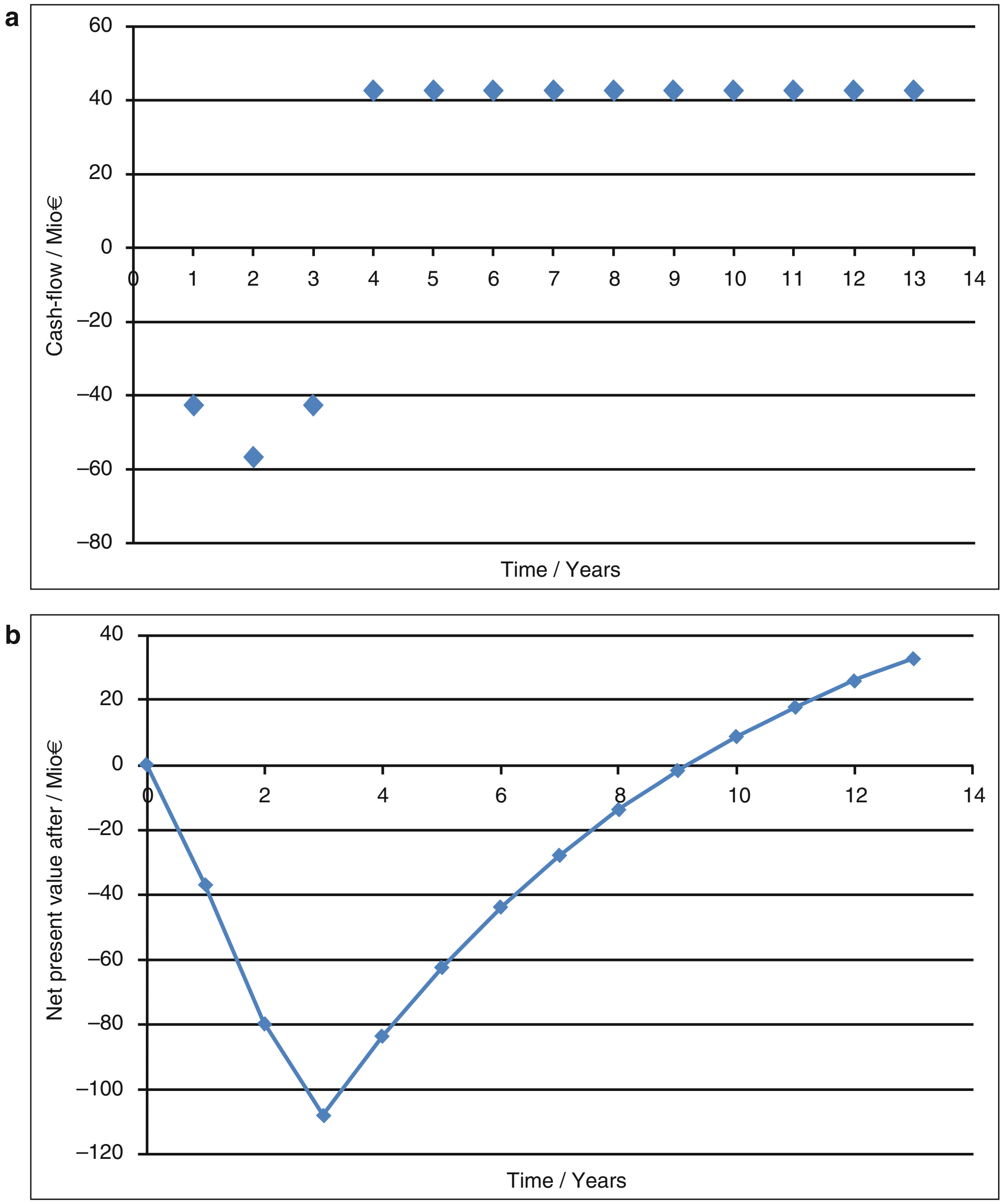


Fig. 7.22 Cash flow and net present value curves for a 3-year investment period

References

AACE International (2016) Cost estimate classification system. As applied in engineering, procurement, and construction for the process industries (AACE International Recommended Practice No. 18R-97)

Antal MJ Jr, Mok WSL (1990) Mechanism of formation of 5-(hydroxymethyl)-2-furaldehyde from D-fructose and sucrose. Carbohydr Res 199(1):91–109

Baerns M (2013) Technische Chemie, 2 erw Aufl. Wiley, Weinheim

Boukis N, Galla U, Müller H et al (2007) Biomass gasification in supercritical water. Experimental progress achieved with the VERENA pilot plant. In: 15th European conference & exhibition. Berlin, 7 May 2007

Brandenberger M, Matzenberger J, Vogel F et al (2013) Producing synthetic natural gas from microalgae via supercritical water gasification: a techno-economic sensitivity analysis. Biomass Bioenergy 51:26–34. https://doi.org/10.1016/j.biombioe.2012.12.038

Bridgwater A, Czernik S et al (eds) (1999) Fast pyrolysis of biomass: a handbook. CPL Press, Newsbury

Dahmen N, Henrich E, Kruse A et al (2010) Biomass liquefaction and gasification. In: Vertès AA, Qureshi N, Blaschek HP, Yukawa H (eds) Biomass to biofuels: strategies for global industries. Wiley, Chichester, pp 89–122

Dahmen N, Henrich E, Dinjus E et al (2012) The bioliq® bioslurry gasification process for the production of biosynfuels, organic chemicals, and energy. Energy Sustain Soc 2:3. https://doi.org/10.1186/2192-0567-2-3

Dahmen N, Abeln J, Eberhard M et al (2016) The bioliq process for producing synthetic transportation fuels. WIREs Energy Environ. https://doi.org/10.1002/wene.236

Davda RR, Shabaker JW, Huber GW et al (2005) A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts. Appl Catal B: Environ 56(1–2):171–186

Demirbas A, Ahmad W, Alamoudi R et al (2016) Sustainable charcoal production from biomass. Energy Sources, Part A 38(13):1882–1889

Dreher M, Johnson B, Peterson AA et al (2013) Catalysis in supercritical water: pathway of the methanation reaction and sulfur poisoning over a Ru/C catalyst during the reforming of biomolecules. J Catal 301:38–45

Elliott DC (2008) Catalytic hydrothermal gasification of biomass. Biofuels Bioprod Biorefin 2(3):254–265

Elliott DC, Peterson KL, Muzatko DS et al (2004) Effects of trace contaminants on catalytic processing of biomass-derived feedstocks. Appl Biochem Biotechnol 113(16):807–825

Elliott DC, Hart TR, Neuenschwander GG (2006) Chemical processing in high-pressure aqueous environments. 8. Improved catalysts for hydrothermal gasification. Ind Eng Chem Res 45(11): 3776–3781

Feng W, Hedzer J, de Swaan Arons J (2004) Biomass conversions in subcritical and supercritical water: driving force, phase equilibria, and thermodynamic analysis. Chem Eng Process 43(12):1459–1467

Goudriaan F, Peferoen DGR (1990) Liquid fuels from biomass via a hydrothermal process. Chem Eng Sci 45(8):2729–2734

Gucho EM, Shahzad K, Bramer EA et al (2015) Experimental study on dry torrefaction of beech wood and miscanthus. Energies 8(5):3903–3923. https://doi.org/10.3390/en8053903

Hirschberg HG (1999) Handbuch Verfahrenstechnik und Anlagenbau. Chemie, Technik, Wirtschaftlichkeit. Springer, Berlin

Hofbauer H (2009) Gasification-technology overview. In: Bridgwater AV, Hofbauer H, van Loo S (eds) Thermal biomass conversion. CPL Press, Newbury

Hornung A (ed) (2014) Transformation of biomass: theory to practice. Wiley, Chichester

Huber GW, Chheda JN, Barrett CJ et al (2005) Production of liquid alkanes by aqueous-phase processing of biomass-derived carbohydrates. Science 308 (5727):1446–1450

IndexMundi: Eisenerz monatlicher Preis – Dollar pro trockener metrischer Tonne. Online verfügbar unter http://www.indexmundi.com/de/rohstoffpreise/?ware=eisenerz&monate=360. Accessed 29 Jun 2016

Kan T, Strezov V, Evans TJ (2016) Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters. Renew Sustain Energy Rev 57:126–1140

Kruse A (2008) Supercritical water gasification. Biofuels Bioprod Biorefin 2(5):415–437

Kruse A (2009) Hydrothermal biomass gasification. J Supercrit Fluids 47(3):391–399

Kruse A, Dahmen N (2015) Water – a magic solvent for biomass conversion. J Supercrit Fluids 96:36–45

Kruse A, Dinjus E (2007) Hot compressed water as reaction medium and reactant: properties and synthesis reactions. J Supercrit Fluids 39(3):362–380

Kruse A, Funke A, Titirici MM (2013) Hydrothermal conversion of biomass to fuels and energetic materials. Curr Opin Chem Biol 17(3):515–521

Kumula D (2011) Completing the puzzle: 100% plant-derived PET. Bioplast Mag 6:14–17

López Barreiro D, Samori C, Terranella G et al (2014) Assessing microalgae biorefinery routes for the production of biofuels via hydrothermal liquefaction. Bioresour Technol 174:256–265

López Barreiro D, Bauer M, Hornung U et al (2015a) Cultivation of microalgae with recovered nutrients after hydrothermal liquefaction. Algal Res 9:99–106

López Barreiro D, Beck M, Hornung U et al (2015b) Suitability of hydrothermal liquefaction as a conversion route to produce biofuels from macroalgae. Algal Res 11:234–241

López Barreiro D, Gómez BR, Hornung U et al (2015c) Hydrothermal liquefaction of microalgae in a continuous stirred-tank reactor. Energy Fuels 29(10):6422–6432

Luo N, Fu X, Cao F et al (2008) Glycerol aqueous phase reforming for hydrogen generation over Pt catalyst – effect of catalyst composition and reaction conditions. Fuel 87(17–18):3483–3489

Oasmaa A, Kuoppala E, Solantausta Y (2003) Fast pyrolysis of forestry residue. 2. Physicochemical composition of product liquid. Energy Fuels 17(2):433–443

Pütün A, Özbay N, Pütün E (2006) Effect of steam on the pyrolysis of biomass. Energy Sources Part A 28 (3):253–262

Seifert T, Sievers S, Bramsiepe C et al (2012) Small scale, modular and continuous: a new approach in plant design. Chem Eng Process Process Intensif 52:140–150

Serrano-Ruiz JC, Luque R, Sepulveda-Escribano A (2011) Transformations of biomass-derived platform molecules: from high added-value chemicals to fuels via aqueous-phase processing. Chem Soc Rev 40 (11):5266–5281

Silla H (2003) Chemical process engineering. Design and economics. Chemical Industries. Marcel Dekker, New York

Sinnot R, Towler G, Sinnott RK (2009) Chemical engineering design, 5th edn. Coulson & Richardson's chemical engineering series. Butterworth-Heinemamn, Oxford

Stoeckel M, Lidolt M, Stressler T et al (2016) Heat stability of indigenous milk plasmin and proteases from Pseudomonas: a challenge in the production of UHT milk products. Int Dairy J 61:250–261. https://doi.org/10.1016/j.idairyj.2016.06.009

Teong SP, Yi G, Zhang Y (2014) Hydroxymethylfurfural production from bioresources: past, present and future. Green Chem 16(4):2015–2026

Titirici MM, White RJ, Brun N et al (2015a) Sustainable carbon materials. Chem Soc Rev 44(1):250–290

Titirici MM, Funke A, Kruse A (2015b) Hydrothermal carbonization of biomass. Recent advances in thermochemical conversion of biomass. In: Pandey A, Bhaskar T, Stöcker M, Sukumaran R (eds) Recent advances in thermochemical conversion of biomass. Elsevier, Oxford, pp 325–352

Valdez PJ, Vincent JT, Savage PE (2014) A general kinetic model for the hydrothermal liquefaction of microalgae. Bioresour Technol 163(0):123–127

Wildschut J, Mahfud FH, Venderbosch RH et al (2009) Hydrotreatment of fast pyrolysis oil using heterogeneous noble-metal catalysts. Ind Eng Chem Res 48 (23):10324–10334

Yin S, Pan Y, Tan Z (2011) Hydrothermal conversion of cellulose to 5-hydroxymethyl furfural. Int J Green Energy 8(2):234–247

Markets, Sustainability Management and Entrepreneurship

8

In the year 2013, the turnover of the total European (EU 28) bioeconomy, including the primary sectors agriculture and forestry as well as the sectors of food, pulp and paper, forestry-based industries, bioenergy and others, was 2.1 trillion euros (based on Eurostat data of 2013). Roughly half of this is accounted for by the food and beverages sector, almost a quarter by the primary sectors (agriculture and forestry), while the other quarter comes from biobased industries, such as bio-chemicals, bio-plastics, pharmaceuticals, pulp and paper products, forest-based industries, textiles, biofuels and bioenergy (see Fig. 8.1).

The relevance of the different bioeconomic sectors may differ between regions and countries. However, it becomes clear that, presently, food production is the economically most important sector in the bioeconomy, followed by agriculture, forest-based industry and pulp and paper production (Fig. 8.1). The resources for the forest-based industry and pulp and paper production mainly come from forestry. Most other biobased resources used in the bioeconomy, especially for food production but increasingly also for chemicals, plastics, pharmaceuticals, textiles and other products, stem from agricultural production and therefore may indirectly, via land use, or directly, via use of edible raw material, interfere or compete with food supply. Markets for biobased resources therefore overlap with food markets to a large extent. To avoid negative effects on food security, it is necessary to understand how markets for biobased products function. Thus, in Sect. 8.1 explains market mechanisms and market influencing factors of biobased resource and product markets, e.g. an increasing demand for biobased resources for biofuel production and policy instruments, such as subsidies.

The precondition for a sustainably growing bioeconomy is that sustainably produced biobased products are brought onto the market. Section 8.2 therefore provides guidance on how companies, as central economic players, can engage in sustainability management and contribute their share towards sustainability. Actors of sustainability in society are named and the relevance of sustainability management for companies is discussed. Important elements and tools of sustainability management from the areas of sustainability accounting and management control as well as of sustainable supply chain management are introduced to provide a first glimpse of possibilities for companies to engage with sustainability. Life-Cycle Sustainability Assessment (LCSA) is so far the most comprehensive methodology for sustainability assessment and Life-Cycle Assessment (LCA) is a tool broadly used by companies to assess the ecological and energetic performance of biobased value chains. These tools and their use are described in Sect. 8.3.

Finally, the bioeconomy will only grow if entrepreneurs take the initiative to develop novel and innovative biobased products and

I. Lewandowski (ed.), *Bioeconomy*, https://doi.org/10.1007/978-3-319-68152-8_8

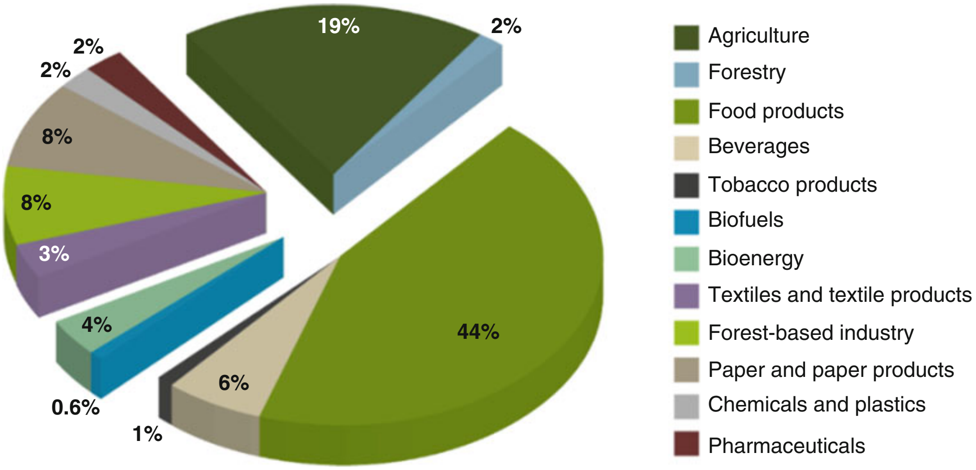
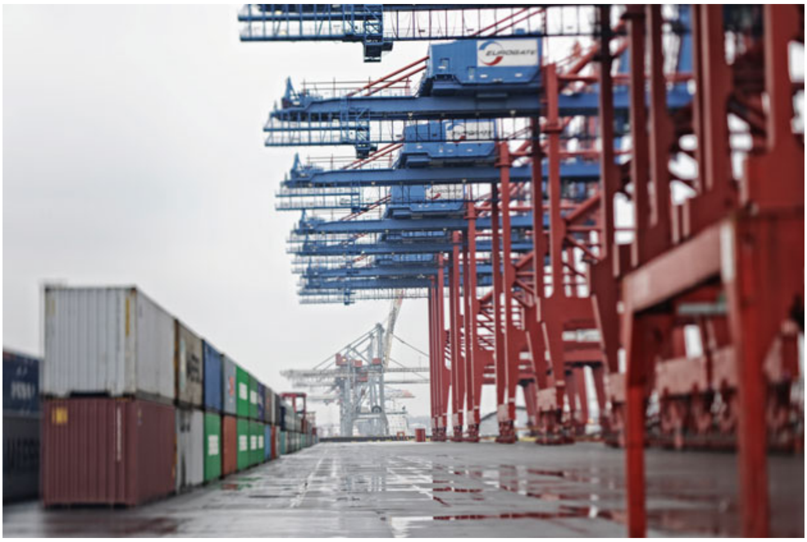


Fig. 8.1 Turnover in the European (EU 28) bioeconomy in the year 2013 (Piotrowski et al. 2016)

bring them onto the market. The bioeconomy offers great entrepreneurial opportunities. Section 8.4 introduces the business model canvas, a useful tool to break down the idea generation process and manage the entrepreneurial process. This tool makes it possible to clearly describe the value proposition of a new venture in the bioeconomy. This lean start-up approach can help entrepreneurs in the bioeconomy to move efficiently through the entrepreneurial process and to quickly develop a value proposition and a validated business model.

8.1 Markets of Biobased Resources and Products

Kirsten Urban, Ole Boysen, and
Carolina Schiesari



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Abstract This chapter takes a closer look at the global market for biobased products and resources and its interactions with agricultural and food markets. In particular, it describes the effect of increasing demand for biobased products on market prices and thus the quantity of agricultural resources demanded and supplied. Furthermore, we discuss factors that may drive or limit demand and supply of biobased products. We analyse the market for biobased resources and products, considering products that are already established in the market, such as biofuels, as well as products that could acquire a substantial market acceptance in the future, such as bio-plastics. In addition, we briefly introduce selected policy instruments applied to support biobased products.

The chapter provides a simple example of a perfectly competitive market for biobased products to introduce the market model. It starts by presenting the supply and demand curves and discussing the differences between price changes and those of other determinants of supply and demand with respect to their effects on the respective curve. It then explains how the supply and demand curves jointly determine the equilibrium price and quantity on the market and how the market price regulates surpluses and shortages under the assumption of an autarkic country. We apply this market model to demonstrate the effect of one particular policy for promoting the production of biobased products on the equilibrium market price and quantity.

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Learning Objectives
After reading this chapter, you should be able to

- Understand the challenges on the market for biobased products, and explain driving and limiting forces of supply and demand for biobased products
- Understand the functioning of resource and product markets and the price mechanism
- Analyse the effects of supply and demand shocks on the market for biobased products, and understand interlinkages with food and feed markets
- Explain policy effects and how they can be used to influence the markets for biobased products

8.1.1 Introduction

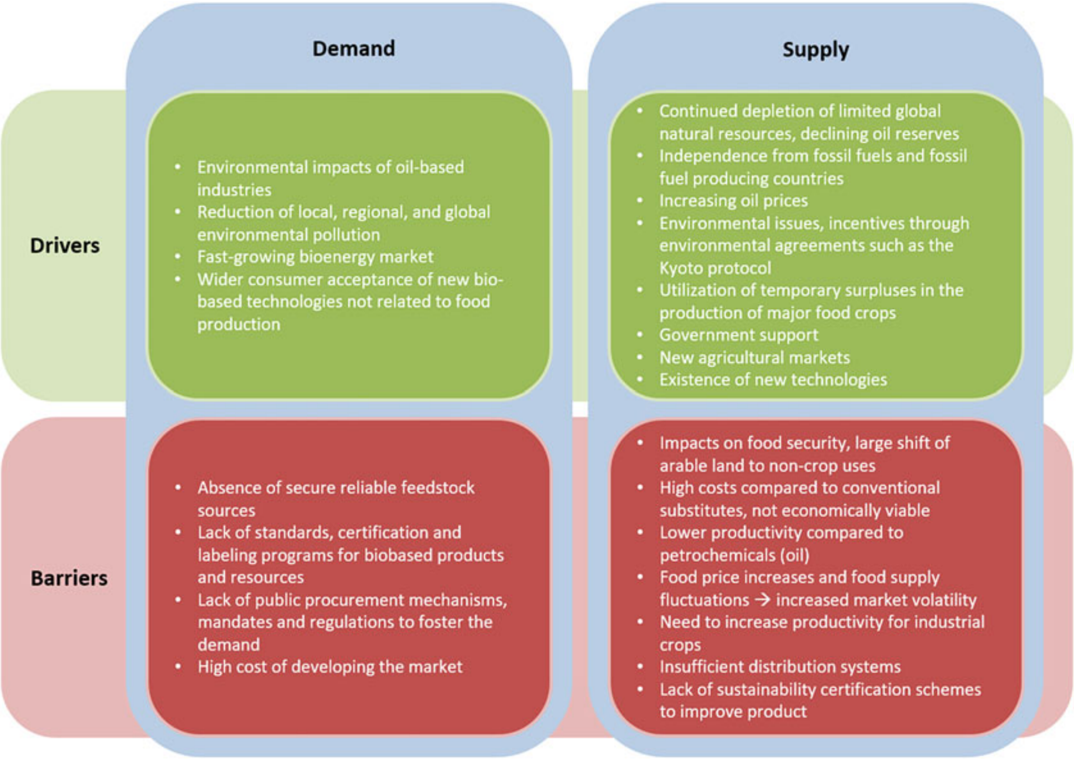
Concerns about the exhaustion of natural resources and climate change have raised interest in the production of biobased products. This has been driven in particular by the depletion of limited global natural resources such as oil reserves (Sect. 2.1), the dependency on oil-producing countries and the increasing number of agreements on environmental protection and climate change mitigation. As a consequence, governments are increasingly endeavouring to support the production of biobased products through policies. The associated political objectives include sustainable production and achievement of sustainable development goals, reduction of environmental pollution, mitigation of climate change effects, and increased self-sufficiency in energy production thus lowering dependence on oil-producing countries, such as Organization of the Petroleum Exporting Countries (OPEC) members and other politically unstable regions.

However, the market for biobased resources and products also faces several limiting factors. The production costs of biobased products are much higher than those of “unsustainable” products already established on the market. As a result, biobased products are often not competitive at current market prices. Their future competitiveness requires continued research and development, which—due to market failures—may not occur without some temporary government intervention, such as subsidies, public procurement, blending mandates and the establishment of labelling or certification programs that distinguish these products from traditional ones, attesting their higher value and thus justifying the charging of viable prices. Figure 8.2 lists the major driving and limiting factors in the demand and supply of biobased products and resources.

The continuous growth in global population, together with changes in diets through improved living standards, has led to sharp increases in the demand for food and feed products. On the other hand, climate change and finite resources are driving additional demand for biobased products. Since biobased products are often at least partly based on primary agricultural commodities, this creates a conflict with food security objectives through the competition for limited resources, such as land, water and other inputs to agricultural production. For example, additional demand for agricultural products as feedstock for biofuels production has been identified as one factor that triggered the food price spikes in 2007/2008 and 2011. These interdependencies with food demand and supply and thus food security hamper the implementation of policy instruments to support sustainable production, because this requires comprehensive consideration of the entire nexus between development, food security and environmental objectives.

8.1.2 Developments on the Markets for Biobased Products (and Resources?)

The OECD (2012) defines biobased products as goods excluding food and feed that are “*composed in whole or in significant parts of biological products, forestry materials, or renewable domestic agricultural materials, including plant, animal or marine materials*”. In



	Demand	Supply
Drivers	• Environmental impacts of oil-based industries • Reduction of local, regional, and global environmental pollution • Fast-growing bioenergy market • Wider consumer acceptance of new bio-based technologies not related to food production	• Continued depletion of limited global natural resources, declining oil reserves • Independence from fossil fuels and fossil fuel producing countries • Increasing oil prices • Environmental issues, incentives through environmental agreements such as the Kyoto protocol • Utilization of temporary surpluses in the production of major food crops • Government support • New agricultural markets • Existence of new technologies
Barriers	• Absence of secure reliable feedstock sources • Lack of standards, certification and labeling programs for biobased products and resources • Lack of public procurement mechanisms, mandates and regulations to foster the demand • High cost of developing the market	• Impacts on food security, large shift of arable land to non-crop uses • High costs compared to conventional substitutes, not economically viable • Lower productivity compared to petrochemicals (oil) • Food price increases and food supply fluctuations → increased market volatility • Need to increase productivity for industrial crops • Insufficient distribution systems • Lack of sustainability certification schemes to improve product

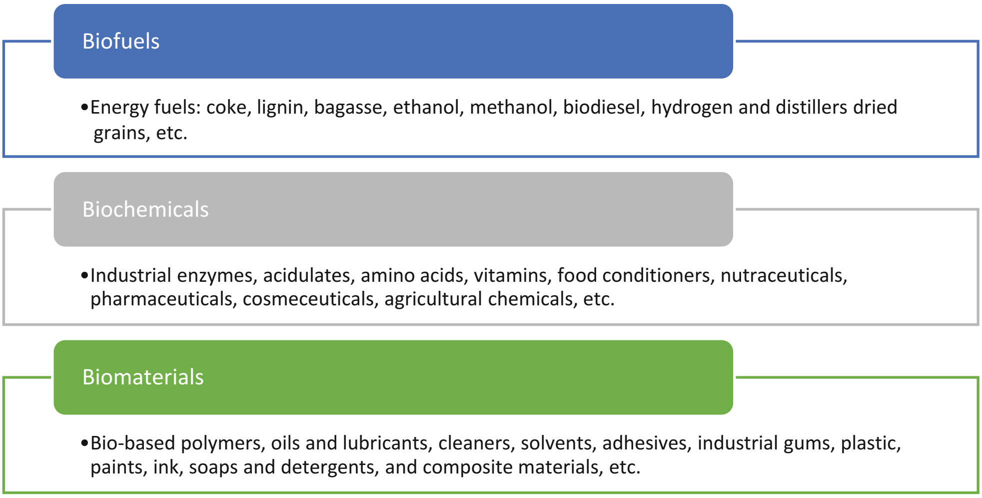
Fig. 8.2 Major driving and limiting forces in demand and supply of biobased resources and products

this section, we briefly introduce market developments for biobased products that can be divided into three main categories: biofuels, biochemicals and biomaterials (see Fig. 8.3 for further explanations).

First, we take a closer look at the market for biofuels, the largest of the three biobased product groups and one which has existed for more than three decades. Markets for the other two, biochemicals and biomaterials, are still in development and information on these is scarce.

Global liquid biofuel production has continuously increased over the last three decades. Figure 8.4a shows the development of the world ethanol and biodiesel production from 2007 to 2015. In 2015, global biofuel production amounted to 146 billion litres, almost double that of 2007. Ethanol production accounts for nearly 80% of total biofuel production (OECD/FAO 2016). In 2015, North America was the major producer of biofuels, followed by Latin America (including the Caribbean) and the European Union (Fig. 8.4b). According to Gallagher (2008), around 1% of total global cropland was used for biofuel production in 2006. OECD/FAO (2016) predicts an increase in production of 11.1% for biodiesel and 31.1% for ethanol by 2025.

As a result of the 1973 oil embargo initiated by OPEC, which led to a dramatic increase in oil prices, Brazil started the production of ethanol from sugar cane with a view to becoming less dependent on oil-producing countries. This move was facilitated by the low international sugar prices at that time and by Brazil's implementation of several policies promoting the further expansion of ethanol production. In 2009, Brazil produced around one third of global ethanol, only exceeded by the USA with a share of more than 50%, mainly produced from maize (Janda et al. 2012). The EU is the major producer of biodiesel (80%). In Germany, 760,000 ha of agricultural land were cultivated with rapeseed in 2016 for the production of biodiesel and vegetable oil



Biofuels

- Energy fuels: coke, lignin, bagasse, ethanol, methanol, biodiesel, hydrogen and distillers dried grains, etc.

Biochemicals

- Industrial enzymes, acidulates, amino acids, vitamins, food conditioners, nutraceuticals, pharmaceuticals, cosmeceuticals, agricultural chemicals, etc.

Biomaterials

- Bio-based polymers, oils and lubricants, cleaners, solvents, adhesives, industrial gums, plastic, paints, ink, soaps and detergents, and composite materials, etc.

Fig. 8.3 Categories of biobased products

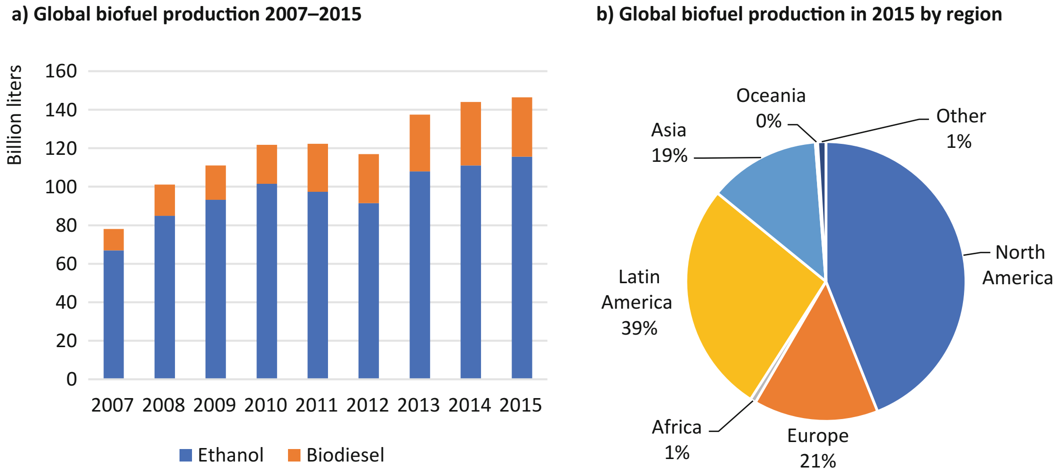


Fig. 8.4 Development of global liquid biofuel production (OECD.Stat 2016)

(FNR 2017). However, the production of biodiesel from soybean is increasing in the USA. Figure 8.5 depicts the development in demand for three crops used for biofuel production from 2000 until 2015. It becomes obvious from these graphs how much biofuel production has increased the demand for the agricultural products maize, sugar cane and vegetable oils. While the biofuel demand for sugar cane (vegetable oils) accounted for around 11% (less than 1%) in 2000 it increased to 21% (more than 12%) in 2015. The graph for sugar cane demand in particular highlights the food price spikes in 2007/2008 and 2011 and shows increased demand for biofuels due to very high oil prices with one year lag.

A high crude oil price may be an important factor for the competitiveness of biofuels. However, energy also contributes to the total production cost of biofuels. The extent differs between countries and crops used for production. Van Lampe (2007) assess biofuel production costs by considering energy, processing and feedstock costs and subtracting the value of by-products. A simple indicator of the biofuel competitiveness can be derived from the ratio of crude oil to

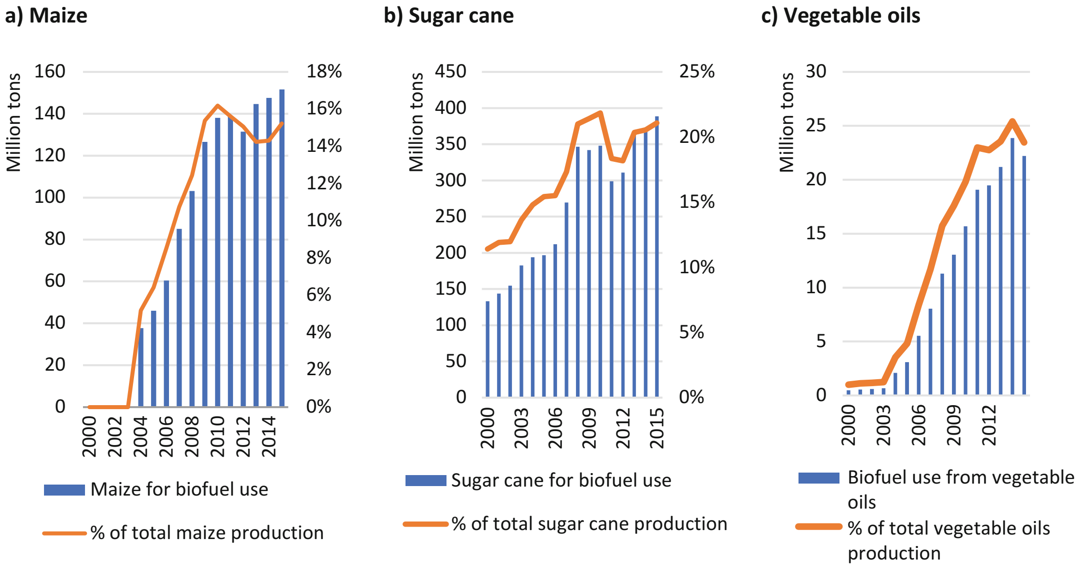


Fig. 8.5 Crop product demand for biofuel production (OECD.Stat 2016). Note: Red line: % of total crop production, blue bars: biofuel use in tons

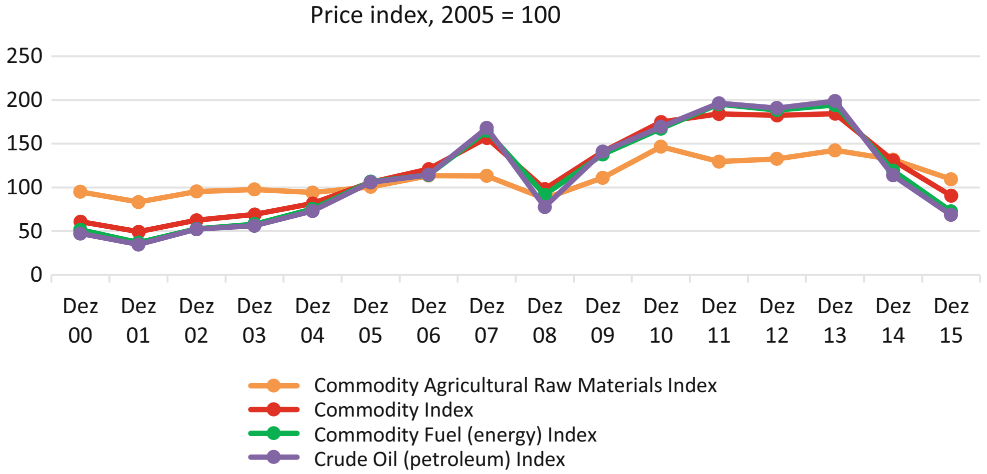


Fig. 8.6 Price indices for different commodity aggregates (IMF 2016 and World Bank 2016). Note: Commodity Agricultural Raw Materials Index includes timber, cotton, wool, rubber and hides price indices. Commodity Index includes both fuel and non-fuel price indices. Commodity Fuel (energy) Index includes crude oil (petroleum), natural gas, and coal indices. Crude Oil (petroleum) Price index is simply the average of three spot prices: Dated Brent, West Texas and the Dubai Fateh

biofuel feedstock prices. The demand for alternative fuels, such as biofuels, increases with rising crude oil prices. This, in turn, increases the demand for agricultural commodities, such as maize, rapeseed and sugar cane, and raises their prices. Consequently, higher oil prices increase biofuel production and feedstock costs. In addition, the contribution of by-products may diminish, because outlets become satiated, increasing biofuel production costs even further. Figure 8.6 reveals that the price index for commodity fuels tracks the price index for crude oil,

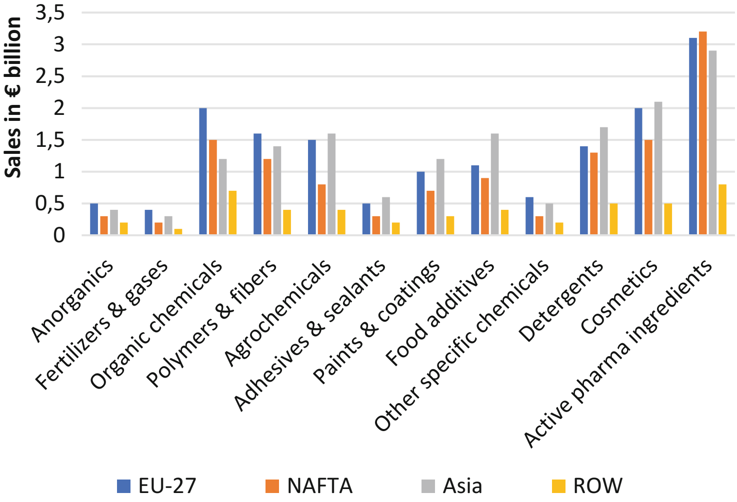


Fig. 8.7 The market for biochemicals (adapted from OECD 2011, p 52). Note: Biotechnology sales per segment 2007 in EUR billions; ROW = rest of the world

whereas the index for agricultural raw materials follows to a lesser extent. During the crude oil price spikes in 2007/2008 and 2011–2014, biofuel feedstock prices, represented by the index for agricultural raw materials, increased less than the crude oil price, thus increasing the competitiveness and economic viability of biofuels.

The markets for biochemicals and biomaterials are less developed than that for biofuels. Biochemicals and biomaterials can still be regarded as infant industries but they could acquire a substantial market acceptance in the future.

Both the number of biochemicals produced from biomass and the range of products made from these biochemicals are very high. Due to this diversity, the OECD (2011) classifies the biochemical market according to the different chemical industry segments. In 2007, the sale of chemicals made from biobased raw materials in the chemical industry amounted to EUR 48 billion, which represents only a minor fraction (3.47%) of the total output produced (Festel 2010).

In 2007, the EU 27, North America including Canada, the USA and Mexico (NAFTA), and Asia dominated the market for biochemicals, accounting for more than 90% of total sales. All other countries (ROW = rest of the world) made up the remaining 10%. Active pharma ingredients, organic chemicals and cosmetics are of particular importance (Fig. 8.7).

The EU is the major player in the biochemicals market. In 2013, around 6% of total chemical products can be considered as biobased. However, at EU member state level we see large differences. Denmark and Latvia reach shares of biochemicals of over 35%, while France, Germany and the Netherlands only of around 5%, and many of the newer member states of even less (Piotrowski et al. 2016). According to Hatti-Kaul et al. (2007), the EU average is estimated to increase to 20% in 2020. In the USA, the share of biochemicals in total chemicals sales is less than 4%. Asia is gradually increasing its market share.

The market for bioplastics dominates the category biomaterials and increased substantially in recent years. Bioplastics are plastics derived from renewable biomass sources, such as vegetable fats and oils, starches, cellulose, biopolymers and a variety of other materials. In 2013, 300 million tons of plastic are produced annually of which only 1% can be categorised as bioplastic (European Bioplastic 2016). However, due to the high rise in the demand for bioplastics, this market has the potential to boost its market share. Estimates indicate that the production of

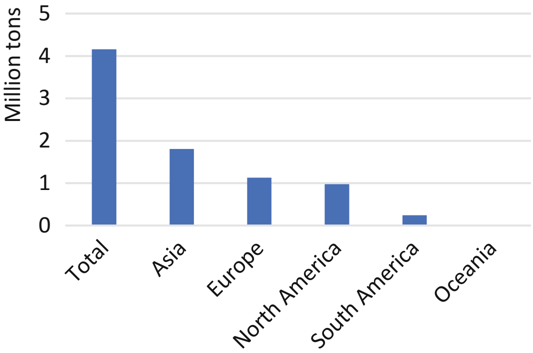


Fig. 8.8 The market for bioplastics (European Bioplastic 2016). Note: Bioplastic Production in 2016 in million tons by region

bioplastics could increase from 4.2 million tons in 2016 to approximately 6.1 million tons in 2021 (European Bioplastic 2016).

Figure 8.8 presents the market for bioplastics in 2016 which is clearly dominated by Asia (1.81 million tons) followed by Europe (1.13 million tons) and North America (0.97 million tons). The land used to grow the renewable feedstock for the production of bioplastics was about 0.68 million hectares in 2014, around 1% of the global agricultural land (European Bioplastic 2016). Within the bioplastics industry, bio-based Polyethylene Terephthalate (PET) and Polylactic Acid (PLA) are the leading biobased plastics products and grow faster than others. Baltus et al. 2013 state a production capacity of bio-based PET equal to around 5 million t per year in 2020. PLA is used mainly in packaging but it also has a large number of other durable applications. The world’s PLA production has doubled within the time period 2011–2015 to around 400,000 t per year and has been projected to increase even faster in the near future, by around 800,000 t per year in 2020 (Baltus et al. 2013). The company “Nature Works” from Thailand and the USA holds a PLA market share of almost 80% in 2011 (140,000 t from a total of 180,000 t per year), whereas the other producers have a current capacity varying between 1500 and 10,000 t per year (bioplastic Magazine 2012).

Of the global agricultural land in 2008, 18% were allocated to food, 71% to animal feed, 4% to bioenergy and 7% to material use (Raschka and Carus 2012).

In this section, we have briefly introduced the recent developments on the markets for biobased products and how these developments are reflected in the demand for agricultural commodities, land use and prices. How does this additional demand for maize, sugar cane and vegetable oils (on top of food and feed demand) affect the market for agricultural commodities? To answer this question, we analyse supply and demand on the market for maize, exemplary for an input to the production of biobased products.

8.1.3 The Market for Biobased Resources and Products: Deriving Demand and Supply Curves

How supply and demand on a market interact and how they depend on and affect other markets is explained using a market diagram. Here, we are going to use the maize market as an example for introducing the market diagram due to its omnipresence in all areas of the bioeconomy, i.e. food, feed, biofuels, bioplastics as well as biochemicals. For a comprehensive introduction to theory of markets, the reader is referred to standard textbooks of microeconomics, e.g., Varian (2014). In the market diagram presented

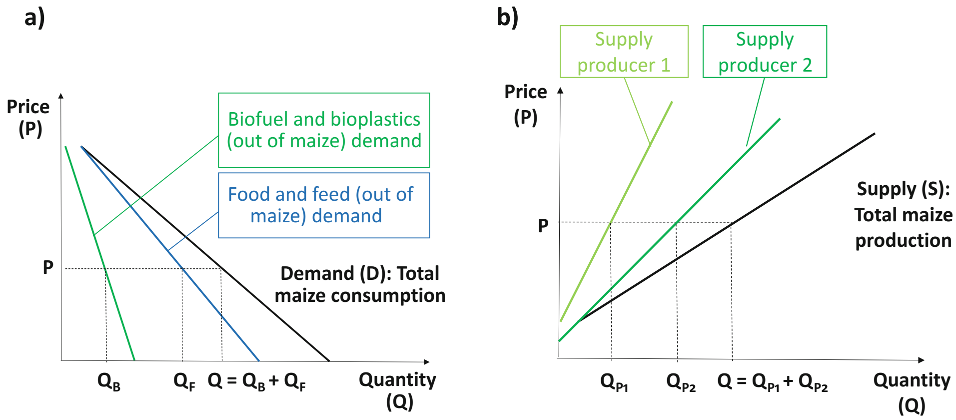


Fig. 8.9 Supply and demand functions

in Fig. 8.9a, the horizontal axis represents the quantity demanded, whereas the vertical axis represents the price. The demand curve (D) shown in black depicts the relationship between the price for maize and the quantity of maize consumers are willing and able to buy at each particular price where—according to the law of demand—the quantity demanded depends negatively on the price. This normal, negative demand reaction to price increases is the result of two separate effects: (1) If the maize price increases, the consumer can afford less quantity of maize at the given income and thus demands less. This is the income effect. (2) When the price of maize increases, the consumer will look for alternative products similarly satisfying the need and thus substitute some of the consumption of maize, for instance, with wheat. This is the substitution effect. Both effects will cause the consumer to buy less maize if its price increases, so that the total quantity of maize demanded will decrease. Usually, a demand curve in a market reflects the aggregate demand of all consumers in the market. In Fig. 8.9 we assume that consumer 1 (blue curve) represents the maize demand by food and feed producers, whereas consumer 2 (green curve) represents the maize demand by producers of for example biofuels and bioplastics. Both curves together add up to the total maize demand.

If the price for maize increases, both consumers want to buy less of it. The strength of the consumers' reaction to the price increase is measured by the price elasticity of demand.[1] A price elasticity of demand equal to one means that for example a 20% increase in the price for maize leads to a 20% decrease of the quantity demanded. A price elasticity of demand of less than one means the fall in demand is less than 20% and the demand curve is steeper and the demand is said to be less elastic. If the elasticity is greater than one, then the quantity demanded increases by more than 20% and the demand curve is flatter and the demand more elastic.

Figure 8.9b displays the supply side of the maize market in the same type of diagram. The supply curve (S) shown in black depicts the relationship between the price for maize and the quantity of maize producers in the country are willing and able to supply. Usually, supply is positively related to the price due to factors causing production costs to increase with increasing level of production output, depending on the particular product market. This is illustrated by two examples. Increasing the production of maize could be achieved, for example, by allocating additional land or using more

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[1] More precisely, the price elasticity of demand measures by what percentage the quantity demanded decreases if the price increases by 1%. In general, the price elasticity of demand is a negative number but the minus sign is often omitted for the sake of simplifying the discussion of the value.

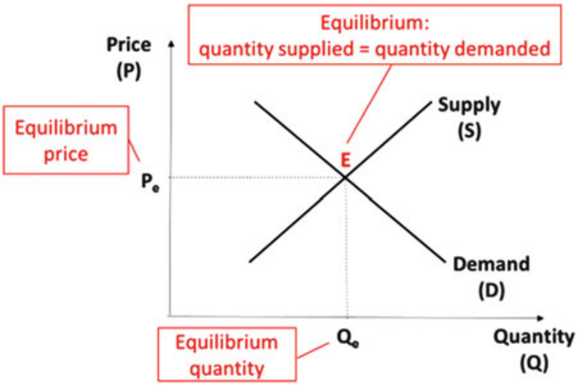

Fig. 8.10 The equilibrium of supply and demand

fertilizer. Both would increase the production costs of a ton of maize: Commonly, all good quality, suitable land is already under productive use and thus the farmer would need to offer a higher land rental price than others to obtain additional land. Likewise, applying additional fertilizer increases the maize yield but the particular gain in yield per hectare for the next unit of fertilizer applied is the lower, the more fertilizer is already applied to the field (diminishing marginal productivity). Thus, the quantity of maize that can be profitably produced increases with the market price of maize and the quantity supplied to the market increases. The supply curve represents the aggregated supplies of all sellers, here supplier 1 and 2, just as the demand curve is the sum of the demand of all consumers.

This simple example of a market is general and equivalently applies to the demand and supply of any other market, such as those for sugar, fuels or bioplastics.

8.1.4 The Market for Biobased Resources and Products: Determining the Equilibrium Price and Quantity

In the previous section, we have graphically analysed the demand and supply curves using the example of maize. Now, we combine demand and supply curves in a market diagram to determine the equilibrium quantity and price at which a good is traded in the market.

Figure 8.10 represents the market by combining the supply and demand curves in a single diagram. The market equilibrium (E) is the point at which the demand and supply curves intersect. This point defines the market price (equilibrium price) at which the quantity supplied on the market equals the quantity demanded, thus the price at which the market is cleared. Usually, the market price automatically settles in the equilibrium due to the interactions between consumers and producers. Let's consider again our maize example. Suppose that in the initial situation the market price for maize is higher than the equilibrium price. At this price, the quantity supplied is larger than the quantity demanded (excess supply or surplus). As a result, not all suppliers are able to sell their maize at the current price and they reduce their prices. At a lower price, consumers demand more maize and producers supply less. This process of lowering the price of maize and the corresponding reactions of buyers and sellers will continue until the quantity of maize supplied equals the quantity demanded, equivalent to movements along the demand and supply curves, respectively, towards the equilibrium point.

Besides the market price, there are other factors which determine the quantities supplied and demanded, respectively. We can observe movements along the demand curve and shifts of the demand curve. Continuing the example, if the price for maize decreases, the result is an increase in the quantity demanded which is equivalent to a movement along the demand curve. Similarly, the price decrease declines the quantity of maize supplied and is equivalent to a movement along the supply curve. By contrast, an increase (decrease) of the quantity demanded at a given price reflects a shift of the curve to the right (left) and analogously for the quantity supplied. What are causes for such shifts of the demand and supply curves?

Let us start with the demand side. Usual factors that lead to a shift of the demand curve are: changes in the price of goods related to the observed good, income changes, changes of tastes and preferences and changes in expectations. In our maize example, concerns about the climate impacts of fossil oil-based industries increase the demand for biofuels. This results in a shift of the demand curve for biofuels to the right and consequently also in a shift to the right of the demand curve for the biofuel feedstock maize (change in preferences). Conversely, a decrease in the fossil oil price would lead to a decrease in biofuel demand and thus also decreases the demand for maize shifting the demand curve to the left (change in the price of a good related to biofuels).

From an economic perspective, biofuels are a substitute for fossil oil. Products are called substitutes, if an increase in the price of one commodity (fossil oil) leads to an increase in the demand for the other commodity (biofuels). However, in other cases an increase in the price of one commodity would lead to a decrease in the demand of another commodity, e.g. fossil oil and cars. Such products are called complements.

How are the equilibrium price and quantity on a market affected by a price increase of a related product?

Figure 8.11 presents the effects of a rise in the oil price on the market for biofuels (Fig. 8.11a) and on the market for the biofuel input maize (Fig. 8.11b). Due to the increase in the fossil oil price, the market price for fuels also increases so that biofuels become relatively cheaper and demand for biofuels increases at every price, indicated by the demand curve shift to the right ($D_1 \rightarrow D_2$). At the old price (P_1) demand exceeds now supply. This excess demand induces suppliers of biofuels to raise the price. Consequently, the increased oil price raises the equilibrium price for biofuels ($P_1 \rightarrow P_2$) and the equilibrium quantity of biofuels sold ($Q_1 \rightarrow Q_2$).

An increase of the equilibrium biofuel quantity in diagram (a) raises the demand for its inputs such as maize. This is shown in diagram (b). At every price, the demand for maize is increased as represented by a shift of the demand curve to the right ($D_1 \rightarrow D_2$). This results in an increase of the equilibrium price and quantity for maize, which in turn affects biofuel producers.

Shifts of the supply curve are usually caused by changes in input prices, technological changes or changes in expectations. For the production of biofuels several inputs are required, among them maize. If the price of maize increases as described in Fig. 8.11b, this increases the input costs of biofuel production and therefore leads to a reduction of biofuel quantity supplied at every price, as represented by a shift of the supply

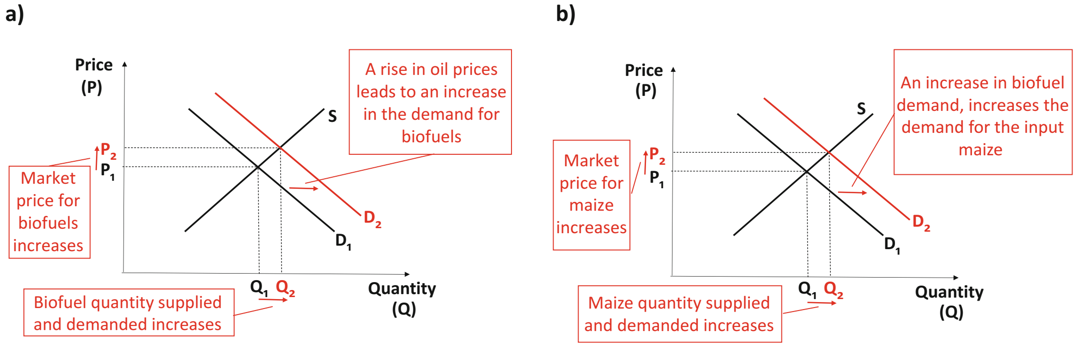

Fig. 8.11 Supply and demand effects on the resource market

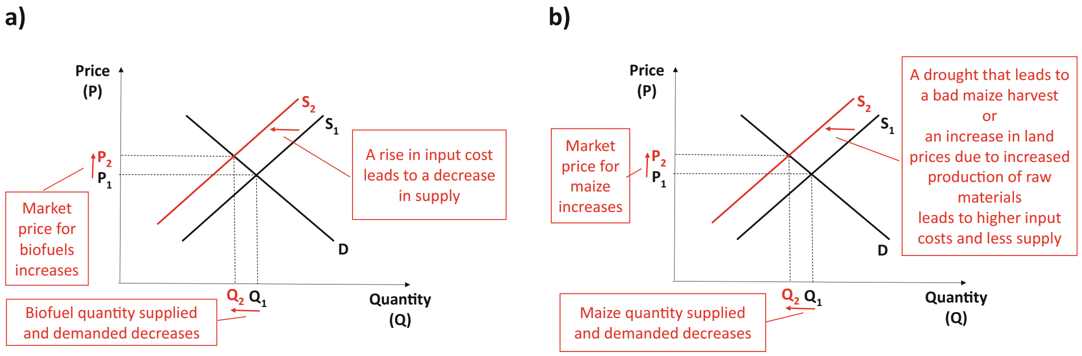

Fig. 8.12 Supply and demand effects on the market for biobased products

curve to the left (Fig. 8.12a), Whereas technological progress decreases the production costs of biofuels and shifts the supply curve to the right. If biofuel producers expect a further increase in oil prices and therefore decide to expand the biofuel production, the supply curve shifts to the right.

Effects on the supply of inputs that cause increased input prices are for example a drought that leads to a reduced maize harvest, an increase in the rental price for land, and an increase in fertilizer prices (effects shown in Fig. 8.12b). The effects of increased input costs are shown in Fig. 8.12a. The reduced supply of biofuels leads to an increase in the equilibrium price and a reduction of the equilibrium quantity.

When analysing the effects on the market for biobased products and resources, we also need to consider the effects on factor markets, e.g. land. In the real world, we have to cope with limited land supply. The options for gaining additional land area for farming via for example deforestation or polder landscape are limited. In addition, desertification and soil erosion cause loss of land. Therefore, an increase in the demand and supply of biobased products and consequently an increase in the amount of crops produced for the biobased market are only possible by a reallocating land from the production of food to the production of biobased resources. This increase in the demand for land leads to an increase in the price of land, which increases input costs and thus makes production of biobased products less cost efficient.

So far, we treated the markets for fossil oil, agricultural raw materials and biobased products in the same way. However, as stated in the introduction, most of the biobased products are relatively new so that the corresponding production processes often need substantial further research and development before the products eventually might become competitive with their established non-biobased substitutes. Figure 8.13 shows the average cost curves for fossil fuel and biofuel production. Currently, Q_1 litres of fossil fuel are sold on the market at price P_1. At this price, the average cost curve for biofuels lies below the average cost curve for fossil fuel implying that biofuels potentially could be sold cheaper. However, the fossil fuel industry got established first and is able to sell fuels at price P_1, which is below the start-up cost of C_0 of the biofuel industry. Due to the current lack of experience and market share to gain from economies of scale, the biofuel industry cannot compete on the market, due to its higher production costs. This provides a reason for temporary support of the biofuel industry through the government—often referred to as the infant industry argument. Through the support (or protection) of the biofuel industry at its initial development stages, the industry can develop and reduce its production costs through the development of new technologies and economies of scale so that it might be able to compete with the fossil fuel industry in the future. Another argument for government support of the biofuels sector could be made due to

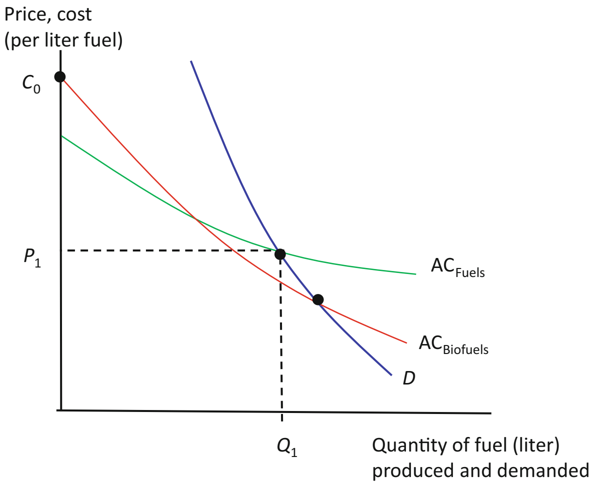

Fig. 8.13 Developing markets and the infant industry argument

the additional environmental costs fossil fuels cause and which are not included in their price. This will be discussed in a later chapter under the concept of externalities (see Chap. 10).

8.1.5 Policy Instruments to Support Biobased Products

In the previous sections, we have introduced the drivers of and barriers to the demand and supply of biobased products. Objectives such as sustainable development, energy security, independence from fossil fuels, food security, waste reduction and climate change mitigation require an increase in the production and the use of biobased products. However, the only recently developed biobased products have a disadvantage in the market due to their particularly high production costs compared to products already established in the market (see Fig. 8.13). Conventional products based on fossil energy sources (e.g. crude oil, natural gas or coal) have an advantage over renewable fuels/energy, because they have gained from economies of scale due to mass production and learning effects which have decreased their production costs over time. However, the use of these products is associated with high carbon dioxide and GHG emissions that lead to additional cost for society, e.g. through increasing occurrences of severe weather events, melting ice caps and increasing air pollution. These external costs, equal to the value of agricultural production losses, health costs, costs of destruction through storms and flooding, and the like, are not covered by the market price of these products, leading to an inefficient allocation of resources, i.e. a market failure.

In light of the reasons pushing the development of biobased products listed in the introduction to this chapter, governments aim to correct the market failures associated with the use of fossil energy sources and to provide an enabling environment for renewable alternatives which should allow these industries to mature and become competitive. To this end, governments introduce various policy instruments that aim to promote the development of biobased products by enabling the development of better technologies, to increase the production quantity and thus the market share, and to discourage the use of fossil fuels (see Chap. 10). Technological progress and economies of scale would then lead to a decrease in production costs and consequently increase the competitiveness of biobased products.

The comparison of the policy landscape of different biobased products clearly reveals that the policies implemented to support bioenergy and liquid biofuels are the most advanced.

Biochemicals and biomaterials are found to be at a relative disadvantage, because many of the policies applied to support biofuel and bioenergy production reward the use of biomass in these industries. According to the Renewable Energy Policy Network for the twenty-first century (REN21), nearly all countries worldwide (146 countries) apply policies to support the provision of renewable energies (REN21 2016). Most of them established bioenergy targets. In general, countries use manifold ways and policies to support biofuel production, e.g. establishing targets for the share of bioenergy in total energy use (more than 70 countries), applying policy instruments to support the production of biofuels (more than 100 countries), and imposing policy instruments which improve market access (more than 50 countries) (OECD 2014).

A large number of policy instruments have been applied to stimulate bioenergy and biofuel production. In this section, we provide a general but brief overview of applied instruments to support biobased products, particularly used for bioenergy and biofuels, and explain their economic rationale using the example of energy and carbon taxes.

Different instrument types are applied to support biobased products. One distinction can be made between direct policy instruments, e.g. *tariffs and subsidies* on different (biobased) products either domestically produced or traded, and indirect policy instruments, e.g. *environmental taxes* (carbon tax) or *voluntary agreements*. Direct policy instruments can either be provided to support renewable products, e.g. a subsidy on the production of biobased products or a subsidy on agricultural products, such as maize, sugar or grains, to enhance the production of biomass or a tariff on the imports of biobased products to support domestic producers. Governments provide subsidies across the entire biomass value chain to facilitate suitable conditions for biobased product deployment. By contrast, indirect policies are mainly applied to fossil-based products by taxing these products to account for their negative external effects on the environment. This will be further explained instantly. All of these policies are price-driven, e.g. in the case of a subsidy on biobased products, the policy drives a wedge between the market price and producer price, so that the producers achieve a price higher than the market price. *Feed-in tariffs* serve as another example for creating price-driven incentives that are often applied in the renewable energy market. Producers of renewable energy can feed-in the full production of green electricity at fixed prices. This policy provides specific support to producers of renewable energies for a defined period. Specifically, the producer price for renewable energies equals the market price for energy plus the feed-in tariff rate, so that producers of renewable energies are paid a cost-based price for their energy supply that exceeds the fossil energy source-based price. Governments also promote the use of biobased products, particularly biofuels, through *excise tax reductions or exemptions* that decrease the price paid by consumers.

Box 8.1 Energy and Carbon Taxes

Energy and carbon taxes are imposed to restrain the production of for example energy from fossil fuels and enhance the production of biofuels. This simple instrument provides product group specific taxes and aims to correct a market failure by charging a price for GHG emissions, e.g. fossil fuel production is taxed due to the high GHG emissions of its use.

What is the underlying economic rationale behind a policy instrument such as energy and carbon taxes impose additional costs on the use of fossil energy sources such as oil, natural gas and coal in proportion to the amount of carbon these resources contain. These additional costs to the use of fossil energy sources is passed through to the price of the final good such as fuels, electricity or any goods that use these sources intensively. The policy instrument corrects the market failure by incorporating these additional

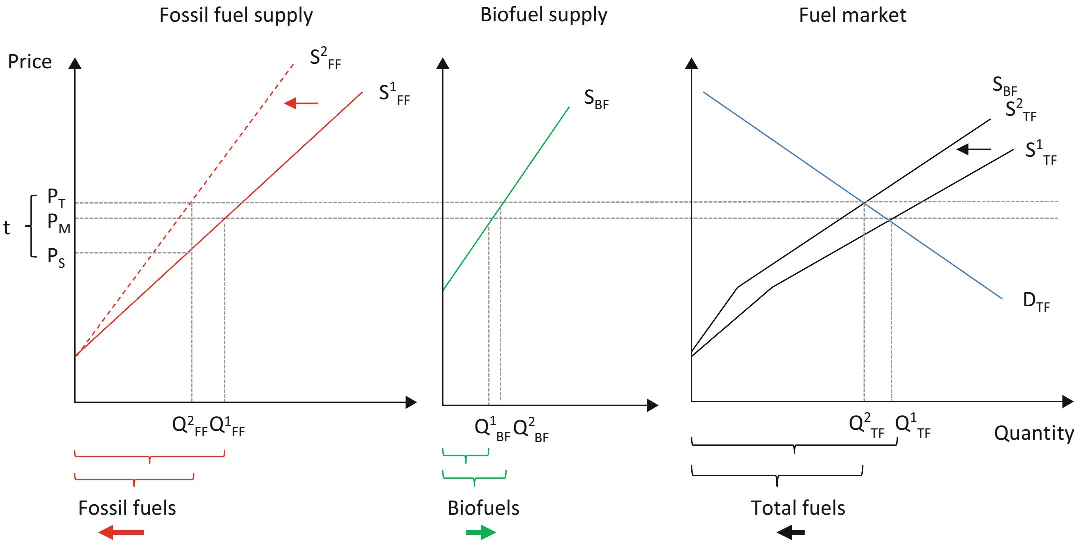

Fig. 8.14 Effects of a carbon tax on fossil fuel

environmental costs into the market price, thereby modifying the incentives for producers and consumers such that the quantity produced and consumed is decreased.

Figure 8.14 presents the effects of energy and carbon taxes and shows how these policy instruments stimulate the production of biofuels. Let us assume that all energy products based on fossil fuels are taxed by an ad valorem tax t that drives a wedge between the market price P_M and the producer price P_S equivalent to the size of the tax.

$$P_S = P_M(1 + t) \qquad (8.1)$$

For each quantity of energy from fossil fuels sold on the market producers have to pay the tax. Consequently, they receive less per unit of output and reduce their supply on the market, which in turn leads to a market price increase.

In Fig. 8.14 we analyse the effects of energy carbon taxes on the fuel market considering both the supply of fossil fuel and biofuel. S^1_{TF} represents the total supply of fossil fuels and biofuels together ($S^1_{FF} + S_{BF} = S^1_{TF}$), whereas D_{TF} shows the total demand on the fuel market. The supply curve is upward-sloping indicating that the supply of fuel increases as the market price increases. The demand curve is downward-sloping showing that a price increase leads to a decrease in fuel demand. In the equilibrium (intersection of S^1_{TF} and D_{TF}) at the market price P_M the quantity Q^1_{TF} is sold on the market of which Q^1_{FF} are fossil fuels and Q^1_{BF} are biofuels. What happens when the government decides to impose an energy and carbon tax? This tax affects the fossil fuel producers, because they pay now a tax per unit of output based on fossil fuels, therefore, the supply curve of fossil fuels shifts to the left in the panel (a) of Fig. 8.14 reflecting that at every price producers sell less fossil fuel due to the tax. However, the tax does not directly affect biofuel producers. Consequently, the biofuel supply curve in panel (b) of Fig. 8.14 does not change. In accordance with the change in panel (a), the total fuel supply curve in panel (c) also shifts to the left (S^2_{TF}). At any market price for fuel less quantity is supplied. The new market equilibrium reveals a decrease in the quantity of fuels supplied and demanded at a higher price. However, at this higher price biofuel producer sell a higher quantity of biofuels at the market so that the share of biofuel relative to fossil fuel quantity has increased due to the implementation of carbon taxes.

After this excursus on the economic rationale of a price-driven policy, we now briefly introduce other types of policies also often imposed in the markets for bioenergy and biofuels. Examples for quantity-driven policies are, e.g. *blending mandates* that define a specific share of biofuels in transport fuel sold on the market. This policy is relatively cost neutral for the government, however, it increases the demand for biofuels at the expenses of the final consumer due to higher production costs of biofuels. Also *(tradable) green certificates* provide quantity-driven incentives to increase the production of biobased products. They are based on a quota-like-mechanism that obliges producers to produce a specified fraction of their supply from renewable resources. These instruments are successfully applied to support bioenergy, e.g. low carbon energy.

In addition to price- or quantity-driven policy instruments, governments provide other budgetary support measures such as *investment subsidies and new technology support*. These subsidies are available in a large variety of different designs. Examples are funding for capital investments associated with a new project, or subsidised loans/interest rates or grants for production facilities. The objective is to increase the efficiency of biomass use for the production of biobased products to increase supply and reduce production costs. Other measures are support provided to research or rural development.

Why is the amount of support provided to biofuels much higher than the amount provided to biochemicals and biomaterials? According to OECD (2014) the share of crude oil used for energy production exceeds 90% in most of the countries. In addition, simpler and a smaller number of standards is applied to biofuels compared to biochemicals. Consequently, controls on the chemicals market are much higher which increases the number of obstacles that need to be overcome by new products to enter the market. Plastic is a material used for a large variety of purposes, which in return increases the number of expectations on the properties of plastics compared to fuel (OECD 2014). This large variety with regard to standards, applications and expectations aggravates the design and implementation of policy instruments to support biochemicals and biomaterials. By contrast, the development of all three product groups depends on the same resource (biomass) and related technologies. Crude oil prices determine their competitiveness in the market and there are beneficial effects from sharing production facilities.

8.1.6 Conclusions

This chapter provides a brief introduction to the market of biobased products that might become increasingly important in the future. The future global challenges lead to an increasing demand and supply of biobased products. In addition, this market is highly interlinked with the demand and supply of primary agricultural commodities and thus food security. We introduce market diagrams representing the demand and supply functions for biobased products to show how the equilibrium price on the market is determined. We apply these diagrams to show the effects of supply and demand side shocks on the market for biobased products, but also on the market for agricultural commodities and fossil fuels. The particularly high production costs of the relatively new developed biobased products compared to conventional products already established in the market, which are often based on fossil fuels, create a disadvantage for biobased products. In addition, the prices for conventional products do not include the additional environmental costs they create due to for example high carbon emissions, and thus lead to a market failure corresponding to an inefficient allocation of resources. Politicians use these two arguments as major justifications for implementing policies to support biobased products. We provide a brief overview of selected policy instruments and explained the effects of carbon taxes on prices, and demand and supply on the market for biofuels using a graphical market model.

Review Questions

1. Name and discuss reasons why the production of biobased products has gained importance in recent years?
2. Explain how high crude oil prices influence the demand for biofuels?
3. What are the challenges on the market for biobased products?

   a. Explain driving and limiting forces for the supply of biobased products using 1 example for each.
   b. Explain driving and limiting forces for the demand of biobased products using 1 example for each.

4. The demand for bioplastics is expected to considerably increase in the future.

   a. How would this increase in the demand for bioplastics affect the market price and quantity sold of bioplastic material? Please use a market diagram to illustrate and explain the results.
   b. In addition, the government aims to support the production of bioplastics. Please explain and discuss appropriate policy instruments the politicians might introduce.

5. Assume that the bioplastics industry is able to considerably decrease their costs for producing bioplastics due to technological change.

   a. How would this affect the supply of bioplastics? Please use a market diagram to show and explain the effects.
   b. Bioplastics are produced from starch. How would therefore an increase in the production of bioplastics affect the market for wheat, maize and potatoes? Is there empirical evidence for the effect?
   c. What would be potential effects on prices and supply of food products and thus food security?

6. Governments often use the infant industry argument to justify the introduction of policy instruments to support relatively new industries such as biofuel producers. Please explain and discuss this argument using biofuels as an example.
7. Please use a graph similar to the initial situation in Fig. 8.14 as starting point. Assume that the government starts to pay a specified amount of euros to the producer for each ton of biofuel produced (a subsidy).

   a. How does this output subsidy for biofuels affect the market equilibrium of biofuels (producer price, market price, quantity)?
   b. What are the effects on the total fuel market (equilibrium price and quantity)?

8.2 Sustainable Development and Sustainability Management

Rüdiger Hahn

Agrophotovoltaic plant in combination with potato production © Andrea Ehmann

Abstract In the last decade(s), the idea of sustainable development has become a widely acknowledged topic which is supported by many actors in modern society.

Companies, as central economic players, are increasingly pressured by a wide set of stakeholders to engage in sustainability management and to contribute their share towards sustainability. Against this background, this chapter first introduces the general idea of sustainable development with its elements of intragenerational and intergenerational justice and illustrates the roots of sustainable development as a normative-anthropocentric concept. Since sustainability is a contested idea with many different notions, the different understandings of weak, strong and quasi-sustainability are introduced and the status quo of sustainability in society is highlighted.

Following this general introduction, actors of sustainability in society are named and the relevance of sustainability management for companies is discussed. In the remainder of this chapter, three base strategies to achieve sustainability (i.e. eco-efficiency, eco-effectiveness and sufficiency) are explained along with their opportunities and limitations in achieving sustainability. Finally, some exemplary elements and tools of sustainability management from the areas of sustainability accounting and management control as well as of sustainable supply chain management are introduced to provide a first glimpse of possibilities for companies to engage with sustainability.

Keywords Sustainability; SDGs; Stakeholder; Eco-efficiency; Eco-effectiveness; Sufficiency

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Learning Objectives
After studying this chapter, you will be able to:

- Characterise sustainable development with its various conceptual elements and understandings.
- Discuss the main actors of sustainability management and their influence on corporate sustainability.
- Distinguish eco-efficiency, eco-effectiveness and sufficiency as base strategies in sustainability management and highlight their potential and limitations.
- Exemplarily illustrate elements of sustainability management.

8.2.1 Sustainable Development: Characterisation and Historical Roots

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 41). This probably most widely cited characterisation of sustainable development stems from the 1987 report of the United Nations World Commission on Environment and Development (WCED; also called Brundtland report after the chairperson of the commission, then Norwegian Prime Minister Gro Harlem Brundtland).

This broad characterization covers the two main pillars upon which sustainable development rests: Intragenerational and intergenerational justice. Meeting the needs of the present (i.e. within today's generation) verbalizes the idea of intragenerational justice and was already at the centre of thinking in the WCED report despite often being less prevalent in many discussions around sustainable development. In fact, the report highlights the overriding priority for needs of the poor and gives a voice to the large group of unprivileged poor in the world. Fulfilling these needs, for example, in terms of providing enough food, safe drinking water, sanitation, or minimum social security is thus a cornerstone without which sustainable development cannot be achieved. At the same time, the concept of sustainable development gives future generations a voice through the idea of intergenerational justice, which calls for preserving societal and ecological systems in a way that future generations are not inhibited in their own development.

This latter perspective, which mainly focuses on natural sources and sinks, is also included in the historical roots of sustainable development, which trace back to the times of medieval forestry. Already here, central aspects of a sustainable resource utilisation (i.e. permitting only as much logging as could be grown again) were known and practiced. Both elements of justice illustrate that sustainable development is a normative (i.e. relating to an ideal standard or model) and anthropocentric (i.e. relating to the influence of human beings on nature) concept. As such, it is widely acknowledged but still contested and there is no rule of nature that determines whether or not mankind has to adhere to the principles of sustainable development, but it is instead an ethical decision (see for example Hahn 2009, 2011).

Box 8.2 Intragenerational and Intergenerational Justice and the Role of the Bioeconomy

Some products and activities from the bioeconomy sector provide a good perspective on why intragenerational and intergenerational justice are sometimes difficult to align and why achieving sustainability is such a complex task. Take the example of biofuels or bioplastics made from renewable energy sources such as plant material. From an intergenerational perspective, such products are favourable because they potentially allow for carbon-neutral products, which have no or at least less impact on climate change compared to conventional fuel sources or plastics. However, the production of the renewable agricultural raw material for

(continued)

Box 8.2 (continued)

the biobased products might lead to a crowding out of staple crops on limited cultivable surfaces. This could have detrimental effects on intragenerational justice if food prices increase or if, in extreme cases, food supply is limited (also known as food vs. fuel debate; see, for example, Kuchler and Linnér 2012).

But when would sustainable development be achieved? Despite providing some general yardsticks for orientation, the above-cited characterisation still allows for different interpretations and some even note that sustainable development is a journey that will never be finished. For others, however, sustainable development is easier to achieve. This is especially the case when following an interpretation of sustainable development known as "weak sustainability" (for overviews of the different concepts see Sect. 10.2; Ayres 2007; Hediger 1999; Neumayer 2013). In this perception, sustainability is achieved if the total sum of anthropogenic (i.e. man-made) capital and natural capital are held constant. This bears the main assumption that natural capital can generally be substituted by anthropogenic capital and still ensure the continuation of human well-being on earth. Main strategies to achieve sustainability under this assumption are a focus on efficiency (i.e. achieving the same output with less input or more output with the same input) and consistency (i.e. entirely closed systems with no input of raw materials and no emissions and waste production) through technology, growth, and markets. The drawback of this notion of sustainability is, however, that a full substitutability of natural with man-made capital is likely to be impossible due to technical limitations and laws of nature. Once all non-renewable resources as well as the Earth's biodiversity and biocapacity are depleted, it is unlikely by all known standards that mankind can still survive at the same level of prosperity as before, if at all.

The counterpart to weak sustainability is "strong sustainability" (see Sect. 10.2). The general idea of this perception of sustainability is to live only from the "interest" of the natural capital, that is, to use only those natural goods and services that are continuously added. It would thus not be permitted to use non-renewable resources (because they are not reproduced and hence generate no "interest") and renewable resources can only be utilised below their regeneration capacity. If followed through, this would mean renouncing any further growth of consumption and production due to the status quo of intergenerational justice as further depicted below. To walk this path, society would need to aim at sufficiency (i.e. asking how much is enough) and efficiency at the individual and political level. The drawback of this notion of sustainability is that is has a rather metaphorical character. A complete abdication of any growth is unlikely and would also mean that intragenerational justice could only be achieved through a very drastic (and thus unrealistic) redistribution of worldwide wealth.

Weak, Strong, and Quasi/Critical/Ecological Sustainability

These are different understandings of sustainability, which lead to fundamentally different implications for actions and strategies.

The middle ground between the two extremes is occupied by the idea of "quasi", "critical", or "ecological" sustainability. It builds upon the principle of prudence and puts critical levels or critical boundaries, for example, of the Earth systems into the middle of thinking (for an explanation of such critical boundaries see, for example, Steffen et al. 2015). Such thresholds should not be exceeded and, for example, a substitution of natural capital by man-made capital has to be well justified. To achieve this, a mixture of the three strategies might be needed but the technological feasibility and the socio-political enforceability of these strategies is uncertain.

8.2.2 Status Quo of Sustainable Development

When looking at the current state of the world, it seems to be safe to say that neither intragenerational nor intergenerational justice have been achieved despite some scientific debates and uncertainties on specific issues. Although the last 25 years have seen some progress, today still more than 830 million people live in extreme poverty (earning less than US$1.25 per day), 6 million children under the age of five die annually, 2.4 billion people have no access to improved sanitation and almost 800 million people are illiterate (United Nations Human Development Programme 2015), while at the same time less than 10% of the world's population accumulate almost 85% of total wealth (Stierli et al. 2015). Looking at rich versus poor countries, people living in high-income countries use roughly six times more natural resources than those living in low-income countries (WWF International 2016). This directly links to the perspective of coming generations. Today's human population uses almost double the amount of the world's available biocapacity, thus already at present living at the expense of future generations. In their seminal study, Steffen et al. (2015) identified seven planetary boundaries which, if crossed, bear a high risk of destabilising the Earth system. Of these seven boundaries, two (biosphere integrity and biochemical flows) have certainly already been exceeded according to scientific standards and two others (climate change and land-system change) are marked with an increasing risk so that the need to act is urgent if sustainable development is a favoured goal.

Eventually, however, the concepts of intragenerational and intergenerational justice need to be broken down into actionable pathways and concrete fields of action, no matter what perception of sustainability one follows. Therefore, in 2015 the United Nations proposed a set of seventeen aspirational "Sustainable Development Goals (SDGs)" with 169 sub-targets as depicted in Fig. 8.15. The SDGs are supposed to influence and provide guidance not only to worldwide politics but also to businesses and individuals in their actions to serve the idea of sustainable development.

Another often-mentioned reference to reduce complexity is the so-called "IPAT-Equation" (e.g. Meadows et al. 2004, pp. 124–126), which illustrates the human impact on ecological ecosystems. The "Impact" refers to the ecological footprint of any population or nation upon the planet's sources and sinks. "Population" counts

Fig. 8.15 The sustainable development goals (Maria Gershuni; CC BY-SA 4.0 via https://commons.wikimedia.org)

the number of people influencing the ecological footprint. “Affluence” is determined by the impact or throughput generated by the material, energy, and emissions associated with consumption. “Technology” illustrates the damage caused by the particular technologies chosen to support that affluence (i.e. the energy needed to make and deliver material flows, multiplied by the environmental impact per unit of energy). Changes in any factor of the equation lead to changes in the ecological footprint we leave on the Earth system.

IPAT-Equation
It illustrates the human impact on Earth systems through the term: Impact = Population × Affluence × Technology.

8.2.3 Actors and Understandings of Sustainability Management

To steer the world society in the direction of sustainable development and to promote the SDGs, multiple actors need to play along (see Fig. 8.16). Politicians need to recognise the need to embed sustainability goals and principles into rules and regulations at different levels, consumers need to recognise how their behaviour adds up and contributes to or hinders sustainability, civil society organizations need to recognise their influence on other players and advocate different elements of sustainability, and of course companies, as central and powerful players in modern society, need to contribute their share by means of various elements of sustainability management either through reducing their environmental and social footprint or through actively and positively contributing to sustainable development with sustainability-oriented business models, goods, and services.

To make a company more sustainable (or less unsustainable), the management needs to balance a multitude of interests and bring in line various actors (see Fig. 8.16). Certain types of investors or stockholders, for example, might pressure a company to actively pursue the idea of sustainability while others fear that measures of sustainability management are costly and could thus reduce their earnings. Many potential employees nowadays are increasingly demanding when it comes to the social responsibility of their future employer and at the same time many people still do not see the need to change their own behaviour and, for example, do not switch off the computer monitor when leaving the office. Customers often claim to value sustainability and the market for organic and

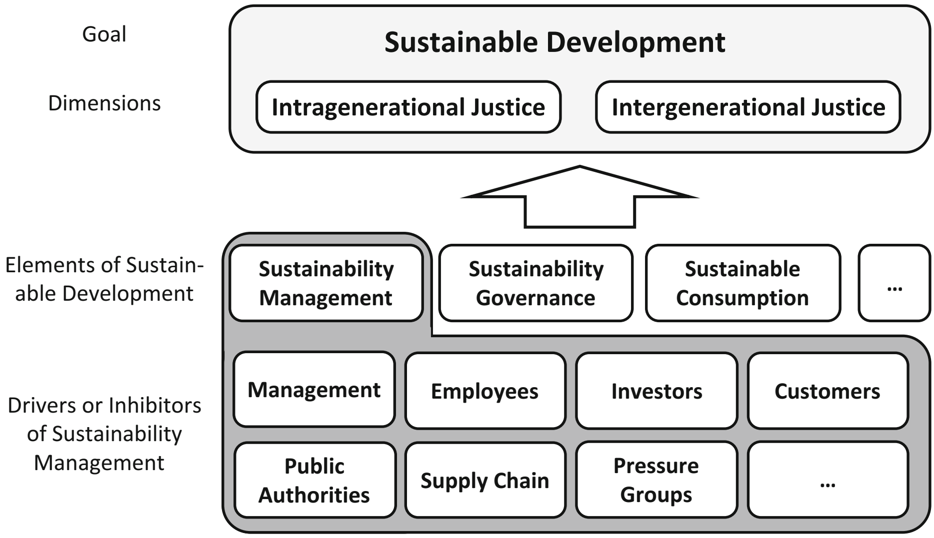


Fig. 8.16 Elements and actors of sustainable development and sustainability management

fair-trade products is constantly growing around the world but the willingness to pay a higher price for fair and sustainable products is still often limited. Supply chains and networks of most goods and services are extremely complex and easily cover thousands of suppliers, which makes it difficult for companies to monitor the sustainability performance, while at the same time many pressure groups actively advocate better working conditions and environmental standards. In sum, the management of sustainability is a complex endeavour.

Stakeholder
"Any group or individual who can affect or are affected by the achievement of the firm's objectives" (Freeman 1984, p. 25). This encompasses internal (e.g. employees, management and owners/stockholders) and external stakeholders (e.g. suppliers, government, customers, creditors and society).

But why then should a company embrace the idea of sustainable development at all? First, it is the pressure of many different stakeholder groups, for example regulators, governments, or sustainability-oriented activists who demand a responsible business conduct and who lobby for sustainability management. Second, a growing sustainability-consciousness among consumers and businesses as well as changing regulations produce new market opportunities in this area and companies with a distinct sustainability profile might also reap reputation benefits. Third, sustainability management can lead to reduced costs when, for example, more resource- or energy-efficient products and processes lead to material or energy savings. Fourth, some consider sustainability management to also be part of an active risk management, because many of the most pressing risks companies face are connected to sustainability issues (e.g. reputation risks in (un)sustainable supply chains, raw material shortages or price volatilities, natural catastrophes and extreme weather events, social instability).

However, beyond such examples of a business case for sustainability management (i.e. beyond win-win paradigms in which sustainable management is good for the financial bottom line of a company), there are also numerous tensions and trade-offs companies have to cope with (Hahn et al. 2015b). For example, various measures in sustainability management require substantial upfront investments, which may put pressure on short-term financial objectives and benefits of sustainability management are sometimes hard to measure so that a (financial) quantification is not always straightforward. Another example from the area of the bioeconomy illustrates such dilemmas on a larger scale. Individual organizations usually strive for efficiency and they are likely to adopt similar solutions when acting under similar external conditions (e.g. monocultures as efficient means of cultivating agricultural produce). Such a homogenization, however, could lead to a lower resilience of the entire agricultural system due to a loss of (bio)diversity. Society is called to recognise such trade-offs and tensions and develop solutions to cope with such difficulties (see again Hahn et al. 2015b, for initial suggestions).

As can be seen from these remarks, sustainability management is a task with a myriad of potential fields of action, not all of which are relevant for each and every company in the same way. To make the elusive concepts of intragenerational and intergenerational justice within sustainable development more comprehensible and manageable at the company level, the concept is often broken down into three distinct pillars of action in which companies present their actions: economic, ecological, and social responsibility (e.g. Elkington 1997), sometimes also termed the 3P of *people, planet and profit*. In the corporate domain, the economic pillar ("profit") is usually understood as the responsibility of a company to generate profits to be sustainable in an economic sense. Furthermore, aspects such as economic prosperity and development are also often mentioned. In the ecological pillar ("planet"), topics such as environmental protection and resource preservation and respective corporate actions to achieve these goals are discussed. The social dimension ("people") covers topics such as social justice and equal opportunity and is often connected to employees and suppliers with issues such as fair compensation, diversity, labour conditions, work–life balance and so on. This also shows that the distinction of previously often separately covered topics such as sustainability and corporate social responsibility (CSR) is in fact very blurred. Nowadays, some companies have a CSR department or CSR manager while others have a sustainability officer, both of which often cover similar tasks and also in academia the concepts and terms are increasingly used interchangeably (see, e.g. Hahn 2011).

8.2.4 Base Strategies in Sustainability Management

As illustrated in the beginning, the road to sustainability can only be successfully taken if intragenerational and intergenerational justice are pursued simultaneously. This implies that we need to decouple the human development on the one hand from the ecological impact caused and the consumption of resources on the other hand. To achieve such a decoupling, three basic sustainability strategies are often discussed: eco-efficiency, eco-effectiveness/consistency and sufficiency (for an overview see, e.g. Hahn 2008).

Eco-efficiency

The general approach of eco-efficiency is to aim at a more efficient use of natural resources or of emissions caused in producing goods or services. It thus follows the idea of relative improvements through the quantitative reduction of resource usage and emissions of products "from cradle to grave" (i.e. from raw material extraction at the beginning of a product life cycle to the final disposal at the end of the cycle). With successful examples of eco-efficiency, less resources or emissions are needed to produce the same amount of goods and services compared to a previous status quo (i.e. easing the environmental burden for a constant level of consumption) or more goods and services can be produced with the same amount of resources and emissions (i.e. enabling development without further deteriorating the environment). This strategy mainly aims at technological solutions and innovations either at the product level (i.e. more energy-efficient electrical household consumer devices, fuel-efficient cars etc.) or already in the production stage (i.e. more resource or energy efficient processes) and there are numerous examples of successful eco-efficiency innovations. Different academics point to the enormous potential of eco-efficient products and processes which could lead to an improved efficiency of resource and energy consumption of up to factor 4 or 10 (Schmidt-Bleek 1998; Weizsäcker et al. 1996). The strategy is comparably easy to translate into the corporate domain because companies already regularly aim at an efficient use of various (especially financial) resources and technological innovations are an established means of progress in many firms. However, the success of the eco-efficiency strategy (as well as the success of the other strategies discussed below) is limited by the so-called rebound effect (for an overview see for example Figge et al. 2014; Hahn 2008). This effect illustrates that an improved eco-efficiency is often counteracted by increased consumption. The improved efficiency often, for example, leads to cost savings, which in turn lead to a disproportionate growth in overall demand for goods and services, if the reduced costs are associated with lower prices. The same pattern might occur in a psychological dimension when, for example, improved eco-efficiency can induce people to buy more products or buy products that they do not need just because they are supposedly eco-friendlier than before. Furthermore, the introduction of a partly sustainable product or process might have negative impacts on other aspects of sustainability, which have not been considered before. The automotive industry, for example, increasingly substitutes metal with lightweight synthetic and composite materials to help improve fuel efficiency. However, such materials can cause problems during the production and disposal processes (e.g. if their production requires hazardous substances and/or if they are difficult to disassemble for recycling).

Eco-effectiveness

Other than eco-efficiency, eco-effectiveness (or consistency) tries to decouple economic development from environmental burden by organising economic processes entirely without waste, emissions, or other environmental impacts through closed-loop systems. It thus aims for a qualitative change of material flows by way of fundamental structural change (e.g. Braungart et al. 2007; Huber 2000; McDonough and Braungart 2002). The idea of the "cradle-to-cradle" thinking of eco-effectiveness is the abdication of using (finite) natural resources and/or of generating waste by creating non-polluting production and consumption processes in which each end-product of a consumption or production process serves as a basis for other processes. Closed-loop systems can come either in form of biological loops or of technological loops (Ellen MacArthur Foundation 2013). Biological loops are closely related to processes in the bioeconomy. Biological materials are farmed, processed to goods, which are then used or consumed and finally end up in the biosphere again as biological waste products. Examples are compostable clothing, houses made from organic building materials etc. In technological loops, recyclability of materials is ideally already included in the design phase of products, which then, for example, allow for easy disassembling or maintenance and refurbishment. Following the use phase, products are disassembled and either used as parts again in new products or materials are recycled to be used in new production processes. If it is feasible to develop and implement such kinds of sustainable innovations, they provide the opportunity to fully decouple growth and development from environmental impact by aligning nature and technology. However, such closed biological or technological loops usually require some fundamental changes in terms of extensive technological innovations and organizational transformations usually beyond the boundaries of a single company, which are not easy to find or implement. Furthermore, critiques describe rebound effects also for the eco-effectiveness strategy especially in the form of growth effects and psychological effects (see again above). Furthermore, uncertainties about the future side effects of innovations are another obstacle. Since innovations are, by definition, the introduction of something new, their ecological, economic, and social impacts cannot be entirely assessed ex ante.

Sufficiency

While eco-efficiency and eco-effectiveness are mainly driven by (technological) innovations, sufficiency is a behaviour-based concept which seeks an appropriate level and forms of consumption (e.g. Bocken and Short 2016; Schneidewind et al. 2012). A sustainable lifestyle following this strategy reduces the absolute amount of consumption and/or changes consumption in a qualitative way, both leading to absolute resource savings. Sufficiency in terms of a quantitative reduction of consumption requires a downgrading of individual aspiration levels and consequently also of the accumulated macro-economic intensity of resource utilisation especially in developed countries with their resource-intensive lifestyle. Sufficiency in terms of a qualitative change of consumption patterns seeks a flexible adjustment of needs and/or a substitution of non-sustainable by sustainable (or at least less harmful) forms of consumption. Examples include reuse of products and relying on services instead of owning products (e.g. through new business models in the so-called sharing economy), longevity of consumer goods, moderated mobility (e.g. regional holidays rather than air travel abroad), or an increased regional perspective (e.g. in supply chains or for food products). The direct impact of successful sufficiency efforts can relieve environmental pressures in a similar way to the eco-efficiency approach. In contrast to the unpredictable outcomes of technology-based innovations, sufficiency measures may achieve reliable and measurable outcomes. Problems with the implementation of sufficiency measures, however, arise when unsustainable consumption patterns are deeply anchored in the consumer's mind and also in businesses' mind-sets. Finally, there might again be the issue of rebound effects if the achieved savings from reduced consumption in one area lead to additional consumption in other areas.

Sharing Economy (also Collaborative Consumption, Peer Economy etc.)
Economic and social activities that deviate from individual, linear consumption patterns. Builds upon an effective management of repeated shared use of used, common, or idle resources as opposed to acquiring new resources for private use and final disposal (e.g. Roos and Hahn 2017).

Given the different opportunities and obstacles of the three basic strategies, it seems that an isolated pursuit of these approaches offers only limited chances of success so that a combination of strategies might be needed depending on the respective products, production and consumption patterns, cultural contexts, and so on.

8.2.5 Exemplary Elements of Sustainability Management

Due to the diverse nature of topics discussed in the broader context of sustainable development, corporate sustainability management is vast and crosses all functional areas of businesses. Aspects of corporate sustainability can nowadays be found in areas such as sustainability marketing, sustainable finance, sustainability accounting and management control, sustainable human resource management, sustainable operations, sustainable supply chain management, sustainable innovation management and so on. In the following section, the areas of sustainable accounting and control and of sustainable supply chain management will be briefly introduced and exemplary management tools and approaches are highlighted to provide a first glimpse of possible courses of action for companies.

Sustainability accounting and management control deals with instruments and systems that internally provide the management of a company with the means to make decisions which enable a (more) sustainable business conduct (sustainable management control) and externally provides interested stakeholders with information about a company’s conduct and performance with regard to sustainability aspects (sustainability accounting). Internally, a company needs adequate information about the sustainability performance of its products, processes, and supply chains to be able to pursue a purposeful sustainability management. Internal information systems, for example, should provide detailed information on material flows, and emissions. Several tools have been developed to assess the sustainability performance of products and processes. In a life cycle analysis (LCA; Finnveden et al. 2009; see also Sect. 8.3), for example, inputs, outputs and sustainability-related impacts of a product system are compiled and evaluated throughout the entire life cycle of a product. While ecological LCAs are widespread and often already standardised, social LCAs are slowly beginning to develop as well (Arcese et al. 2016; Kühnen and Hahn 2017). It is not enough, however, to simply assess performance. Actions need to be put in place to improve performance. In this regard, management systems, which coordinate and systemise corporate activities are widely used also in a sustainability context. Such systems follow defined and documented control and feedback mechanisms. They are usually subject to an external audit, which is supposed to check the implementation of the respective system in a firm. Environmental management systems such as those defined by standards such as ISO 14001 or EMAS III (Neugebauer 2012) aim at improving the organization of environmental management and thus ultimately of a company’s environmental performance. Social management systems such as SA8000 (Sartor et al. 2016) also exist. They are, however, much less widespread than environmental management systems. Another tool to integrate sustainability aspects into management processes is the Sustainability Balanced Score Card (Hansen and Schaltegger 2016), which aims at linking long-term strategic objectives of sustainability with short-term actions and tries to illustrate how sustainability aspects are linked to financial goals.

When turning to the external perspective, sustainability accounting has become a major issue in sustainability management. Companies are increasingly pressured (by various stakeholders or even through governmental regulations) to not only publish information on their financial situation (as, for example, in annual reports) but also to disclose sustainability information. In the European Union, for example, most companies with more than 500 employees are required to publish information on their sustainability strategies and performance and many other countries have similar regulations in place. While publishing certain sustainability information is increasingly mandatory, the modalities of disclosure are often not prescribed. Many companies publish sustainability reports which broadly cover environmental and social aspects, others integrate financial and sustainability information into one single report, or they disclose specific information on issues such as climate change (Hahn and Kühnen 2013; Hahn et al. 2015a). Two trends seem to consolidate, though. First, the voluntary standard for sustainability reporting published by the non-governmental Global Reporting Initiative has become a de facto standard in sustainability reporting and most companies implicitly or explicitly refer to these specifications. Second, especially large companies increasingly acquire an external assurance for their sustainability disclosure, because they want to receive expert advice on their reporting practices or because they want to increase the perceived reliability of their reports (Gürtürk and Hahn 2016; Reimsbach et al. 2017). Such an external assurance is usually mandatory for financial reports (e.g. annual reports) but it is voluntary for sustainability reporting.

Another area of sustainability management is sustainable supply chain management which can be characterised as “the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e. economic, environmental and social, into account which are derived from customer and stakeholder requirements.” (Seuring and Müller 2008, p. 1700). The main question of this area of sustainability management is how can supply chains be organised and managed so that they are economically stable and at the same time reduce ecological burdens and allow for decent working conditions? Regular media reports, for example, on horrible working conditions and on forms of modern slavery especially in developing countries as well as and on the environmental burden of contemporary production systems illustrate that the economic success of modern supply chains very often builds on otherwise unsustainable practices. Finding an answer to the mentioned question is an inherently complex task due to the highly complex and intransparent nature of many modern supply chains which regularly include several thousand suppliers and many upstream (raw material extraction and processing etc.) and downstream (manufacturing of finished goods, several distribution channels etc.) stages. The literature roughly distinguishes between supplier management for risks and performance as a rather reactive approach and supply chain management for sustainable products as a rather proactive approach (Seuring and Müller 2008).

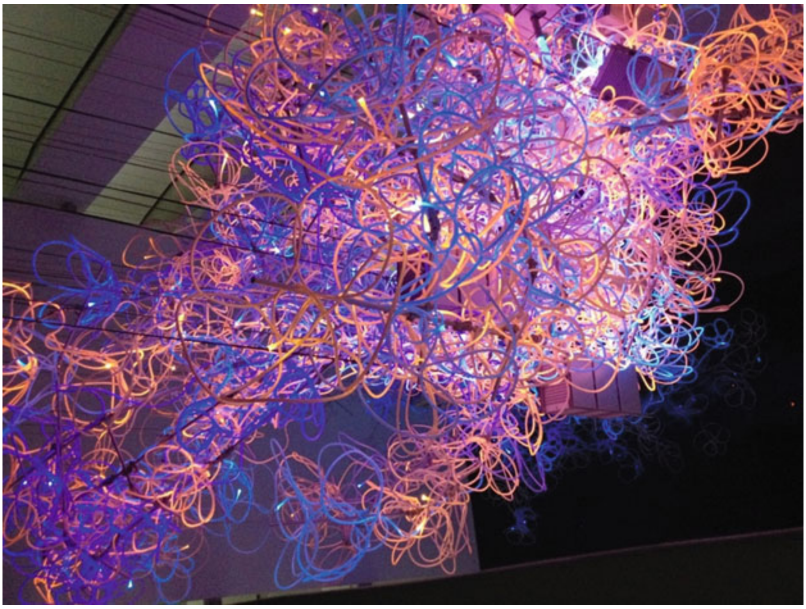
In a supplier management for risks and performance, focal companies (i.e. those companies in the centre of the supply chain that usually design the product, that are visible for the end consumers often through a brand name, and that chose suppliers and distributors and thus orchestrate main parts of the supply chain) try to minimise risks in their supply chains and ensure a certain minimum performance to avoid social and environmental scandals which could, in extreme cases, even bear the risk of chain termination. Prevalent instruments are a supplier management, which includes the selection of suitable suppliers, their auditing and monitoring, as well as the development of suppliers through trainings, incentives, and a close integration into relevant processes. Often, companies have their own codes of conduct which suppliers are supposed to adhere to and some companies actively ask their suppliers to have environmental management systems (such as EMAS III or ISO 14001) or, albeit much less prevalently, a social management system (such as SA8000). With a supply chain management for sustainable products (e.g. Seuring 2011) companies move one step further and try to implement products that are (more) sustainable from the beginning. This includes defining minimum sustainability standards, which might require environmental and/or social LCAs to be conducted to determine the impact of the product throughout its lifespan. To arrive at sustainable products, an extensive cooperation throughout the supply chain is necessary to ensure that sustainability aspects are considered in all phases. Furthermore, chain-wide controlling systems need to be active and accompanying sustainability marketing measures should be put in place to convince the consumer of the product.

Review Questions

- How do "weak", "strong" and "quasi sustainability" differ in their understanding of how sustainable development can be achieved?
- What is the status quo of intragenerational and intergenerational justice?
- What are the different base strategies for decoupling development and environmental burden and what are their opportunities and limitations?
- Why is sustainability management a complex endeavour?

8.3 Life-Cycle Sustainability Assessment

Moritz Wagner and Iris Lewandowski



Rosalie: Lichtwirbel 2016, Schauwerk Sindelfingen © Ulrich Schmidt

Abstract The bioeconomy is based on the three pillars of sustainability and aims to balance the environmental, economic and social aspects. For this task, tools are required that provide qualitative and quantitative information on the environmental, economic and social performance of biobased products and on the trade-offs between the goals of the three dimensions of sustainability. In this chapter, a methodological approach for a Sustainability Assessment based on 'Life-Cycle Thinking' is presented. This approach combines the use of three forms of assessment: Life-Cycle Assessment (LCA) for the environmental aspects, Life-Cycle Costing (LCC) for the economic aspects and Social Life-Cycle Assessment (sLCA) for the social aspects. Together these form the most comprehensive methodology for sustainability assessment: Life-Cycle Sustainability Assessment (LCSA). A hypothetical example of an LCSA is elaborated for a biobased product to illustrate the different assessment steps.

Keywords Value chain assessment; System analysis; Life-cycle thinking; Life-cycle assessment; Life-cycle costing; Social life-cycle assessment; Life-cycle sustainability assessment

Learning Objectives
In this chapter, you will:

- Gain an understanding of the requirements of system analysis and value chain assessment in the bioeconomy

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- Learn methods for environmental, social and economic sustainability assessments and their combined application

8.3.1 The Requirements for System Analysis and Value Chain Assessment in the Bioeconomy

The bioeconomy is expected to contribute towards meeting global challenges such as climate change and food security. However, bioeconomic activities are not sustainable per se. The controversial discussions surrounding the topic of modern bioenergy make this all too apparent (see Lewandowski 2015). Bioenergy is one important sector of the bioeconomy. Although the introduction of advanced bioenergy in Europe has been a success story with regard to the achievement of the GHG emission reduction goals (about 64 million tonnes of CO_2-equivalent emissions were reduced through bioenergy in Germany, 25% of the German GHG reduction goal), it requires subsidies to be economically viable. In addition, the reputation of bioenergy is suffering from the possible competition between food and fuel production. The development of bioenergy has been accompanied by many unintentional and unanticipated environmental, social and economic side effects. It has become obvious that there are various trade-offs between the achievement of environmental, economic and social goals. The example of bioenergy makes it clear that the introduction of sustainable bioeconomic products requires prior assessment which:

- Takes into account their effect on the bioeconomy system as a whole and not only the isolated optimization of specific bioeconomic sectors or activities (to avoid competition leading to food supply problems);
- Gives consideration to and finds a balance between economic, environmental and social aspects, instead of focusing on the optimization of the performance of just one of these sustainability aspects;
- Identifies and models potential trade-offs between economic, environmental and social goals.

When planning a bioeconomic activity, the combined environmental/social/economic assessment, referred to here as "Sustainability Assessment", should ideally be performed ex-ante. This means it should be performed well in time to serve as a source of information for the discussion process with stakeholders, the negotiation of best compromises and as decision support for the planning of the activity. Based on the results of this sustainability assessment, potential trade-offs between economic, ecological and social targets can be identified and—where appropriate methods are available—also quantified.

Trade-offs

A trade-off describes a negative correlation. It is a situation in which the methods of achieving two goals are opposed to each other and a balance has to be struck between them.

An example of an environmental trade-off can be seen in the production of miscanthus-based bioethanol and its subsequent use in a combustion engine. The use of bioethanol in place of fossil fuels makes a positive contribution to GHG emission reduction and thus to climate change mitigation. However, at the same time, the cultivation of miscanthus, in particular the application of nitrogen fertilizer, has a negative impact on the eutrophication potential.

The assessment of the three dimensions of sustainability needs to be based on a Life-Cycle Thinking approach (see Fig. 8.17). This approach ensures:

- The recognition and modelling of trade-offs between the fulfilment of economic, social and environmental goals. It does not make sense to improve one step of the life cycle if

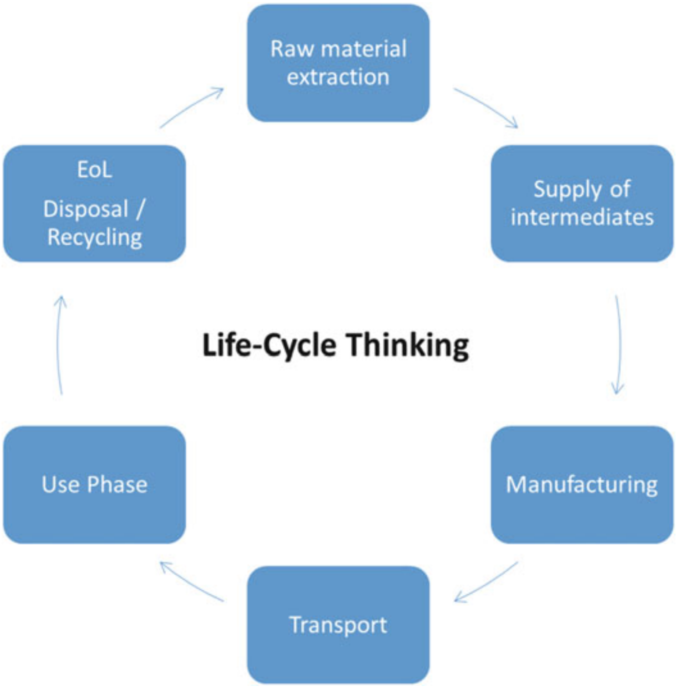

Fig. 8.17 The concept of life-cycle thinking

that improvement has negative consequences for other parts of the system which may outweigh the advantages achieved.

- The assessment of the "true" costs of a product. These include environmental and social costs in addition to production costs.
- The identification of "hot spots" in the environmental, social or economic performance of the life cycle or value chain of a biobased product, and starting points for improvement.
- The identification of "future" problems (negative impacts that will become apparent in the future, for example global warming effects) and ways of avoiding transferring such problems into the future.

Life Cycle

The life cycle of a product comprises all steps of a production process, from raw material extraction, through supply of intermediates, manufacture, transport and use phase, to the End-of-Life (EoL) of the product, which can be disposal and/or recycling (i.e. from "cradle to grave"). It includes all stakeholder interactions in each of the above steps.

This understanding of a life cycle is different from the product life cycle in economics, which refers to the life cycle of products on the market.

The difference between 'value chain' and 'life cycle' is that 'value chain' does not necessarily include the life cycle stages product use and End-of-Life (EoL); often it just refers to the production of a product.

Following a life-cycle approach in bioeconomic sustainability assessment enables an understanding of the system behind the production and supply of biobased products and services. A biobased value chain is the sequence of processes from biomass production through to manufacture of the biobased product, together with its opportunities for value generation, including economic, social and environmental values (see Sect. 5.2). An integrated biobased value chain optimizes the interaction of these processes and the material flows involved, with the objective of enhancing the overall performance in economic, environmental, social and thus sustainability terms (Lewandowski 2015). As can be seen for the case of bioenergy, a value chain can only perform sustainably if all processes involved are sustainable. A biofuel, for example, cannot be considered sustainable if its use contributes to the reduction of GHG emissions (by substituting a fossil reference) but its feedstock supply (biomass production) does not comply with rules for sustainable agricultural production (see Sect. 6.1.11).

A sustainability assessment performed for the whole value chain—also described as "along the life cycle"—can evaluate the overall performance of a biobased product or service, and at the same time identify "hot spots" of low or non-performance. This is true for ex-ante assessments as well as for the analysis of existing bioeconomic activities. In the latter case, a sustainability assessment can steer the optimization process.

8.3.2 Methodology for Sustainability Assessment

The combination of Life-Cycle Assessment (LCA), Social Life-Cycle Assessment (sLCA) and Life-Cycle Cost Assessment (LCC) is seen as the most advanced and comprehensive approach to sustainability assessment. All of these three methods embrace Life-Cycle Thinking and together they cover the three dimensions of sustainability. Here, the methods LCA, sLCA and LCC are first described, and then the case study of ethanol production from miscanthus and sugar cane is presented to show how these three methods can be combined to form an overall Life-Cycle Sustainability Assessment (LCSA). In this context, the term "product" is used in the broad sense of goods and services.

8.3.2.1 Life-Cycle Assessment (LCA)

Life-Cycle Assessment, most commonly referred to as LCA, is a standardised (ISO 14040 and 14044) method of assessing the potential environmental impacts of products, processes and services in relation to a 'functional unit'. The basic approaches underlying LCA are Life-Cycle Thinking and the aggregation of environmental interventions into impact categories.

Functional Unit and Reference Flow

According to ISO 14040, the *Functional Unit* (FU) is the "quantified performance of a product system for use as a reference unit" (ISO 14040 2006, p. 10). The results of all impact categories can be related to this reference unit. In the case of energy-producing systems, such as bioethanol production, it could be, for example, 1 GJ. This enables a comparison with other bioenergy sources or with a fossil reference.

The *Reference Flow* is the output from processes in a given product system that is necessary to fulfil the function expressed by the FU. So, with a FU of for example 1 GJ, the reference flow (e.g. in litres) is higher for bioethanol than for fossil gasoline, because the energy content of bioethanol is lower.

In LCA, emissions, use of energy and resources, and material streams are assessed for all defined process steps or modules along the whole life cycle of a product. In the following sections, the life cycle of bioethanol from miscanthus (a perennial C4 grass, for more information see Lewandowski et al. 2016) is used as an example. The process tree for this example is shown in Figs. 8.18 and 8.19 and concrete examples of process modules are "soil preparation" and "planting and establishment" for the process of biomass production, and "shredding" and "pre-treatment" for the process of biomass conversion to ethanol. Material streams are shown as inputs (e.g. "fertilizer") or outputs

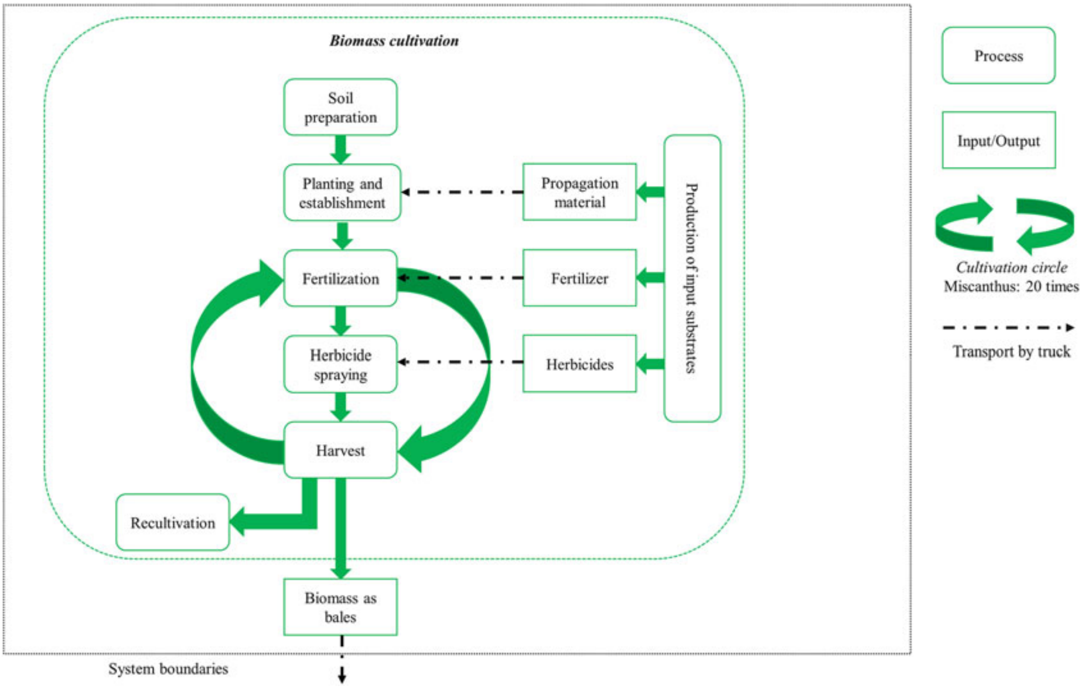

Fig. 8.18 Life-cycle description and system boundaries for miscanthus biomass cultivation

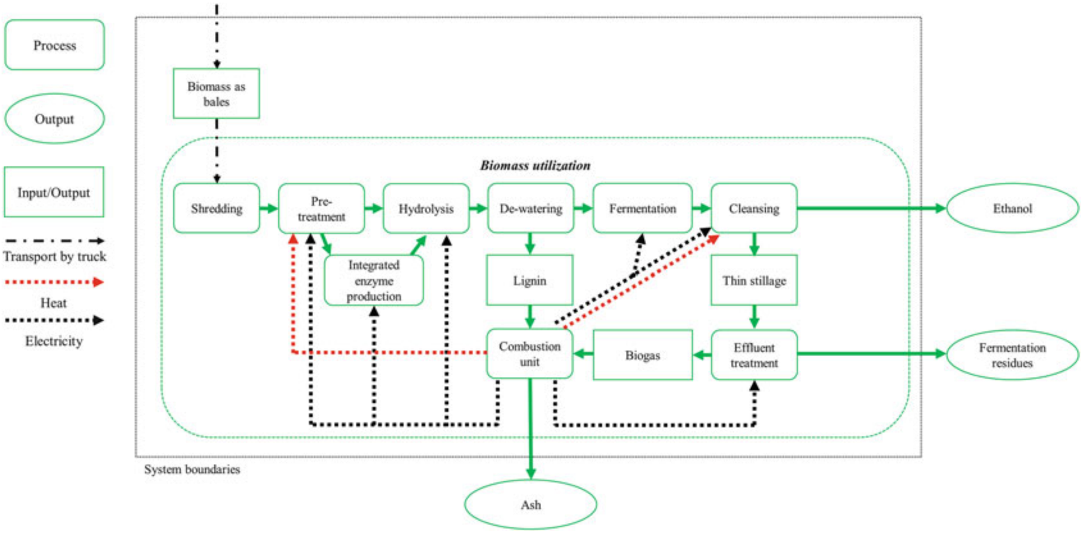

Fig. 8.19 Life-cycle description and system boundaries for the conversion of miscanthus biomass to ethanol

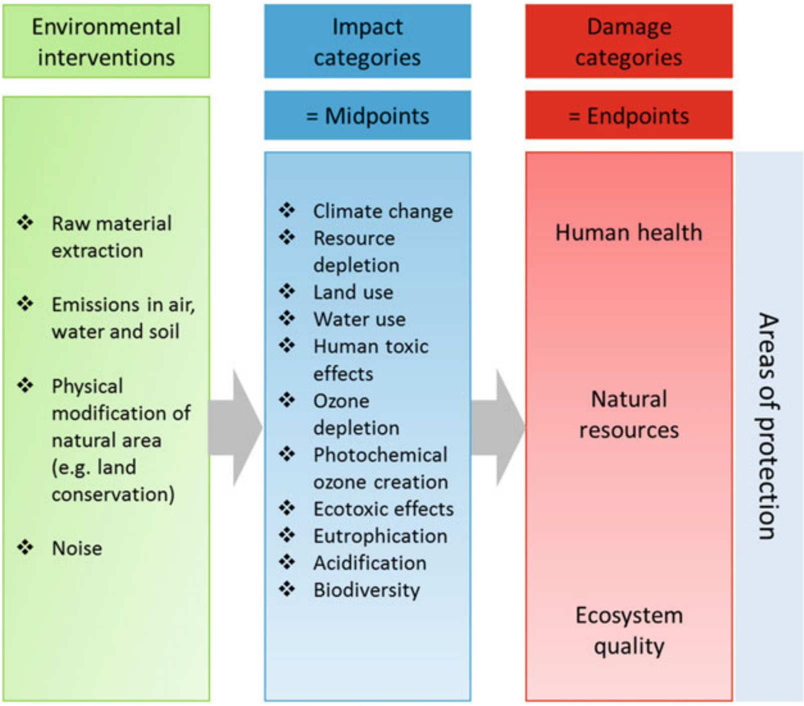

Fig. 8.20 Overall framework linking environmental interventions via the midpoint categories to damage categories (adapted from Jolliet et al. 2003)

(e.g. "ethanol") (see Figs. 8.18 and 8.19). Emissions, such as GHGs, are an output from process modules. At the beginning of an LCA study, the so-called "system boundaries" of a life cycle are defined (see Figs. 8.18 and 8.19). These should include not only the production process modules, but also the treatment and recycling of wastes and side streams (see Figs. 8.18 and 8.19). If the defined system also includes the use phase and the End-of-Life (EoL) of the product, we refer to this as a "cradle-to-grave" analysis. It is also possible to perform a so-called "cradle-to-gate" analysis. In the example chosen here, this would encompass the biomass cultivation process modules up to the farm gate only, including crop production, harvest and transport from field to farm.

Figure 8.20 shows the aggregation of environmental interventions (e.g. emissions, material streams) into midpoint categories (also called impact categories) and endpoint categories (also called damage categories). The approach for aggregating environmental interventions is comparable for midpoint and endpoint categories. Here this aggregation, which consists of three mandatory steps, is explained using the impact category "climate change" as an example. You can find a more in-depth explanation in the ISO 14044 standard.

Category Indicator and Characterisation Model

According to ISO 14040, the category indicator is the "quantifiable representative of an impact category".

The characterization model describes the relationship between the Life-Cycle Inventory (LCI) results (the environmental intervention) and the category indicator. An example of a characterization model is the GWP_{100}.

GWP_{100}: Potential contribution of a greenhouse gas to the heating of the atmosphere over a 100-year time horizon. The global warming potential (GWP) measures how much energy the emissions of a gas absorbs relative to the emissions of the same amount of carbon dioxide (CO_2).

In the *first* step, the impact category to be analysed (here *climate change*) is chosen. For this impact category, the corresponding category indicator is *infrared radiative forcing* and the characterisation model is *GWP100*. In the *second* step, relevant environmental impacts (or environmental interventions) are assigned to this impact category. An example of an environmental impact of miscanthus cultivation (see Fig. 8.18), which is assigned to the impact category "climate change" is GHG emissions (e.g. CO_2, CH_4 and N_2O). These are mainly caused by the production and application of nitrogen fertilizer. All these GHGs impact the climate and lead to global warming. However, the extent to which they influence the climate varies significantly. For each GHG, there is a characterization factor, which expresses its global warming potential in kg CO_2-equivalents/kg gas based on the characterisation model. For example, N_2O is a much more potent GHG than CO_2. It has a characterization factor of 265, which means that 1 kg N_2O has a global warming potential of 265 kg CO_2-equivalents. This is taken into account in the *third* step, the calculation of the results for this impact category.

The impact category "climate change" belongs to the so-called "midpoint categories". These indicate environmental problems that lie along the environmental mechanism, at an intermediate point between the environmental interventions and the final damage to the area of protection (see Fig. 8.20). An environmental mechanism is defined in ISO 14044 (2006) as a:

> System of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis results to category indicators and to category endpoints (ISO 14040 2006, p. 12).

Midpoint categories quantify, for example, the amount of CO_2 equivalents emitted, but they do not give any information on the effect on the damage category. In our example, this could be the effect of species extinction caused by global warming on the damage category "ecosystem quality". Thus the endpoint categories (damage categories) represent the area of protection affected by the environmental intervention.

One weakness of current LCA approaches is that not all relevant environmental impacts can yet be described by impact categories. This is especially true for impacts on biodiversity and soil quality, both of which are relevant for biomass production. Section 9.3.3 presents approaches on how land use and biodiversity aspects can be integrated into LCA.

The choice of impact categories included in an LCA is not standardised. Climate change and resource depletion are most commonly chosen. However, for biomass production and utilization, relevant potential ecological impacts also include land and water use, marine ecotoxicity, human toxicity and freshwater eutrophication (Wagner et al. 2017). Therefore, it is recommended that those impact categories should be chosen for which relevant impacts are anticipated in the biobased value chain under analysis (Wagner et al. 2017).

An LCA is performed in the following steps:

1. Definition of goal and scope
   Specification of the objective of the study as well as intended application and audience, setting of system boundaries, choice of impact categories to be considered.
2. Life-Cycle Inventory (LCI)
   Data acquisition and derivation of assumptions underlying the study.
3. Life-Cycle Impact Assessment (LCIA)
   Calculating the potential ecological impact according to chosen impact categories.
4. Interpretation
   Description and interpretation of results, development of conclusions and recommendations.

The objectives of an LCA (step 1) can be manifold and include, among others:

- The assessment and quantification of the potential environmental impact of a product or service for one or more environmental impact categories,

- The identification of environmental hot spots in a production process or unit,
- The quantification of environmental trade-offs,
- The provision of decision support for the environmental improvement of a production process or unit,
- The development of a database for customer information and "green" marketing strategies.

The practical performance of an LCA study can be supported by calculation programs, such as Excel, or professional LCA programs, such as GaBi (www.gabi-software.com), SimaPro (www.pre.nl/simapro/default.htm) and Umberto (https://www.ifu.com/umberto/). One example of a licence-free, open-access LCA program, which is very simple to use, is CCalc2 (http://www.ccalc.org.uk/ccalc2.php). However, this program only covers selected impact categories and is limited in its utilization possibilities. An example of an open-access LCA software with features comparable to those of professional programs is openLCA (http://www.openlca.org/). The major benefit of using LCA programs is that they offer structured data processing and performance of the impact assessment step. Users can back these up with their own data banks for the inventory analysis. LCA data can also be accessed from commercial databases, such as ecoinvent (www.ecoinvent.ch), or open-access databases, such as the ELCD database (http://eplca.jrc.ec.europa.eu/ELCD3/), the NEEDS Life Cycle Inventory database (http://www.needs-project.org/needswebdb/) and ProBas (www.probas.umweltbundesamt.de) from the German Umweltbundesamt.

8.3.2.2 Life-Cycle Costing (LCC)

Life-cycle costing, abbreviated to LCC in the following sections, is the economic equivalent of LCA. "Environmental" LCC was actually developed as an economic counterpart to LCA and sLCA. LCC summarizes all costs of the physical life cycle of a product or service that are borne by one or more of the parties involved in the life cycle (e.g. farmers, producers, consumers/users). This is different from conventional cost accounting in that "true" costs are assessed, including costs of waste removal and recycling, and "hidden" costs, such as for environmental protection and financial risks. These are then clearly attributed to a particular product system. This allows the costs of environmental intervention to be assessed (Swarr et al. 2011).

Overall, LCC can serve as a tool:

- To understand the cost drivers of a product system,
- To gain a realistic evaluation of costs beyond production prices,
- To perform a trade-off evaluation (such as price-versus-disposal costs),
- To assess "ignored costs" or externalities,
- To identify options for improvement,
- To validate pricing strategies,
- For decision support.

In order to avoid double accounting with LCA, the costs assessed in "environmental" LCC must relate to real money flows and thus do not include monetarised environmental impacts (Swarr et al. 2011). That means, if for example CO_2 emissions are quantified in the LCA, they should not be priced in the LCC for instance in form of costs of CO_2 certificates. In LCA, environmental impacts are quantified in physical units (e.g. kg CO_2eq.); in LCC, costs are quantified in monetary units (Euro or other currencies). Besides internal also external costs are included, if these impacts are not already accounted for in the LCA or sLCA.

Internal and External Costs

Internal costs are costs for the production, use and end-of-life of a product that are paid by an entity or stakeholder directly involved in the product system value chain.

External costs are costs that are borne by third parties outside the product system value chain (e.g. waste recovery fees, indirect health costs) (Swarr et al. 2011).

LCC adopts the structure given in ISO 14040 for LCA. It also uses corresponding product system boundaries, a functional unit and defines indicators that are quantifiable, measurable and monitorable. But in LCC, the only unit of measurement is the currency. For this reason, the life-cycle impact assessment stage is not included and so LCC only consists of the three steps: (1) Definition of goal and scope, (2) Inventory analysis and (3) Interpretation. There is no impact assessment, because the aggregated data provide a direct measure of impact.

Through LCC, the cost assessment can be performed from the different perspectives of multiple agents along the life cycle. This means that, for our example of bioethanol production, the costs can be assessed from the perspective of a manufacturer of bioethanol, a consumer of bioethanol and a municipality intending to support the establishment of miscanthus production for a bioethanol plant. In practical application, LCC can support the assessment of CO_2 mitigation costs for miscanthus-based ethanol production.

8.3.2.3 Social Life-Cycle Assessment (sLCA)

Social life-cycle assessment, abbreviated here to sLCA, is the social counterpart of LCA. The UNEP/SETAC Life Cycle Initiative defines sLCA as a

> Social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle (Benoıˆt and Mazijn 2009, p. 100).

It has the same structure as LCA with the steps (1) Definition of goal and scope, (2) Inventory analysis, (3) Impact Assessment and (4) Interpretation. It also follows the life-cycle approach, but with significant differences to LCA as no standards comparable to ISO 14040/44 have been established and the social impact categories in sLCA are less well developed than the environmental impact categories of LCA.

Social aspects assessed in sLCA are the consequences of positive or negative pressures on social endpoints (e.g. well-being of stakeholders). These social endpoints are comparable to damage categories in LCA. The social aspects assessed are generally related to: (1) the behaviour (e.g. decision taking), (2) socio-economic processes (downstream effects of socio-economic decisions), or (3) impacts on human, social or cultural capital (Benoıˆt and Mazijn 2009). In sLCA, sub-categories are defined as socially significant themes or attributes. Two complementary sub-category classification schemes have been proposed: classification according to stakeholder and classification according to social impact pathway. These lead to two methods of categorising social impact categories (Benoıˆt and Mazijn 2009):

1. Classification of social impact categories according to the stakeholder affected e.g. worker, consumer, local community, society, value chain actors not including consumers (see Table 8.1). The indicator results of the sub-category are aggregated into impact categories. However, there are no characterization models available for this that are generally accepted by sLCA practitioners.
2. Classification of social impact categories according to the social impact pathway, e.g. human rights, working conditions, health and safety (see Fig. 8.21).

Results can be aggregated over the life cycle, for example 75% of the life cycle of a certain product are free from child labour.

At each geographical location in the value chain, the social and socio-economic inputs may be performed by five main stakeholder groups: workers, local communities, society (national to global), consumers and value chain actors (see Table 8.1).

> A stakeholder category is a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product system (Benoıˆt and Mazijn 2009, p. 101).

Table 8.1 shows sub-categories for the different stakeholder groups. These sub-categories are assessed through the use of inventory indicators,

Table 8.1 Classification of social impact categories according to the stakeholder affected (Benoıt̂ and Mazijn 2009)

Stakeholder categories	Sub-categories
Worker	Freedom of association and collective bargaining
	Child labour
	Fair salary
	Working hours
	Forced labour
	Equal opportunities/ discrimination
	Health and Safety
	Social benefits/social security
Consumer	Health and Safety
	Feedback mechanism
	Consumer privacy
	Transparency
	End-of-life responsibility
Local community	Access to material resources
	Access to immaterial resources
	Delocalization and migration
	Cultural heritage
	Safe and healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
	Secure living conditions
Society	Public commitments to sustainability issues
	Contribution to economic development
	Prevention and mitigation of armed conflicts
	Technology development
	Corruption
Value chain actors not including consumers	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

which can be either quantitative or qualitative. An example of an inventory indicator for the stakeholder "worker" in the sub-category "*Freedom of association and collective bargaining*" could be evidence that this freedom is restricted. You can find more detailed information on the sub-categories and their inventory indicators in the puplication "*The methodological sheets for subcategories in social life cycle assessment (s-lca)*" (see further reading).

The identification and selection of subcategories for a planned sLCA should be performed in consultation with the stakeholders.

8.3.2.4 Life-Cycle Sustainability Assessment (LCSA)

The aggregation of LCA, LCC and sLCA into an LCSA reveals any trade-offs between the three pillars of sustainability.

The conditions for an LCSA are:

- The use of consistent system boundaries for all three assessments,
- The assessment is based on the physical (not marketing!) life cycle of a product, i.e. a cradle-to-grave approach,
- The use of compatible inventory approaches for all three assessments.

The first step in an LCSA is the choice of appropriate functional unit. According to Benoıt̂ and Mazijn (2009), the following steps are required to define the functional unit:

- Description of the product by its properties, including its social utility (which encompasses various social functions for the consumer such as convenience and prestige);
- Determination of the relevant market segment;
- Determination of relevant product alternatives;
- Definition and quantification of the functional unit, in terms of the obligatory product properties required by the relevant market segment;
- Determination of the reference flow for each product system.

8.3.2.5 Case Study LCSA

This section describes how an LCSA of ethanol production for the European market, based either on European miscanthus production or Brazilian sugar cane production, could be approached.

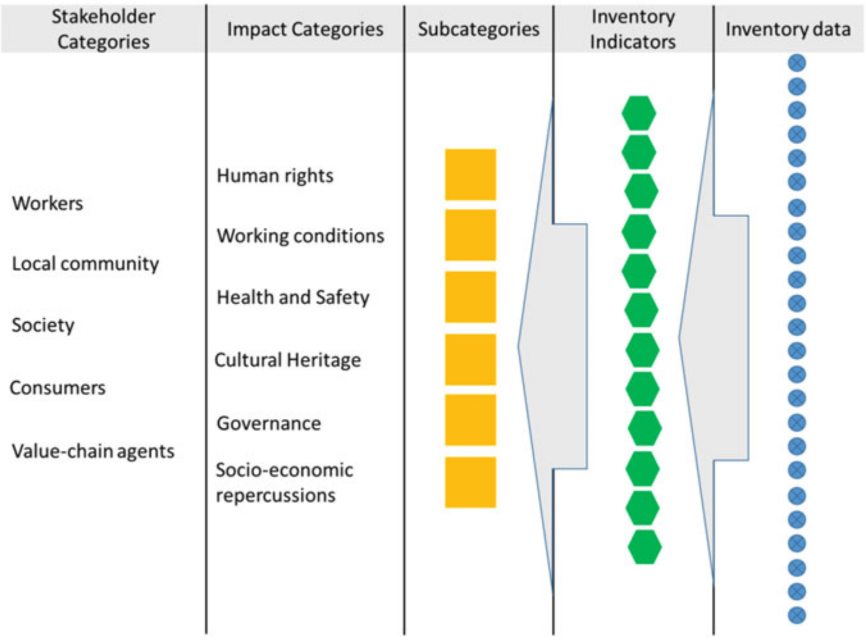

Fig. 8.21 Classification of social impact categories according to the social impact pathway (Benoit̂ and Mazijn 2009)

Definition of Goal and Scope

The goal of the study is to assess the sustainability of ethanol-based biofuels from various production options. The assumption is that, from an environmental, social and economic point of view, ethanol-based biofuel is more sustainable than the fossil reference gasoline. Although Brazilian sugar cane ethanol is state of the art and an economically viable option, ethanol produced regionally from lignocellulosic biomass derived from perennial non-food crops is perceived to be a more sustainable alternative for the European market.

The function we are looking for here is the supply of energy in the form of transportation fuel. Therefore, the functional unit chosen is 1 GJ (ethanol or gasoline).

The system boundaries for our analysis encompass: cultivation of the biomass including production of input substrates, transport of the biomass to the conversion plant, conversion into ethanol, transport of the ethanol to the end user/customer, and final use. The major differences between the production systems of ethanol from miscanthus and ethanol from sugar cane are: (a) the location of the biomass production (miscanthus in Europe, sugar cane in Brazil); (b) the form of transport as well as the transport distance; and (c) the conversion technology. The largest transport distance in the miscanthus chain is the transport of bales from the farm to the ethanol plant (<100 km). By contrast, sugar mills with integrated ethanol plants are located directly by the sugar cane fields, because sugar cane biomass needs to be processed immediately. The largest transport distance for sugar cane ethanol is that of the intercontinental shipping from Brazil to Europe (>8000 km), which occurs after the ethanol has been brought from the sugar mill to the harbour (<100 km). The conversion of polysaccharides into ethanol requires energy. In the case of a sugar cane ethanol plant, this can be fully supplied from the bagasse, which can even provide excess electricity. The conversion of lignocellulosic biomass from miscanthus into ethanol requires several pre-treatment steps, including the use of enzymes, and is thus very energy-intensive (Gilpin and Andrae 2017).

The environmental impact categories most relevant for perennial crop-based value chains are, among others: climate change, fossil fuel depletion, eutrophication and acidification (Wagner et al. 2017). These were therefore chosen for the LCA.

As working conditions in sugar cane plantations are often reported to be poor, we choose "workers" as the most relevant stakeholder group for the current example and included them in all sub-categories listed in Table 8.1. However, when analysing the impacts of biobased value chains, also other stakeholder categories, such as the "local community", could be affected and should be considered.

For the LCC, all direct costs, including labour, material, energy and transport costs, were assessed.

Inventory Analysis

Figure 8.22 shows the midpoint and endpoint categories chosen for our ethanol case study. The data inventory can be performed through a literature search, from online databases (e.g. ILO for labour conditions) or commercially available databases (ecoinvent for life-cycle data on material and energy flows), from company and/or government online resources, and from measurements and stakeholder interviews.

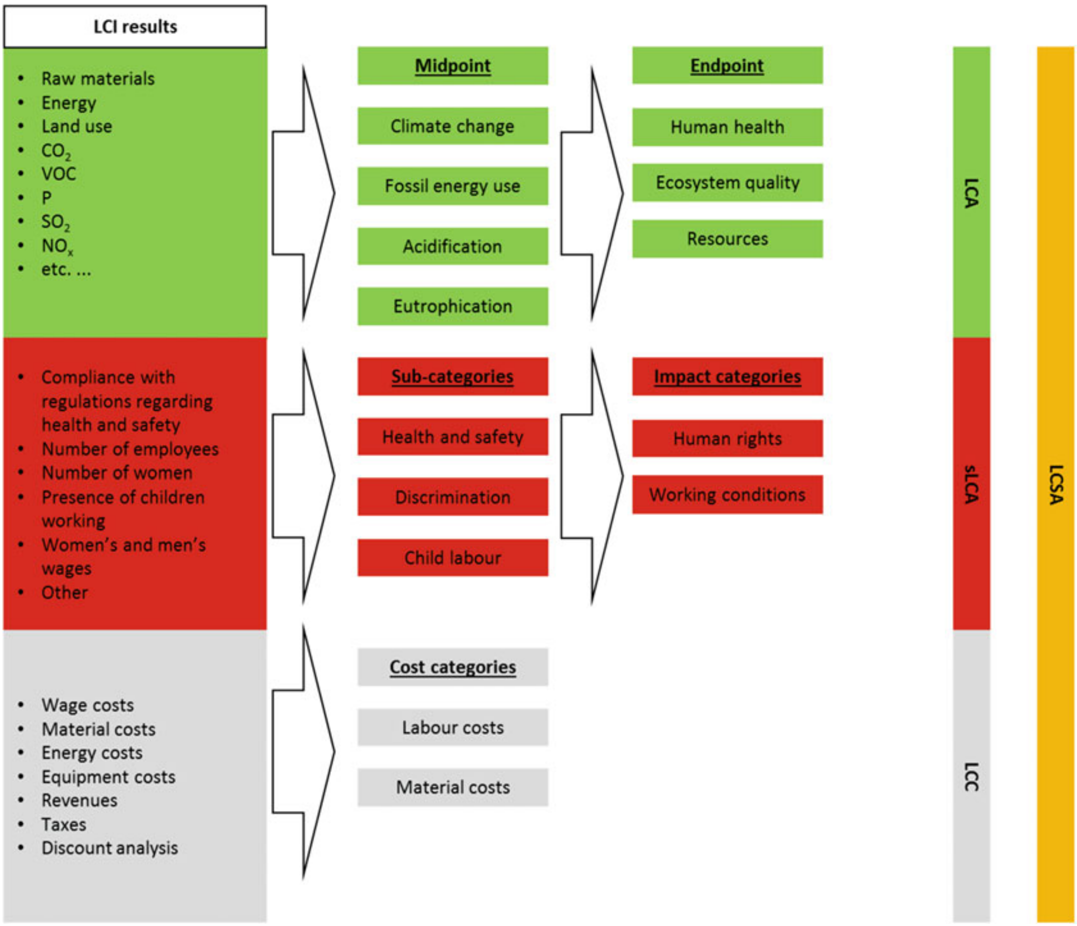

Fig. 8.22 Midpoint and endpoint categories, sub-categories of stakeholders and cost categories assessed in the case-study LCSA on bioethanol (adapted from Valdivia et al. 2011)

Stakeholder interviews for data acquisition require the most effort, involving travel and performance of the interviews, both of which are time-consuming. The assessment of data for the production of ethanol from miscanthus is challenging, because this value chain has not yet been implemented and the conversion technology is still at the R&D stage. For this reason, many assumptions have to be made in the LCI of this chain. For the LCA, environmental and impact assessment data for ethanol produced from miscanthus were based on the authors' own calculations (unpublished). The environmental data for sugar cane-based ethanol production were taken from Muñoz et al. (2014) and Seabra et al. (2011). For the sLCA and the LCC, no data were acquired; instead best guesses were used.

The reference values for gasoline were taken from the ecoinvent database (Weidema et al. 2013).

Impact Assessment

Figure 8.23 shows a high-level summarised approach for the qualitative presentation of the (hypothetical) results of the LCSA. The results were ranked in relation to the alternatives. That means, of the three systems (miscanthus-based ethanol, sugar cane-based ethanol and gasoline) the one with the lowest impact is shown in green and the one with the highest impact in red. As mentioned above, the LCA data stem from the literature (Muñoz et al. 2014; Seabra et al. 2011), but no real data were available for the LCC and sLCA, and therefore the cost and social impact information given in Fig. 8.23 is hypothetical. It is included here to show how LCA, LCC and sLCA can be integrated into an LCSA.

Interpretation

Miscanthus-based ethanol is the most beneficial alternative from a social viewpoint, because working conditions in Europe are well defined and regulated. Another positive aspect is the fact that the production of miscanthus ethanol creates new jobs in Europe. By contrast, working conditions in sugar cane plantations are poor (Rocha et al. 2010) and human rights violations can occur, such as forced or child labour. Also, wages are low and work is only available seasonally. However, this social assessment ignores the question of the need for these jobs and income opportunities in Brazil.

The overall environmental performance is best for sugar cane. The efficient recycling of nutrients, the full autonomy of energy supply through bagasse, and low fertilizer demands lead to the best environmental performance with regard to GWP and FFD, and a better performance than miscanthus with regard to EP and AP. Both biobased ethanol production pathways perform better environmentally than the fossil alternative with regard to GWP and FFD. However, they perform worse with regard to AP and EP, mainly due to fertilizer-induced emissions.

Miscanthus-based ethanol production carries the highest production costs because wages in Europe are higher and the second generation ethanol production technology is much more expensive than that for sugar crops. Anticipated transport costs for the import of sugar cane ethanol to Europe are relatively low because it is transported by ship.

Overall, miscanthus-based ethanol is to be preferred from a social point of view and sugar cane ethanol from an environmental point of view (for those impact categories considered in the LCSA).

Here, the results are only demonstrated qualitatively. When conducting an LCSA, quantitative data are used for all impact categories to quantify the relative performance and trade-offs between the product pathways.

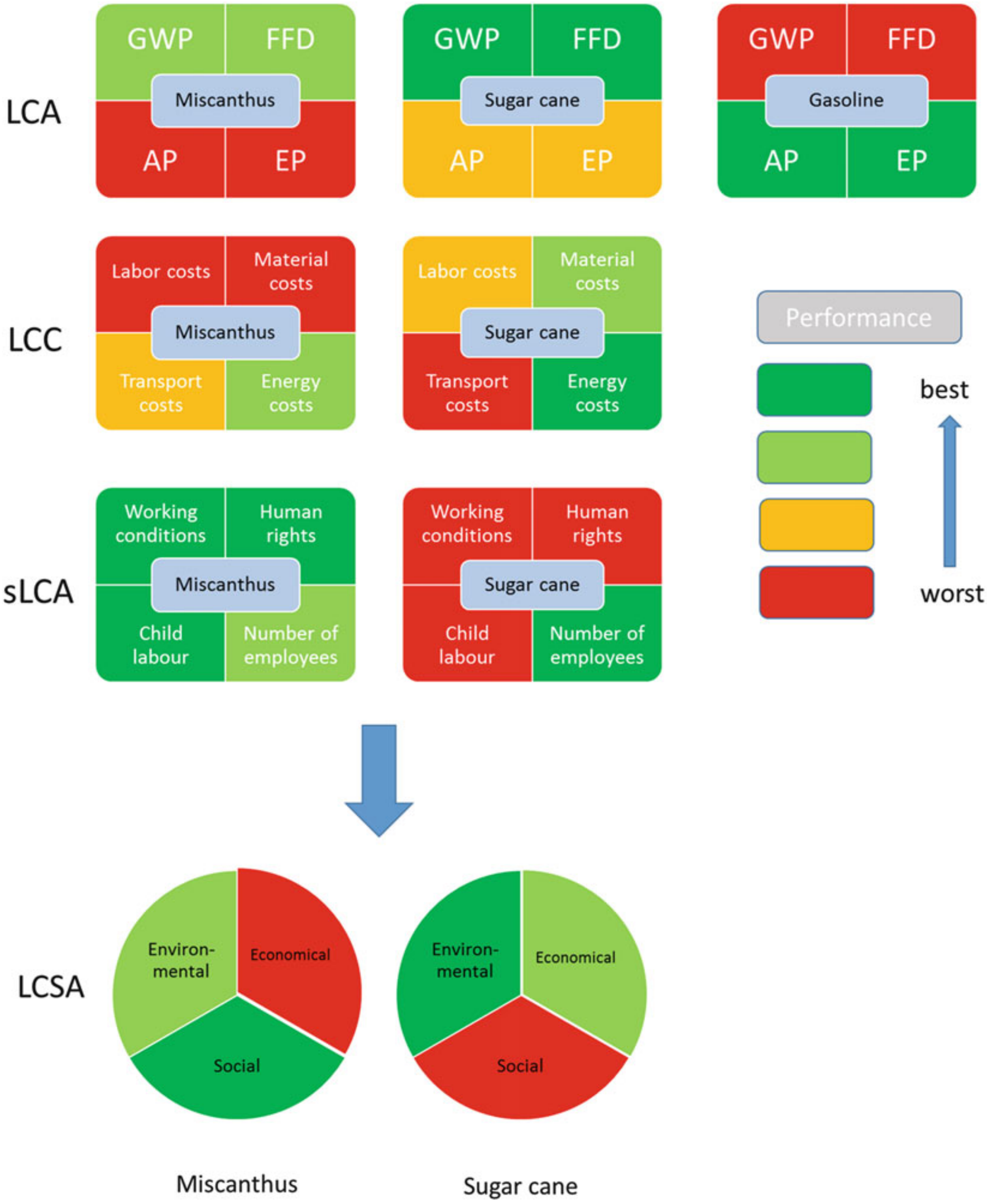

Fig. 8.23 Comparative results for the LCA, LCC and sLCA assessment and its compilation into an LCSA; performed for ethanol production from miscanthus and sugar cane. Results for the LCA were taken from Muñoz et al. (2014) and Seabra et al. (2011). Results for the LCC and sLCA are hypothetical. *GWP* Global Warming Potential, *FFD* Fossil Fuel Depletion, *AP* Acidification Potential, *EP* Eutrophication Potential

Review Questions and References

- What are the purposes and goals of system and value-chain/life-cycle assessments in the bioeconomy
- What is Life-Cycle Sustainability Assessment (LCSA)?
- What are the conditions and methodological steps for the performance of a consistent LCSA?
- What can the results of an LCSA be used for and by whom?

Further Reading

Baumann H, Tillman AM (2004) The Hitch Hiker's guide to LCA: an orientation in life cycle assessment methodology and applications. Studentlitteratur, Lund

Benoît Norris C, Traverso M et al (2009) The methodological sheets for subcategories in social life cycle assessment (s-lca). Available on: http://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf

8.4 Entrepreneurial Ventures and the Bioeconomy

Andreas Kuckertz, Elisabeth S.C. Berger, and
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Starting up and growing © Singkham/Fotolia

Abstract Entrepreneurship is based on entrepreneurial opportunities and the bioeconomy offers a plethora of such opportunities. As the bioeconomy—at least partially—addresses humanity's greatest challenges, it consequently offers the greatest entrepreneurial opportunities as well. One useful tool to break down the idea generation process and manage the entrepreneurial process is the business model canvas, which makes it possible to clearly describe the value proposition of a new venture in the bioeconomy. The lean start-up approach can help entrepreneurs in the bioeconomy to move efficiently through the entrepreneurial process and to quickly develop a value proposition and a validated business model.

Keywords Entrepreneurial opportunity; Business model; Start-up process

Learning Objectives
After studying this chapter, you will be able to:

- Understand the challenges the bioeconomy faces and to be able to interpret them as entrepreneurial opportunities.
- Know the key tools that entrepreneurs in the bioeconomy can use to manage the start-up process.
- Get an initial idea of the first steps necessary to become an entrepreneur in the bioeconomy.

8.4.1 Entrepreneurial Opportunities and the Bioeconomy

Humans being conscious of their footprint on this planet is not a novelty. More than 40 years ago the Club of Rome (Meadows et al. 1972)

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introduced the world to different model-based scenarios that illustrated the limits of economic growth, which directly correlate with the finite natural resources of planet earth. Despite significant public awareness, those same issues remain pressing and relevant. The bioeconomy addresses these challenges, but the transition to it will not happen overnight.

Government interventions might be one solution, but private initiative from entrepreneurs has promising potential too (Kuckertz and Wagner 2010). Providing business solutions to accomplish the switch from our current fossil fuel based economy is the main task of entrepreneurs in the bioeconomy. Entrepreneurs are likely to provide valid answers to questions like how we might produce more with less and how we can secure more high quality food, more energy, and more social stability with fewer resources, less space, less water, less energy, and less risk.

Addressing those challenges with a meaning in mind and not with a given fixed set of objectives and resources is an ongoing process, in which entrepreneurs use their existing networks to accomplish targets that will eventually lead to newly established companies addressing the challenges of the bioeconomy. This is not just an altruistic mindset but also the starting point for a business opportunity in areas such as energy, food security and resource efficiency.

There are several barriers hindering the development of the bioeconomy. Companies and individuals might be aware of the threats to planet earth, but at the same time business practices today often do not value, for instance, free natural assets. Therefore, natural assets are especially prone to abuse by society and individuals (Dorfman 1993). Governments might provide funds and support to reduce this market failure. However, at the same time this market failure with an environmental impact provides grounds for many entrepreneurial opportunities in the bioeconomy.

Entrepreneurial Opportunity
The opportunity to establish a new firm which in the bioeconomy often results from market failure. Huge market failures provide huge opportunities for entrepreneurs to establish new ventures that create value by addressing the challenges facing humanity.

If the market failure creates a problem, an individual can engage in entrepreneurial activity and generate profit by discovering the opportunity to provide a solution, evaluating the opportunity, and ultimately exploiting it by providing the solution (Shane and Venkataraman 2000; Dean and McMullen 2007). When providing such bioeconomic solutions, entrepreneurs contribute to the mitigation of the market failure and hence to the development towards the bioeconomy. The Visioverdis case study is a perfect example of the tremendous creativity that entrepreneurs can apply to address the huge challenges of the bioeconomy.

Box 8.3 Case Study Visioverdis: The GraviPlant

Alina Schick, a biologist with expertise in botany with focus on plant physiology who received her PhD in agricultural sciences from the University of Hohenheim in Germany, has been wondering about one of those big challenges for society. More specifically, Alina has been asking herself: How should the cities of the future be designed? If population density concentrates in metropolitan areas, how can air pollution be minimised? Pollution concentration in major cities also brings two major side

(continued)

Fig. 8.24 The GraviPlant ©Alàbiso/Visioverdis

Box 8.3 (continued)

effects: Green areas tend to disappear and land prices increase exponentially making it almost impossible to have parks in the city or to maintain existing green areas.

Alina's start-up called Visioverdis (Visioverdis 2017) solves this problem with the GraviPlant, a tree that can be installed on building facades and grows perpendicular to the wall (see Fig. 8.24). The idea is based on Alina's doctoral studies during which she managed to grow trees horizontally by rotating them in their own axis and giving them precise doses of water and nutrients (Clinostat). After testing different types of trees and building the first prototype she proved the existence of a business opportunity for her research by participating in and winning several start-up idea competitions. In 2017, Visioverdis managed to acquire a contract to integrate trees into the facade of the building designed for the world show that celebrates the 500th anniversary of the protestant reformation in Wittenberg, which offers an opportunity to present the idea to a global audience.

The tree rests in a sealed container with a high-tech plant care system. The container is just docked to a water pipe and the tree grows fully independently, requiring no maintenance for a four-year period. Currently available solutions (like vertical planting systems or creeper plants) in contrast require constant maintenance to prevent damage to the building's infrastructure. Visioverdis' goal is not only to conquer the European market, but also to unleash the potential of the GraviPlant in countries that currently suffer from severe air pollution and drought such as China and Saudi Arabia.

What exactly constitutes an entrepreneurial opportunity has been debated in the academic literature for quite some time (Kuckertz et al. 2017). There seems to be consensus that the process of recognising entrepreneurial opportunities involves being alert, actively searching for them, and gathering information about new ideas on products or services. Economic theory (Schumpeter 1934; Kirzner 1973; Drucker 1984) suggests that entrepreneurs should particularly look for four different types of trends and developments, as these are likely to trigger entrepreneurial opportunities. These are:

- Information asymmetries and incongruences
- Exogenous shocks
- Changes in demand
- Changes in supply

For instance, it appears obviously incongruent that each year eight million people die of hunger caused by scarcity of water and agricultural land (Conforti 2011), whereas at the same time in the developed world "redundant" food is being destroyed. Resolving such incongruity constitutes an opportunity for bioeconomy entrepreneurs. Similarly, climate change [or other earth system processes that are in danger (Rockström et al. 2009)] could be interpreted as exogenous shocks that are likely to be addressed with new technologies brought to the market by innovative entrepreneurs. In a similar vein, such exogenous shocks can prompt changes on the demand side: End consumers now tend to want ethical, green, and sustainable products and services, and entrepreneurs can cater for such desires with new offerings.

Given the sometimes enormous failure rates of entrepreneurial ventures, entrepreneurs need to assess whether a particular opportunity has the potential to be turned into a profitable business. There is obviously no way to do so in an objective and completely reliable manner, however, to assess whether an entrepreneurial opportunity is interesting, it may help to think about these opportunities as a professional investor would. That investor might be a venture capital firm (Kollmann and Kuckertz 2010) or a unit investing in promising start-ups on behalf of a larger corporation (Roehm et al. 2017). Such investors would look for opportunities:

- Where entrepreneurs can create significant value for customers or users
- Where the opportunity matches the experience and competence of the entrepreneur or the venture team
- Where an important problem is addressed or needs will be met for which customers are willing to pay a significant premium
- Where they can be active in a large and growing market
- Where there is a balance of risk and potential

The potential to become entrepreneurially active in the bioeconomy is therefore enormous, as an equilibrium of natural sources and an ideal bioeconomy is unfortunately not yet in sight. The potential is also reflected by the current estimated value of the bioeconomy exceeding two trillion euros and employing 22 million people in Europe (agriculture, forestry, fisheries, food, and chemicals) (European Commission 2012). Each euro invested in the bioeconomy is estimated to generate 10 € of added value by 2025. This is fertile ground for entrepreneurial activity.

8.4.2 Managing the Start-Up Process in the Bioeconomy

In general, entrepreneurship deals with the question of how individuals effectively organise any growth-oriented creation process on the basis of opportunity (Kuckertz and Mandl 2016). Having an idea of what product or service in the bioeconomy customers could benefit from is thus often the first step towards exploiting such an entrepreneurial opportunity and founding a start-up (Kuckertz et al. 2017). However, traditional market research instruments often fail to assess the potential of a product or service, which does not yet even exist. The only way to find out is to develop and test the product early.

Business Model
Explains the key components of a business and how they relate to each other in order to create value.

A popular approach to become entrepreneurially active is the lean start-up method, which describes founding a business in a very lean and resource-conscious manner. It stands in opposition to more traditional approaches of managing the start-up process that usually include writing a detailed business plan and approaching the market only when a close-to-perfect offering has been developed. The lean start-up method is related to the Japanese car manufacturer Toyota's lean manufacturing, an approach seeking to eliminate as much waste as possible from production processes (Womack and Jones 1996). Similarly, the lean start-up method seeks to eliminate as much unnecessary effort as possible from start-up processes.

Eric Ries (2011) is credited with applying lean principles to founding start-ups. The lean start-up method is an iterative and agile method to develop a start-up based on listening to the needs of potential customers and testing their willingness to pay for the service or product offered by the start-up. During the process, the focal question is whether the product or service solves a real problem from real customers and whether a valid business model can be developed. Instead of planning far into the future, the aim is to learn by doing, and by introducing the product or service to the market as early as possible. This naturally involves a risk of failure, but as failure never can be completely avoided, it is reasonable to embrace it as early as possible. Failure creates opportunities to learn and to try again to succeed (Blank 2013a) and thus many entrepreneurs go through many failed projects before they eventually find a valid business model (Mandl et al. 2016).

The first step of the lean start-up method involves making basic assumptions concerning possible customer requirements and the potential market. Assumptions should initially be validated by talking to and listening to potential customers. The potential failure and learning then needs to be enabled quickly by developing a so-called minimum viable product. For instance, the German start-up betula manus is currently trying to establish whether there is money making potential in tree bark, which is a waste product from the paper industry (Betula Manus 2017). To do so, betula manus is testing the market potential of tree bark with different minimum viable products in different industry segments such as bicycles and door handles.

Minimum Viable Product
Constitutes a reduced offer that is subjected to customer feedback as quickly and often as possible in order to test a start-up's hypotheses about actual market needs.

The minimum viable product represents a prototype that might be far from perfect, but which works. Once there is a minimum viable product, the build-measure-learn cycle can be initiated (Blank 2013b). The cycle aims to enable validated learning by continuously improving the minimum viable product based on customer feedback. The development of the minimum viable product towards a functioning business model might include numerous incremental changes, but might also require a pivot, that is, a more radical correction from the original idea towards a new value creation if some underlying assumptions prove invalid.

Especially in the bioeconomy with potentially highly innovative products, customers and entrepreneurs might need to discover the product's added value together in order to arrive at a functioning business model. The minimum viable product illustrated in Fig. 8.25 exemplifies the incremental change in farming tools according to the needs of the farming sector. Even the first approach to a farming tool is fully functional, but it takes several iterations to arrive at the final, smart solution. While a minimum viable product helps to test the market, it is not sufficient to build a company around it. Instead entrepreneurs need to think in terms of business models, which answer the question of what key components of the company interact to generate value for the customer and therefore provide a competitive advantage for the company.

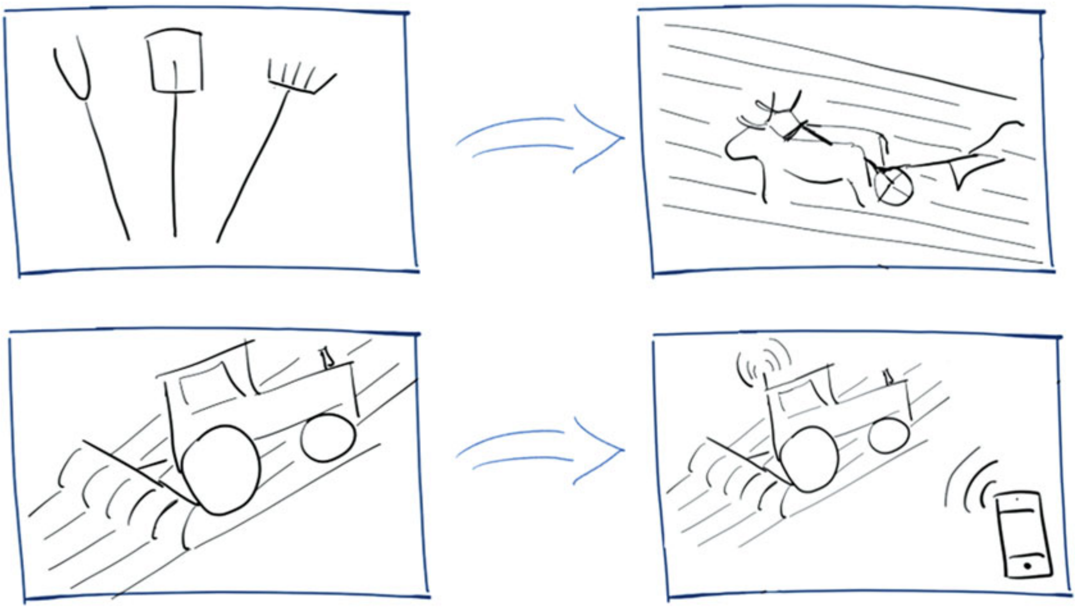
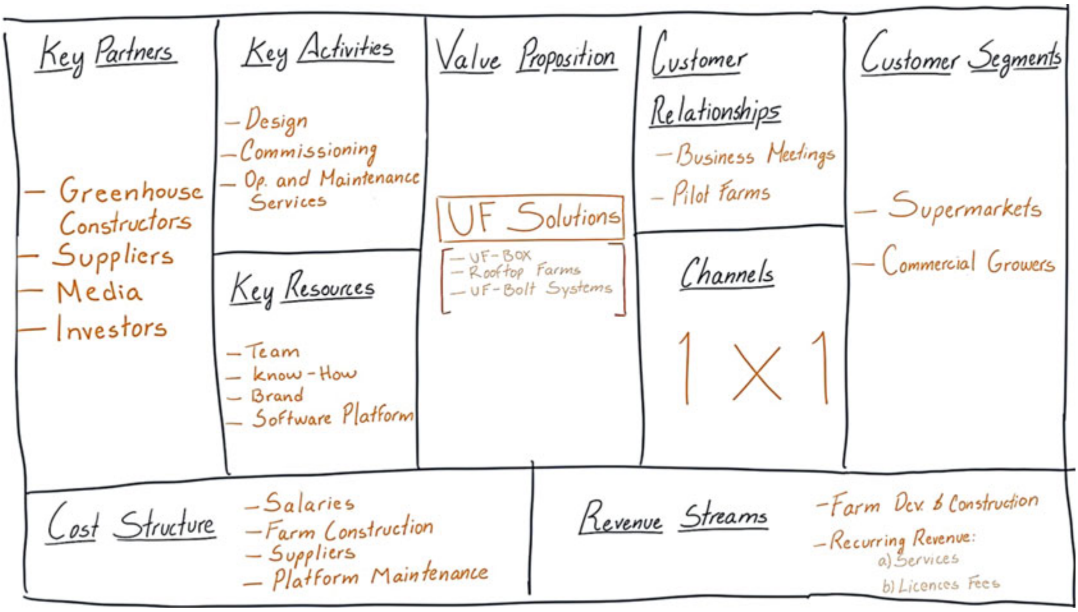


Fig. 8.25 Minimum viable product of basic farming tools developing into software-based precision agriculture



Key Partners
- Greenhouse Constructors
- Suppliers
- Media
- Investors

Key Activities
- Design
- Commissioning
- Op. and Maintenance Services

Key Resources
- Team
- know-How
- Brand
- Software Platform

Value Proposition

UF Solutions
- UF-Box
- Rooftop Farms
- UF-Bolt Systems

Customer Relationships
- Business Meetings
- Pilot Farms

Channels

1 X 1

Customer Segments
- Supermarkets
- Commercial Growers

Cost Structure
- Salaries
- Farm Construction
- Suppliers
- Platform Maintenance

Revenue Streams
- Farm Dev. & Construction
- Recurring Revenue:
  a) Services
  b) Licences Fees

Fig. 8.26 UrbanFarmers business model (Osterwalder and Pigneur 2010, applied to UrbanFarmers 2013)

The business model canvas is a powerful, iterative tool (see Fig. 8.26) to think beyond a specific idea or product and develop the business model. The canvas consists of nine distinct components that describe how an organization creates, delivers, and captures value (Osterwalder and Pigneur 2010). The business model canvas is useful to understand and visualise the interplay of the different components creating value. While it might be helpful to understand existing business models, the business model canvas is also suitable to design business model innovations, which describe novel approaches towards the design of single components and the interplay of such components.

The canvas can be compared to a theatre. The left side of the canvas represents the backstage, the creative arena of the organization, which is usually not visible to customers. The right side of the canvas represents the stage, the value part of the organization, which needs to be clear to customers. The nine components of a business model are described below on the basis of the bioeconomy start-up UrbanFarmers. This company has spent the last six years delivering a commercial scale aquaponic solution. Aquaponics is the integration of two separate established farming technologies: recirculating water fish farming (aquaculture) and soil-less plant farming (hydroponics).

The combination of food production systems creates a symbiotic relationship that requires a minimum input as all the water and its nutrients are recirculated in a closed loop system where both fish and plant production can take place (Carlsson 2013).The combination results in production yields higher than are available from soil-based cultures (Savidov et al. 2007), a sustainable use of natural resources like the elimination of 90% of the fresh water requirement (Blidariu and Grozea 2011), and an organic production method free from pesticides and antibiotics. The aquaculture (fish farming) wastewater (effluent) is used as organic fertilizer for plants, with significant water savings. The use of the aquaculture wastewater as an organic fertilizer negates the need for fossil-based fertilizers.

Business Model Canvas
Combines nine components associated with a firm to illustrate how value is created and can be utilised to understand existing business models, but also to create innovative business models.

Central to the business model is the value proposition, which addresses the added value the company provides to its customers. The value proposition of UrbanFarmers is a functional aquaponics branded urban farm (this includes design, development, operations, and sales). It offers its customers a system that is 20 times more productive than a conventional soil-based greenhouse. The value proposition might be different for each customer segment, the term to describe who the company creates value for. UrbanFarmers is a business to business company and its customer segments include supermarkets and commercial growers. The channels are used to reach customers and point out the value proposition to them. UrbanFarmers approaches potential customers through business meetings, and makes presentations to investors and potential farm buyers. Moreover, UrbanFarmers uses the UrbanFarmers-BOX (a container-sized demonstrator) and its pilot farms in Basel and The Hague to create interest in the firm’s products. Media coverage of their current reference projects showing the interest of end consumers in UrbanFarmers’ salad and UrbanFarmers’ fish production is an important proof of concept of a profitable business for future investors and farm buyers. The customer relationships describe how the relationship with the relevant customer segment is created and maintained. Revenue streams are generated through selling the value proposition. In other words, it answers the question of where the money is made. UrbanFarmers generates one time revenues from the development and construction of a farm and recurring revenues from the technical service, audits, key account management, and communication services of the farm. Recurring revenues also include royalty fees for licensing the UrbanFarmers proprietary software and using the UrbanFarmers brand.

Whether the revenue streams are sufficient to make the business model work depends on the components on the left side of the model. The key activities are required to create the value proposition. In the case of UrbanFarmers, its key activities are the farm design, commissioning, operations and maintenance services and brand management. The key resources are needed to realise the key activities. To achieve a functional farm, the key resources of UrbanFarmers are the team, software platform, the brand, and the expertise in delivering a functional aquaponic farm to its customers acquired over the past six years. The activities and resources might be internal or come from a key partner outside the organisation. UrbanFarmers cooperates with several key partners such as greenhouse constructors that can deliver commercial greenhouses modified for aquaponic production purposes, and suppliers of consumables such as the fish food and seedlings. Another important key partner for UrbanFarmers is the media helping to popularise and sustain the brand UrbanFarmers. Investors and commercial producers who do not want to get involved in the operations and maintenance of the farm can also be key partners. As a whole the left side of the business plan creates costs, which form the cost structure of the business model. In other words, the left side of the plan answers the question of how much it costs to create the value. UrbanFarmers is becoming an international company with a franchise model, and its cost structure is currently a combination of salaries, farm construction, payment to suppliers, and maintenance of the platform.

The goal of any entrepreneur is thus to create a business model that not only creates value, but that also creates a favourable balance of cost structure and revenue streams. Only when this goal has been achieved can a firm say it has a viable business model.

Box 8.4 Hands on: Let's Get Started!

If you have an idea, that is great! We just managed to motivate you to change the world. Here, you will find a simplified set of steps that can help you to get started. First, check your idea. To create a better world is always a great starting point for any start-up. However, at some point you will need money to progress your idea. Therefore, the basis for a financially sustainable company is an idea with market potential. Use the following "W" questions to test the market viability of your idea. If you cannot answer all the questions that is ok, answering them all is a learning process you will have to go through. Remember? Build, measure, learn!

1. What is the business idea?
2. What makes your idea special?
3. Who are the customers and how big is the target group?
4. What is the business model?
5. Who are the competitors? (includes products/solutions similar to yours)
6. Who is part of the founder team? Who is missing?

Once you can answer all these questions, you should take four steps that can help to develop your idea further and move towards a sustainable business model in the bioeconomy:

1. Join a start-up event in your city and get to know the start-up scene in town. These events are the perfect place to network and exchange your ideas with others.
2. Pitch your idea and discuss it with people you do not know. In this way, you can obtain valuable input about the first problems your idea may encounter.
3. Find a team that can help you to make your idea a reality. Only when the entire team shares the same vision, can objectives be accomplished.
4. Work with the business model canvas intensively. And look for a mentor who can provide valuable feedback.

Review Questions

- What is an entrepreneurial opportunity and why is the bioeconomy likely to offer many entrepreneurial opportunities?
- What is a business model and how can it be described? Try to identify start-ups in the bioeconomy and describe their business model.

- What is a minimum viable product and why is it preferable to a wholly developed product, especially at the point of starting up?

References

Arcese G, Lucchetti MC et al (2016) State of the art in S-LCA: integrating literature review and automatic text analysis. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-016-1082-0

Ayres RU (2007) On the practical limits to substitution. Ecol Econ 61(1):115–128

Baltus W, Beckmann J, Carrez D, Carus M, Dammer L, Essel R, Kaeb H, Ravenstijn J, Sanz Mirabal A, Scholz L, Sibilla F, Zepnik S (2013) Market study on bio-based polymers in the world-capacities, production and applications: status quo and trends towards 2020. Nova-Institut GmbH, Huerth, Germany

Benoıt̂ C, Mazijn B (eds) (2009) Guidelines for social life cycle assessment of products. United Nations Environment Programme, Paris

Betula Manus (2017) Home – Betula Manus. http://www.betula-manus.de/en/home-en. Accessed 28 Mar 2017

Bioplastic Magazine (2012) Growth in PLA bioplastics: a production capacity of over 800,000 tonnes expected by 2020. Bioplastics MAGAZINE. Polymedia Publisher GmbH. http://www.bioplasticsmagazine.com/en/news/meldungen/PLA_Growth.php. Accessed 15 Dec 2016

Blank S (2013a) The four steps to the epiphany: successful strategies for products that win, 1st edn. BookBaby, Portland

Blank S (2013b) Why the lean start-up changes everything. Harv Bus Rev 91(5):63–72

Blidariu F, Grozea A (2011) Increasing the economical efficiency and sustainability of indoor fish farming by means of aquaponics-review. Sci Papers Anim Sci Biotechnol 44(2):1–8

Bocken N, Short SW (2016) Towards a sufficiency-driven business model: experiences and opportunities. Environ Innov Soc Trans 18:41–61

Braungart M, McDonough W, Bollinger A (2007) Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. J Clean Prod 15(13–14):1337–1348

Carlsson D (2013) Aquaponics system: potentials in Northern latitude. http://miun.diva-portal.org/smash/record.jsf?pid=diva2:633765. Accessed 22 Feb 2017

Conforti P (2011) Looking ahead in world food and agriculture: perspectives to 2050. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/docrep/014/i2280e/i2280e.pdf. Accessed 23 Jan 2017

Dean TJ, McMullen JS (2007) Toward a theory of sustainable entrepreneurship: reducing environmental degradation through entrepreneurial action. J Bus Ventur 22(1):50–76

Dorfman R (1993) Some concepts from welfare economics. Econ Environ 3:79–96

Drucker PF (1984) Converting social problems into business opportunities: the new meaning of corporate social responsibility. Calif Manage Rev 26(2):53–63

Elkington J (1997) Cannibals with forks: the triple bottom line of twenty-first century business. Capstone, Oxford

Ellen MacArthur Foundation (2013) Towards the circular economy. http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/pdfs/towards_the_circular_economy.ashx

European Bioplastic (2016) Bioplastics market data. http://www.european-bioplastics.org/market/. Accessed 19 Dec 2016

European Commission (2012) Investing in success – research and innovation to boost growth and jobs in Europe. Publications Office of the European Union. http://ec.europa.eu/research/horizon2020/pdf/success-stories-h2020_2012.pdf. Accessed 13 Feb 2017

Festel G (2010) Industrial biotechnology: market size, company types, business models, and growth strategies. Ind Biotechnol 6(2):88–94

Figge F, Young W, Barkemeyer R (2014) Sufficiency or efficiency to achieve lower resource consumption and emissions?: the role of the rebound effect. J Clean Prod 69:216–224

Finnveden G, Hauschild MZ et al (2009) Recent developments in life cycle assessment. J Environ Manage 91(1):1–21

FNR (2017) Fachagentur für nachwachsende Rohstoffe e.V. https://energiepflanzen.fnr.de/. Accessed 18 Apr 2016

Freeman RE (1984) Strategic management: a stakeholder approach. Pitman, Boston, MA

Gallagher E (2008) The Gallagher review of the indirect effects of biofuels productions. Renewable Fules Agency. https://www.researchgate.net/publication/235704395 The_Gallagher_Review_of_the_Indirect_Effects_of_Biofuel_Production. Accessed 18 Apr 2017

Gilpin GS, Andrae ASG (2017) Comparative attributional life cycle assessment of European cellulase enzyme production for use in secondgeneration lignocellulosic bioethanol production. Int J Life Cycle 22(7):1034–1053. https://doi.org/10.1007/s11367-016-1208-4

Gürtürk A, Hahn R (2016) An empirical assessment of assurance statements in sustainability reports: smoke screens or enlightening information? J Clean Prod 136:30–41

Hahn R (2008) Sustainable development at the BoP – on integrated approaches beyond trade-off-thinking. In: Kandachar P, Halme M (eds) Sustainability challenges and solutions at the base of the pyramid: business, technology and the poor. Greenleaf, Sheffield, pp 446–461

Hahn R (2009) The ethical rational of business for the poor – integrating the concepts bottom of the pyramid, sustainable development, and corporate citizenship. J Bus Ethics 84(3):313–324

Hahn R (2011) Integrating corporate responsibility and sustainable development. J Global Respons 2 (1):8–22

Hahn R, Kühnen M (2013) Determinants of sustainability reporting: a review of results, trends, theory, and opportunities in an expanding field of research. J Clean Prod 59:5–21

Hahn R, Reimsbach D, Schiemann F (2015a) Organizations, climate change, and transparency: reviewing the literature on carbon disclosure. Org Environ 28(1):80–102

Hahn T, Pinkse J et al (2015b) Tensions in corporate sustainability: towards an integrative framework. J Bus Ethics 127(2):297–316

Hansen EG, Schaltegger S (2016) The sustainability balanced scorecard: a systematic review of architectures. J Bus Ethics 133(2):193–221

Hatti-Kaul R, Törnvall U et al (2007) Industrial biotechnology for the production of bio-based chemicals – a cradle-to-grave perspective. Trends Biotechnol 25 (3):119–124. https://doi.org/10.1016/j.tibtech.2007.01.001

Hediger W (1999) Reconciling “weak” and “strong” sustainability. Int J Soc Econ 26(7/8/9):1120–1144

Huber J (2000) Towards industrial ecology: sustainable development as a concept of ecological modernization. J Environ Policy Plan 2(4):269–285

IMF (2016) Primary commodity prices. http://www.imf.org/external/np/res/commod/index.aspx/. Accessed 15 Dec 2016

International Standard Organization (2006) ISO 14040: environmental management – life cycle assessment – principles and framework

Janda K, Kristoufek L, Zilberman D (2012) Biofuels: policies and impacts. Agric Econ Czech 58 (8):372–386

Jolliet O, Brent A, Goedkoop M et al (2003) Final report of the LCIA definition study. Life Cycle Impact Assessment Programme of the Life Cycle Initiative

Kirzner IM (1973) Competition and entrepreneurship. University of Chicago Press, Chicago

Kollmann T, Kuckertz A (2010) Evaluation uncertainty of venture capitalists’ investment criteria. J Bus Res 63 (7):741–747

Kuchler M, Linnér BO (2012) Challenging the food vs. fuel dilemma: genealogical analysis of the biofuel discourse pursued by international organizations. Food Policy 37(5):581–588

Kuckertz A, Mandl C (2016) Capturing the complexity and ambiguity of academic fields: determining consensual definitions for small business research, entrepreneurship and their shared interface. In: Berger ESC, Kuckertz A (eds) Complexity in entrepreneurship, innovation and technology research – applications of emergent and neglected methods. Springer, Berlin, pp 417–438

Kuckertz A, Wagner M (2010) The influence of sustainability orientation on entrepreneurial intentions—investigating the role of business experience. J Bus Ventur 25(5):524–539

Kuckertz A, Kollmann T et al (2017) Understanding, differentiating, and measuring opportunity recognition and opportunity exploitation. Int J Entrep Behav Res 23(1):78–97

Kühnen M, Hahn R (2017) Indicators in social life cycle assessment: a review of frameworks, theories, and empirical experience. J Ind Ecol. https://doi.org/10.1111/jiec.12663

Lewandowski I (2015) Securing a sustainable biomass supply in a growing bioeconomy. Glob Food Sec 6:34–42

Lewandowski I, Clifton-Brown J et al (2016) Progress on optimizing miscanthus biomass production for the European bioeconomy: results of the EU FP7 project OPTIMISC. Front Plant Sci. https://doi.org/10.3389/fpls.2016.01620

Mandl C, Berger ESC, Kuckertz A (2016) Do you plead guilty? Exploring entrepreneurs’ sensemaking-behavior link after business failure. J Bus Ventur Insights 5:9–13

McDonough WJ, Braungart M (2002) Cradle to cradle: remaking the way we make things, 1st edn. North Point Press, New York

Meadows D, Randers J, Behrens WW (1972) The limits to growth. Universe Books, New York

Meadows DH, Randers J, Meadows DL (2004) Limits to growth: the 30-year update. Chelsea Green Publ, White River Junction

Muñoz I, Flury K et al (2014) Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19:109. https://doi.org/10.1007/s11367-013-0613-1

Neugebauer F (2012) EMAS and ISO 14001 in the German industry – complements or substitutes? J Clean Prod 37:249–256

Neumayer E (2013) Weak versus strong sustainability, 4th edn. Edward Elgar, Cheltenham

OECD (2011) Future prospects for industrial biotechnology, OECD Publishing, Paris. https://doi.org/10.1787/9789264126633-en

OECD (2012) Recommendation of the council on assessing the sustainability of bio-based products – 17 July 2012 – C(2012)112 – C(2012)112/CORR1. http://webnet.oecd.org/OECDACTS/Instruments/ShowInstrumentView.aspx?InstrumentID=283&InstrumentPID=298&Lang=en&Book=False 17 July 2012 - C(2012)112 - C(2012)112/CORR1. Accessed 16 Jan 2017

OECD (2014) Biobased chemicals and bioplastics: finding the right policy balance. OECD Science, Technology and Industry Policy Papers No. 17 OECD Publishing, Paris. https://doi.org/10.1787/5jxwwfjx0djf-en

OECD/FAO (2016) OECD-FAO agricultural outlook 2016–2025. OECD Publishing, Paris. https://doi.org/10.1787/agr_outlook-2016-en

OECD.Stat (2016) OECD-FAO agricultural outlook 2016–2025 data. http://stats.oecd.org/viewhtml.aspx?QueryId=71240&vh=0000&vf=0&l&il=&lang=en. Accessed 16 Dec 2016

Osterwalder A, Pigneur Y (2010) Business model generation: a handbook for visionaries, game changers, and challengers. Wiley, Hoboken

Piotrowski S, Carus M, Carrez D (2016) European bioeconomy in figures. Ind Biotechnol 12(2):78–82. https://doi.org/10.1089/ind.2016.29030.spi

Raschka A, Carus M (2012) Industrial material use of biomass – basic data for Germany, Europe and the world. nova Institute of Ecology and Innovation. http://bio-based.eu. Accessed 12 Apr 2017

Reimsbach D, Hahn R, Gürtürk A (2017) Integrated reporting and assurance of sustainability information: an experimental study on professional investors' information processing. Eur Account Rev. https://doi.org/10.1080/09638180.2016.1273787

REN21 (2016) Renewables 2016 – global status report. Renewable Energy Policy Network for the 21st Century. http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf. Accessed 12 Apr 2017

Ries E (2011) The Lean startup: how today's entrepreneurs use continuous innovation to create radically successful businesses. Random House, New York

Rocha FLR, Marziale MHP, Oi-Saeng H (2010) Work and health conditions of sugar cane workers in Brazil. Rev Esc Enferm USP 44(4):978–983. https://doi.org/10.1590/S0080-62342010000400017

Rockström J, Steffen W et al (2009) A safe operating space for humanity. Nature 461(7263):472–475

Roehm P, Koehn A et al (2017) A world of difference? The impact of corporate venture capitalists' investment motivation on startup valuation. J Bus Econ. https://doi.org/10.1007/s11573-017-0857-5

Roos D, Hahn R (2017) Does shared consumption affect consumers' values, attitudes, and norms? A panel study. J Bus Res 77:113–123

Sartor M, Orzes G et al (2016) The SA8000 social certification standard: literature review and theory-based research agenda. Int J Prod Econ 175:164–181

Savidov NA, Hutchings E, Rakocy JE (2007) Fish and plant production in a recirculating aquaponic system a new approach to sustainable agriculture in Canada. Acta Hortic (742):209–221. 10.17660/ActaHortic.2007.742.28

Schmidt-Bleek F (1998) Das MIPS-Konzept: Weniger Naturverbrauch – Mehr Lebensqualität durch Faktor 10. Droemer, Munich

Schneidewind U, Palzkill A, Scheck H (2012) Der Beitrag von Unternehmen zur großenTransformation. In: Hahn R, Janzen H, Matten D (eds) Die gesellschaftliche Verantwortung des Unternehmens: Hintergründe, Schwerpunkte und Zukunftsperspektiven. Schäffer Poeschel, Stuttgart, pp 497–528

Schumpeter JA (1934) The theory of economic development: an inquiry into profits, capital, credit, interest, and the business cycle. Transaction, Piscataway

Seabra JEA, Macedo IC et al (2011) Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. Biofuels Bioprod Bioref 5:519–532. https://doi.org/10.1002/bbb.289

Seuring S (2011) Supply chain management for sustainable products – insights from research applying mixed methodologies. Bus Strateg Environ 20(7):471–484

Seuring S, Müller M (2008) From a literature review to a conceptual framework for sustainable supply chain management. J Clean Prod 16(15):1699–1710

Shane SA, Venkataraman S (2000) The promise of entrepreneurship as a field of research. Acad Manage Rev 25(1):217–226

Steffen W, Richardson K et al (2015) Sustainability. Planetary boundaries: guiding human development on a changing planet. Science 347(6223):1259855. https://doi.org/10.1126/science.1259855

Stierli M, Shorrocks A et al (2015) Global wealth report 2015. Zürich. https://publications.credit-suisse.com/tasks/render/file/?fileID=F2425415-DCA7-80B8-EAD989AF9341D47E

Swarr TE, Hunkeler D et al (2011) Environmental life cycle costing: a code of practice. Society of Environmental Toxicology and Chemistry (SETAC), Pensacola

United Nations Human Development Programme (2015) Human development report 2015: work for human development. Human development report, vol 2015. United Nations Development Programme, New York

Urban Farmers (2013) Business model. https://urbanfarmers.com/company/business-model/. Accessed 20 Feb 2017

Valdivia S, Ugaya CML et al (eds) (2011) Towards a life cycle sustainability assessment – making informed choices on products. UNEP/SETAC Life Cycle Initiative. ISBN: 978-92-807-3175-0

Van Lampe M (2007) Economics and agricultural market impacts of growing biofuel production. Agrarwirtschaft 56:232–237

Varian HR (2014) Intermediate microeconomic, 9th edn. W.W. Norton, New York

Visioverdis (2017) Company. http://visioverdis.com/english/company.html. Accessed 2 Mar 2017

von Weizsäcker EU, Lovins AB, Lovins LH (1996) Faktor Vier: Doppelter Wohlstand – Halbierter Naturverbrauch. Droemer, Munich

Wagner M, Kiesel A et al (2017) Novel miscanthus germplasm-based value chains: a life cycle assessment. Front Plant Sci. https://doi.org/10.3389/fpls.2017.00990

WCED (1987) Our common future. Oxford University Press, Oxford

Weidema BP, Bauer C et al (2013) The ecoinvent database: overview and methodology. Data quality guideline for the ecoinvent database version 3

Womack JP, Jones DT (1996) Beyond Toyota: how to root out waste and pursue perfection. Harv Bus Rev 74 (5):140–158

World Bank (2016) World bank GEM commodities. http://data.worldbank.org/data-catalog/commodity-price-data. Accessed 19 Dec 2016

WWF International (2016) Living planet report 2016: risk and resilience in a new era. WWF International, Gland

Part III

Transition to a Sustainable Bioeconomy

9

Modelling and Tools Supporting the Transition to a Bioeconomy

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Abstract

The strategy of using biogenic resources in a bioeconomy could be seen as one answer to the geopolitical challenges the world is facing in the twenty-first century. One of those challenges is the closing of the prosperity gap between rich and poor countries. However, considering the current global population growth and anthropogenically induced climate change, it is expected that efforts to achieve this goal will be accompanied by an increasing demand for food, feed, products, and energy, which cannot be satisfied by the expected supply of non-biogenic raw materials and resources.

Transforming an economy is extremely complex: domestic and international obligations, traditional practices, and divergent interests and wishes need to be taken into consideration. This requires the development of an appropriate strategy and adequate instruments and tools to support it.

This chapter discusses a range of possible knowledge-based instruments and tools that take a systemic view of the challenges in such transformation processes.

Keywords

Scenarios • Scenario building • Economic models • Ecological and biophysical models • Life cycle assessment • Integrated assessment models

Learning Objectives

After studying this chapter, you should:

- Understand how transformation theory can support transition processes.
- Have an overview of main instruments and tools to quantify and assess transition developments.
- Be acquainted with the main challenges, strategies and drivers to facilitate the transition to a bioeconomy.

9.1 Introduction

One core geopolitical challenge in the twenty-first century is closing the prosperity gap between rich and poorer countries. However, this needs to be achieved in a world with a growing population, unevenly distributed growth and anthropogenically induced climate change with significant regional variation in its impact. Since rich countries are unlikely to renounce their wealth, closing the prosperity gap will be accompanied by an increasing demand for food, feed, products, and energy. It is expected, however, that in the longer run, increasing demand will not be satisfied by the available supply of metals, minerals, and fossil fuels. Recycling strategies can reduce the pressure on primary resources, but even with technological progress, excess demand for non-renewable materials will not be sufficiently lowered.

Climate change and increasing pressure on the natural environment demand a change in strategy. For this reason, the European Commission, among others, proposes a radical change in “its approach to production, consumption, processing, storage, recycling and disposal of biological resources” (European Commission 2012). This bioeconomic strategy needs to:

- Ensure food security.
- Manage natural resources.

- Reduce dependence on non-renewable resources.
- Mitigate and adapt climate change.
- Create jobs and maintain competitiveness especially—but not exclusively—in rural areas.

Whereas the challenges to be addressed are widely known and accepted, the question of how these goals can be achieved, i.e. how an economy can be transformed into a bioeconomy, is still at the centre of scientific, political, and societal debate.

Historical evidence from recent decades demonstrates society's essential role in any successful transformation of systems. Norms, values, and thus behavioural patterns, along with the degree of acceptance and the willingness to support changes, are as important as technological and economic factors (Verbong and Loorbach 2012). These norms and values shape the preferences of what a future bioeconomy should look like. Any thinking about the future is accompanied by uncertainties and relevant but as yet unknown processes within and outside the control of stakeholders.

The development of potentially successful strategies for dealing with uncertainties on the way to a bioeconomy requires instruments and tools to depict possible transition paths. This chapter provides the reader with a number of instruments and tools, without claiming to be comprehensive.

To identify future possibilities, scenarios have increasingly been used in the past decades. They address complexities and uncertainties by explicitly acknowledging that different futures are possible and that reliable, long-term predictions in the field of sociotechnical transition are not possible (Grunwald 2011). Scenarios aim to explore and develop potential or desirable future states and development pathways. One established approach is to combine scenarios with models (Poganietz et al. 2000). Models can reveal interdependencies between resources, production, consumption, markets and sectors, and the environment.

9.2 Scenarios: Revealing the Trails into the Future

This section presents the scenario approach. First, the necessity of scenarios is explained (Sect. 9.2.1), followed by a discussion of their function in science and the public (Sect. 9.2.2). Because scenarios are used in different contexts, a typology of scenario approaches is shown in Sect. 9.2.3. Section 9.2.4 aims to assist the development of scenarios. The section ends with some concluding remarks (Sect. 9.2.5).

Scenarios

Scenarios describe complex pictures of the future that are seen as plausible. The described future can be modelled according to current knowledge of the system. However, scenarios do not give information on which future is likely or desired.

9.2.1 Why Do We Need Scenarios?

The transformation of a system requires future-oriented system knowledge. Not only are current elements of a system and their interdependencies of relevance but also possible future changes. New elements could enter the system, and established ones could lose their significance. Also the interrelationship between the elements could change, or new ones may be established. To control a system transformation, i.e. to identify and implement suitable pathways, strategic thinking is highly recommended, in particular in the case of complex systems. Strategic thinking requires particular tools and instruments for predicting and assessing alternative futures and pathways to achieve the desired future.

Prediction and controllability of the future were the main pillars of economic policy in the first half of the twentieth century, not only in socialist countries. For example, Japanese economic development after World War II was based on a "plan-oriented market economy system" (Johnson 1982). The Japanese Ministry of International Trade and Industry (MITI) acted

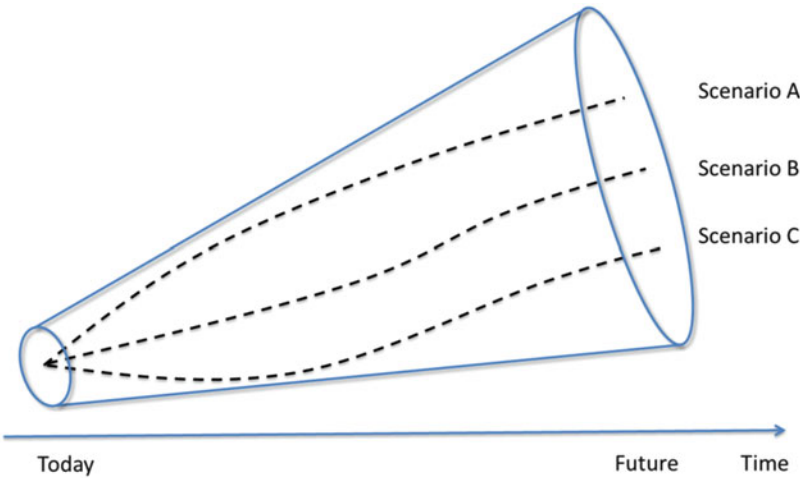

Fig. 9.1 Scenario filter funnel

like a central planner, yet was not always successful (Johnson 1982; Jansen 2002). Prediction has to be understood as a statement about an uncertain future based on experience or knowledge. In that context, prediction is achieved through rigorous mathematical or statistical methods (Rescher 1998). Controllability describes the requirement that a system must be controllable so that the system status can be changed to a desired status. The target status of a system is achievable by manipulating the relevant control variables (Kalman 1963). The "planning optimism" collapsed in the aftermath of the first oil crisis in 1974 (Wack 1985).

Despite this "planning optimism" after the Second World War, future-oriented activities started in the RAND Corporation in the 1960s (Wack 1985; Schwartz 1996), evolving from a prognostic approach to the future to a scenario-based one (Grunwald 2002). In contrast, a scenario approach denies the possibility of predicting and controlling the future due to the complexity of systems and the impossibility of capturing all relevant elements and their interdependencies. Therefore, scenarios aim to describe a "space of possibilities" of future developments, meaning that different futures are possible, at least from today's perspective (Fig. 9.1; Kosow and Gaßner 2008). If the future is not predictable and controllable, strategic thinking is of utmost importance. Scenarios are a useful tool to support such thinking.

Scenarios describe complex pictures of the future that are seen as plausible. Plausible means that the described future may happen given today's knowledge of the system under investigation. But plausibility does not mean the described future is likely or even desirable. Scenarios can include extreme situations, which are seemingly not likely yet plausible. Common to all scenarios is the use of consistent assumptions about possible future developments, leading to divergent futures (Grunwald 2002; Kosow and Gaßner 2008).

9.2.2 Functions of Scenarios

Scenarios fulfil several functions, which can also overlap:

- Knowledge function
- Communication function
- Goal-setting function
- Strategy-forming function

From a scientific point of view, the knowledge function is considered the most important. It has two aspects. The first aspect is a consequence of using scenarios for analysing systems. Scenarios can help improve knowledge about the cause-and-effect relationship within systems and the kind and degree of possible consequences of developments, decisions, or policy measures. Scenarios can also help detect unwanted consequences of actions, “blind spots”, or even contradictions in decisions or policy measures as well as dilemmas. The latter means different aims cannot be achieved simultaneously. As such, trade-offs between targets may exist. To give an example, intensification of farming that targets the enhancement of yields may contradict the aim of environment-friendly agriculture.

The second aspect stems from the process of scenario building. Scenarios can capture only part of a complex system. The analysed system must be “simplified” by dispensing with irrelevant elements or reducing the complexity of interrelationships between elements to focus on those that provide knowledge for the intended aim. For example, in agricultural economics, model-based scenarios often exclude nonagricultural activities such as forestry (Balkhausen et al. 2008). However, a sine qua non for reducing the complexity is the awareness of what is considered relevant for a particular question and what is not. In this way, scenarios reduce complexity in a systematic and transparent manner to a cognitively measurable level. Specifically, the scenario-building process enables the systematic and targeted integration of different information types, i.e. findings and theses from different disciplines, as well as qualitative and quantitative data. In principle, scenarios also offer the possibility to integrate social objectives, norms or values in a transparent way (Kosow and Gaßner 2008).

In cases where scenarios are developed in collaboration with stakeholders, they can serve as an integrative platform for players from different fields and thereby help structure topics and arguments. This can assist the parties involved in better understanding their respective positions or interests and working out priorities. It can also encourage them to discuss the subject matter in a long-term perspective (Havas 2014). Thus, scenarios have a communication function that should not be underestimated.

From a more strategic perspective, scenarios can also assist in the development or specification of goals (goal-setting function). They can help stakeholders to reflect on their perspectives or positioning (Minx and Böhlke 2006). In addition, they can provide orientation in planning processes (strategy-forming function), such as testing the robustness of strategies and comparing different alternatives (Kosow and Gaßner 2008).

9.2.3 Scenario Approaches

As there are different ways of thinking about the future and possible paths towards it, there are many approaches to structuring scenarios. Most commonly, they are subdivided into three types, and this subdivision points to central differences in their development and application. According to Börjeson et al. (2006), these can be designated:

- Predictive
- Explorative
- Normative scenarios

Predictive Scenarios

Predictive scenarios are typically used to forecast the most likely future. Here, scenario analysts aim to answer questions like “what will happen in the future?” or “what can be expected?”. Answers are typically provided by “just” updating or extrapolating past trends into the future. For example, to predict the production of biofuels in Germany in a specific year, say 2025, it can be assumed that the future growth rate will follow the same trend as, for example, in the last 10 years. Implicitly, this type of scenario disregards any change in market conditions or other relevant decision-making parameters.

It is arguable whether predictive scenarios should be counted as scenarios at all. Strictly speaking, they strongly resemble predictions, which by definition are not scenarios. Instead, although relatively cumbersome, they should be called “scenario-like forecasts”. Scenarios assume that different futures are possible, whereas forecasts tend to look for the right future. The early developers of scenarios such as Kahn and Wiener (1967) would certainly have refused to use the term scenario here.

We include predictive scenarios here for pragmatic reasons. First of all, it makes the distinction between the other two types, i.e. explorative and normative scenarios, clearer. Additionally, the concept of scenarios is often extended to predictive approaches by practitioners. A reference scenario is often constructed on the basis of trend extrapolation, representing how the world would look if everything continued as before. This is often referred to as a "business-as-usual" or BAU scenario. Predictive approaches can also inform investors or managers of expected developments (Börjeson et al. 2006). A BAU or reference scenario can then be compared with other, explorative or even normative scenarios. A reference or BAU scenario is not assigned a probability: a future where everything continues as before is no more likely than one characterized by dramatic changes. In this case, the "predictive scenario" is just one scenario among others.

Explorative Scenarios

Explorative scenarios attempt to show possible futures. It does not matter whether these futures are desired or likely. Analysts use explorative scenarios to answer questions like "what would happen, if . . .?" or "what is possible?". Here, exploring past trends plays a minor role. The most important step in building explorative scenarios is identifying the main drivers of development of the elements of the system and their interdependencies. Another step is to identify plausible assumptions regarding the development of such drivers (cf. Sect. 9.3.4).

Since these assumptions are based on today's knowledge, it is also possible to consider events that are unlikely or unpredictable but can greatly influence developments. For example, the impact of a comet in 2032 would darken the atmosphere for several years through scattered dust. This could lead to a slowdown in climate change, but it might also have a long-lasting impact on agriculture: lower yields and higher food prices could intensify the competition for arable land. Wild cards or black swans, as they are often called, need not be so drastic. A breakdown of the EU Common Agriculture Policy or the successful market penetration of a new product type, e.g. in vitro meat, is also a possible wild card.

Whereas predictive scenarios have their starting point in the present, this is not obligatory for explorative scenarios. For example, scenarios considering the impacts of future political intervention have a year in the future as starting point (Börjeson et al. 2006).

Explorative scenarios are particularly suitable for long-term horizons of 20–40 years. Statements on these timescales are exceptionally difficult when they concern complex systems with a high degree of uncertainty, such as the bioeconomy.

However, the surroundings in which these aims are to be achieved are not static over time. Examples of dynamically changing factors are, on the demand side, population, dietary habits, preferences for biogenic and non-biogenic products, and income and on the supply side technological progress within the food, agricultural industry and forestry-based industry, energy conversion technologies, and both traditional and innovative material processing industries.

To capture the uncertainties and identify a "space" of possible futures, it is recommended to build several, distinctly differing scenarios. An example is presented in Table 9.1 (see also Box 9.1).

The focus of each scenario is on the potential cause-and-effect relationships. The addressees can then develop strategies for action or rethink existing strategies. Political or business strategies can be tested for their robustness. For example, one could be concerned with the question of how biomass would develop as an energy carrier if strong societal demands ("saving the cultural landscape") hinder cultivation of energy plants.

Depending on the purpose of a scenario, it may also be important to vary both external and internal factors (Börjeson et al. 2006). External factors are those that cannot be influenced by actions of the principal, e.g. the government or

Table 9.1 Example for distinct scenarios

Scenario	Demand for biomass for material and energy	Biomass supply	Remark
Scenario A: bio-modesty	Low growth rate	Medium growth rate	–
Scenario B: bio-boom	High growth rate	High growth rate	Supply of biomass matches demand
Scenario C: bio-scarcity	High growth rate	Medium growth rate	Supply of biomass cannot match demand

Based on Kovacs (2015)
Note: The study discusses possible future developments of a European bioeconomy up to 2050

company. Internal factor are those that can be influenced by the principal. Varying these factors makes it possible to test the robustness of action strategies in the context of alternative developments, which consequently allows flexible and adaptive strategies to be identified. Likewise, an organization can be sensitive to signals ("weak signals") that indicate important future changes (Börjeson et al. 2006). By varying internal factors, strategic scenarios can be developed (ibid.). The starting point is formed by various action strategies, which are tested for their possible effects and subsequently compared.

Box 9.1: Possible Futures Towards a Wood-Based Bioeconomy: A Scenario Analysis for Germany (Hagemann et al. 2016)—An Example

In this analysis, six key influencing factors relevant for the future development of a wood-based bioeconomy in Germany were identified through literature research and expert survey, including:

- Biomass Availability and Forest Structure
- Globalisation and Global Economic Development
- Impulses from Energy and Climate Policy
- Supply and Demand for Wood
- Willingness to Pay for Bio-based Products
- Innovation Along the Wood Value Chain

Four scenarios were elaborated, each assuming a different development of the influencing factors:

Scenario 1—"Government as a driver": The government is sustainability oriented and drives the transformation towards a bioeconomy. Companies remain cost oriented, consumers reluctant to bio-based products, and voters not convinced.

Scenario 2—"Trend towards sustainability": Similar to Scenario 1, the government is sustainability oriented, yet in contrast to the first scenario, consumers and producers perceive the long-term trend towards greater sustainability as an opportunity.

Scenario 3—"Keep going": Due to the government's and society's affinity with traditional values and established structures, no risks are taken to implement changes.

Scenario 4—"State as obstacle": Whereas companies are confident in new technologies and society shows some commitment, the government is reluctant to implement supporting conditions.

For further scenario analyses, see:

- Kovacs B (ed) (2015) Sustainable agriculture, forestry, and fisheries in the bioeconomy. A challenge for Europe.

(continued)

Box 9.1 (continued)

4th SCAR Foresight Exercise. doi:10.2777/179843
- Kalt G, Baumann M et al. (2016) Transformation scenarios towards a low-carbon bioeconomy in Austria. Energy Strategy Reviews 13:125-135. doi:10.1016/j.esr.2016.09.004

The definition of *normative scenarios* makes the difference to explorative scenarios clear. Norms and values are deliberately and clearly identified along with their target, i.e. a specific future. They try to answer questions such as “How can a specific target be reached?” (Kosow and Gaßner 2008; Schippl and Leisner 2009). Although the target is typically desirable, this is not a sine qua non for a normative scenario. Normative scenarios are often used for major social transformations, such as the transformation towards a bioeconomy, but can also be used for less complex questions. The target situation may not necessarily be different from the current one. In the case of environmental issues in particular, maintaining the present state may be desirable, e.g. preventing climate change or conserving biodiversity.

A typical form of normative scenarios is called “backcasting”. Here, targets are selected that are to be achieved at a certain point in the future (see Fig. 9.2, No. 1). This could be, for example, increasing the share of renewable energies in Germany to 80% by 2050. In a second step, the chances of achieving the target under the current conditions or trends are analysed using forecasts (No. 2 in Fig. 9.2) or a business-as-usual scenario. If these trends are not sufficient to achieve the target, a third step is carried out: “images” of the future that would achieve the goal are sketched from today’s point of view as consistently as possible (No. 3 in Fig. 9.2). Then, in a last step, paths that can lead to these future images are identified (No. 4 in Fig. 9.2), and precise options for action to attain the goal are formulated. This is a very comprehensive and inclusive approach, which can result in the elaboration of far-reaching policy measures.

Some authors also follow the approach of Alcamo (2008), who speaks of anticipatory scenarios (sometimes called “prescriptive scenarios”), which have their starting point in the future. Table 9.2 summarizes the presented types of scenario approaches.

The classification outlined here is often helpful in structuring scenarios. Of course, they are rarely found in a pure form when put into practice. For instance, explorative scenarios are usually not entirely without normative assumptions. Deciding which parameters are important and thus to be included or varied necessarily involves a certain evaluation.

Fig. 9.2 Backcasting in four steps (based on Höjer and Mattsson 2000)

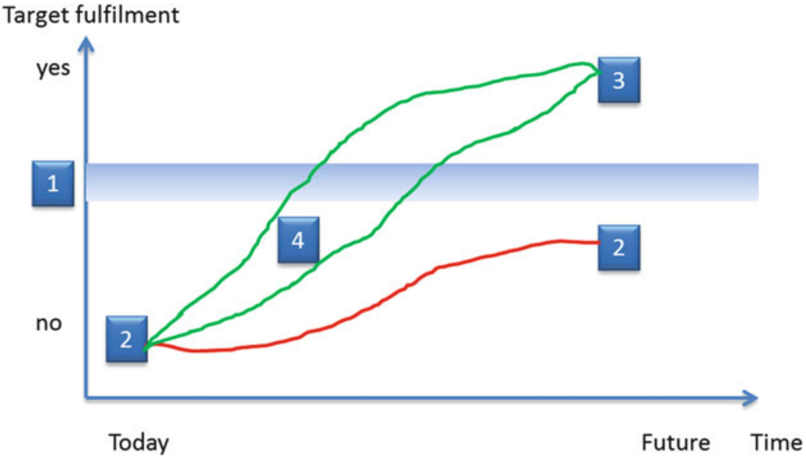

Table 9.2 Scenario approaches

	Predictive scenarios	Explorative scenarios	Normative scenarios
Characteristic questions	What will happen? What can be expected?	What could happen, if...? What is possible?	How can a specific target be reached?
Aim	To predict the most likely future	To analyse possible futures	Analysis of paths to reach the target
Method	Extrapolation of trends	Identification of main drivers	Backcasting

Table 9.3 Advantages and disadvantages of qualitative and quantitative scenarios (Alcamo 2008)

	Qualitative scenarios	Quantitative scenarios
Advantages	Can integrate the views of different experts or stakeholders Can describe very complex systems Well-written "storylines" can provide an understandable and appealing communication about the future	Deliver figures that are needed for certain questions Assumptions can be transparent and accessible (i.e. underlying numbers, equations, coefficients) Many scenarios use models that have already been published and have thus been scientifically evaluated Can be used to test the consistency of qualitative scenarios
Disadvantages	The scenarios are often based on "mental models" which may be difficult to understand Their underlying assumptions are difficult to identify, analyse, and test When it comes to the achievement of concrete target values, qualitative approaches by definition cannot offer figures	The figures suggest a high precision of the results which can obscure the fact that they are estimates Model-based scenarios are often based on a very large number of assumptions that are difficult to verify (especially for non-specialists) For practical (e.g. no available data) and methodological reasons, models cannot depict systems completely. The process of reducing the complexity is driven by an available model and not necessarily by the challenge Data availability, as well as methodological reasons, tends to model only well-documented system interrelations

In the literature, scenarios are also distinguished by the way they are described and identified: in so-called qualitative scenarios, characterized by the use of narratives ("storylines"), and so-called quantitative scenarios, typically associated with algebraic models presenting futures or transformation paths as numerical data (see Sect. 9.3). This classification can also be applied to the types of scenarios described above.

Both types of scenarios have advantages and disadvantages. These are summarized in Table 9.3.

The choice between qualitative or quantitative scenarios depends on various factors, like the availability of data or the user/client demands. For example, the discussion on energy transformation is dominated by model-based (quantitative) scenarios (see, e.g. Appelrath et al. 2016). A good example of bioeconomy-related qualitative scenarios is OECD (2009) (Kovacs 2015; Hagemann et al. 2016).

In practice, however, quantitative and qualitative approaches are often mixed. Narratives are underlined by numbers or serve as a starting point for more complex modelling. A highly systematic combination of qualitative and quantitative approaches can be found in Alcamo (2008), who describes his approach as a story-and-simulation (SAS) approach (Weimer-Jehle et al. 2016).

Although future-oriented scenarios can be a strong tool to structure discussions or to support decision-makers, they have a substantial disadvantage. Scenarios do not offer truth claims in the sense of scientific knowledge. For the latter it must be possible to verify (to confirm) or falsify (reject) a statement (Popper 2008). This is, of course, not possible for developments that do not yet exist because they occur in the future. On one hand, scenarios reflect today's perception of future problems and today's knowledge on how challenges can be overcome. On the other hand, scenario builders are exposed to stakeholder representatives or lobbyists, who try to influence the future of political decision-making processes through specific future images. This could involve deliberately constructing futures that are opposed to other futures and suggesting decisions that benefit particular interests. In this context, Brown et al. (2000) refer to contested, i.e. controversial, futures.

This disadvantage can backfire on scenario-based decisions if the underlying scenarios are perceived as worthless, resulting in them being dismissed as arbitrary speculation. However, it is essential to have a meaningful perspective at the political or business level—and this is one of the central objectives of scenarios—that scenarios are not completely arbitrary but based on comprehensible validity criteria. Decisions require more reasoned and thus not purely speculative future images. But this is not a trivial challenge.

As mentioned before, validity criteria or scientific methods are not available. In the literature, a few central criteria have been proposed for the assessment of scenarios (Grunwald 2002; Kosow and Gaßner 2008):

- Plausibility: Described developments must be plausible, but not necessarily likely or desirable.
- Consistency: Images of the future as well as paths to the future should not contradict one another.
- Comprehensibility/traceability: The level of granularity/aggregation of the scenarios should be determined by the aim of the scenarios, i.e. they should not be too complex or too detailed.
- Selectivity: Alternative scenarios should represent different future designs. The different designs should not just be the result of a "mere" variation in a certain parameter; rather they should present different complete blueprints of a future.
- Transparency: Relevant assumptions and decisions (and the criteria used) should be disclosed. A high degree of intersubjective comprehensibility can be achieved through reflection on the procedure.

These criteria are valid for all scenario types, irrespective of whether they are qualitative or quantitative. As mentioned before, they can only help to reduce the arbitrariness of scenarios; they cannot be used to reject assumptions—in marked contrast to other methods, for example, those used in science. That means the findings of scenarios do not deliver "accurate" scientific knowledge. This peculiarity is often not emphasized enough when scenarios and their results are referred to. Scenarios are applied when uncertainty is involved.

9.2.4 Scenario Building

There are various ways of building scenarios; this section lists the most important steps (Heinecke and Schwager 1995). The following references reflect only a small part of the available literature: von Reibnitz (1988), Godet and Roubelat (1996), Schwartz (1996), Schwab et al. (2003), Börjeson et al. (2006), and Bishop et al. (2007). Note that the approaches presented in the literature may differ in detail, e.g. by focusing on particular steps or aggregating others.

The approach presented here is comprised of eight stages:

1. Problem analysis: The central objective of this stage is to provide a sufficiently precise identification and description of the problem to be investigated, explained for all persons involved in the scenario analysis, and to facilitate common understanding among the stakeholders. This serves as starting point

for the definition of individual steps in subsequent stages.

The problem analysis should include:

- A statement on the purpose of the scenarios to be developed, differentiating between normative and explorative objectives. This influences the definition of relevant target variable(s).
- A statement on the timeline over which the scenarios are to be developed.
- A statement on the operational (e.g. the company) or sectoral (e.g. bioeconomy) framework in which the analysis is to take place.
- A statement on the spatial framework, i.e. whether the investigation applies to a city, a region, or the world.

The four aspects mentioned are, of course, closely related and mutually interdependent.

2. Analysis of the framework: The objective is to specify the basic conditions in which the scenarios are to be developed and thus to define the final framework in which the scenario analysis is to take place.

   The analysis of the framework (sometimes also problem field), comprises four steps:
   - Specification of the system boundaries: Which elements of a system, e.g. sectors, should be included.
   - Determination of the relevant descriptors: Descriptors are values that characterize or describe partial aspects of the problem, for example, population trends, developments of market prices, and events.
   - Classification of the descriptors with regard to the control possibilities.
   - Identification of system interdependencies.
3. Assessment system: To evaluate the results of the scenario analysis, an assessment system has to be implemented. This may be fairly simple with just one indicator, e.g. income growth rate, or it may be an elaborated system with numerous indicators. The purpose of the scenarios determines the choice of indicators.
4. Scenario building (in the narrow sense of the word): Scenarios are developed based on the results of stages 1 and 2. Scenario development can be divided into five steps:
   (i) Identification of critical and noncritical descriptors: Noncritical descriptors are parameters whose changes in the planned timeline are considered to be relatively precise in their foreseeability. It is assumed that there will be no breaks in chronological trends or that any changes are relatively foreseeable (Heinecke and Schwager 1995). Noncritical descriptors can also include parameters considered unimportant for the overall system but which should be considered in the analysis for other reasons such as consistency. For example, in many scenarios the growth rate of gross domestic product is seen as noncritical. Critical descriptors, in contrast, are characteristics whose development is either regarded as essential to the analysis of the problem or whose future changes are subject to unforeseeable breaks in trends.
   (ii) Definition of the development of noncritical descriptors: in most cases, simplified forecasts.
   (iii) Definition of the development of critical descriptors: Since the influence of critical descriptors is per definition crucial to the system, an elaborated analysis of possible developments is highly recommended. Therefore, these descriptors also form the core of any sensitivity analysis.
   (iv) Formation of (raw) scenarios.
   (v) Compilation of complete (end) scenarios.
5. Scenario implementation: Each scenario developed in stage 4 describes a consistent set of assumptions regarding the development of the descriptors. These are inputted into the analysis framework defined in stage 2, to determine their effects on the causal problem or target variable(s). If the analysis framework

is captured, for example, by an algebraic model, the descriptors correspond to the exogenous variables of the model. Specifically, the effects of the descriptors on the target variable (s) can be calculated using an adequate solution algorithm. The results can be understood as alternative representations of future images with respect to the overall system under investigation.

6. Scenario evaluation: The future images determined in stage 5 are assessed in several steps:
    - Plausibility check: Are the findings plausible? For example, a negative gross demand is not plausible.
    - Consistency check: Are the findings consistent with respect to the assumptions? For example, if a close, positive correlation between demand and income is postulated, a decreasing demand with increasing income is inconsistent.
    - Sensitivity analysis: How robust are the findings with changes in relevant parameters?
    - Assessment of the findings, using the assessment system defined at stage 3.
    - Analysis of possible implications: This depends on the type of scenario. In exploratory scenarios, additional effects not covered in the scenario can be investigated. For example, an exploratory scenario could examine the effects of an increasing share of algae-based biogas on the future electricity mix, but not its effect on agriculture. The analysis of possible implications might address the latter aspect. In normative scenarios, questions on the implications of these prospects for the potential decision-maker may arise, e.g. which tools are available to the decision-maker to realize the respective future image? Which internal corporate groups or stakeholders should be taken into account by the decision-makers in order to identify the relevant instruments and to make their implementation more concrete?
7. Recommendations for action: If scenarios are used in decision-making contexts, the findings from stage 6 are expected to lead to recommendations for action. In contrast, if the analysed scenarios are solely for orientation purposes, i.e. explorative scenarios, information on possible developments is systematically generated. This stage can be dispensed with if the project is not based on a concrete decision-making situation.

    The recommendations strive to identify action alternatives for the decision-makers in order to solve the original challenge. They should include suitable instruments for solving the problem and describe their design. To increase the success of decisions, analysis of possible implications should also identify relevant groups, including stakeholders, who should be included in the decision-making process.
8. Summary: The results should be summarized in a form understandable to the client/addressee and enable them to make decisions where necessary. The summary should contain:
    - Central results
    - Central assumptions
    - Essential recommendations for action

The eight stages should not be understood as strictly sequential, but rather to be carried out according to specific requirements in the literature. This means that at each stage, newly acquired knowledge should be used to examine whether the chosen approach or assumptions, as well as the results from previous stages, need to be revised or adapted. Figure 9.3 demonstrates the interrelation between the individual steps.

In practice, a clear separation of the individual stages is not always possible. The correct order of stages 1–3 is arguable, and it soon becomes apparent that this is a chicken-and-egg situation. Ultimately it is up to the developers to decide at what stage they want to start or if they can even combine stages 1–3. For new participants, we would recommend separating these three stages

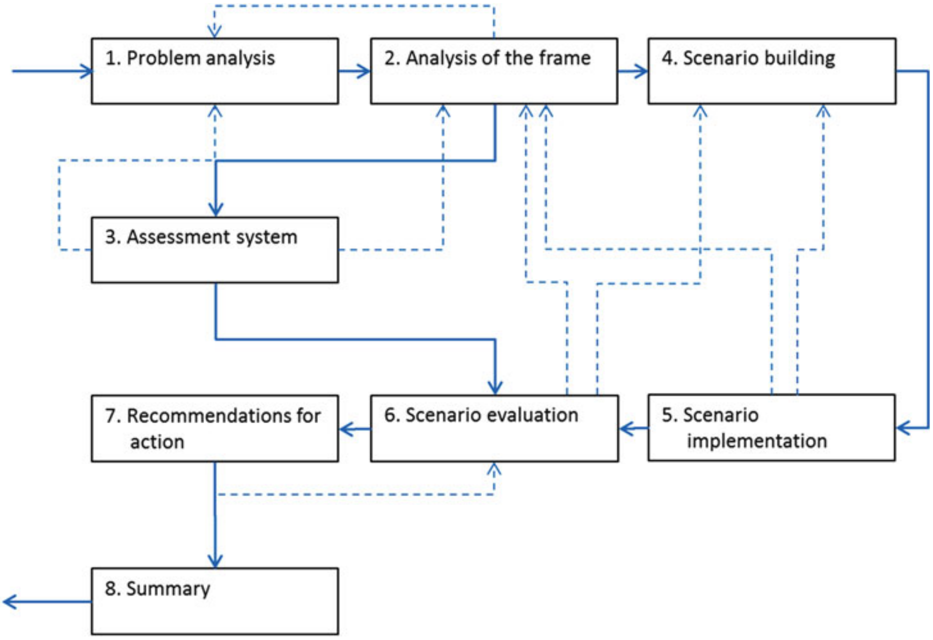

Fig. 9.3 Stages in scenario building

in order to keep track. Likewise, the order shown above has proven advantageous. By analysing the problem and the framework precisely at the beginning, the defining of utopian or irrelevant goals can be avoided. A reiterative approach can, however, also be recommended.

Finally, it should be emphasized once again that, in the creation of scenarios, it is extremely important to make clear what is being done where and for what reason. Even if in practice there are many deviations and special cases (see, e.g. "backcasting"), the structure shown here helps to make practitioners aware of the necessary steps and available options.

9.2.5 Conclusions

Scenarios can be a strong instrument in structuring discussions and supporting decision-makers, in particular if the object is the transformation of complex systems. But scenarios are not a panacea in the formation of a desired future:

- Scenarios are not forecasts or predictions; this also applies to reference or BAU scenarios. Scenarios never represent true future events.
- Scenario findings always depend on the initial conditions or "ingredients" with which they are created. Their selection always depends to a certain extent on the priorities set by the scenario builder. Therefore, they are never completely objective or impartial. As such, the initial conditions should remain as transparent as possible.

Scenarios do not offer a truth claim in the sense of scientific knowledge. The criterion of the falsifiability of scientific theories is not applicable. Therefore, it is necessary that scenarios fulfil the criteria discussed above (see Sect. 9.2.3).

9.3 Integrated Model Approaches: Identifying the Ways and Means

Models can make valuable contributions to the analysis of potential scenarios for a future bioeconomy. Due to the extensive interdisciplinary approaches and the high degree of economic integration in bioeconomy models, the requirements are however enormous. A central challenge for holistic modelling is that both economic and ecological connections and future social developments must be taken into account. Currently, there is no modelling approach that can cover all aspects of a developing bioeconomy (O'Brien et al. 2015).

Several studies have considered the necessary structure and requirements of model networks for the assessment of a prospective bioeconomy, including the project "Systems Analysis Tool Framework for the EU Bio-Based Economy Strategy" (SAT-BBE) within the EU 7th Framework Programme. This study elucidated the dependencies in modelling and showed how existing model approaches can contribute to the analysis of the entire "bioeconomy" complex. The study indicated that existing model approaches can be linked, however, some deficits and gaps in mapping the entire bioeconomy still have to be closed (van Leeuwen et al. 2015).

A multitude of drivers, such as demographic development and consumer preferences, influence the development of a bioeconomy (Fig. 9.4). In addition to drivers, societal challenges such as food security need to be taken into account. At the same time, natural (e.g. water, land scarcity) and socio-economic (e.g. education level, labour demand) constraints must also be considered. These data can be used to derive policy strategies for different sectors and protected subjects (van Leeuwen et al. 2015).

Based on this network of coherencies, it is possible to derive both substantive requirements and modelling levels for a comprehensive model network of the aforementioned relationships. The competition for land and forestry biomass for food, feed, fuel, and fibre can thus be represented

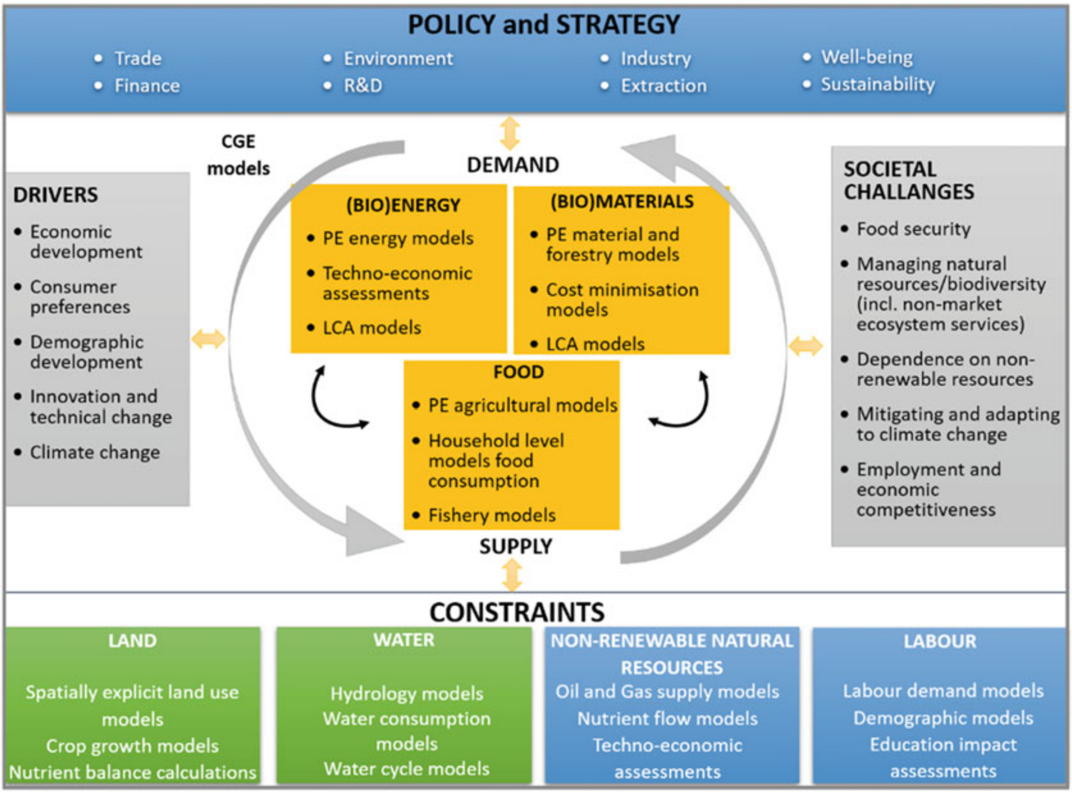

Fig. 9.4 System overview of the framework of a developing bioeconomy (based on van Leeuwen et al. 2015)

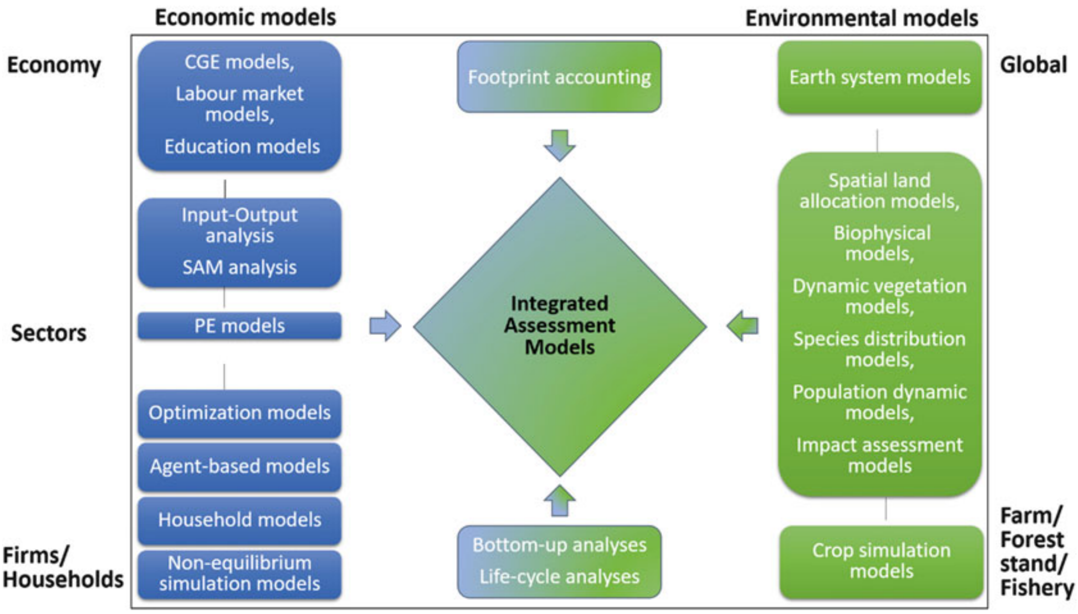

Fig. 9.5 Overview of model types and groups when evaluating development pathways of a bioeconomy (based on van Leeuwen et al. 2015)

by computable general equilibrium (CGE) models. However, a more precise assessment of possible competitive pressures should also be done at a sector or farm level. Since an increase in demand for biomass in a bioeconomy, e.g. in an industrialized country like Germany, will always be associated with a global impact, such impacts must be included in addition to the national perspective (Fig. 9.5).

9.3.1 Economic Models

This section provides an overview of different economic modelling approaches. Although the presented models were not originally developed for the bioeconomy context, they can still be used for modelling biomass supply and demand. The focus is on macroeconomic, computable general equilibrium (CGE) models and partial equilibrium (PE) models as well as bottom-up approaches for detailed analysis of specific questions within a bioeconomy.

Macroeconomic Models

CGE models are based on the general equilibrium theory; an economic theory, in simplified terms, seeks to explain the balance between supply and demand. These models are often used for trade analysis. PE models are also based on this neoclassical theory, but they focus on a specific market or sector. They are useful in obtaining a more detailed understanding of a particular sector.

1. Examples of CGE models

The *GTAP* (Global Trade Analysis Project) is a global network of researchers conducting quantitative analysis of international policy issues, coordinated by Purdue University in Indiana, USA. It provides a generalized CGE modelling framework along with a comprehensive database used for analysis in other CGE models. The standard GTAP model is a recursive dynamic CGE model. Its main applications are multilateral trade analysis and the effects of trade liberalization. It represents the linkages between sectors such as agriculture and energy and has been extended to the bioenergy field, specifically ethanol, biodiesel, and their by-products; the agricultural residue corn stover; the energy crops switchgrass and miscanthus for second-generation ethanol production; and palm oil residues (Wicke et al. 2015). The statistical base of a CGE is a so-called social accounting matrix (SAM). A SAM builds on a circular flow conception like input-output approaches and thus could be used independently of a CGE for macroeconomic analysis (cf. Poganietz et al. 2000).

The *MAGNET* (Modular Applied GeNeral Equilibrium Tool) is a recursive dynamic CGE model developed at the Landbouw Economisch Instituut (LEI; Wageningen University and Research, Netherlands) and builds on the GTAP database. It is the succession model of LEITAP (Landbouw Economisch Instituut Trade Analysis Project). It has a modular set-up with modules for mapping the EU Common Agricultural Policy (CAP) and biofuels and evaluates long-term, economy-wide upstream and downstream effects including price (Van Meijl et al. 2006). MAGNET was applied to analyse the macroeconomic impacts of large-scale deployment of biomass resources in the Netherlands (Hoefnagels et al. 2013), the macroeconomic impacts of a bio-based economy in Malaysia (van Meijl et al. 2012), and the global leakage effects of EU biofuel consumption (Smeets et al. 2014). Recently, MAGNET has been extended by additional bio-based sectors such as second-generation biofuels, bioelectricity, biochemicals, and biomass supply sectors for both residues from agriculture and forestry and pretreatments of agricultural residues that are utilized by other sectors (Banse et al. 2014). This extension specifically allows the impacts of developing and implementing new biomass conversion technologies to be evaluated.

2. Examples of PE models

GLOBIOM (Global Biosphere Management Model) is a global, economic partial equilibrium model for the agriculture and forestry sectors with high-resolution representation of global agriculture, forestry, and land-use change. It forms part of an integrated modelling framework at the International Institute for Applied Systems Analysis (IIASA; www.globiom.org). The model encompasses all countries including aggregations into 28 global regions. Its crops and forest sector details are based on physical parameters supplied by the more specialized models G4M for forestry and EPIC (Izaurralde et al. 2012) for agriculture. The global agricultural and forest market equilibrium is computed by choosing land-use and processing activities to maximize the sum of producer and consumer surplus subject to resource, technological, and policy constraints. GLOBIOM can be linked to energy models through information on macroeconomic indicators and bioenergy demand. The latter is split into first-generation biofuels, second-generation biofuels, bioenergy plants, and direct biomass use for energy. Issues analysed by GLOBIOM include the competition for land supply between agriculture, bioenergy, and forestry; examples are land-use change impacts of bioenergy policies, climate change mitigation policies, and food-versus-environment trade-offs (Kraxner et al. 2013).

CAPRI (Common Agricultural Policy Regionalised Impact) analysis is a spatial PE model focussing on the agricultural sector in Europe. It was developed to evaluate ex ante impacts of the EU Common Agricultural Policy and trade policies on agricultural production, income, markets, trade, and the environment from a global to regional scale. CAPRI can analyse a broad range of policy measures while taking agro-environmental impacts into account. The comparative-static economic model is split into a supply module and a market module. The supply module consists of independent non-linear programming models that represent activities of all farmers at regional or farm-type levels as captured by the economic accounts for agriculture. The market module delivers prices used in the supply module and enables market analysis at global, EU, and national scales as well as welfare analysis. The link between the supply and market modules is based on an iterative procedure. These modules are linked to regional CGE models for each European country with a specific focus on rural development measures under the second pillar of the CAP (www.capri-model.org).

ESIM (European Simulation Model) is a global PE model for the agricultural sector that represents agricultural production, various processing activities, and demand for agricultural products as well as international net trade (see Box 9.2). With its comprehensive model of the EU CAP, it is used to analyse EU agricultural and trade policies. It covers the EU member states and accession countries, the USA, and the rest of the world (the latter as one aggregate). It comprises the processing of oil seeds for biodiesel production and of cereals, sugar beet, and sugar cane for bioethanol; the production, use, and foreign trade in biofuels; and the production and use of side products (oil seed cakes, gluten feed) in livestock production (Deppermann et al. 2014). Recently, it has been extended to include lignocellulosic biomass such as miscanthus and poplar.

EFI-GTM (European Forestry Institute-Global Trade Model) is a multi-product, multiregional PE model for the global forest sector. It integrates increasing forest resources, timber supply, wood-using industries (e.g. carpentry, pulp, and paper industries), and demand for forest products and wood-based energy as well as international trade in forest products. The model specifically calculates periodic production, consumption, import and export quantities, and product prices for forest sector products. It has global coverage with a focus on Europe. It also allows detailed impact analysis of the forestry sector and detailed trade impacts through bilateral trade flow. It has been used to address issues such as increased investments in forest plantations in Asia and South America, increased demand for bioenergy, impacts of carbon emission prices and fossil fuel prices on the use of wood biomass for energy, and impacts of trade policies and forest conservation policies.

Economic Bottom-Up Models

There are a variety of bottom-up models that can answer a wide range of questions within the framework of an overall bioeconomic complex. For the most part, these models analyse very detailed technologies and processes as well as the behaviour of different players such as farms or energy plants. Furthermore, a large number of models exist that work at different spatial levels. This is of particular interest when analysing the availability and supply of biomass along with the related economic and ecological effects as well-defined system boundaries are included. These models can provide detailed insight into specific issues. However, as a rule, bottom-up models are not capable of producing indirect or induced effects (e.g. price responses, competition, replacement effects, and technological or structural changes) beyond their relatively narrow system limits (Wicke et al. 2015). For such purposes, they would need to be linked, for example, to the CGE or PE models mentioned above. Several examples of economic bottom-up models for different sectors and disaggregation levels are provided below:

1. Examples of agro-economic supply models

The model approaches presented here are suitable for simulating the adaptation reactions of farms or regions to changing political or technological conditions. Their methodology predominantly consists of mathematical linear or non-linear programming models that result in the quantity of agricultural products produced under relevant conditions. They are often developed in research projects for specific issues or locations only and are not used after the end of the project (Janssen et al. 2010). However, the following models, which are exemplary of the large number of existing agricultural bottom-up models, are firmly established in research facilities and have been continuously used and developed for various economic and environmental assessments of agricultural systems. Some farm-based models can be used at regional or sectoral levels with the help of projection methods.

FSSIM (Farm System Simulator) is an optimization model that maximizes the total gross margin under a set of resource and political constraints. It is a component-based framework with modules for mapping farmer objectives, risk, calibration, and both agricultural and environmental policy instruments as well as current, alternative, and future production activities. The model is designed as a generic bioeconomic farm model. Through its flexible design, it can be used for a variety of climate zones, soil types, farm types, research applications, and data sources (Janssen et al. 2010; Louhichi et al. 2010). For instance, FSSIM has been applied to 13 regions in the EU and to different farm types. FSSIM is also used to analyse the farm level (Ewert et al. 2011) within SEAMLESS ("System for Environmental and Agricultural Modeling; Linking European Science and Society"), an integrated modelling approach (see Sect. 8.4.3).

EFEM (Economic Farm Emission Model) simulates agricultural production on micro (farm)- and meso (regional)-levels. It is a supply model based on static linear programming. The prices for producers, production costs, and capacities for typical farms are exogenously determined. The model considers the most important agricultural production methods in animal and plant production in Germany. On a regional level, it differentiates with regard to yields, intensities, productivity, and costs. To display the required farm model capacities, either data from the Farm Accountancy Data Network (FADN) or survey data can be used. The model also calculates greenhouse gas emissions, other nitrogen fluxes, and carbon balances from agriculture production (Schwarz-v. Raumer et al. 2017). It has already been linked to various biophysical models (see Sect. 8.3.2) (Neufeldt et al. 2006; Wagner et al. 2015). For analysing possible bioeconomy development scenarios, it can be used in conjunction with other models in the "Competence Network Modelling the Bioeconomy" (see Box 9.2).

FARMIS (Farm Modelling Information System) is a comparative-static programming model for farm groups based on datasets from FADN. It maps agricultural production activities in detail at the farm level and accounts for competition between farms on important factor markets. Using a positive mathematical programming procedure, the model is calibrated to a respective base year. The use of aggregation factors enables the representation of agricultural sector production (Deppermann et al. 2014). It can currently be applied to the analysis of agricultural sectors of Germany, Great Britain, the Netherlands, Hungary, and Switzerland. Together with the CGE and PE models of the Thünen Institute, it has also been used to model the linkage between agricultural, energy, and agricultural markets in the context of the bioeconomy (Banse et al. 2016).

2. Examples of techno-economic optimization models for biomass supply chains

Biorefineries and bioenergy production sites often present two challenges that are difficult to combine in models. On the one hand, they require a certain plant size in order to operate economically. On the other hand, larger plants need a significant feedstock and associated supply area. Logistical costs often play an important role in the cost-effectiveness of such plants. For this reason, more and more optimization models have been developed in recent years to determine possible sites for bioenergy combustion plants or biorefineries. Two such models are presented below.

BeWhere is a spatially explicit, techno-economic engineering model for optimizing renewable energy systems. It is a mixed linear programming model and is used at the International Institute for Applied Systems Analysis (IIASA) to evaluate localization, size, and technology of the renewable energy system (IIASA 2017). It can be applied at both national and EU level. In the area of biomass use for energy purposes, BeWhere minimizes the costs of the complete bioenergy supply chain, including biomass harvest and transport, conversion, transportation, and delivery of biofuel and heat and electricity sales. A great variety of feedstocks can be considered in the model. Nevertheless, the focus is on second-generation biofuels, and therefore crop residues, forestry waste, and lignocellulosic industrial waste are included (Wetterlund et al. 2013).

BiOLoCaTe (Biomass value chain integrated Optimization for Location, Capacity, and Technology planning) is also a mixed linear programming model that is used to optimize biomass supply chains. This techno-economic assessment includes supply, logistics, and conversion processes and is based on achievable profit from revenue generated from selling either electricity and thermal energy or bio-based materials. The model results can be used to support decisions in regional planning of biomass-based value chains (Rudi et al. 2017). In contrast to BeWhere, it is not only used for evaluating renewable energy systems but also bio-based material production systems. Currently it is only applied in Baden-Wuerttemberg (a federal state in southwest Germany) but can also be adapted to other regions or countries. Like EFEM, it is used for holistic analysis of possible developmental paths of a bioeconomy in the "Competence Network Modelling the Bioeconomy" (see Box 9.2; Schultmann and Rudi 2017).

3. Example of an energy system model

The energy sector is generally integrated either through CGE models or with the help of PE models. An example of a disaggregated, bottom-up model is *TIMES PanEU* (Pan-European TIMES model), which has been applied in several analyses of the European energy system (see Box 9.2). The model minimizes an objective function by representing the total discounted system costs from 2010 to 2050 and assumes perfect competition among various technologies and pathways of energy conversion and supply. It is a multiregional model that covers, at the country level, all sectors connected to energy supply and demand. TIMES PanEU includes all countries of the EU28 along with Switzerland and Norway. In addition, both GHG emissions and pollutant emissions are included by incorporating process-specific emissions.

The model is flexible in terms of regionalization (for instance, within Germany), and both energy and nonenergy bioenergy use options in the energy system or modelled technology pathways. A detailed analysis of competition between alternative technologies and energy use of biomass paths can be taken into account for the overall economic perspective (Blesl et al. 2012; Deppermann et al. 2016).

9.3.2 Ecological and Biophysical Models

The transformation from a petroleum-based economy to a bio-based economy will inevitably lead to increased demand for agricultural and forestry biomass. This may result in increased biomass production in certain countries and on a global scale. However, this may also lead to a conflict of interest with environmental and nature conservation. As such, not only the economic aspects but also the ecological effects of a developing bioeconomy should be taken into account. Since agricultural and forestry production is systematically linked to the use of natural resources, a large number of models have been developed over the past few decades to simulate these environmental effects.

Biophysical models are process-based models that represent biological, geological, and chemical processes in environmental systems. These include, but are not limited to, crop growth and soil physical models. Some models examine a wide range of environmental impacts of agricultural and forestry management systems. Others also examine different scales from plot to farm, region, and global levels. Some models were originally developed and validated for smaller area units but were extended to regional and global scales due to greater demand for agricultural and environmental policy assessment measures. At the beginning of 2000, substantial political and scientific focus was put on evaluating agricultural greenhouse gas emissions, which resulted in numerous economic models being combined with biophysical models at a regional level. In particular, soil greenhouse gas emissions could be clearly captured, and at the same time, the costs of possible mitigation options could be assessed. For example, the models CAPRI and EFEM mentioned above were linked with the biophysical models DNDC (DeNitrification-DeComposition) and EPIC (Environmental Policy and Integrated Climate) (Neufeldt et al. 2006; Britz and Leip 2009; Schwarz-v. Raumer et al. 2017). EPIC is also integrated into various integrated assessment models (Kraxner et al.

2013; Zessner et al. 2017) and is described below as an example of the functions of biophysical models.

Examples of Ecological and Biophysical Models
EPIC (Environmental Policy and Integrated Climate) was originally developed at the US Department of Agriculture to study the effect of agricultural production on erosion and soil productivity. Since its creation, it has been further developed by several research institutes into a comprehensive terrestrial ecosystem model for simulating numerous ecosystem processes that can also take a wide range of land-use management options into account (e.g. tillage, harvest, fertilization, irrigation, drainage, liming, burning, and pesticide application). The main components in EPIC are crop growth, weather simulation, hydrology, nutrient and carbon cycling, soil temperature and moisture, soil erosion, tillage, and plant environment control (Izaurralde et al. 2012; Balkovič et al. 2013). When combined with economic models or model networks to assess agricultural and forestry biomass production, EPIC can be used to address two major research questions: the effect of changing environmental conditions on biomass production, e.g. forecast crop yields impacted by climate change ((Kraxner et al. 2013; Kirchner et al. 2015), and the impacts of different management options for biomass production on the environment, e.g. erosion, nitrogen leaching, or soilborne greenhouse gas emissions (Schwarz-v. Raumer et al. 2017).

The soil-crop model *CERES-EGC* functions in a similar way to EPIC. It has been used for more than 20 years to investigate the environmental effects of crop cultivation such as nitrate leaching, soil greenhouse gas emissions, and ammonia and nitrogen oxides (Durandeau et al. 2010). CERES-EGC can also be used to predict yields of the most important agricultural crops (Mavromatis 2016). Both models can be used at field and regional scales.

LPJmL (Lund-Potsdam-Jena managed Land) is an example of a Dynamic Global Vegetation Model (DGVM) that was designed to simulate the global terrestrial carbon cycle as well as the response of carbon and vegetation patterns to climate change. It was developed by a consortium of scientists from the Max Planck Institute for Biogeochemistry in Jena, the Potsdam Institute for Climate Impact Research, and Lund University. To study the role of the biosphere in the anthroposphere, it is crucial to represent both natural and agricultural ecosystems in a single, internally consistent modelling framework. The model is designed to simulate composition and distribution of vegetation as well as stocks and land-atmosphere exchange flows of carbon and water for both natural and agricultural ecosystems. Using a combination of plant physiological relations, generalized empirically established functions, and plant trait parameters, the model simulates processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, run-off, evapotranspiration, irrigation, and vegetation structure. Consequently the model facilitates integration of agricultural systems into the global climate-vegetation system (PIK 2017; Bondeau et al. 2007). Within the framework of the PIK model network, LPJmL is linked to MAgPIE (Model of Agricultural Production and its Impact on the Environment) and REMIND, a global multiregional model incorporating the economy, climate system, and a detailed energy sector.

9.3.3 Land Use and Biodiversity in Life Cycle Assessment

Although a bioeconomy strives to be sustainable, associated technologies consume resources and cause environmental impacts. These technological, process-, or product-related impacts can be calculated and compared using the standardized life cycle assessment (LCA) method. Specifically, in order to obtain a holistic view of the product chain, a life cycle perspective is necessary. A more in-depth description of LCA is given in Sect. 8.3. In this chapter, the focus is on integrating land use and biodiversity aspects into LCA.

The importance of land and its related ecosystem services gained attention through the Millennium Ecosystem Assessment (MEA). It was conducted from 2001 to 2005 under the auspice of the United Nations. The aim of the MEA was to assess the consequences of anthropogenic changes in ecosystems on human well-being and to provide the scientific basis for needed measures for a sustainable use of ecosystems (Millennium Ecosystem Assessment 2005). The study underscored the global dependency of mankind on nature with ecosystem services as the basis for a healthy and safe life. As about 50% of earth's land area is strongly affected by mankind (Hooke et al. 2012), land use has enormous effects on ecosystem services and biodiversity. Therefore, in order to cover all relevant environmental impacts of a product or process, land-use aspects that impact ecosystem services and biodiversity ought to be integrated into analysis methods such as life cycle assessment. In recent years, methods for considering impacts on ecosystem services and biodiversity have been successfully developed and applied in LCA.

Fundamental to integrating effects on ecosystem services and biodiversity in LCA is the concept of occupation and transformation of land use. The term occupation means the situation of a studied patch of land, while it is used. It is assumed that there is no change in ecosystem quality during the entire period of use (e.g. 20 years for a short rotation coppice). Occupation is expressed as the level of ecosystem quality during use compared to a specific reference quality. In contrast, the term transformation defines a change in ecosystem quality of a studied patch that occurs between the initial quality of the ecosystem and the end quality after the use phase ends and the land is regenerated.

LANCA® (Land Use Indicator Value Calculation Tool) is an approach to integrate the impacts on ecosystem services into LCA (Beck et al. 2010; Bos et al. 2016). It was developed at the University of Stuttgart, Department of Life Cycle Engineering (Baitz 2002) and has been applied in many projects. In LANCA®, indicator values are calculated that describe the environmental impacts of land-intensive processes on various ecosystem services, which are then integrated into the life cycle assessment. The following environmental impact categories are calculated on the basis of (geo-)ecological methods: erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration, and biotic production. In 2016, LANCA® 2.0 was produced which allowed for GIS-based calculations of the five land-use-related environmental impact categories. Country-specific characterization factors (CF) can now be calculated (Bos et al. 2016).

The *biodiversity potential field approach* (Lindner 2015) understands biodiversity as a fuzzy object. Existing approaches integrating biodiversity aspects into LCA often focus on species richness of landscape types (Koellner and Scholz 2007, 2008; Baan et al. 2013; Chaudhary et al. 2015). According to the biodiversity potential field approach, biodiversity of a patch of land is defined as a function of several parameters, e.g. structural elements, pesticide input, nutrient balance, biomass utilization rate, and crop diversity. The biodiversity potential field of a region thus describes the relationships within that region. For aggregating impacts of global value chains, weighting factors are defined for the respective regions. These are based on the species richness of the regions and the rarity of the species occurring in the regions. The result of this approach is a universal measure of biodiversity that is sensitive with regard to the most important influencing factors.

LCA has a bottom-up perspective and can give evidence for the environmental performance of a product. Therefore, the results of a LCA can serve as input data for other models such equilibrium models:

- If models like EFEM for regional supply of agricultural biomass are, for example, extended to the aspect of land use and biodiversity through a linkage with LANCA®, comprehensive statements can be made about the supply of agricultural biomass and its environmental impacts.
- By integrating LCA results, e.g. for impact categories such as climate change and acidification, in partial equilibrium models such as ESIM, these models can be strengthened by the LCA results as environmental statements

on the shifting effects of changing demand for certain agricultural products can be drawn in addition to economic statements.

9.3.4 Integrated Assessment Models

The idea of integrated assessment models (IAMs) is to design and assess interactions between human activities and the natural environment. To do so, models that depict either anthropogenic or (bio)physical systems are coupled. The envisaged integration can refer to the analysis of coherent problems and to the integration of stakeholders, disciplines, processes, and models at both temporal and spatial scales. This can be done in interdisciplinary and integrated approaches as stand-alone models or in a framework of multiple, coupled models that focus on various topics or scales and which originate from different disciplines (Wicke et al. 2015). All models described above can be part of such a modelling collaboration.

Integrated Assessment Models (IAMs)
IAMs describe and assess the interactions between human activities and (global) environmental processes. They include descriptions of socio-economic systems as well as environmental systems and the interactions between the two.

The main advantage of IAMs is they overcome the limits of models that focus on specific topics, e.g. on the agricultural or the energy sector, without considering impacts of human activities on (bio)physical systems. By coupling different models, IAMs can cover a range of different disciplines and fields of research including economics, energy analysis, agriculture analysis, and biophysical science, thus bridging the economic, social, and environmental dimension of bioeconomic developments. With respect to a bioeconomy, IAMs could elucidate implications for both energy systems and natural systems such as land and water use and interactions with global cycles such as carbon in an integrated manner.

Models can be linked in several ways to achieve an integrated assessment (Wicke et al. 2015):

- Align and harmonize input data for the different models and levels of aggregation, e.g. the number of economic sectors and scenario definitions.
- Align and harmonize core assumptions: if this is not possible, at least a systematic comparison of results and sensitivities should be carried out to reveal differences between models to a greater depth.
- Link models: integrate model ranges by using results from one model as inputs for another model (one-way data exchange) or iterating inputs (two-way data exchange) through partial integration via a simplified version of one model in another model, or full integration solving models simultaneously is also a way.

An alternative distinction within linking models is often made between soft links, i.e. where models are connected exogenously through transferring outcomes of model runs from one model to another, and hard links, i.e. where models directly exchange information and are solved iteratively so that the solutions are internally consistent between the models. Soft links allow for more components to be included but require careful coordination of data flows to avoid unnoticed inconsistencies between models. In contrast, hard links allow for more consistent representation of the systems yet increase complexity and reduce transparency (Leimbach et al. 2011).

One well-known transdisciplinary IAM is IMAGE (Integrated Model to Assess the Global Environment), developed at PBL Netherlands Environmental Assessment Agency. IMAGE simulates global environmental change induced by human activities and can be applied in the DPSIR framework for reflecting a systems analysis view on the relationship between

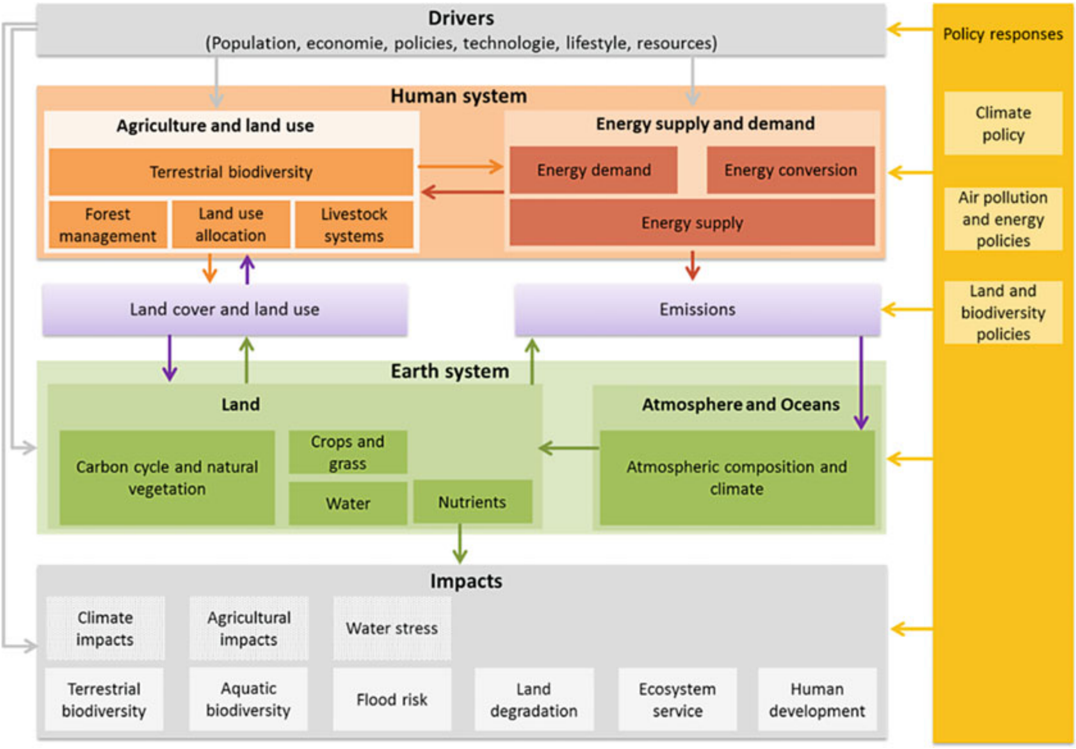

Fig. 9.6 The IMAGE 3.0 framework (http://themasites.pbl.nl/models/image/index.php/IMAGE_framework)

environmental system and anthropogenic system. The framework consists of drivers, pressures, state, impact, and responses (Smeets and Weterings 1999).

IMAGE combines a number of existing models such as MAGNET (agricultural economics), GLOBIOM (biodiversity), and FAIR (climate policy). The objective of IMAGE is to model the long-term dynamics of global change caused by demographic, technologic, economic, social, cultural, and political factors (Fig. 9.6).

Table 9.4 lists a comprehensive overview of previously described model approaches. The application areas of the different model approaches along with their strengths and weaknesses make clear that only the use of multiple approaches at different modelling levels will provide a holistic view of a complex bioeconomy. This can be achieved by either coupling otherwise independent model approaches or within the framework of an IAM.

Box 9.2: Competence Network Modelling the Bioeconomy

The competence network modelling the bioeconomy established within the Bioeconomy Research Programme Baden-Württemberg is another example of a modelling network aimed at integrated assessments bridged across disciplines and scales. Besides the models EFEM, ESIM, TIMES PanEU, BiOLoCaTe, and GaBi a LCA Software, the competence network integrates the CGE model PACE and the material flow model CarboMoG. The models in the network are linked at various stages (Fig. 9.7). All models were harmonized with regard to defined bioeconomy scenarios. The goal of the competency network was to compare and evaluate both the direct and indirect economic, material, and ecological effects of different

(continued)

Box 9.2 (continued)

biomass usage pathways. Such a framework allowed for comparing economic costs and benefits of different bioeconomy scenarios. Economic benefits resulted from the improvement of environmental quality or the further development of certain sectors of the economy, while economic costs arose from income losses as well as increased biomass imports, which could have impacts on the environment in other parts of the world.

Table 9.4 Overview and characteristics of the most important model approaches for holistic modelling and assessing a bioeconomic development path (based on Wicke et al. 2015)

	CGE models	PE models	Bottom-up analysis	IAMs
Application	Economy-wide impacts of biomass and bioenergy policies, including subsequent effects on land-use change and GHG emissions induced by these policies Indirect substitution, land use, and rebound effects due to multiple sectors and production factors	Sectoral impacts of bioenergy policies on agriculture, forestry, land-use change, energy system, and GHG emissions	Wide variety of specific (technical) aspects of biomass production, conversion, and use Validation of other studies with a broader scope, such as PE and CGE models and IAMs	Bioenergy resource potentials under different assumptions (incl. sustainability criteria) Possible contribution of bioenergy to long-term climate policy Impacts of bioenergy policies on global land use, water, and biodiversity
Typical timeframe	Short to long term	Short to medium term	Short to long term	Long term
Strengths	Comprehensively covers both economic sectors and regions to account for interlinkages Can explicitly models limited economic resources Measures the total, economy-wide, and global effects of bioenergy policies (including indirect and rebound effects)	Covers in detail sectors of interest with full market representation Explicitly represents biophysical flows and absolute prices Usually gives more details on regional aspects, policy measures, and environmental indicators	Gives detailed insights into techno-economic, environmental, and social characteristics and impacts of bio-based systems	Integrates various relevant systems into one modelling framework Possibility to analyse feedbacks between human and nature systems and trade-offs and synergies of policy strategies Built around long-term dynamics
Limitations	Level of aggregation may mask variation in underlying constituent elements Scope of CGE models necessitates simplified representation of agent choices, in particular favouring smooth mathematical forms and reduced number of parameters required to calibrate the models Often none or few explicit representations of quantities for biophysical flows	Optimizes agent welfare, but only for the sectors included in the model Does not consider macroeconomic balances and impacts on not-represented sectors Needs large number of assumptions for long-term projections	Indirect and induced effects outside the boundaries of the study not included, i.e. interactions with other sectors often deliberately ignored	Too high a level of aggregation or systems too complex Unsuitable for short-term assessments Requires large number of assumptions (and communication of these to the public)

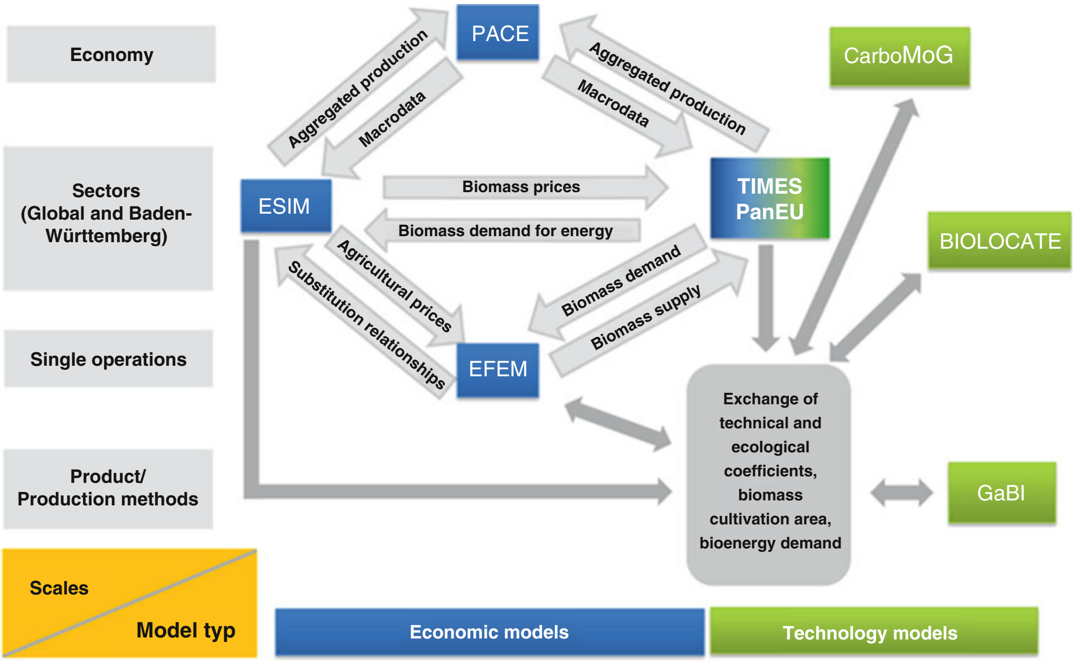

Fig. 9.7 Competence network modelling the bioeconomy Baden-Württemberg

9.4 Conclusions: So What?

Increasing scarcity of fossil and metal resources in addition to the tremendous impacts on both the natural environment and human health during extraction as well as during manufacturing, use, and disposal requires a radical change in current strategy of generating wealth and income. Yet, as described, transforming an economic development strategy at first and consequently the entire economy must be done in a rather complex environment. Not only are the underlying economic and physical interdependencies not always known in detail, but also the preferences, interests, and ideas on how a future economy should work differ widely in society. Therefore, instruments are required to help society elaborate the "best" future.

In this chapter, two widely used instruments are presented: scenarios and algebraic models. Whereas scenarios strive to help "reveal the possible trails" of possible futures, models are used in "identifying the ways and means" of future paths. In practice, models are often directly linked to scenario exercises.

Scenarios can present alternative futures based on assumptions and modelling results from diverse tools like CGE models, IAM models, and environmental profiles of products from life cycle assessments. As scenarios cannot present the realistic future, they instead give an indication of how the transformation would look like if certain objectives were reached as well as what could happen if there was no change in lifestyle. A discussion of scenarios or modelling results is especially helpful in raising awareness of possible unwanted and unsustainable development.

Through interdisciplinary networking, exchanging, and production of data, various models can be made more consistent thus resulting in more harmonized and realistic results. The higher the quality of the input data in representing possible and achievable future conditions, the more realistic is the output of the scenarios in question. That means discourse in analytics, science, politics, business, and society on objectives and system boundaries of the global future is required in order to draw a common picture of our future.

Within this chapter, the following was provided: an overview of the scenario approach, different types of models and their possibilities, and both the chances and limits of using scenarios to forecast the future. There are many models and assessment tools that can be used to support the transition process to a bioeconomy when using their modelling results in scenarios. Our selection of included models is only a small part of the variety of modelling approaches and is certainly not the be-all and end-all. Modelling approaches and theories are undergoing constant development and must also be constantly reconsidered.

All the presented models, tools, and different types of scenarios can assist in picturing possible futures and can support transitioning to a bioeconomy. However, by no means can they predict the future. Still, the transformation cannot take place through maintaining the present, Western civilization lifestyle nor by expanding this lifestyle to the whole world. Humanity must change its way of life to reach a sustainable bioeconomy.

Review Questions

- The expectations for a viable bioeconomy are enormous. What drivers and societal challenges affect a developing bioeconomy? Thus, what difficulties result for a holistic modelling of future scenarios of bioeconomy?
- A main disadvantage of scenarios is often seen in their shortcoming to offer verifiable scientific knowledge. Why could this be seen as a disadvantage in the building of a strategy for a viable bioeconomy? Are there any approaches to limit the risks resulting from the above-mentioned disadvantage?
- Börjeson et al. (2006) differ between three types of scenarios. How the three types could be characterized? Under which understanding predictive scenarios are not mere predictions? Why explorative scenarios could need normative elements?

References

Alcamo J (2008) Environmental futures: the practice of environmental scenario analysis. Elsevier, Amsterdam

Appelrath HJ, Dieckhoff C et al (2016) Consulting with energy scenarios. Requirements for scientific policy advice, München

Baan L de, Alkemade R, Koellner T (2013) Land use impacts on biodiversity in LCA: a global approach. Int J Life Cycle Assess 18(6):1216–1230.

Baitz M (2002) Die Bedeutung der funktionsbasierten Charakterisierung von Flächen-Inanspruchnahmen in industriellen Prozesskettenanalysen: Ein Beitrag zur Ganzheitlichen Bilanzierung. Dissertation, Universität Stuttgart, Stuttgart.

Balkhausen O, Banse M, Grethe H (2008) Modelling CAP decoupling in the EU: a comparison of selected simulation models and results. J Agric Econ 1(59):57–71

Balkovič J, van der Velde M et al (2013) Pan-European crop modelling with EPIC: implementation, up-scaling and regional crop yield validation. Agric Syst 120:61–75

Banse M, Junker F et al (2014) Global impact of multinational biofuel mandates on land use, feedstock prices, international trade and land-use greenhouse gas emissions. Landbauforschung Volkenrode 64 (2):59–72

Banse M, Janzen N et al (2016) Modelling the bioeconomy: linkages between agricultural, wood and energy markets. Johann Heinrich von Thünen-Institut, Braunschweig. http://literatur.thuenen.de/digbib_extern/dn056932.pdf. Accessed 29 Mar 2017

Beck T, Bos U et al (2010) LANCA®: Land use indicator value calculation in life cycle assessment. Fraunhofer, Stuttgart

Bishop P, Hines J, Collins T (2007) The current state of scenario development: an overview of techniques. Foresight 9:5–25

Blesl M, Kober T et al (2012) Implications of different climate protection regimes for the EU-27 and its member states through 2050. Clim Pol 12(3):301–319

Bondeau A, Smith PC et al (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biol 13 (3):679–706

Börjeson L, Höjer M et al (2006) Scenario types and techniques: towards a user's guide. Futures 38:723–739

Bos U, Horn R et al (2016) LANCA®—Characterization factors for life cycle impact assessment. Version 2.0. Fraunhofer, Stuttgart

Britz W, Leip A (2009) Development of marginal emission factors for N losses from agricultural soils with the DNDC–CAPRI meta-model. Agric Ecosyst Environ 133(3):267–279

Brown N, Rappert B, Webster A (2000) Contested futures: a sociology of prospective techno-science. Taylor and Francis, Florence

Chaudhary A, Verones F et al (2015) Quantifying land use impacts on biodiversity: combining species-area models and vulnerability indicators. Environ Sci Technol 49(16):9987–9995

Deppermann A, Grethe H, Offermann F (2014) Distributional effects of CAP liberalisation on western German farm incomes: an ex-ante analysis. Eur Rev Agric Econ 41(4):605–626

Deppermann A, Blesl M et al (2016) Linkages between the energy and agricultural sectors: insights from European Union greenhouse gas mitigation scenarios. Mitig Adapt Strat Global Change 21(5):743–759

Durandeau S, Gabrielle B et al (2010) Coupling biophysical and micro-economic models to assess the effect of mitigation measures on greenhouse gas emissions from agriculture. Clim Change 98(1-2):51–73

European Commission (2012) Innovating for sustainable growth: a bioeconomy for Europe

Ewert F, van Ittersum MK et al (2011) Scale changes and model linking methods for integrated assessment of agri-environmental systems. Agric Ecosyst Environ 142(1–2):6–17

Godet M, Roubelat F (1996) Creating the future: the use and misuse of scenarios. Long Range Plann 29 (2):164–171

Grunwald A (2002) Technikfolgenabschätzung: Eine Einführung. Edition Sigma, Berlin

Grunwald A (2011) Energy futures: diversity and the need for assessment. Futures 43:820–830

Hagemann N, Gawel E et al (2016) Possible futures towards a wood-based bioeconomy: a scenario analysis for Germany. Sustainability 8(2):98

Havas A (2014) The benefits of foresight. volta 06:16–18

Heinecke A, Schwager M (1995) Die Szenario-Technik als Instrument der strategischen Planung, Braunschweig

Hoefnagels R, Banse M et al (2013) Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level—a combined approach for the Netherlands. Energ Pol 59:727–744

Höjer M, Mattsson LG (2000) Determinism and backcasting in future studies. Futures 32(7):613–634

Hooke RL, Martín-Duque JF, Pedraza J (2012) Land transformation by humans: a review. GSA Today 22 (12):4–10

IIASA (2017) BeWhere Model description. http://www.iiasa.ac.at/web/home/research/modelsData/Bewhere/BEWHERE1.en.html. Accessed 4 Apr 2017

Izaurralde RC, McGill WB, Williams JR (2012) Development and application of the epic model for carbon cycle, greenhouse gas mitigation, and biofuel studies. In: Liebig M, Franzluebbers AJ, Follett RF (eds) Managing agricultural greenhouse gases, 1st edn. Academic, Cambridge, MA, pp 293–308

Jansen MM (2002) The making of modern Japan, 3rd edn. Harvard University Press, Cambridge, MA

Janssen S, Louhichi K et al (2010) A generic bio-economic farm model for environmental and economic assessment of agricultural systems. Environ Manag 46(6):862–877

Johnson C (1982) MITI and the Japanese miracle: the growth of industrial policy, 1925-1975. Stanford University Press, Stanford

Kahn H, Wiener A (1967) The year 2000: a framework for speculation on the next thirty-three years. Macmillan, New York

Kalman RE (1963) Mathematical description of linear dynamical systems. J Soc Ind Appl Math Ser A Contr 1(2):152–192

Kirchner M, Schmidt J et al (2015) Ecosystem services and economic development in Austrian agricultural landscapes—the impact of policy and climate change scenarios on trade-offs and synergies. Ecol Econ 109:161–174

Koellner T, Scholz RW (2007) Assessment of land use impacts on the natural environment: Part 1: An analytical framework for pure land occupation and land use change. Int J Life Cycle Assess 12(1):16–23

Koellner T, Scholz RW (2008) Assessment of land use impacts on the natural environment: Part 2: Generic characterization factors for local species diversity in Central Europe. Int J Life Cycle Assess 13 (1):32–48

Kosow H, Gaßner R (2008) Methods of future and scenario analysis: overview, assessment, and selection criteria. German Development Institute, Bonn

Kovacs B (ed) (2015) Sustainable agriculture, forestry and fisheries in the bioeconomy: a challenge for Europe. 4th SCAR Foresight Exercise. Publications Office of the European Union, Luxembourg

Kraxner F, Nordström EM et al (2013) Global bioenergy scenarios—future forest development, land-use implications, and trade-offs. Biomass Bioenergy 57:86–96

Leimbach M, Popp A, Lotze-Campen H, Bauer N, Dietrich JP, Klein D (2011) Integrated assessment modelsthe interplay of climate change, agriculture and land use in a policy tool. In: Handbook on climate change and agriculture, p 204

Lindner JP (2015) Quantitative Darstellung der Wirkungen landnutzender Prozesse auf die Biodiversität in Ökobilanzen. Universität Stuttgart, Stuttgart

Louhichi K, Kanellopoulos A et al (2010) FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agric Syst 103(8):585–597

Mavromatis T (2016) Spatial resolution effects on crop yield forecasts: an application to rainfed wheat yield in north Greece with CERES-Wheat. Agric Syst 143:38–48

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. A report of the Millennium Ecosystem Assessment. Island Press, Washington, DC

Minx E, Böhlke E (2006) Denken in alternativen Zukünften. IP Dezember:14–22

Neufeldt H, Schäfer M et al (2006) Disaggregated greenhouse gas emission inventories from agriculture via a coupled economic-ecosystem model. Agric Ecosyst Environ 112(2):233–240

O'Brien M, Wechsler D et al (2015) Sachstandsbericht über vorhandene Grundlagen und Beiträge für ein Monitoring der Bioökonomie: Systemische Betrachtung und Modellierung der Bioökonomie. Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal

OECD (2009) The bioeconomy to 2030: designing a policy agenda, 1st edn. OECD, Paris

PIK (2017) LPJmL—Lund-Potsdam-Jena managed Land. https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml

Poganietz WR, Zezza A et al (eds) (2000) Perspectives on agri-culture in transition: analytical issues, modelling approaches, and case study results. Vauk, Kiel

Popper KR (2008) The logic of scientific discovery, Repr. 2008 (twice). Routledge, London

Rescher N (1998) Predicting the future: an introduction to the theory of forecasting. State University of New York Press, Albany, NY

Rudi A, Müller AK et al (2017) Biomass value chain design: a case study of the Upper Rhine Region. Waste Biomass Valorization 31(6):657

Schippl J, Leisner I (2009) Backcasting in transport: scenarios for the future of European long-distance transport. Technikfolgenabschätzung—Theorie und Praxis 18(2):63–69

Schultmann F, Rudi A (2017) Quantitative assessment of regional biomass-based value chains. http://www.bioeconomy-research-bw.de/en/tp116. Accessed 5 Apr 2017

Schwab P, Cerutti F, von Reibnitz C (2003) Foresight-using scenarios to shape the future of agriculture research. Foresight 5(1):55–61

Schwartz P (1996) The art of long view: planning for the future in an uncertain world. Doubleday, New York

Schwarz-v. Raumer HG, Angenendt E et al (2017) Economic and ecological impacts of bioenergy crop production—a modeling approach applied in Southwestern Germany. AIMS Agric Food 2:75

Smeets E, Weterings R (1999) Environmental indicators: typology and overview. European Environment Agency, Copenhagen, p 19

Smeets E, Tabeau A et al (2014) The impact of the rebound effect of the use of first generation biofuels in the EU on greenhouse gas emissions: a critical review. Renew Sustain Energ Rev 38:393–403

van Leeuwen M, Van Meijl H, Smeets E (2015) Design of a systems analysis tools framework for a EU bioeconomy strategy (Deliverable 3.3): overview of WP3 in the EU FP 7 SAT—BBE project. Funded by the European Commission, DG Research, Brussels. http://www3.lei.wur.nl/satbbe/PublicationDetail.aspx?id=19. Accessed 18 May 2017

Van Meijl H, Van Rheenen T et al (2006) The impact of different policy environments on agricultural land use in Europe. Agric Ecosyst Environ 114(1):21–38

van Meijl H, Smeets E et al (2012) Macro-economic impact study for biobased Malaysia: LEI report 2012-042

Verbong G, Loorbach D (eds) (2012) Governing the energy transition: reality, illusion or necessity? Routledge, New York

von Reibnitz UH (1988) Scenario techniques. McGraw-Hill, Hamburg

Wack P (1985) Scenarios: uncharted waters ahead. Harv Bus Rev 63:72–79

Wagner S, Angenendt E et al (2015) Costs and benefits of ammonia and particulate matter abatement in German agriculture including interactions with greenhouse gas emissions. Agric Syst 141:58–68

Weimer-Jehle W, Buchgeister J et al (2016) Context scenarios and their usage for the construction of socio-technical energy scenarios. Energy 111:956–970

Wetterlund E, Leduc S et al (2013) Optimal use of forest residues in Europe under different policies-second generation biofuels versus combined heat and power. Biomass Convers Biorefinery 3(1):3–16

Wicke B, van der Hilst F et al (2015) Model collaboration for the improved assessment of biomass supply, demand, and impacts. GCB Bioenergy 7(3):422–437

Zessner M, Schönhart M et al (2017) A novel integrated modelling framework to assess the impacts of climate and socio-economic drivers on land use and water quality. Sci Total Environ 579:1137–1151

10

Environmental Economics, the Bioeconomy and the Role of Government

Michael Ahlheim

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Abstract

The bioeconomy serves the goals of resource saving and of reducing environmental pollution and is, therefore, in accordance with principles of sustainable development. Since private markets alone fail to serve these goals successfully, the government is called for to promote the bioeconomy in order to ensure a sustainable development of the economy.

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In this chapter the concept of sustainability, which is essentially an intertemporal concept, is introduced. Thereafter, the basic principles of resource economics, i.e., the optimal use of natural resources over time, are discussed using a simple intertemporal model. Reasons for market failure in the environmental sector are discussed along with various governmental instruments and policies to address the different kinds of market failure.

Keywords
Social welfare • Utility function • Pareto optimum • Sustainability • Market failure • Government policies • Externalities • Public goods • Common-pool goods

Learning Objectives
After studying this chapter, you should know:

- The main concepts of sustainability
- The optimal exploitation of a nonrenewable resource over time
- The main causes of market failure in an environmental context
- Instruments of government policy in the bioeconomy

10.1 Introduction

Article 56 of the German Basic Law states the oath of office that has to be taken by the Federal President, the Federal Chancellor, and the Federal Ministers of the German Government:

> I swear that I will dedicate my efforts to the well-being of the German people, promote their welfare, protect them from harm, uphold and defend the Basic Law and the laws of the Federation, perform my duties conscientiously, and do justice to all. So help me God. (Art. 56 Basic Law for the Federal Republic of Germany)

Expressed in terms of welfare economics, this means that the government is required to maximize a social welfare function, the arguments of which are the individual utility functions of the citizens of the respective country:

$$W = w\left(u_1(x^1, z), u_2(x^2, z), \dots, u_H(x^H, z)\right); \quad \left(\frac{\partial w}{\partial u_h} > 0 \; (h = 1, 2, \dots, H)\right) \tag{10.1}$$

In (10.1), W denotes the level of social welfare, while w is the welfare function. The (well-behaved) individual utility functions u_h describe the wellbeing of citizens h ($h = 1, 2, \dots, H$) as strictly monotonically increasing functions of their individual market consumption bundles $x^h = \left[x_1^h, x_2^h, \dots, x_N^h\right]$ and the vector of environmental quality parameters $z = [z_1, z_2, \dots, z_L]$ where the parameters z_l ($l = 1, 2, \dots, L$) represent, e.g., water quality, air quality, the area covered with forests, the state of biodiversity, etc., which are the same for all citizens. From (10.1), it becomes obvious that if the government wants to maximize social welfare, its main action parameters are the provision of market commodities x and the provision of environmental quality z, all other things being constant. This is illustrated in Fig. 10.1. While market goods are produced in the economic sector, environmental quality accrues from the environmental sector. A welfare-maximizing government is responsible for both sectors.

From the first-order conditions of a welfare maximum, it follows that every welfare maximum is also a Pareto optimum, i.e., a state of the economy, where it is not possible to increase

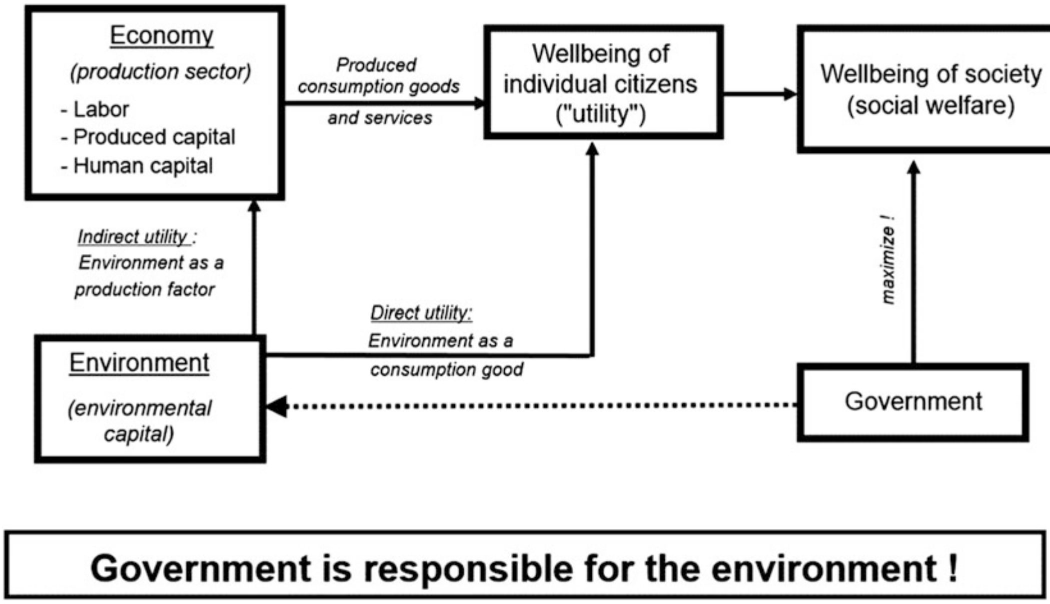

Fig. 10.1 The role of government

the wellbeing or utility of one individual without reducing the wellbeing or utility of some other individuals (Fig. 10.1), while the inverse implication does not hold. Therefore, a Pareto-optimal allocation of resources in the private as well as in the environmental sector is a necessary, but not sufficient, condition for a welfare maximum. Pareto optimality is a pure efficiency criterion, while a welfare maximum considers also distributional issues as represented by the welfare weights $\partial w / \partial u_h$ which describe the relative importance of the wellbeing of a household h from the perspective of the welfare-maximizing government (Fig. 10.2). It should be noted that in Fig. 10.2, it is assumed that the environmental variable z represents a pure public good, i.e., it is rival in consumption, and nobody can be excluded from consuming it.

Rivalry in Consumption and Exclusion Principle

Rivalry in consumption means that the marginal utility of consuming a rival good decreases if some other person consumes the same good. For non-rival goods like clean air or a beautiful landscape or political leadership or national pride, the (marginal) utility of enjoying these goods is not reduced if others enjoy the same goods.

The exclusion principle holds if the owner of a commodity can exclude others from consuming this commodity. Market commodities like a bottle of water are typical examples of goods where the exclusion principle holds, while public goods like clean air or political leadership are examples of goods where this principle does not hold.

MRS stands for “marginal rate of substitution” and *MRT* for “marginal rate of transformation.” Nonnegative values of the implicit production function $F(\bullet)$ describe the production possibilities of the economy for a given vector $\bar{y}$ of available input quantities. Efficient production requires that $F(\bullet) = 0$. To keep the notation simple, the two households are denoted by the indices A and B. $L(\bullet)$ is the Lagrangian function, which equals the sum of the objective function $w(\bullet)$, which we want to maximize, and the product of the Lagrangian multiplier μ and the restriction function $F(\bullet)$. It is

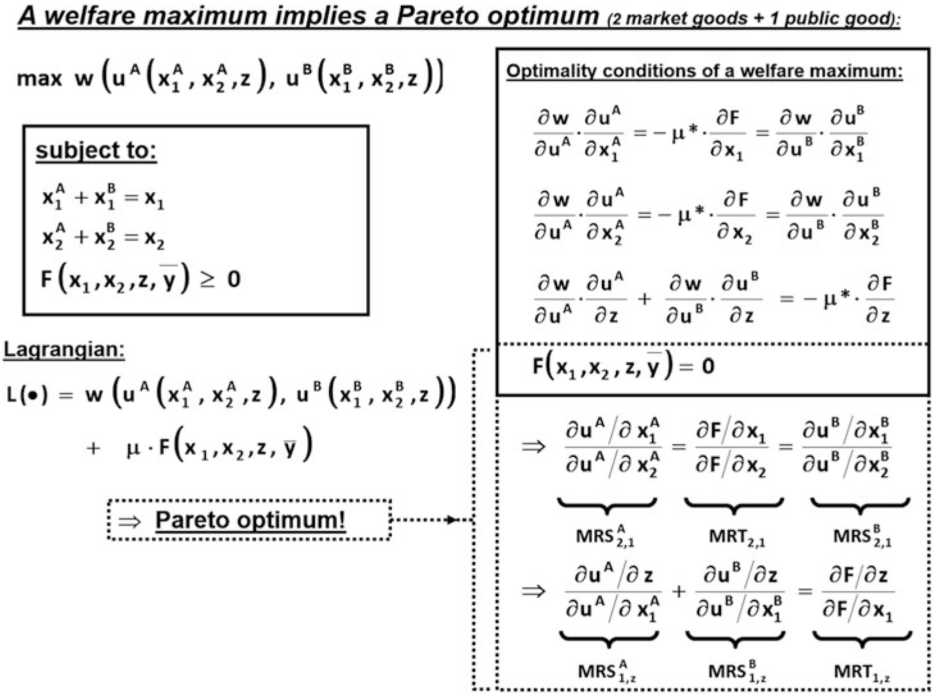

Fig. 10.2 Welfare maximum and Pareto optimum

well known from the theory of nonlinear optimization that a saddle point (x^*, z^*, μ^*) of the Lagrangian function (maximum *w.r.t.* x and z, minimum *w.r.t.* μ) at the same time characterizes a maximum $w(x^*, z^*)$ of the objective function under the restriction $F\left(x^*, z^*, \bar{y}\right) \geq 0$ (cf., e.g., Silberberg and Suen 2001, p. 432 ff.). The optimal value of the Lagrangian multiplier μ^* indicates by how much the optimal value of the objective function changes if the restriction is relaxed infinitesimally. The multiplication of the restriction function by the Lagrangian multiplier converts the units in which the restriction function is defined into the units of the objective function.

While the private markets in the economic sector are (at least in principle and under ideal conditions) able to implement a Pareto-efficient allocation of resources according to the main theorem of welfare economics (cf., e.g., Feldman and Serrano 2006, p. 3), this does not hold for the environmental sector where we have to face various kinds of market failure and where for many environmental goods like biodiversity, landscape beauty, etc., no markets exist at all. Therefore, the government must intervene in the environmental sector in many different ways if it wants to maximize social welfare. In this chapter, we will discuss various problems of market failure in the environmental sector and the possibilities of governments to address these problems.

When maximizing social welfare, a responsible government does not consider only the wellbeing or utility of the present generation of people but also the interests of future generations. Therefore, welfare maximization has also an intertemporal aspect which requires to ensure a sustainable development of the economy in question. We have to make sure that we pass on our planet to future generations in a state which enables also future generations to pursue their own happiness to the same extent as we do. This implies that we strive for no or only modest pollution of our environment and that we preserve a sufficient part of our natural resources for them. This is where the bioeconomy cuts in, since the transition to a bio-based economy serves the goal of resource preservation, because in the bioeconomy, the use of nonrenewable resources is substituted by the use of renewable resources. Since the bio-based economy cuts back the utilization of fossil fuels, it serves the goal of slowing down global warming to improve the living conditions of future generations. The bioeconomy produces also less waste than the traditional economy since many of its products can be composted naturally after use or can be reused as inputs in new production processes. Summing up, the bioeconomy serves the goals of resource saving and of reducing environmental pollution and is, therefore, in accordance with principles of sustainable development. Since private markets alone fail to serve these goals successfully, the government is called for to promote the bioeconomy in order to ensure a sustainable development of the economy.

The rest of this chapter is organized as follows: in Sect. 10.2, we will introduce the concept of sustainability which is essentially an intertemporal concept. In Sect. 10.3, we will discuss the basic principles of resource economics, i.e., the optimal use of natural resources over time, using a simple intertemporal model. Section 10.4 deals with market failure in the environmental sector and discusses various government instruments and policies to address the different kinds of market failure. Section 10.5 contains some concluding remarks.

10.2 Sustainability

The goal of striving for a sustainable development of society and economy is motivated by the concept of "spaceship earth". In his seminal paper on "The economics of the coming Spaceship Earth", Kenneth Boulding (1966) described our planet as a spaceship, i.e., a closed system, drifting through the outer space where no possibility exists to exchange matter between the spaceship and its environment (cf. also Spash 2013). After we will have used up all resources on our planet, we will not be able to take on board new supplies. And when we will have filled our planet up to the rim with our waste, there will be no chance to get rid of it. This notion of our planet as a spaceship where only energy, but no matter, can be exchanged with the outer space, makes it necessary to trigger a transition from what Boulding calls the "cowboy economy" ("… the success of the economy is measured by the amount of the throughput from the 'factors of production', a part of which, at any rate, is extracted from the reservoirs of raw materials and noneconomic objects, and another part of which is output into the reservoirs of pollution"—Boulding 1966, p. 11) to a "spaceman economy" ("… in the spaceman economy, throughput is by no means a desideratum, and is indeed to be regarded as something to be minimized rather than maximized. The essential measure of the success of the economy is not production and consumption at all, but the nature, extent, quality, and complexity of the total capital stock, …"—Boulding 1966, p. 11). The basic idea of Boulding's spaceman economy is very similar to the idea of today's bioeconomy, since both are aiming for a sustainable use of scarce natural resources. Already more than 50 years ago, Boulding described his idea of a sustainable economy as follows:

> In the spaceman economy, what we are primarily concerned with is stock maintenance, and any technological change which results in the maintenance of a given total stock with a lessened throughput (that is, less production and consumption) is clearly a gain. (Boulding 1966, p 11)

Looking into the literature on sustainable development, one finds a vast variety of different definitions of sustainability which often differ only in small details. These concepts can roughly be subdivided into two main categories, strong and weak sustainability, but there are also definitions of very strong and very weak sustainability, and within each category, one can find different definitions of one and the same kind of sustainability. Especially the older concepts of sustainability are defined in physical or value terms. Konrad Ott (2003) summarizes the basic idea of weak sustainability as follows:

> Weak sustainability argues that what counts is the overall value of the bequest package. Natural and artificial capital are, in principle, substitutes. Therefore, the depreciation and degradation of natural capital is permissible under the idea of intergenerational justice if artificial capital is produced at the same rate. Note that 'capital' is just shorthand for 'means of production'. (Ott 2003, p. 62)

Of course, it is difficult to derive practical rules for sustainable development from definitions like that, since it is not clear, e.g., by how much physical production capital or human capital must be built up in order to compensate for burning one ton of crude oil. Things become even more complicated if we want to follow the concept of strong sustainability, according to which natural and artificial capital are no substitutes but complements:

> Strong sustainability, in contrast, emphasises that the human sphere is embedded in a natural system ('biosphere') and assumes that natural limits ought to constrain our actions. Artificial capital can only sometimes substitute for natural capital. In general, both kinds of capital are complementary. . . . Strong sustainability argues in support of a constant-natural-capital rule. (Ott 2003, p. 62)

Following this concept of sustainability, each generation has to pass on a "constant-natural-capital bequest package" to the next generation, while the weak definition of sustainability requires only a "constant-overall-capital bequest package". According to the weak definition, it is possible to compensate a reduction of natural capital by building up the stock of artificial capital, while with the strong definition of sustainability, only substitution within the natural capital sector is allowed. Burning a ton of crude oil can be compensated by planting additional trees, but not by building up the production sector of the economy or by technological progress, since the overall natural capital stock has to be passed on to future generations without reduction. Like with the weak definition of sustainability, one has to ask here what the "exchange rate" between renewable (trees) and nonrenewable resources (crude oil) should be. The trade-off between different kinds of capital cannot be solved based on these definitions. Further, it is not clear why we should follow at all such physical "book-keeping" types of sustainability rules.

From a welfare economic perspective, the definition of sustainability by the World Commission of Environment and Development (1987), stated in the so-called Brundtland Report, appears to be much more plausible. Here "sustainability" is defined as

> humanity's ability to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. (World Commission of Environment and Development 1987, p. 41)

This definition does not aim at the transfer of physical units of natural and produced capital to future generations but at the satisfaction of human needs that can be generated by using this capital. Not the transferred capital has to be constant over generations, but the satisfaction or utility it generates for different generations has to be constant. In the context of biology, this means that it is not the ecosystems that have to be counted and preserved for future generations but the ecosystem services and the utility they generate. Obviously, the Brundtland definition of sustainable development is an anthropocentric definition, while weak and strong sustainability in the traditional sense are purely physical definitions. An obvious interpretation of the Brundtland definition is that it aims at the maximization of an intertemporal social welfare function according to (10.3) where the utility functions u_t are interpreted as the level of satisfaction of different generations. This leads us to the next section of this chapter where we will briefly discuss the principles of intertemporal welfare maximization with a limited and nonrenewable resource stock.

10.3 Welfare Maximization with Nonrenewable Natural Resources

In this section, we consider the optimization problem of a government that wants to maximize social welfare over different generations in the sense of a sustainable development. For simplicity's sake, we assume that in this economy, there prevails perfect information with a uniform interest rate for lending and borrowing. We further assume that society is equipped with a given stock R of a nonrenewable resource which can be consumed directly after extraction, i.e., there is no further refinement or production process between extraction and consumption of this resource. This kind of model is also known as the "cake-eating" model of nonrenewable resources. The government is supposed to maximize social welfare over $T_s + 1$ generations or time periods $t = 0, 1, 2, \ldots, T_s$. We assume that the utility of each generation depends on its consumption x_t of the resource R where overall consumption of all generations is restricted by the constraint

$$\sum_{t=0}^{T_s} x_t \leq R \tag{10.2}$$

The government maximizes the intergenerational welfare function

$$W = w\left(u_0(x_0), u_1(x_1), \ldots, u_{T_s}(x_{T_s})\right); \quad \left(\frac{\partial w}{\partial u_t} > 0 \; (t = 0, 1, \ldots, T_s)\right) \tag{10.3}$$

under restriction (10.2). The respective first-order Kuhn-Tucker conditions are shown in Fig. 10.3.

Applying the interpretation of the Lagrangian multiplier μ^* according to function L above to our optimization problem in Fig. 10.3, we find that μ^* indicates by how much maximum attainable social welfare increases if the restriction parameter R is increased by one unit. Therefore, μ^* expresses the marginal social value of the resource stock R or its shadow price (cf., e.g., Silberberg and Suen 2001, p. 167). From condition (i), it follows that μ^* is positive if the marginal welfare of consumption $\frac{\partial w}{\partial u_t} \cdot \frac{\partial u_t}{\partial x_t}(x^*)$ is positive for at least one generation t. In this case, the resource will be completely depleted after generation T_s according to condition (iv). From condition (ii), it follows that maximizing intergenerational welfare implies a resource allocation such that for all generations with a positive consumption x_t, marginal overall welfare is the same for all generations:

$$\frac{\partial w}{\partial u_t} \cdot \frac{\partial u_t}{\partial x_t}(x^*) = \frac{\partial w}{\partial u_{t'}} \cdot \frac{\partial u_{t'}}{\partial x_{t'}}(x^*) \times (t, t' \in \{0, 1, \ldots, T_s\}) \tag{10.4}$$

Shadow Price

A shadow price is a hypothetical or virtual price that is never actually paid. Like a market price, it indicates the marginal value of a good or resource, but this good or resource is not traded in markets, and, therefore, the shadow price is only of theoretical importance.

From (10.4), we can see that generations with a high welfare weight $\partial w / \partial u_t$ will be granted higher consumption quantities x_t (because of the diminishing marginal utility of consumption $\partial^2 u_t / (\partial x_t)^2 < 0$), while generations which are considered less important by the central planner

Fig. 10.3 Welfare maximization with a nonrenewable resource

Lagrangian:

$$L(x, \mu) = w\left(u_0(x_0), u_1(x_1), \ldots, u_{T_S}(x_{T_S})\right) + \mu \cdot \left(R - \sum_{t=0}^{T_S} x_t\right)$$

First-order conditions:

$$\text{(i)} \quad \frac{\partial L}{\partial x_t}(x^*, \mu^*) = \frac{\partial w}{\partial u_t} \cdot \frac{\partial u_t}{\partial x_t}(x^*) - \mu^* \leq 0 \quad (t = 0, \ldots, T_S)$$

$$\text{(ii)} \quad \frac{\partial L}{\partial x_t}(x^*, \mu^*) \cdot x_t^* = \left(\frac{\partial w}{\partial u_t} \cdot \frac{\partial u_t}{\partial x_t}(x^*) - \mu^*\right) \cdot x_t^* = 0$$

$$\text{(iii)} \quad \frac{\partial L}{\partial \mu}(x^*, \mu^*) = R - \sum_{t=0}^{T_s} x_t^* \geq 0$$

$$\text{(iv)} \quad \frac{\partial L}{\partial \mu}(x^*, \mu^*) \cdot \mu^* = \left(R - \sum_{t=0}^{T_s} x_t^*\right) \cdot \mu^* = 0$$

$$\text{(v)} \quad x_t^* \geq 0 \quad (t = 0, \ldots, T_S) \quad , \quad \mu^* \geq 0$$

are given lower consumption quantities. If all generations have the same importance for government so that

$$\frac{\partial w}{\partial u_t} = \frac{\partial w}{\partial u_{t'}} \left(t, t' \in \{0, 1, \ldots, T_s\} \right) \tag{10.5}$$

it follows from (10.5) that the resource is distributed over the different generations such that their marginal utility of consuming this resource is the same for all generations:

$$\frac{\partial u_t}{\partial x_t}(x^*) = \frac{\partial u_{t'}}{\partial x_{t'}}(x^*) \left(t, t' \in \{0, 1, \ldots, T_s\} \right) \tag{10.6}$$

This corresponds closely with the definition of sustainability by the Brundtland Report "Our Common Future" stated above. This principle of a sustainable development has reached enormous prominence not only among scientists but also among politicians and broad parts of the public. It forms the guideline for most political negotiations on environmental preservation and climate policy. Condition (10.6) is, of course, a marginal criterion which does not imply that each generation should be able to consume the same quantity of natural resources as, e.g., the strong sustainability criterion requires. It is an anthropocentric criterion which aims at the (marginal) satisfaction of the needs of people and not at the resources at their disposal.

Viewed in the context of a more general setting criterion, (10.6) can be interpreted as an encouragement of the transition from a fossil-based to a bio-based economy. Differently from the strong and weak criteria explained above, sustainability in the sense of (10.6) is defined in terms of utility, no matter from which resource this utility is derived. If fossil resources become scarcer or are not available at all from some generations on, we have to make sure that this generation has substitutes for these fossil resources at their hands to guarantee the fulfillment of condition (10.6). This will be possible only after we will have developed new technologies which can produce the same satisfaction of human needs from renewable or bio-based resources that we enjoy today from the consumption of fossil resources. Therefore, the transition of our economy to a bio-based economy can be interpreted as an immediate consequence of the maximization of an intergenerational social welfare function.

10.4 Market Failure in the Environmental Sector and Government Policy for a Bio-Based Economy

The bioeconomy aims not only at the preservation of natural resources for future generations but also at an optimal management of the environmental sector for the present generation. Therefore, we will focus on a comparative static analysis of the interaction between the economy and the environment in this section, instead of an intertemporal analysis as in the previous section. First of all, the question arises what we understand by an "optimal" management of the environmental sector. In Sect. 10.1, we learned that the government is expected to maximize a social welfare function as a strictly monotonically increasing function of the individual utility functions of all citizens, where each of these utility functions is strictly monotonically increasing in market consumption x and environmental quality z. In Fig. 10.2, we saw that a welfare maximum implies the realization of a Pareto optimum. The difference between the two concepts is that the welfare maximum also considers the distributional justice ideals of government as represented by the welfare weights $\partial w / \partial u_h$, while a Pareto optimum is a pure efficiency criterion. For each economy, there exists an infinity of different Pareto-optimal allocations each of which implies a different distribution of individual well-being or utility. Based on the welfare weights $\partial w / \partial u_h$, the government chooses one of these Pareto optima for a welfare maximum. Since we are not interested in distributional issues here and since the welfare weights $\partial w / \partial u_h$ cannot be determined on scientific grounds anyway, we concentrate on the implementation of Pareto-optimal allocations of x and z in this section. Our main interest here is if private markets, when left alone, are able to implement a Pareto optimum without any government intervention. If this is not the case, we speak of market failure.

Public Goods

From Fig. 10.2 we saw that a Pareto optimum requires that the marginal rates of substitution (MRS) between any pair of two market goods are equal for all households and equal to the marginal rate of transformation (MRT) between these two market commodities. The economic interpretation of this condition is that in a Pareto optimum, the marginal utility of consuming a market commodity (in relation to the marginal utility of some other market commodity) is equal for all consumers and is also equal to the marginal production cost of that commodity (in relation to the marginal production cost of the other market commodity). Therefore, no reallocation of consumption or production could lead to a utility increase of one consumer without reducing the utility of some other consumer. Because of the rivalry property of market goods, each unit of a market good can be consumed by one person only. Therefore, the individual marginal utility of consuming a market good equals the "social" marginal utility accruing from that good, so that our conditions in Fig. 10.2 say that in a Pareto optimum, the social marginal utility of consuming a market good should be equal to its social marginal cost.

We could also see in Fig. 10.2 that the sum of the marginal rates of substitution between a market good x and an environmental public good z equals the marginal rate of transformation between the market good x and the environmental good z. This optimality condition follows from the fact that in Fig. 10.2 we assumed that z is a pure public good. While market goods are characterized by the criterion of rivalry in consumption and the exclusion principle, these criteria are not fulfilled for public goods like clean air, the climate in a specific region, biodiversity, etc. The economic interpretation of the optimality condition in Fig. 10.2 says that in a Pareto optimum, the sum of the marginal utilities of consuming the public good (in relation to the marginal utility of consuming some market good) should equal the marginal production cost of the public good (in relation to the marginal production cost of that market good). Because of the non-rivalry of public goods, all households consume the same quantity and quality of such a good simultaneously. Therefore, the social marginal utility accruing from the consumption of a public good equals the sum of the individual marginal utilities. The optimality condition in Fig. 10.2, therefore, says that in a Pareto optimum, the social marginal utility should equal the marginal production cost. This is, in principle, the same condition that holds for market goods. The difference between both conditions is that the social marginal utility of consumption equals the individual marginal utilities for a market good and the sum of the individual marginal utilities for a public good.

Since the consumption of a public good is non-rival and since the exclusion principle fails, there is no incentive for private agents to invest in the provision of a public good because they will not be able to earn their money back. If all households were willing to pay a price for the consumption of a public good according to their marginal utility of consuming that good, an optimal provision of public goods in the sense of our optimality condition would be feasible. But, again, the non-rivalry in consumption and the failure of the exclusion principle make such a so-called Lindahl solution (s. Lindahl 1919) impossible. Private consumers have no incentive to pay for enjoying the public goods since they cannot be prevented from consuming it for free without even compromising its quality. Therefore, free riding is the optimal strategy for a strictly rational "homo oeconomicus", and, as a consequence, nobody will be willing to invest in the provision of a public good.

Though we know that psychological motives like altruism, social norms, the need for social approval, etc., set incentives also for a private provision of public goods, these effects will not be strong enough to trigger a Pareto-optimal provision, at least not with larger groups of people. Therefore, governments have to intervene to ensure a sufficient, if not optimal, provision of public goods. This is why the transition to a bio-based economy, which serves the goal of providing the public good "world climate" in a sustainable quality, will not happen without government support.

Common-Pool Goods

In the context of environmental protection and sustainability, the group of so-called common-pool goods plays an important role. These are goods which are rival in consumption, so that their quality is diminished when they are consumed (i.e., the marginal utility of consuming them is the smaller the more people are consuming them), while nobody can be excluded from utilizing them. Because of this combination of rivalry in consumption and the failure of the exclusion principle, rational individuals will consume as much as possible of such a good as fast as possible. The dominance of this consumption strategy will lead to what Garrett Hardin (1968) called the "tragedy of the commons", i.e., a fast overuse of such resources which will lead to their premature extinction, if the government does not intervene. Examples of common-pool goods suffering from this kind of market failure are fish stocks in the open sea where everybody can catch as much as he desires, but also groundwater aquifers, rivers, or lakes which are exploited by different private parties or different countries, rain forests in countries where no government regulation for their exploitation is enforced, etc. Without strict utilization regimes which are enforced by governments, these resources will be lost within a short time. Besides setting up strict utilization schemes for such goods, the government can support their preservation also by encouraging the provision of alternative commodities serving the same purpose as the common-pool goods. In the case of endangered fish stocks, the government can, e.g., support financially the development of new kinds of marine food like algae-based nutrition. This branch of the bioeconomy has been flourishing over the past years, but this development has been possible only because of government subsidies. Therefore, the bioeconomy depends on government intervention also with respect to the preservation and sustainable provision of common-pool goods.

Externalities

The most important cause of market failure in the environmental sector is the existence of so-called external effects. An external effect exists, if an economic activity of one economic agent (household or firm) has an impact on another economic agent's objective function (e.g., a utility function or profit function) where this agent has no control over the effect. If the external effect is positive, we speak of an external benefit; if it is negative, it is called an external cost. Especially external costs are responsible for the deterioration of environmental quality. Examples are the pollution of air, soil, and water as a by-product of the production or consumption of market goods. If a river or lake or a groundwater aquifer is polluted by the toxic wastewater of a production plant, this has consequences for the profits of other firms (e.g., fishermen living at the same lake or river or producers of mineral water from that aquifer), but also households using that lake for recreation or receiving their drinking water from that groundwater aquifer are affected. Without government regulations, they have no possibilities to influence the extent of pollution or to stop it. But also households can cause externalities affecting other households (e.g., car driving leading to particulate matter pollution in our cities) or firms (e.g., by burning garden rubbish in the neighborhood of a hotel or an open-air restaurant). Households and firms together cause negative externalities on the world climate by releasing carbon dioxide into the atmosphere, thereby affecting the profit functions of producers (e.g., farmers) and the utility functions of households all over the world. The bioeconomy addresses especially this problem by developing new alternative products and new technologies which use less carbon-based inputs and cause less CO_2 emissions than traditional production processes. Markets alone ignore the existence of external costs and benefits since the prices of market commodities equal the marginal utility of households consuming these commodities on the one hand and the marginal production cost of producers on the other. The external costs of production in the form of pollution are borne by society as a whole, but no price is charged for them, as long as we live in a laissez-faire economy with no government intervention. Therefore, we have a situation here where the bioeconomy, which leads to a reduction of external costs, will not develop without government support, since the development of bioeconomic production technologies is costly and nobody will be willing to pay for it voluntarily.

If the government decides to reduce negative externalities (and to boost positive externalities), the question arises which level or extent of externalities is optimal. Reducing, e.g., pollution accruing from the production of market goods to zero would in many cases mean that also the production of these goods would be reduced to zero, which probably would not be optimal for society. Economic intuition would advise us to apply the Pareto optimality rule derived above in Fig. 10.2 also to the present problem. This would mean to expand the production of a market good that causes a negative (positive) externality up to the point where the social marginal benefits accruing from that commodity equal its marginal social cost. The marginal social cost consists of the marginal production cost plus the marginal external costs imposed on society as a whole, while the social marginal benefits consist of the individual marginal consumption benefits plus the marginal external benefits.

Our intuition is confirmed if we solve the optimization problem leading to a Pareto optimum with external effects as shown in Fig. 10.4. As before, we deal here with an economy with two households *A* and *B*, two market goods x_1 and x_2, and an externality s accruing from the consumption (or production) of commodity 1. The externality affects the wellbeing of both households. In the case of a negative externality, good 1 could be, e.g., car driving leading to air pollution with particulate matter. A positive externality could accrue from using electric cars by both households, which would lead to less air pollution and less noise.

The conditions for a Pareto optimum with externalities are shown in Fig. 10.5. The first three terms correspond with the optimality conditions for market goods as known from Fig. 10.2. The numerator of the last term captures the marginal external costs or benefits accruing from commodity 1. $\partial s/\partial x_1$ is the marginal effect of consuming one more unit of commodity 1 (e.g., driving one more kilometer by car) on the externality (e.g., PM pollution), while the term in parentheses expresses the overall effect

Fig. 10.4 Pareto optimum with externalities

Pareto efficiency with externalities

$$\max\ u^A\left(x_1^A, x_2^A, s(x_1^A + x_1^B)\right), \qquad s = s\Big(\overbrace{x_1^A + x_1^B}^{x_1}\Big)$$

- externality from the consumption or production of good 1

Constraints: $u^B\left(x_1^B, x_2^B, s(x_1^A + x_1^B)\right) \geq U^B \;\; ; \;\; F\left(x_1^A + x_1^B,\ x_2^A + x_2^B, \bar{y}\right) \geq 0$

Lagrangian: $L\left(x_1^A, x_2^A, x_1^B, x_2^B, \mu, \nu\right) = u^A\left(x_1^A, x_2^A, s(x_1^A + x_1^B)\right)$

$$+ \nu\left[u^B\left(x_1^B, x_2^B, s(x_1^A + x_1^B)\right) - U^B\right] + \mu F\left(x_1^A + x_1^B, x_2^A + x_2^B, \bar{y}\right)$$

Fig. 10.5 Pareto optimality conditions with externalities

$$\underbrace{\frac{\partial u^A/\partial x_1^A}{\partial u^A/\partial x_2^A}(*)}_{MRS_{2,1}^A} = \underbrace{\frac{\partial u^B/\partial x_1^B}{\partial u^B/\partial x_2^B}(*)}_{MRS_{2,1}^B} = \underbrace{\frac{\partial F/\partial x_1}{\partial F/\partial x_2}(*)}_{MRT_{2,1}} - \underbrace{\frac{\left(\frac{\partial u^A}{\partial s} + \nu^* \cdot \frac{\partial u^B}{\partial s}\right)(*) \cdot \frac{\partial s}{\partial x_1}(*)}{\partial u^A/\partial x_2^A}}_{\substack{> 0 \text{ for a negative externality} \\ < 0 \text{ for a positive externality}}}$$

of one more unit of the externality on the wellbeing of all households. The last term drives a wedge between the marginal rate of substitution between commodities 1 and 2 on the one hand and the marginal rate of transformation on the other. Considering external costs explicitly leads to a new Pareto-optimal allocation where the MRT is smaller than the MRS of the households, while the existence of external benefits require an allocation where the MRT is larger than the MRS of the households.

If a Pareto-optimal allocation according to Fig. 10.5 is to be implemented in a market economy, this can be done, e.g., by imposing a uniform per-unit tax on a commodity causing external costs (or by granting a uniform per-unit subsidy on commodities causing external benefits). The price a household would have to pay for a commodity causing a negative externality would then comprise the marginal production cost of that commodity plus the marginal external cost in terms of the tax. If this tax amount equals exactly the external costs, it is called a Pigovian tax (cf. Pigou 1920 or Sandmo 2008). It will implement a Pareto-optimal allocation. In practice it will not be possible to assess the exact amount of such a tax since the necessary information, especially the marginal utilities of households (cf. Fig. 10.5), is not available. Therefore, the Pigovian tax represents a theoretical ideal only. A practical instrument for the reduction of a negative externality is the so-called pricing and standards approach (PSA), suggested by Baumol and Oates (1971). The PSA recommends to impose a uniform per-unit tax on goods causing negative externalities because this will lead to a more efficient allocation than in the initial situation with a minimum of overall abatement costs. In the case of externalities caused by SO_2 or CO_2 emissions, an analogous effect can be reached by introducing an emission trading system, where emitters have to pay a uniform price per unit of the respective emission. Reducing pollution by regulatory or command-and-control policy, where certain emission caps are defined by government and any transgression of these emission limits will be prosecuted, leads also to a reduction of negative externalities but not with minimum abatement costs like with emission taxes according to the PSA or the Pigovian tax approach.

Since with emission taxes or a cap-and-trade policy polluters have to pay for every single ton of emissions, i.e., for every unit of a negative externality, there exists always an incentive to develop new abatement technologies to reduce the emission costs. Therefore, the taxation of negative externalities (external costs) and the subsidization of positive externalities (external benefits) are important instruments to trigger the transition from a fossil-based to a bio-based economy with minimum overall cost.

10.5 Concluding Remarks

In this chapter, it has been argued that the government is responsible for environmental management in an economy and, especially, for the organization of the transition from a fossil-based to a bio-based economy. The existence of various causes of market failure in the environmental sector prevents the implementation of a Pareto-efficient allocation of environmental resources without the help of government. In an intertemporal context, an optimal allocation of a nonrenewable natural resource requires the maximization of an intergenerational social welfare function where the interests of the different generations are considered in form of their utility functions. Private markets alone will only consider the wellbeing of the present generation and, maybe, also of the next. Neglecting the interests of all following generations prevents a sustainable use of such resources in the sense of the Brundtland definition. In a comparative static context, the existence of public goods, common-pool goods, as well as of external costs and benefits of market consumption and production lead to market failure in the sense that without government intervention the implementation of a Pareto-optimal resource allocation will not be possible. The principles and conditions of such an optimal resource allocation were derived, and different instruments for their practical implementation were discussed in this chapter.

Review Questions

- Why is government responsible for the preservation of the environment in general and, especially, for the development of the bioeconomy?
- Which are the most important concepts of sustainability? What are their main characteristics?
- Please explain the characteristics of the so-called cake-eating model of intertemporal resource use and its relation to the concept of very weak sustainability.
- What are the main reasons for market failure in the environmental sector and which are the most important instruments of government policy in this context?
- What are the causes of the so-called tragedy of the commons?
- Why is the government responsible for the provision of public goods? What could be the incentives for private people to contribute to the provision of public goods?
- Please explain the first-order conditions for a Pareto-optimal regulation of external effects.
- What is the significance of the concept of shadow prices in the context of environmental policy?

References

Baumol WJ, Oates WE (1971) The use of standards and prices for environmental protection. Swed J Econ 73, pp 42–54

Boulding KE (1966) The economics of the coming spaceship earth. In: Jarrett H (ed) Environmental quality in a growing economy. John Hopkins University Press, Baltimore, pp 3–14

Feldman AM, Serrano R (2006) Welfare economics and social choice theory, 2nd edn. Springer, New York

Hardin G (1968) The tragedy of the commons. Science 162 (3859), pp 1243–1248

Lindahl E (1919) Just taxation-a positive solution. In: Musgrave R, Peacock A (eds) Classics in the theory of public finance, 1st edn. Macmillan, London, pp 98–123

Ott K (2003) The case for strong sustainability. In: Ott K, Thapa P (eds) Greifswald's environmental ethics. Steinbecker, Greifswald, pp 59–64

Pigou AC (1920) The economics of welfare. Macmillan, London

Sandmo A (2008) Pigouvian taxes. The new Palgrave dictionary of economics, 2nd edn. Palgrave Macmillan, London

Silberberg E, Suen W (2001) The structure of economics: a mathematical analysis. McGraw-Hill, New York

Spash CL (2013) The economics of Boulding's spaceship earth. In: Dolfsma W, Kesting S (eds) Interdisciplinary economics: Kenneth E. Boulding's engagement in the sciences. Routledge, London, pp 348–363

World Commission of Environment and Development (1987) Our common future. Oxford University Press, Oxford

Economic Growth, Development, and Innovation: The Transformation Towards a Knowledge-Based Bioeconomy

11

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Abstract

To improve sustainability, the global economic system has to undergo severe transformation processes. This chapter deals with the possibility of an innovation-triggered transformation towards a knowledge-based bioeconomy, which is supposed to overcome the current lock-in into a fossil fuel-based CO_2-intensive production. To do this, a neo-Schumpeterian view is applied that highlights the complex interplay in knowledge generation and knowledge diffusion processes between firms, consumers, and government institutions. By applying the neo-Schumpeterian approach, it becomes obvious that innovation and economic growth are part of the solution and not part of the sustainability problem. The shift from quantitative growth to qualitative development makes the difference and affects all agents and institutions in an economic system, which needs to be designed as a dedicated innovation system supporting the transformation towards a knowledge-based bioeconomy.

Keywords

Knowledge-based bioeconomy • Neo-Schumpeterian approach • Economic growth • Development • Innovation system • Economics of change

Learning Objectives

After studying this chapter, you should:

- Understand the technological, political, and social shifts that are necessary to achieve a transformation to a sustainable bio-based economy.
- Be able to assess the differences between the two approaches: (1) conservation of resources by growth abstinence and (2) decoupling of growth and exploitation of resources.
- Understand the foundations of the neo-Schumpeterian framework in the analysis of radical innovations.
- Be able to thoroughly discuss the challenges, opportunities, and consequences of innovations such as the “sharing economy,” “biofuels,” and “digitalization” in the transformation towards a knowledge-based bioeconomy.

11.1 Introduction

The sustainability of modern economic growth, as it developed in the todays Western industrialized economies from the beginning of the industrial revolution at the end of the eighteenth century, has been questioned at the latest since 1972 when the book *The Limits to Growth* was published by the *Club of Rome* (Meadows et al. 1972). After more than 200 years of industrial production, large parts of the world population are richer than ever before. However, industrial production in its current form is also closely linked with the exploitation of natural resources and the strong accumulation of greenhouse gases in the atmosphere, endangering human survival. In economics two fundamentally different solution strategies are discussed as a reaction on man-made climate change and irreversible environmental damages: (1) *conservation of resources by growth abstinence* and (2) *decoupling of growth and exploitation of resources*. In this chapter, we show that the first perspective with its emphasis on the efficiency of price competition is not suited to conceive a transformation of the production system towards a knowledge-based bioeconomy. Only the emphasis of the superiority of innovation competition, inherent to the second perspective, allows for the inclusion of the required transformative perspective.

The supporters of the first approach (e.g., Blewitt and Cunningham 2014; Kallis et al. 2014), summarized under the headings of *abstinence* and *downscaling*, claim a renunciation of our lifestyles based on consumption and increasing deployment of resources. This is considered the only way to enable a sustainable and environment-friendly lifestyle and form of economic activity. At first sight, it might look surprising that these growth-hostile approaches are strictly in line with the thinking put forward in mainstream neoclassical growth theories. This follows from the fact that the standard neoclassical approach relies on the assumption of stable economic structures and an understanding of economic growth as a continuous increase in the quantity of the goods that are produced. Figure 11.1 depicts the impressive growth performance of the German economy, where—in particular in the period of the so-called *Wirtschaftswunder* after 1945—income per head skyrocketed: at the beginning of the twenty-first century, per capita GDP is approximately four times higher than three generations earlier. But does this mean that German consumers today have four Volkswagen Beatles in their garages? Obviously not! Today we have completely different goods and services in our consumption baskets, we acquire different competences in universities, we work in different jobs, etc. Restricting economic growth analysis to a quantitative dimension only dismisses these most important qualitative dimensions. Such an analysis can only serve for a very short-term observation.

The alternative approach of neo-Schumpeterian economics (e.g., Hanusch and Pyka 2007) challenges this quantitative orientation and instead emphasizes the importance of qualitative aspects, which make fundamental changes of economic structures over longer periods visible. Without the consideration of the qualitative levels of economic growth, the quantitative figures cannot tell much about the massive technological and socio-economic developments. The neo-Schumpeterian approach highlights that innovations, market forces, structural change, and urban ways of life are both part of the problem and part of the solution to the sustainability problem. Innovation-triggered development generates both quantitative, i.e., income-increasing growth, and qualitative, i.e., structure-changing development. Only the creative solutions characteristic for capitalistic-organized economies will enable to reform our future economy in the sense of sustainability, thereby supporting the UN’s sustainability goals and simultaneously ensuring growth and development (Mazzucato and Perez 2015).

The central role of innovation in neo-Schumpeterian economics highlights that abstinence in the sense of economic downscaling is neither the first nor the only solution. This does not mean that all ideas of the proponents of the camp are rejected: in perfect accordance, certain

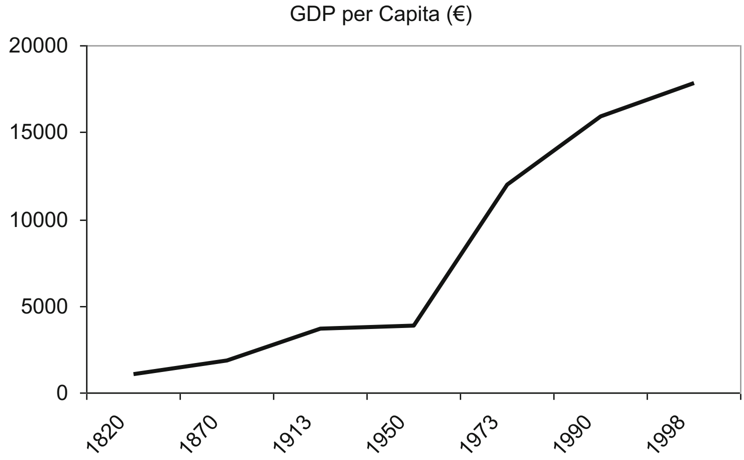

Fig. 11.1 GDP per capita in Germany (Maddison 1995)

past patterns like the high *energy intensity* of production because of too low oil prices not covering the total environmental costs or so-called planned obsolescence in consumption require urgent adjustments. Especially concepts resulting in a more intensive use of goods and therefore contributing to the economization of resources like the *sharing economy* or displacing physical goods by digital goods are promising. The same applies for closed-loop material cycles, recycling systems, and intelligent waste avoidance and treatment. These concepts are perfectly applicable to foster learning and behavioral changes on the supply and the demand side. The core idea of neo-Schumpeterian economics, however, is the *supply of and demand for* new technological solutions within a comprehensive economic transformation process (Geels 2002), i.e., different goods and services are produced and demanded in different, namely, sustainable ways. Exploring and exploiting the technological possibilities of the bioeconomy not only creates new investment opportunities but is also the condition sine qua non for the required socioeconomic and cultural changes. The consumers' acceptance of bio-based products and their demand are indispensable for a successful transformation. Innovations and changed consumer attitudes are complementary conditions for the creation of a sustainable production system.

Change can be either of an incremental type in terms of small improvements step-by-step along well-known technological trajectories, or it can be fundamental, leading to structural changes and the emergence of new and the disappearance of old industries. To simplify, we assume in this chapter that incremental technological changes are based on existing technological solutions, whereas radical technological changes question major existing production processes. They might lead to massive upheaval in the global production system in the sense of *creative destruction* (Schumpeter 1943). Because this chapter deals with the fundamental transformation of current production systems, radical technological innovations are in the spotlight which encompass the overcoming of the lock-in situation in fossil fuels (Unruh 2000) and the establishment of a knowledge-based bioeconomy (Pyka 2017; Pyka and Buchmann 2016). Without doubt this transformation process is radical, qualitative, and long term. It was already in *Business Cycles*, published in 1939, when Schumpeter revitalized Kondratieff's theory of *long waves* in order to explain such processes as regular processes in long-term economic development. His illustration of the discontinuous nature of economic development is famous: "Add successively as many mail coaches as you please, you will never get a railway thereby" (Schumpeter 1934, p. 64). So far, the literature highlights five long waves: The beginning industrialization around the year 1800 represented the first long wave and was fueled by the steam engine and by cotton processing. Then, starting around the year 1850, the widespread availability of steel and the diffusion of railways constituted a second long wave. Again, in the early twentieth century, this Kondratieff cycle was replaced by electricity and chemicals. In the postwar period, the third long wave gained momentum by mass production and the automobile as well as the petrochemical industries. Since then, manufacturing activities built on oil as a second fossil fuel apart from coal. From the 1980s, one refers to the fifth long wave, which is reflected in the fast and ubiquitous diffusion and application of information and communication technology. Now, at the beginning of the twenty-first century, another paradigmatic change is in the air, being characterized, however, by one major difference to previous situations of radical change: whereas previous cycles were driven by technological bottlenecks and their overcoming, in the twenty-first century, we face the vital question of how to restore environmental sustainability of economic activities. The knowledge-based bioeconomy plays a key role in this transformation process which, of course, like previous radical changes, still is confronted by fundamental uncertainty (Knight 1921).

The literature provides many alternative terms for the massive change, shaking global production systems: Freeman (1991) and Dosi (1982) call them techno-economic paradigm changes; Sahal (1985) uses cartographic analogies and refers to technological guideposts that are pointing to technological avenues. All authors highlight the confrontation with profound changes economic systems are faced with over longer periods of time, which question all established production approaches. Not a single technology is responsible for this phenomenon but several complementary developments that include, apart from a package of mutually dependent technologies (e.g., combustion engine, petrochemistry, assembly line production), numerous infrastructural developments (e.g., road structure, filling station network), behavioral changes (e.g., suburbs and commuter flow, shopping malls outside the city centers), as well as institutional changes (e.g., spatial planning and commuter allowance, etc.). The old paradigm will not be replaced by the new one until all these elements interact.

The neo-Schumpeterian approach provides us with crucial hints on the process of the forthcoming change. For this purpose, we discuss in the following section how innovations are supported by the discovery and successful diffusion of new knowledge. Knowledge-based economies organize innovation systems composed of different actors which establish a creative environment for mutual learning and knowledge creation. No innovation would have ever been established if it had not attracted consumers' interest and if it had not been leveraged by their purchasing power. We will focus on these questions in Sect. 11.3. Knowledge-based societies consider new concepts in the sense of *responsible innovation* that are decisive in bringing an entire economy on a new sustainable path-shaping growth and development. Section 11.4 deals with the massive economic impacts originating from these technological and knowledge-driven changes. It requires, besides technological change, also institutional change in a coevolutionary fashion, if new sustainable technologies are to achieve the aspired transformation of the economic system.

11.2 Innovation Systems and Knowledge

Neo-Schumpeterian scholars (e.g., Dosi et al. 1988; Lundvall 1992, 1998; Nelson 1993) strongly emphasize the systemic character of innovation processes. So-called innovation systems are composed of different actors (companies, research institutions, political actors, consumers, etc.) and linkages between these actors (flows of goods, R&D cooperation, knowledge transfer relationships, user-producer relationships, etc.). These linkages are required to ensure mutual learning and common knowledge development to solve complex innovation challenges. Such systems are characterized by their dynamic and coevolutionary nature and are thus enormously complex, as both actors and their knowledge and linkages and interactions between actors may change over time.

Dosi (1982) takes this systemic conception as a starting point in defining technological paradigms as "[. . .] set of procedures, or a definition of the 'relevant' problems and of the specific knowledge related to their solution." Transferred to the knowledge-based bioeconomy, the core idea is substitution, i.e., replacing carbon-based materials and energy with bio-based materials and energy. This can only be achieved by applying a variety of technological processes in the entire breadth and depth of the value-added chain. In this process the exploration of economic complementarities in terms of cross-fertilization of different knowledge fields matters. For example, to a large extent, digitalization allows for an extension of value chains by increasing the added value in new sustainable production sectors in a CO_2-neutral way (e.g., by electric mobility based on renewables, by establishing so-called smart grids, etc.). The concept of technological paradigms also illustrates that a paradigm shift is not possible at any time. A *window of opportunity* will only occasionally be opened and allow for a paradigm shift when several interconnected technologies are established and the creation of conducive demand side and institutional conditions happens simultaneously. This, of course, also holds for the emergence of a new bioeconomic innovation system and requires a sound balance of the various actors and their activities. For this reason, we introduce the notion of a *dedicated innovation system*.

The theory of industrial life cycles, which emphasizes the strong dynamics in the emergence and decline of industries, gives a first hint on the meaning of the development of a dedicated innovation system supporting the transformation towards a knowledge-based bioeconomy. Typically, industrial development is divided into four stages: (1) a development phase (new knowledge creates prerequisites for innovation), (2) an entrepreneurial and growth phase (many market entries of smaller innovative firms), (3) a saturation and consolidation phase (formation of industrial standards, mergers, and acquisitions as well as market exits), and (4) a downturn phase (oligopolistic competition in only less innovative industries) (e.g., Audretsch and Feldman 1996). Although the bioeconomy does not represent a well-defined industrial sector, understanding the theory of industrial life cycles is of crucial importance to govern the transformation process towards the knowledge-based bioeconomy. Without doubt, the bioeconomy has to be characterized as cross sectional. On the one hand, several new sectors will emerge, e.g., in the fields of bioplastic, waste management, or biorefineries. On the other hand, already existing sectors in the fields of vehicle construction, battery technology, pharmaceuticals, etc. will gain new momentum by the arrival of bioeconomic approaches. Therefore, we argue that new sectors will emerge by establishing bioeconomic technologies and development dynamics of some already existing industries will receive new impetus at the same time. Adjustments of old and development of new institutions (e.g., in Germany the Renewable Energy Act, the Greenhouse Gas Emissions Trading Law, etc.), adjustments of consumer habits, and the emergence of new educational opportunities in terms of coevolution will accompany these processes and establish the institutional, the industrial, and the consumer pillars of a dedicated innovation system.

The patterns and nature of new businesses in the bioeconomy are thus strongly influenced by national institutions and organizations (Casper et al. 1999; Whitley 1999). Institutions are defined as “a set of rules, formal or informal, that actors generally follow, whether for normative, cognitive, or material reasons.” “Organizations are durable entities with formally recognized members, whose rules also contribute to the institutions of the political economy” (North 1990; Hall and Soskice 2001). In this interplay between organizations and institutions, the knowledge base of an economy is created by the education and research system and represents one of the most important prerequisites for the transformation towards a bioeconomic production system (Geels 2002). This automatically relates to a high level of uncertainty in particular concerning the required future competences. In this complex process, numerous individual knowledge fields are potentially relevant for the transformation and are already identified, e.g., synthetic chemistry, process engineering, genetic engineering, food technology, or informatics. It is decisive to understand the dynamics of these knowledge fields and the possibilities of their recombination with other knowledge fields and adequate actors in order to create an innovation system. In many cases, linkages of different knowledge fields (*cross-fertilization*) are responsible for the emergence of extensive technological opportunities: for instance, a complete new industry, bioinformatics, has been initiated by the fusion of two so far unrelated knowledge fields, database technology and molecular biology. Because linking different knowledge fields is highly uncertain, private actors might not start and governmental innovation policies matter. Knowledge about future potentials, therefore, is essential for supporting research and innovation policies: the analysis of knowledge and network dynamics allows for the identification of development trajectories showing sectors requiring public attention and support concerning research and development in order to close existing knowledge gaps and build bridges between various knowledge domains (Burt 2004; Zaheer and Bell 2005).

11.3 Innovation in Knowledge-Based Societies

It has already been mentioned that also consumer knowledge plays an important role for the development and establishment of sustainable consumption patterns in a knowledge-based bioeconomy (Geels 2002). Therefore, the analysis of the transformation process has to include the interaction of technological development, demand, and acceptance of innovative solutions as well as sociological variables. The latter include education, age, income, and gender. All are important explanatory factors determining attention and readiness to deal with bioeconomic issues. A bioeconomic innovation will only be successful when consumers accept it. The direction of the transformation process is, comparable to the importance of the policy realm, determined by consumers, i.e., an important question has to address consumers' openness to the bioeconomy and its products.

Finally, (real and virtual) social networks matter for the establishment of new consumption patterns. They can contribute significantly to a diffusion of consumers' behavioral patterns and values (Robertson et al. 1996; Valente 1996; Nyblom et al. 2003; Deffuant et al. 2005). Recent studies show that attitudes are substantial for the development of social relationships and that, in turn, social relationships considerably influence behavior and attitudes. In the field of renewable energies, for example, the initiative of municipal utilities' customers has led in many cases to a "green" orientation of regional power supply. In some cases, citizens' networks finally transformed to investment companies that are engaged in wind farms.

Critical issues are to be dealt with in democratic processes in order to be widely accepted. Not everything that is technically possible is also socially desirable. In the field of the bioeconomy, this may, for instance, include the use of genetically modified organisms in agriculture. In fact, these organisms promise efficiency advantages with regard to the consumption of land and water, etc., but their long-term health and environmental risks cannot be completely (as with any new technology) anticipated. Accordingly, technological developments require consumers' acceptance and thus depend on the level of education in an economy. This raises the question of a society's openness towards innovations that are fundamentally associated with uncertainty. The concept of *responsible innovation* summarizes the future-oriented organization of development and is currently discussed with a high priority by European policy makers and institutions. A comprehensive working definition has been developed by Von Schomberg (2011). He describes responsible innovation as "a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society)." This means that innovations are not exclusively evaluated by their economic efficiency, but different aspects (e.g., consumer protection or ecological aspects; see Schlaile et al. 2017) also matter and are to be evaluated. Discussions on biofuels ("fuel vs. food") show that both a pure economic and a one-dimensional ethical perspective are not sufficient. The quality of these discussions depends on the discussants' mutual understanding which in turn depends on the participants' level of knowledge.

Modern plant breeding and production of seeds are bioeconomy fields of innovation in which issues of responsibility are discussed frequently and controversially. German consumers are skeptical about interference with the genome of food crops, but individual points of criticism remain unclear. New breeding techniques introduced, e.g., *genome editing*, enable scientists to selectively modify DNA strands of crop plants. These techniques are considered innovative as they may allow breeding of potentially efficient plants in fast and cheap ways. Species developed this way hardly differ from those of conventional breeding. The Central Advisory Committee for Biological Safety does not classify these techniques as genetic engineering, especially because no new combinations of genetic material are made. As the Genetic Engineering Act does not explicitly address these techniques, legal clarification is still necessary as to whether these techniques are classified as genetic engineering at all. Dissemination potential and acceptance are influenced by this result. Here again, the necessity to include education and information policies becomes evident to support the transformation towards a knowledge-based bioeconomy.

The concept of *social innovation* (e.g., Hanusch and Pyka 2013) emphasizes the importance of active citizenship in innovation. Thus, according to the understanding of the European Commission, this term includes innovations that are social, both in relation to their objective and their instruments. In particular, this includes innovations referring to the development and the application of new ideas (for products, services, and models), covering at the same time social demand and creating new social relationships or collaborations. The whole society should benefit and contribute to generate new impetus for improvement. Social innovations can make a major contribution to rural development and promote economic resilience in these regions by strengthening cooperative behavior. Rural cooperatives (e.g., regional producer and marketing associations, winegrowers' cooperatives, tourism associations, etc.) can help to develop regional competitiveness considering ecological and social aspects. As a consequence, within the framework of a bioeconomy, rural regions that are notably affected by the already imminent demographic change and subsequent depopulation receive new opportunities for economic development.

11.4 The Economics of Change

The sections above illustrate that a transformation of the prevailing economic system towards a bioeconomy is an extremely complex process. Various different actors participating in different roles are contributing different pieces of knowledge. In this process, innovative adjustments in already existing industries as well as the emergence of new and the disappearance of mature industries can be observed simultaneously. In addition to the substitutive relations of new bio-based industries to traditional oil-based industries, there are numerous essential complementary relations giving further momentum for the transformation process. First and foremost, there are the possibilities and application fields of digitalization. Digitalization allows to replace many oil-based products and energy-intensive services simply by bits and bytes. Simultaneously, digitalization offers a wide range of opportunities by coordinating decentralized and very detailed bioeconomic technologies and processes such as energy production and distribution. This affects the composition of individual sectors where a coexistence of large diversified companies and small high-specialized technology companies is a likely solution. Finally, digitalization also offers consumer platforms to efficiently organize "sharing economy" approaches. Finally, successful knowledge generation and diffusion of relevant bioeconomic knowledge depends on dynamic innovation networks (Pyka 2002) in which different actors jointly share and create new knowledge. The consumers, represented, for example, by consumer associations or politics, will play a key role in these innovation networks and will help to establish networks in early stages of technology development.

In a knowledge-based bioeconomy, investment and economic growth still represent a crucial element for employment, international competitiveness, and income generation. The bioeconomy can make important contributions to accelerate investments by providing new investment opportunities generated by fundamental innovations and thereby bringing currently available large quantities of liquidity to a productive use. This, in turn, accelerates the technological paradigm shift (Pérez 2010).

The time path of the transformation process represents another critical component and has been explored only partially so far. On the one hand, it is high time to reduce carbon-based production methods. On the other hand, there will be frictions in the transformation process being caused, for example, by a lack of specialists and required competences. In this context, the so-called sailing ship effects (Howells 2002), frequently observed with radical innovations, could be made of good use. In the middle of the nineteenth century, when the existence of the established sailing ship technology was threatened by the arrival of new steam ships, shipbuilders—not having changed their technologies for many decades, if not centuries—began to innovate again. Due to the threat of innovative technologies, adjustment reactions in predecessor technologies can be observed with the aim to prevent the ancient technologies to be quickly replaced. Such adjustment reactions are, for example, fuel-efficient combustion engines and hybrid technologies as a reaction to the emergence of electric vehicles. These adjustments are advantageous since they pursue the same environmental objectives (e.g., inner-city fine dust and noise reduction, etc.) and thus provide more time to develop new technologies. Accordingly, the transformation process will for longer periods of time feature a coexistence of traditional and bio-based industries. Furthermore, it will be important to concurrently steer the relevant innovation processes in traditional technologies. This coexistence further increases complexity. At the same time, innovation policy is given room for maneuver and yet insufficiently developed technologies are prevented from being introduced prematurely which might cause promising approaches to fail.

Distributional effects of the transformation process are important for social acceptance. A bio-based economy on an industrial scale will largely represent a knowledge-based economy. Consequently, additional demand for high-skilled workers arises whereas opportunities for low-skilled workers decrease. This means a potential loss of jobs for less skilled workers in traditional industrial production. But apart from that, there will be demand for different goods and services whose compensation potential with regard to added value and employment is still unclear. Moreover, it remains open to what extent companies are prepared for this transformation into the bioeconomy. Transformation processes will lead to a devaluation of competences so far responsible for economic success. How do established companies deal with the so-called not-invented-here syndrome, overcome operational blindness, and shape transformation processes actively in order to obtain added value at their established locations?

From this follows that distributional effects have an important regional dimension: does the bioeconomy strengthen divergence processes between regions or does it help to achieve more convergence? The approach of creating networks in the sense of the so-called smart specialization principle (Foray et al. 2009), connecting regional strengths along value-added chains in the best possible way, is promising but only sparsely implemented so far. Thus, in general, polarization tendencies leading to economic as well as political and cultural concentration of power and resulting in strong center-periphery structures can be avoided. But it still remains unclear, how strong and operational meaningful politically induced networks are in comparison to self-organized networks and how policy might exert influence. First findings indicate signs of a potential disintegration of the networks when political support is withdrawn (Green et al. 2013).

Transformation towards a knowledge-based bioeconomic production system is supposed to terminate the existing negative relations between economic growth and environmental pollution, use of resources, climate change, and energy consumption and to promote a sustainable economy. The following questions are closely linked to the basic uncertainty of innovation and cannot be answered ex ante: "which contributions are to be made by individual sectors?," "what complex feedbacks for national and international competitiveness are to be expected?," and "do the so-called rebound effects possibly reduce or even overcompensate the positive effects of the transformation?" Institutional rules, such as a self-commitment of oil-producing countries to reduce their outputs due to the declining demand caused by bioeconomics, are a way to reduce these uncertainties, at least partly. It remains necessary for the leading actors, companies, households, and policy makers to refrain from optimization approaches and profit maximization in this transformation process. The complexity and uncertainty of this process requires the awareness of all actors to experimental behavior (*trial and error*) which always also includes the possibility of failure.

11.5 Conclusions

Socioeconomic systems have been exposed to permanent transformation processes since the industrial revolution. While development processes so far have been driven "only" by result-oriented innovation processes, the character of the bioeconomic transformation process is clearly concretized by society and politics. In the past, mainly bottlenecks caused by scientific-technological restrictions were overcome by vast technological revolutions, shifting the socioeconomic system on new trajectories without giving direct instructions to the direction of the development process. At the beginning of the twenty-first century, however, the massive accumulation of greenhouse gases in the atmosphere since the beginning of the industrial revolution and the vulnerability of our present ecosystems reveal that global thresholds are almost surpassed. Thus, the level of freedom for future developments is restricted in order not to irreversibly damage natural conditions for human life and biodiversity. It is yet unclear whether this transformation process succeeds in the desired way and how it can be governed by political influence to achieve existential objectives of the global human society.

New technological developments alone are not enough to transform the socioeconomic system. In a first step, they only create the necessary potential for radical changes affecting the economy as a whole. Converging trajectories and synergies that may finally introduce the paradigm shift necessarily require a broad social consensus on a specific use of these technologies. This means an initiation of a direction of development which connects investment decisions, innovations, and the tackling of basic uncertainty by politics (Pérez 2013). The "green growth paradigm" based on bio-based technologies can be such a direction bringing together the potential of different technological developments and exploring their full potential. This requires political decisions supporting a new orientation of research and innovation activities, exploitation of new energy sources, improvements in productivity of natural resources, and new sustainable ways of living and producing (Pérez 2013). Moreover, in such a transformation process, catching-up economies have to be provided with new opportunities for economic development without overstretching global natural resources and environment. Thus, a political and social direction is essential for a successful transformation process (Mazzucato and Perez 2015).

Examples include the development of new products within emerging bioeconomic innovation systems. In this perspective, innovations require an interplay of actors along value-added chains which might lead to the development of new industries. In the past, for example, the provision of cheap electricity led to the spread of fridges and freezers in private households which brought innovations in the fields of frozen food and packaging. Similarly, the creation of a *sharing economy* may lead to new digital coordination platforms and the creation of sustainable designs by product manufacturers in the bioeconomy. *Planned obsolescence*, a phenomenon wasting resources and shortening product life cycles, would be eliminated this way, and new sectors, for example, in the field of repair and maintenance services are initiated. Important determinants shaping long-term development are networks and clusters. They help to reduce uncertainty and support self-reinforcing effects. Furthermore, social changes and changing lifestyles are both an expression and a driver of this transformation process (Mazzucato and Perez 2015).

Therefore, the role of governments is not only restricted to the correction of market failures. In fact, by ensuring investment safety and reducing risks and uncertainty, government instruments prepare the emergence and flourishing of new markets (Mowery et al. 2010). A crucial task for policies in the realm of innovation and entrepreneurship is the transition from invention to innovation, i.e., the expansion of bioeconomical activities in a market. Correspondingly, a growth path based on bioeconomics is more than a mere replacement of crude oil by renewable resources or renewable energies. It rather needs a *dedicated innovation system* creating synergies, knowledge transfer, and networks between manufacturers, suppliers, and consumers. It requires a comprehensive reorganization that includes the entire economy and renews production and consumption patterns in their present forms, which were shaped by previous transformation process within the oil-based paradigm.

The technological potential of a bioeconomy is a necessary but insufficient condition for this transformation process. It also requires democratic consensus on the broad development and wide application of this technological potential. This includes the exploration of new trajectories and the fusion of new and existing technological trajectories. Markets in which innovations are profitable do not arise on their own but rather need feedback loops between political decisions, corporate strategies, and consumer preferences.

Review Questions

- Discuss the likely social, economic, and environmental effects of the sharing economy. Put particular emphasis on the rebound effect that could emerge in this context due to the fact that the sharing economy makes the use of resources for individuals cheaper. How can policy makers counter this rebound effect?
- What does "creative destruction" mean? Provide two historical examples, where creative destruction has played a particularly important role.
- What are Kondratieff cycles and which are the inventions that are associated with them?
- Sketch the (1) mutually dependent technologies, (2) infrastructural developments, (3) behavioral changes, and (4) institutional changes that you expect to be necessary in the transformation towards a knowledge-based bioeconomy.
- What is a "dedicated innovation system" and how could it look like in case of the transformation towards a bio-based economy?
- Describe the term "responsible innovation" and discuss its meaning in the context of genome editing.

References

Audretsch D, Feldman MP (1996) Innovative clusters and the industry life cycle. Rev Ind Organ 11 (2):253–273

Blewitt J, Cunningham R (eds) (2014) The Post-Growth Project: how the end of economic growth could bring a fairer and happier society. Green House, e-prints, Aston University

Burt RS (2004) Structural holes and good ideas. Am J Sociol 110(2):349–399

Casper S, Lehrer M, Soskice D (1999) Can high-technology industries prosper in Germany? Institutional frameworks and the evolution of the German software and biotechnology industries. Ind Innovat 6(1): 114–139. https://doi.org/10.1080/13662719900000002

Deffuant G, Huet S, Amblard F (2005) An individual-based model of innovation diffusion mixing social value and individual benefit. Am J Sociol 110(4):1041–1069

Dosi G (1982) Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Res Pol 11(3):147–162

Dosi G, Freeman C, Nelson R et al (eds) (1988) Technical change and economic theory. Pinter, London

Foray D, David PA, Hall B (2009) Smart specialization—the concept. Knowledge Economists Policy Brief. doi: https://doi.org/10.1016/j.pcad.2013.03.008

Freeman C (1991) Networks of innovators: a synthesis of research issues. Res Pol 20(5):499–514

Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Pol 31(8):1257–1274

Green L, Pyka A, Schön B (2013) A life-cycle based taxonomy of innovation networks—with focus on public-private collaboration. In: Gallouj F, Rubalcaba L, Windrum P (eds) Public-private innovation networks in services. Edward Elgar, Cheltenham, pp 113–138

Hall PA, Soskice D (2001) An introduction to varieties of capitalism. In: Hall PA, Soskice D (eds) Varieties of capitalism: the institutional foundations of comparative advantage. Oxford University Press, Oxford, pp 1–68

Hanusch H, Pyka A (2013) Social innovations in the perspective of comprehensive Neo-Schumpeterian economics. In: Ruiz Viñals C, Parra Rodríguez C (eds) Social innovation—new forms of organization in knowledge-based societies. Routledge, London, pp 29–43

Howells J (2002) The response of old technology incumbents to technological competition—does the sailing ship effect exist? J Manag Stud 39(7): 887–906

Kallis G, Kerschner C, Martinez-Alier J (2014) The economics of degrowth. Ecol Econ 84:172–180

Knight FH (1921) Risk, uncertainty and profit. Hart, Schaffner & Marx, Boston

Lundvall BA (1992) National innovation systems: towards a theory of innovation and interactive learning. Pinter, London

Lundvall BA (1998) Why study national systems and national styles of innovation? Technol Anal Strat Manag 10(4):403–422

Maddison A (1995) Monitoring the world economy 1820-1992. OECD, Paris

Mazzucato M, Perez C (2015) Innovation as growth policy. In: Fagerberg J, Laestadius S, Martin BR (eds) The triple challenge for Europe: economic development, climate change, and governance. Oxford University Press, Oxford, p 229

Meadows D, Randers J, Behrens WW (1972) The limits to growth. Universe Books, New York

Nelson RR (1993) National innovation systems: a comparative analysis. Oxford University Press, Oxford

North DC (1990) Institutions, institutional change and economic performance. Cambridge University Press, Cambridge, MA

Nyblom J, Borgatti S, Roslakka J et al (2003) Statistical analysis of network data—an application to diffusion of innovation. Soc Netw 25(2):175–195

Pérez C (2010) Technological revolutions and techno-economic paradigms. Camb J Econ 34(1):185–202

Pérez C (2013) Financial bubbles, crises and the role of government in unleashing golden ages. In: Pyka A, Burghof HP (eds) Innovation and finance. Routledge, Milton Park, pp 11–25

Pyka A (2002) Innovation networks in economics—from the incentive-based to the knowledge-based approaches. Eur J Innovat Manag 5(3):152–163

Pyka A (2017) Die Bioökonomie unter dem Blickwinkel der Innovationsökonomie. In: Pietzsch J (ed) Bioökonomie für Einsteiger. Springer, Berlin

Pyka A, Buchmann T (2016) Die Transformation zur wissensbasierten Bioökonomie. In: Burr W, Stephan M (eds) Technologie, Strategie und Organisation. Springer, Berlin, pp 333–361

Robertson M, Swan J, Newell S (1996) The role of networks in the diffusion of technological innovation. J Manag Stud 33:333–360

Sahal D (1985) Technological guideposts and innovation avenues. Res Pol 14(2):61–82

Schlaile MP, Müller M, Schramm M et al (2017) Evolutionary economics, responsible innovation and demand: making a case for the role of consumers. Philos Manag 16:1–33

Schumpeter JA (1934) The theory of economic development. President and Fellows of Harvard College, Harvard

Schumpeter JA (1939) Business cycles. A theoretical, historical and statistical analysis of the capitalist process. McGraw-Hill, New York

Schumpeter JA (1943) Capitalism, socialism and democracy. Harper, New York

Unruh CG (2000) Understanding carbon lock-in. Energ Pol 28:817–830

Valente TW (1996) Social network thresholds in the diffusion of innovations. Soc Netw 18(1):69–89

Von Schomberg R (2011) Prospects for technology assessment in a framework of responsible research and innovation. In: Dusseldorp M, Beecroft R (eds) Technikfolgen abschätzen lehren: Bildungspotenziale transdisziplinärer Methoden. Springer, Wiesbaden, pp 39–61

Whitley R (1999) Divergent capitalisms: the social structuring and change of business systems. Oxford University Press, Oxford

Zaheer A, Bell GG (2005) Benefiting from network position: firm capabilities, structural holes, and performance. Strat Manag J 26(9):809–825

The Bioeconomist

12

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Abstract
The transition towards a bioeconomy in a challenging and complex environment requires substantial interaction and collaboration between different players on various levels. In this chapter, the concept of a bioeconomy professional is discussed. This actor provides an integrative and connecting role for which the development of basic and key competences is required. The concept of T-shaped profiles, built up from disciplinary expertise and the ability to integrate different disciplines and players holistically, is considered an outstanding feature of bioeconomists. To achieve such profiles, interdisciplinary approaches and new learning environments are required during education process. Bioeconomists have relevant roles in all different stages of the value chain as well as in initially setting them up. Finally, various opinions of experts in bioeconomy fields are presented to get an overview of the potential career opportunities for such professionals.

Keywords
T-shaped profile • Collaboration • Mental model • Interdisciplinary competence • Problem-oriented learning • Bioeconomy professional

Learning Objectives
After studying this chapter, you should:

- Understand the importance of the T-shaped profile in the context of bioeconomy.
- Recognise the basic and key competences of a bioeconomist and its relevant role as collaboration catalyst.
- Realise the benefit of learning in an interdisciplinary environment supported by integrative methods.

12.1 Wicked Problems and Collaboration

The socioecological challenges with which present and future generations are faced at all levels (climate change, food security, poverty alleviation, energy supply, etc.) are highly complex and multidimensional. They demand a special interaction between the players involved to achieve the best solutions. Such challenges are referred to as “wicked problems” (see Chap. 4). These differ from “tame problems” in that they cannot be addressed using the linear logic of conventional rationality or understood through quantitative and objective information alone (Innes and Booher 2016). Pacanowsky (1995) explains that whereas tame problems can be solved by thinking “inside the box”, wicked problems force the solvers to think “outside the box”. Dentoni and Bitzer (2015) affirm that individual actions have limited impact due to coordination failures, and therefore “wicked problems require collective action across societal sectors to generate impactful, transformative change of organizations and systems”. The approach to wicked problems requires a different strategy and logic than those usually applied to tame problems. Innes and Booher (2016) argue that a different kind of rationality, a so-called collaborative rationality “built on collaborative dialogue and multifaceted information”, is needed to deal with wicked problems. This requires the integration of various views and perspectives under a “systems approach”. This type of approach is recommended for the formulation and solution of wicked problems (Rittel and Webber 1973). However, rather than being solved, wicked problems are addressed through effective solutions based on the definition of the problem (Pacanowsky 1995). A collaborative dialogue that engages diverse stakeholders' values, knowledge and perspectives contributes to the reframing of untamed problems, rethinking and defining realistic goals and identifying possible solutions through the emergence of innovation (Innes and Booher 2016; Head and Xiang 2016). Innes and Booher (2016) describe the need for planners, who are professionals in setting up, supporting and performing participative processes, and who have the role of active facilitators, following a collaborative rational approach to solving wicked problems.

A Renewed Role of Science

Seeing wicked challenges through systemic lenses modifies the role of science in society, from a disciplinary to more interdisciplinary, participative and collaborative one. According to various scholars, including Schneidewind et al. (2016) and Batie (2008), the role of science and what society demands of science have changed in the last decades, due to the emergent importance of sustainable development and the need to tackle socioecological problems. Polk (2015) argues that "the role of science is seen as evolving to support more contextualized research processes where the participation and collaboration of different stakeholders and users is central to the ability of the research to create socially relevant and scientifically reliable knowledge", which could contribute to societal change. Schneidewind et al. (2016) depict this new vision of science as one that "does not only observe and describe societal transformation processes, but rather initiates and catalyzes them" (Schneidewind et al. 2016, p. 6). This new role of science is built on the idea of interaction and participation to co-produce knowledge, integrating scientists and non-scientists and using different forms of knowledge, perspectives and experiences to address real-life problems (Polk 2015). Polk uses the term "transdisciplinary co-production" as a research approach that includes practitioners and researchers who interact along the knowledge production process starting with the joint problem formulation.

This new role of science triggers the need for new scientists who play a central role as catalysts, managing and conducting more contextualised research using collaborative and participatory frameworks. Thus, collaboration emerges as a common vision, central for the resolution of wicked problems as well, which demands the active leadership of professionals to enable the interaction among stakeholders and to create participatory solutions to specific challenges. In this chapter, a newly emerging professional, the bioeconomist, is introduced and described as that catalyser and enabler of collaboration for the transition from a fossil-based economy to a bioeconomy, a systemic shift that involves multiple complex challenges, goals and agents. Therefore, bioeconomy professionals are expected to be specialised in one field but also able to understand the scientific language of associated disciplines. Furthermore, the increase focus on innovation and interdisciplinary teamwork has created new student profile expectation to deal with global challenges and find sustainable solutions. In this regard, the formation and development of special competences through inter- and transdisciplinary learning is fundamental.

12.2 Professionals for the Bioeconomy

Competences

The concept of competences supports the description of professional profiles. It aims to conceptualise abilities and thus provides an explicit and commonly shared framework (Wiek et al. 2011).

The Organisation for Economic Co-operation and Development (OECD) describes competences as the ability to meet complex demands, by drawing on and mobilising psychological resources (including skills and attitudes) in a particular context (Ananiadou and Claro 2009; OECD 2005). For example, the ability to collaborate effectively in an interdisciplinary team is a competence that relies on an individual's capacity to understand different scientific languages (knowledge) and the attitude he or she has towards other team members. Skills are designated as the ability to use one's knowledge with relative ease to perform relatively simple tasks, while knowledge is defined as the facts or ideas acquired by study, investigation, observation or experience and refers to a body of information that is understood (OECD 2000).

The fulfilment of complex tasks goes beyond the scope of skills and knowledge but also entails the strategies and routines needed to apply the knowledge and skills, including the proper emotions and attitude and the effective management of these components. The development of competences depends both on the educational institutions (schools) attended by an individual and supplementary sociocultural environment such as family and friends (Rychen and Salganik 2000). Multiple sets of competences have been compiled by various international organisations and scientists. For instance, the World Economic Forum (2015) has elaborated an overview of basic competences required in the twenty-first century resulting from the interaction between skills and attitudes (Fig. 12.1).

Basic competences are required by the majority of professional profiles (see Fig. 12.1) and are fundamental to the development of key competences. Thus, both are equally important, but the latter are specific to a particular scientific field or profession and underline specialised abilities. So far, there is no comprehensive set of key competences for bioeconomy professionals in the literature. As sustainability is considered a core principle of the bioeconomy (see Chap. 3), Wiek et al.'s (2011) set of key competences for sustainability provides a sufficient basis for further elaboration.

Figure 12.2 shows the results of a literature review on key competences for sustainability, amalgamating those identified into five key competences, namely, systems-thinking competence, anticipatory competence, normative competence, strategic competence and interpersonal competence (see Box 12.1 for further explanation) (Wiek et al. 2011).

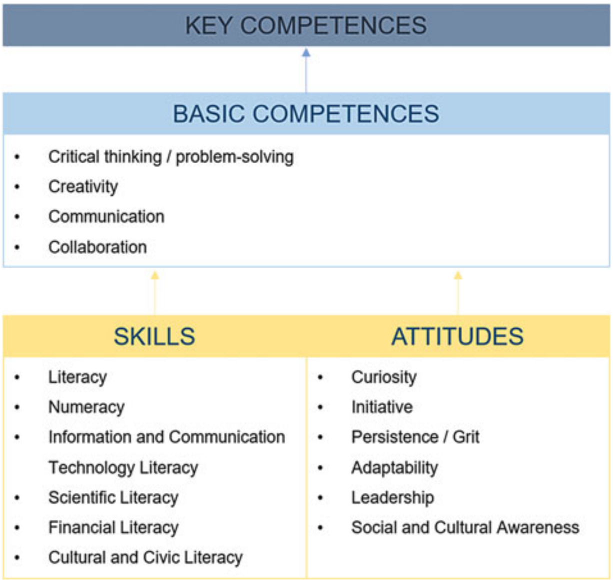

Fig. 12.1 Skills, attitudes and basic competences for the twenty-first century (from World Economic Forum 2015)

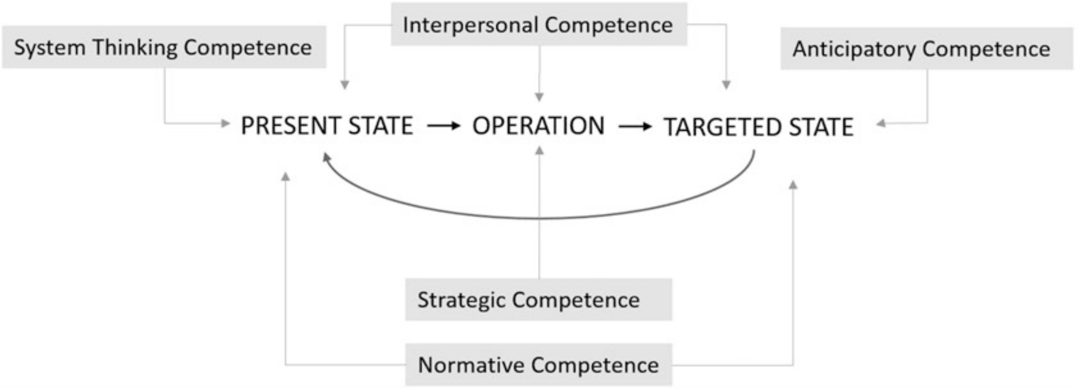

Fig. 12.2 Solving problems—basic structure (see Fig. 4.1) linked to key competences for sustainability

To explain the scope of the emerging key competences, the basic structure of "solving problems" (see Sect. 4.1.2) can be used. According to this framework, problem solving starts with the characterization of the *present state*, commonly the description of a complex problem, the inherent system and the involved stakeholders. Therefore, normative competence is the fundament of exploring the problem, and systems-thinking competence is applied to consider the bigger picture. The *target state* is analysed via anticipatory competence, and normative competence projects values and principles into it. The process towards the target state, the *operation*, demands a sustainable transition strategy designed with the professional's strategic competence. Across the whole process, interpersonal competence facilitates cooperation and is key to a sustainable solution.

Box 12.1: Key Competences for Sustainability (Wiek et al. 2011)

"*Systems-thinking competence* is the ability to collectively analyse complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks." (p. 207)

"*Anticipatory competence* is the ability to collectively analyse, evaluate, and craft rich "pictures" of the future related to sustainability issues and sustainability problem-solving frameworks." (p. 207)

"*Normative competence* is the ability to collectively map, specify, apply, reconcile, and negotiate sustainability values, principles, goals, and targets. This capacity enables, first, to collectively assess the (un-)sustainability of current and/or future states of social-ecological systems and, second, to collectively create and craft sustainability visions for these systems." (p. 209)

"*Strategic competence* is the ability to collectively design and implement interventions, transitions, and transformative governance strategies towards sustainability." (p. 210)

"*Interpersonal competence* is the ability to motivate, enable, and facilitate collaborative and participatory sustainability research and problem solving. This capacity includes advanced skills in communicating, deliberating and negotiating, collaborating, leadership, pluralistic and trans-cultural thinking, and empathy." (p. 211)

With respect to interpersonal competence, a differentiation has to be made between typical sustainability experts and bioeconomy professionals. According to Wiek et al. (2011), interpersonal competence is mostly associated with facilitation and communication skills. However, for bioeconomy professionals, interpersonal competence goes beyond the described set and includes a broad knowledge base. Thus, interpersonal competence in the bioeconomy is extended by interdisciplinary competence. Due to the manifold sectors in the bioeconomy, successful collaboration demands strong interdisciplinary competence and an intermediary professional with the ability to understand the subject matter of all stakeholders along the biobased value chain.

T-Shaped Profile

As indicated in the introduction, complex wicked problems require innovative approaches. The more challenging an issue, the greater the need for the integration of various disciplinary experts and societal stakeholders within comprehensive frameworks to combine diverse knowledge and methods. In order to improve collaboration effectivity, the emergence of shared mental models is beneficial (Madhavan and Grover 1998). As outlined above, this collaborative process may be facilitated by integrative professionals, who use a particular set of competences to set up and support schemes in order to build up trust between different academic and nonacademic players.

(Shared) Mental Model

Rouse and Morris (1986) define mental models as mechanisms in humans that support the description and explanation of purpose, function and (future) states of systems. Accordingly, mental models allow and shape approaches towards and interaction within systems.

In the context of teamwork, shared mental models refer to knowledge structures within the team (the system), which allow members to explain and describe dynamics in order to coordinate and adapt to changes and tasks. Thus, this does not imply identical mental models of individual team members, but rather compatibility of individual mental models enabling a shared understanding of particular situations (Jonker et al. 2011).

Integrative professionals are ideally also disciplinary experts, educated to incorporate and connect different disciplinary knowledge domains and methods. This is referred to as a T-shaped profile, a term first coined by Marco Iansiti (1993). Metaphorically, the vertical stroke of the T symbolises expertise or deep knowledge in a particular field or discipline. By contrast, the horizontal stroke embodies integrative abilities, allowing T-shaped professionals to act effectively across disciplines and, through this, catalyse, manage and conduct contextualised research and innovation processes. These integrative abilities are based on extensive training of collaboration competences. A professional with a T-shaped profile is aware of the variety of practices and methods as well as mental models employed by different disciplines or professions and understands their strengths and limitations.

The concept may be seen in contrast to the more traditional profiles of I- or A-shaped professionals (Fig. 12.3). Currently, the majority of students graduate with an I-shaped profile, educated to become experts in a particular discipline. This means they have a high level of knowledge and expertise in their field of study. However, I-shaped professionals may be disadvantaged in conducting interdisciplinary team efforts. Deficits in the comprehension of fundamental ideas of other disciplines may impede integration and communication with experts from other areas. By contrast, A-shaped professionals have a high degree of expertise and knowledge in two areas, such as engineering and business, and thus may connect at least two fields efficiently (Karjalainen et al. 2009).

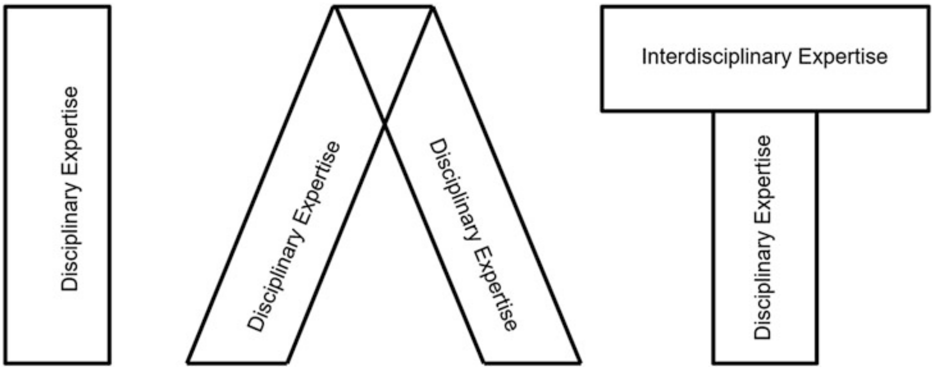

Fig. 12.3 Examples of different professional profiles

The concept of T-shaped profiles goes a step further. These professionals are not only trained to work within multidisciplinary teams but also to facilitate collaboration and connections between experts with various backgrounds. Initially, this idea was derived from “integration teams” in “new product development”, as it ideally contributes to more efficient innovation processes (Iansiti 1993). Originally, Iansiti (1993) emphasised the effectiveness of T-shaped profiles in innovation creation through technology integration in the thriving high-tech sector of the 1990s.

Due to the manifold sectors and disciplines the bioeconomy comprises, the T-shaped profile is designated to exploit the bioeconomy’s full potential. Players within the bioeconomy have to foster integrative approaches and common goals. Accordingly, intermediary bioeconomy professionals require a T-shaped profile, with expertise in a biobased product-chain-related discipline and broad knowledge in associated disciplines (from primary production to commercialisation, with processes, intermediates and products, see Part II of this book). The ability to understand different scientific languages, by knowing their terminology and methods, enables the mediation between stakeholders and the facilitation of collaboration. This allows bioeconomists to form comprehensive frameworks for the collaboration of research or innovation teams with diverse backgrounds within the bioeconomic sector.

Various stakeholders interact within such frameworks. Thus, knowledge and skills are merged in order to address challenges. In this way, the framework represents a road map for cross-fertilisation and the generation of combinatorial innovations. This means that a set of components may be combined and recombined in new ways to create cutting-edge approaches to (wicked) problems. For this, not only an inclusive and open culture is needed, but also a common understanding of goals must be developed. Therefore, an important task for T-shaped integration specialists is to ensure interdependence of individual goals within the group. Different stakeholders are likely to have different peers, ideas and approaches, which means that the overall team success may be influenced by individual research questions and norms. For this purpose, it is necessary to contextualize and assess the systemic impact of individual actions and knowledge and adjust these goals to the scope of the comprehensive framework. Therefore, integrative professionals in the bioeconomy have to be able to think strategically, requiring a goal-oriented and long-term perspective that has to be in alignment with different disciplinary views and practices.

This profile description of a bioeconomist sounds fairly straightforward. In reality, profiles and roles of bioeconomy professionals are highly diverse. Due to the vast size of the bioeconomic sector, there are numerous job possibilities, and thus there is no one-fits-all profile.

12.3 Education for the Bioeconomy

Most higher education programs, especially university programs, are designed to develop an I-shaped profile (Repko et al. 2017). Graduates have profound expertise in one discipline with a specialisation in a particular research field. However, in recent years, education programs with interdisciplinary curricula have been established, especially in the field of sustainability science, which put emphasis on interdisciplinary research. Bioeconomy is an excellent example of an interdisciplinary research field and thus is predestined for such interdisciplinary education programs. Integrated disciplinary expertise from various knowledge domains connected to the biobased value chain benefits the understanding of the challenges within the bioeconomy and support designated bioeconomy professionals to develop a T-shaped profile.

In general, interdisciplinary study programs combine two or more academic disciplines. Students acquire knowledge in these disciplines, learning methods, concepts and theories, as well as their integration and application to complex research problems, within interdisciplinary teams (Repko et al. 2017). In these teams, shared group processes, differing opinions and approaches are not only tolerated but appreciated (Barth and Burandt 2013). Repko et al. (2017) identified key terms in available definitions of "interdisciplinary studies" and brought these together in the following definition:

> Interdisciplinary studies is a cognitive process by which individuals or groups draw on disciplinary perspectives and integrate their insights and modes of thinking to advance their understanding of complex problems with the goal of applying the understanding to a real-world problem. (Repko et al. 2017)

Acquiring the ability to integrate and collaborate is key to the development of interdisciplinary competences (Repko et al. 2017) and thus a main objective of education programs for the bioeconomy. The programs are intended to impart multidisciplinary knowledge and facilitate the development of interdisciplinary competences by means of collaborative curriculum design with innovative learning environments. However, at university level, the coordination of a collaborative curriculum means established disciplinary structures need to be overcome.

The majority of interdisciplinary education programs already established in the field of bioeconomy are master programs (see Box 12.2). With a view to the development of a T-shaped profile, a completed disciplinary bachelor degree would be beneficial. Disciplinary expertise (the vertical stem of the T) already acquired at bachelor level can be extended by interdisciplinary expertise (the horizontal bar of the T) in postgraduate studies. In addition, students from different cultural and academic backgrounds create an international and interdisciplinary atmosphere, which facilitates the learning process. However, the students' diverse academic background is also part of the challenge. The first step of an interdisciplinary education program is to establish a common ground by filling knowledge gaps. In the MSc Bioeconomy program at the University of Hohenheim, the students are introduced to natural science concepts, learn basics of agricultural production and become acquainted with economic thinking.

After a common ground has been established, the focus is on the central topic: the bioeconomy. Students learn what the bioeconomy is, why it is both a chance and a challenge and how the shift towards a bioeconomy can be managed. The concept of biobased value chains and the basics of biobased resources, processes and products along these chains are taught. The open curriculum also enables students to develop their own individual profile.

In addition to this multidisciplinary knowledge, education for the bioeconomy places an emphasis on the development of competences, in particular interdisciplinary competence. This is an integral part of the learning process, because competences are seen as learnable but not teachable (Barth and Burandt 2013).

Barth et al. (2007, p. 4) promote a *new learning culture* which is "enabling-oriented, based on self-organisation and centred on competence". The acquisition of competences is based on the interplay of cognitive (skills) and noncognitive (attitude) components. For instance, the development of complex (shared) mental models is a result of cognitive skills. Noncognitive components include value learning, social interaction and reflective skills. Both cognitive and noncognitive components support the development of new competences. The internalisation of new competences is ensured by applying them to multiple contexts via problem-oriented learning (Barth et al. 2007).

In this light, the *new learning culture* is associated with *open learning environments*, which means that learning takes place in manifold forms and depends on individual learning styles. Open learning environments facilitate competence development by following three key principles (Barth and Burandt 2013):

1. *Self-directed learning* aims to stimulate intrinsically motivated learning. For instance, project-based learning or e-learning emphasises the active development of knowledge. It takes students' varying education levels and learning speeds into account. Shallow supervision can guide students towards learning goals.
2. *Collaborative learning* requests participation and empathy. Project work in groups in particular promotes the development of interdisciplinary competence.
3. *Problem-oriented learning* considers real-world problems. Therefore, the first two principles are prerequisites for a successful problem-oriented approach, often in collaboration with external stakeholders (e.g. companies).

In the context of learning competences, the interplay between formal and informal learning settings is of particular value (Barth et al. 2007). Study courses with open learning environments offer manifold opportunities for learning in a formal environment. However, informal settings, such as volunteering in a student group, also contribute to the personal learning process and competence development. Here, learning is self-directed without the assistance of an educator. In some settings, learning may even be incidental, with no previous intention to learn, but an awareness of having learnt something afterwards. The social component of informal learning settings is an additional factor in the promotion of competence development (Schugurensky 2000).

Whether formal or informal, the proactive shaping of a T-shaped profile is a unique selling point for graduates. The innovative potential of the bioeconomy calls for forward-looking collaboration specialists, driven by the goal of the transition towards a biobased economy.

Box 12.2: Examples of Interdisciplinary Study Programs in the Field of the Bioeconomy

During the last few years, a range of study programs dedicated to the bioeconomy sector has been developed, including Europe's first Bioeconomy degree program at the University of Hohenheim (MSc Bioeconomy). Other examples are MSc Biobased Sciences (Wageningen University); MSc Biobased Materials (Maastricht University); MSc Biocircle (Bioeconomy in the Circular Economy) (University of Bologna, University of Milano-Bicocca, University of Naples Federico II and University of Turin); MSc Management of Bioeconomy, Innovation and Governance (University of Edinburgh) and Master of Engineering Leadership in Green Bio-Products (University of British Columbia). Common elements include the study of entire biobased value chains and the focus on the ecological, social and economic impacts of bioeconomic developments. The general goal is to educate professionals able to identify innovation opportunities through the integration of multi- and interdisciplinary perspectives and diverse knowledge sources. As such, interdisciplinary problem-based group work activities are a common feature of these programs and curriculums.

12.4 The Bioeconomist and the Job Market

The bioeconomy is expected to generate a large number of employment opportunities in the coming years, as documented by various reports and national strategies worldwide (German Bioeconomy Council 2015; European Commission 2015, 2016). With a focus on high added value and creation of new economic activities, the bioeconomy will require skilled professionals along the biobased value chains. Firstly, bioeconomists have an important role in setting up and organising value chains, for which key competences as the ones illustrated in this chapter are necessary (horizontal stroke of the T). Secondly, the various stages of the value chains demand different types of disciplinary expertise (vertical stroke of the T).

For instance, the European Bioeconomy Stakeholders Manifesto, issued in 2016 as a result of the 4th Bioeconomy Stakeholder Conference in Utrecht, emphasised *connectivity as the new productivity*, arguing that "the added value of the bioeconomy lies in the interaction between its diverse areas that provide opportunities for new innovation" (Bioeconomy Stakeholder Conference 2016, p. 4). Based on this, bioeconomic practitioners and researchers with developed key competences (see Sect. 12.2) act as connectors and catalysers of bioeconomy. These roles are to be performed in managerial and leading positions in private, public and third-sector organisations in the field of research and development, rural development, advisory services, sustainability-oriented institutions and policy-making bodies. A special role for bioeconomist due to the T-shape profile is the leading of interdisciplinary teams and projects, performing as a project manager in the context of sustainability and bioeconomy.

Particular career development options are offered by start-ups, which are considered key drivers of innovation in the bioeconomy. The design and implementation of bioeconomy governance structures and policies through the engagement of various players are enriched by the involvement of bioeconomy professionals. In this manner, the understanding, assessing and addressing of possible conflicts and trade-offs are enhanced (German Bioeconomy Council 2015). This supporting role is also to be performed within the knowledge and innovation system (KIS) introduced by the European Commission as a basis for fostering the bioeconomy (Kovacs 2015).

Due to the novelty of interdisciplinary programs for the education of bioeconomists, there is as yet no empirical information on the positions they may hold. This is confirmed by the Global Bioeconomy Summit Manifesto, which states the need "to initiate a dialogue among stakeholders regarding the knowledge, skills and competencies, which will be crucial for implementing the bioeconomy, and to promote mutual capacity building efforts" (German Bioeconomy Council 2015, p. 8). Some thoughts and insights from selected bioeconomy experts with regard to the job market and the role of bioeconomy professionals are presented in the Box 12.3, as a mean of building up this dialogue.

Box 12.3: Excursus Box: Insights from Bioeconomy Professionals

Prof. Dr. Werner Kunz: "In a world of growing complexity, easy solutions are an illusion. In the future, entrepreneurial success and a respectful treatment of the global environment will be interdependent. This challenge requires the connection of various disciplines and, consequently, demands a more comprehensive education and training of future professionals. Ecologists have to be able to communicate with economists and, in turn, both need to have the confidence of engineers and technicians. Life Cycle Assessments will be as important as business plans and the associated process technologies.

With this is mind, I am convinced of the necessity of interface managers ("Schnittstellenmanager"), who will

(continued)

Box 12.3 (continued)

connect relevant players along the value chain. Remarkable progress can already be observed in particular sectors of the bioeconomy. However, at the same time, a deficit in connectivity is impairing more comprehensive development and innovation.

For this reason, I aspire to more interdisciplinary programs in Germany and the entire world. These education programs ought to be committed to the connection of highly complex disciplines and fields in holistic approaches. This will be fundamental for the future and beneficial for society, industry and environment."

Prof. Dr. Werner Kunz is Chair of Physical and Theoretical Chemistry at Regensburg University, where his research is dedicated to solution chemistry. He has performed numerous projects with industrial partners and runs his own company in the field of the bioeconomy (SKH GmbH).

Christiane Grefe: "Education—but for which bioeconomy? There are so many different definitions of what bioeconomy is and what it could or should be (and so many controversies even about whether the term makes any sense at all), that a "bioeconomy professional" cannot be described without further clarification of what his/her role should be tailored to.

In my view, the term bioeconomy must go beyond changing the resource basis from fossil to renewable, as well as beyond applying genome editing to different industrial, medical or plant breeding purposes; it must also go beyond producing "more with less" or creating innovative value chains in order to achieve "green" economic growth. The added value of the concept is to consider all this in its interdependencies and trade-offs in the context of our planetary boundaries and a just distribution of all natural resources. Bioeconomy should be envisaged as a true circular economy, better: as circular economies, which are specific to the ecological, social, and technological diversity of regional and local conditions.

Future "bioeconomy professionals" should therefore not only have knowledge of innovative technologies, as promoted by most governments and industries. They should also understand ecosystems, their cultural aspects included. And they should have training in communication and dialogue capabilities.

The latter should be a priority because a lot of conflicts will have to be resolved. And, even more important: opportunities for efficient uses and re-uses will not be discovered without organising intense cooperation—and thus: communication. A bioeconomy respectful of given natural or cultural limits will only develop fruitfully if industries and city governments, scientists and professionals, citizens and environmentalists all work closely together, coordinated by bioeconomy experts."

Christiane Grefe is a ZEIT journalist and author of the book *Global Gardening—Bioökonomie: neuer Raubbau oder Wirtschaftsform der Zukunft?*, Antje Kunstmann Verlag, München, 2016.

Markus Frank: "Being a professional in the bioeconomic sector requires, besides deep knowledge in one field of expertise, competences in managing scarce biobased resources, and thus, implies fundamental understanding of sustainability. Therefore, education for future professionals in this field should be designed to develop best practices for integrating sustainable management concepts into work routines.

In this context, two concepts are of particular interest. First, life-cycle thinking enables impacts along the entire value chains to be reflected upon, and the

(continued)

Box 12.3 (continued)

displacement of negative environmental, social, and economic impacts to be avoided. Second, learning about stakeholder theory and the engagement of stakeholders promotes the mutual understanding of different players' interests and needs. Both approaches comprise key competences for project managers in the area of biobased economies in order to analyse trade-offs and deal with complex challenges. The learning of these key competences demands practically oriented education environments; a shift from classroom teaching towards project-based social learning through working on real-life problems. In this context, collaboration with companies, political or regulatory stakeholders, NGOs and associations can be of benefit. Supplementary international and interdisciplinary study programs on the science behind project management, strategy development and implementation, marketing, and financial valuation as well as stakeholder engagement should help students to transfer what they have learnt to other case studies in their professional life.

Clearly, there is a demand in the job market for graduates with such competences. However, it is crucial for the employer to also see a "basic skill set" (e.g. in business, natural science, agronomy, or engineering) beside the special focus on bioeconomy and sustainability management: Most, if not all, professionals will be exposed to very different areas inside the organisation.

In a nutshell, the unique value proposition of a graduate combines deep knowledge in the field of biobased value chains, the concepts of life-cycle thinking and stakeholder engagement with a profound background in project management, team working and strategic thinking. To achieve this, project-based learning addressing real-world problems should be emphasised in the curriculum."

Markus Frank works for the department "Global Sustainability & Product Stewardship Crop Protection" at BASF SE. He holds a PhD in Biology and a MBA from Surrey Business School. At the University of Hohenheim, he supervises students within the module "Projects in Bioeconomic Research".

Dr. Michael Schweizer: "As a company within the biobased sector, we recognise the importance of the development of new curricula. Professionals for biobased companies should be characterised by a special set of skills. I would like to emphasize the additional benefit of graduates capable of understanding both the technical and economic dimension of products or services. This is of outstanding relevance in small and medium enterprises (SMEs) in particular, as the conversant use of economic figures and also technological and ecological data is a prerequisite for successful communication with costumers. Correspondingly, employees should ideally have a mindset that allows them to understand terms and mental models of key players active in areas related to the biobased company.

Especially in small enterprises, employees are in constant touch with other disciplinary specialists, as a clear department structure is often not given, and companies are less hierarchically structured. In this context, work is highly dependent on group efforts and therefore social ability and teamwork efficiency are indispensable skills that should not be underestimated. Accordingly, abilities such as team leading, project management and presentation skills are a vital part of relevant education programs.

However, even more important for bioeconomy professionals is openness and

(continued)

Box 12.3 (continued)

proactivity; characteristics I experienced during my contact with Hohenheim bioeconomy students. These qualities should be further strengthened by the education environment. This could be achieved by project learning in collaboration with companies, and other additional activities such as this textbook, visits to conferences, and the organisation of extracurricular lectures. Following this approach, graduates should be well prepared for a career in SMEs, as real-world challenges and everyday work routines are already part of their expertise."

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Review Questions

- Why collaboration is considered as a central aspect to address wicked problems?
- Can someone with a deep disciplinary formation acquire the key competences illustrated in this chapter? How can this happen?
- What are possible opportunities and hurdles of a T-shaped profile with a stronger horizontal than vertical stroke and vice versa?
- Why would a company employ a bioeconomist? How can such professional add value and what roles would he/she performs?

References

Ananiadou K, Claro M (2009) 21st century skills and competences for new millennium learners in OECD countries. OECD Educ Work Pap. https://doi.org/10.1787/218525261154

Barth M, Burandt S (2013) Adding the "e-" to learning for sustainable development: challenges and innovation. Sustainability 5:2609–2622. https://doi.org/10.3390/su5062609

Barth M, Godemann J, Rieckmann M et al (2007) Developing key competencies for sustainable development in higher education. Int J Sustain High Educ 8:416–430. https://doi.org/10.1108/14676370710823582

Batie SS (2008) Wicked problems and applied economics. Am J Agric Econ 90:1176–1191. https://doi.org/10.1111/j.1467-8276.2008.01202.x

Dentoni D, Bitzer V (2015) The role(s) of universities in dealing with global wicked problems through multi-stakeholder initiatives. J Clean Prod 106:68–78. https://doi.org/10.1016/j.jclepro.2014.09.050

European Comission (2015) Sustainable agriculture, forestry and fisheries in the bioeconomy—a challenge for europe. 4th SCAR Foresight Exercise

European Comission (2016) European bioeconomy stakeholders manifesto, building blocks. Bioeconomy Utrecht 2016—4th Stakeholder's Conference

German Bioeconomy Council (2015) Bioeconomy policy (Part II)—Synopsis of national strategies around the world, pp 1–146

Head B, Xiang W (2016) Why is an APT approach to wicked problems important? Landsc Urban Plan 154:4–7. https://doi.org/10.1016/j.landurbplan.2016.03.018

Iansiti M (1993) Real-world R&D: jumping the product generation gap. Harv Bus Rev 71:138–147

Innes JE, Booher DE (2016) Collaborative rationality as a strategy for working with wicked problems. Landsc Urban Plan 154:8–10. https://doi.org/10.1016/j.landurbplan.2016.03.016

Jonker CM, Van Riemsdijk MB, Vermeulen B (2011) Shared mental models. In: De Vos M, Fornara N, Pitt JV, Vouros G (eds) Coordination, organizations, institutions, and norms in agent systems VI. Springer, Berlin, pp 132–151

Karjalainen TM, Koria M, Salimäki M (2009) Educating T-shaped design, business and engineering professionals. In: Proceedings of the 19th CIRP design conference, 30–31 Mar 2009

Kovacs B (ed) (2015) Sustainable agriculture, forestry and fisheries in the bioeconomy. In: Standing Committee on Agricultural Research 4th Foresight Exercise

Madhavan R, Grover R (1998) From embedded knowledge to embodied knowledge: new product development as knowledge management. J Mark 62:1–12

OECD (2005) The definition and selection of key competencies—executive summary

Pacanowsky M (1995) Team tools for wicked problems. Organ Dyn 23:36–51. https://doi.org/10.1016/0090-2616(95)90024-1

Polk M (2015) Transdisciplinary co-production: designing and testing a transdisciplinary research framework for societal problem solving. Futures. https://doi.org/10.1016/j.futures.2014.11.001

Repko AF, Szostak R, Buchenberger MP (2017) Identifying relevant disciplines and gathering information about the problem. In: Introduction to interdisciplinary studies, 2nd edn. Sage, Thousand Oaks, CA

Rittel HWJ, Webber MM (1973) Dilemmas in a general theory of planning. Policy Sci 4:155–169. https://doi.org/10.1007/BF01405730

Rouse WB, Morris NM (1986) On looking into the black box: prospects and limits in the search for mental models. Psychol Bull 100:349–363. https://doi.org/10.1037/0033-2909.100.3.349

Rychen DS, Salganik LH (2000) Definition and selection of key competencies—a contribution of the OCDE program definition and selection of competencies: theoretical and conceptual foundations

Schneidewind U, Singer-Brodowski M, Augenstein K et al (2016) Pledge for a transformative science: a conceptual framework. Wuppertal Pap 28. ISSN: 0949-5266

Schugurensky D (2000) The forms of informal learning: towards a conceptualization of the field

WEF (2015) New vision for education unlocking the potential of technology

Wiek A, Withycombe L, Redman C (2011) Key competencies in sustainability: a reference framework for academic program development. Sustain Sci 6:203–218. https://doi.org/10.1007/s11625-011-0132-6