The Biodiversity of Food and Agriculture (Agrobiodiversity) in the Anthropocene: Research Advances and a Conceptual Framework

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The biodiversity of food and agriculture (Agrobiodiversity) in the anthropocene: Research advances and conceptual framework

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ABSTRACT

Multiple knowledge systems are crucial to understand human-environment interactions of the biodiversity of agriculture and food systems (agrobiodiversity). This article synthesizes these knowledge systems to formulate the novel Agrobiodiversity Knowledge Framework comprised of four themes: (1) ecology and evolution; (2) governance; (3) food, nutrition, and health; and (4) global environmental and socioeconomic changes. Resulting characterization of these knowledge themes, joined with cross-theme integration, demonstrate advances of agrobiodiversity research, management, and policy amid the accelerated global environmental and socioeconomic transformations of the Anthropocene. Framework results guide the presentation of new data from the Agrobiodiversity, Food, and Nutrition project (AFN) in Peru. These results integrate an emphasis on factors of global change, including climate change. The combination of the new knowledge framework and project results is utilized to point toward future directions for research, policy, and management. The Agrobiodiversity Knowledge Framework is essential to address the transformative planetary challenges of the Anthropocene that include sustainable development with nutritional security, biodiversity conservation, social justice, climate change, and nutrient pollution. Strengthening the focus on and analysis of the complex human-environment interactions of biodiversity in agriculture and food is vital as a nexus of science, scholarship, management, and policy in the era of Earth systems dominated by human activity.

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1. Introduction: agrobiodiversity and the anthropocene

1.1. Human-environment interactions of biodiversity of agriculture and food systems

Agriculture and food systems are prominent drivers of changes in global Earth and socioeconomic systems in the “Anthropocene,” a time of intense human interactions with the planet. Agriculture and food systems are also the recipients of major changes. Amid this coupling, the biodiversity of agriculture and food systems has undergirded the long-term development and spread of agriculture beginning 4,000–7,000 years ago (Fuller et al., 2011; Smith and Zeder, 2013). Changes of the modern, industrial period beginning around 1800 (Foley et al., 2013) have subsequently transformed the biodiversity of agriculture and food systems. The human-environment interactions of this biodiversity—referred to as agrobiodiversity—are increasingly recognized as central in planetary-scale changes involving the environmental and social dimensions of sustainability (Zimmerer and De Haan, 2017, 2019). Agrobiodiversity has been overlooked, however, in the major scientific and scholarly advances to-date on the Anthropocene (Ruddiman, 2013; Ruddiman and Thomson, 2001; Steffen et al., 2011; Zalasiewicz et al., 2017).

Addressing this lacuna in understandings of the Anthropocene requires defining the multiple types and scales of agrobiodiversity as a complex, human-interdependent resource system (Table 1, Fig. 1; see also Bioversity, 2017). It also necessitates recognition that to-date the specific sub-domain of research on agriculture and food in the Anthropocene has emphasized impacts on biogeochemistry, earthworks (e.g. terraces and irrigation), and the traits and biogeography of domestication, together with the ecosystems, landscapes, and resources of agriculture and food systems (e.g. Doolittle, 2015; Fuller et al., 2011; Smith and Zeder, 2013; Young, 2014). Such research, while groundbreaking, has not yet addressed the role of agrobiodiversity, neither in the proposal for a new geologic epoch of the Anthropocene (Zalasiewicz et al., 2017) nor with regard to the general phenomenon of Earth systems dominated by human activity (“anthropocene,” Ruddiman et al., 2015). Similarly, agrobiodiversity is not yet a focus of Anthropocene research related to transformative environmental and human changes (social- and political-ecological) at local, national, and global scales (Bennett et al., 2016; Brondizio et al., 2016).

The human-environment interactions of the biodiversity of agriculture and food systems have been integral and are subject to expanding planetary transformations. These interactions include crop and livestock evolution and development, agroecosystem services, and human diets, food, and health (Bioversity International, 2017; Jackson et al., 2007; Jarvis et al., 2007; Nabhan, 2012, 2016; Willett et al., 2019; Zimmerer and De Haan, 2017, 2019). Agrobiodiversity exerts influence on, and is affected by, the factors of environmental and biotic resources (e.g., soil, water, pollinators) together with sociocultural and linguistic practices, development and technologies, and multi-scale institutions and social relations. But agrobiodiversity—including associated sociocultural practices (Table 1, Fig. 1)—has declined steeply during the past 100–150 years. The Food and Agriculture Organization of the United Nations estimates that 75% of crop diversity disappeared between 1900 and 2000 (FAO, 1999a, 1999b). For example, only 10% of the 10,000 wheat varieties produced in China in 1949 are now grown, and fewer than 5% of the apple types recorded in 1900 are being cultivated in the United States (Gepts, 2006).

Table 1
The Multi-Level Definition of Agrobiodiversity.

Level of Agrobiodiversity	Major Definitional Elements (Examples)	Other Specifications
Food and crop biodiversity *per se* in addition to intentional biotic interactions in general (Vandermeer et al., 1998; Zimmerer and De Haan, 2017,2019)	domesticated and semi-domesticated plants and animals; wild foods (Bharucha and Pretty, 2010; Cruz-Garcia and Struik, 2015; Reyes-García et al., 2006)	species, varieties/landraces, genetic and genomic (including functional traits), functional groups (e.g., for dietary diversity analysis); multiple scales (field, farm, community, landscape, region, global) (Jarvis et al., 2008a,b; Zimmerer, 1991b)
Associated Biodiversity (Vandermeer et al., 1998)	wild relatives of domesticated plants and animals; associated organisms including pollinators, dispersal agents, soil organisms, microbes, and trees (Dawson et al., 2014)	species, multiple scales (agroecosystem, landscape, region, global) (Jackson et al., 2007)
Sociocultural and Economic Practices and Management (including agrodiversity; Almekinders et al., 1995; Brookfield, 2001)	sociocultural meanings and economic practices (CBD, 2016; Johns et al., 2013), including knowledge, skills, resource management (seeds, land, water, labor), and foodways	linguistics of naming and classification; social and cultural relations (e.g., gender, ethnic group, socioeconomic resource level)
Institutional Diversity (Zimmerer and De Haan, 2019)	agriculture and development organizations; food and nutrition organizations; climate change and resilience organizations; boundary work and organizations involving the above (Zimmerer, 2015; see also Cash, 2001; Cash et al., 2003; Clark et al., 2016)	community-based resource management (e.g., seed banks); existing seed networks based on social relations; global and international institutions (Bellon et al., 2015; Bioversity International, 2017)

1.2. Agrobiodiversity, global change, diet and nutrition, and domesticated nature

Given the above trends and increasing global climate change and food system transformations, concerns are mounting over the decline of critical agrobiodiversity and entwined sociocultural systems (Bioversity, 2017; Brown and Hodgkin, 2015; Brush, 1995; Gepts, 2006; Gepts et al., 2012; Jarvis et al., 2011, 2016; Zimmerer, 2010; Zimmerer and de Haan, 2017, 2019). The goal of this article is to review representative research to create and utilize a robust framework of the principal knowledge systems of agrobiodiversity. It requires characterizing leading-edge works as well as identifying and conceptualizing the organization of knowledge systems (e.g., Cash et al., 2003; Clark et al., 2016). The resulting Agrobiodiversity Knowledge Framework then guides the presentation of new data and the discussion of future research as well as management and policy. We approach the dynamic, broad-based human interactions of agrobiodiversity as fundamentally engaged with the Earth systems of the Anthropocene (Sections 4.1,4.6).

Just a handful of starchy and oil- and sugar-producing crops have dominated diets amid expanded industrial food systems and the Global Nutrition Transition affecting much of the world's population (Popkin et al., 2012). The massive increases of animal feed production and meat consumption are part of this trend. Global- and national-level institutions and movements addressing malnutrition, the negative health consequences of poor diets (e.g., non-communicable diseases, NCDs), and the associated problems of inadequate access to high-quality foods, especially among the

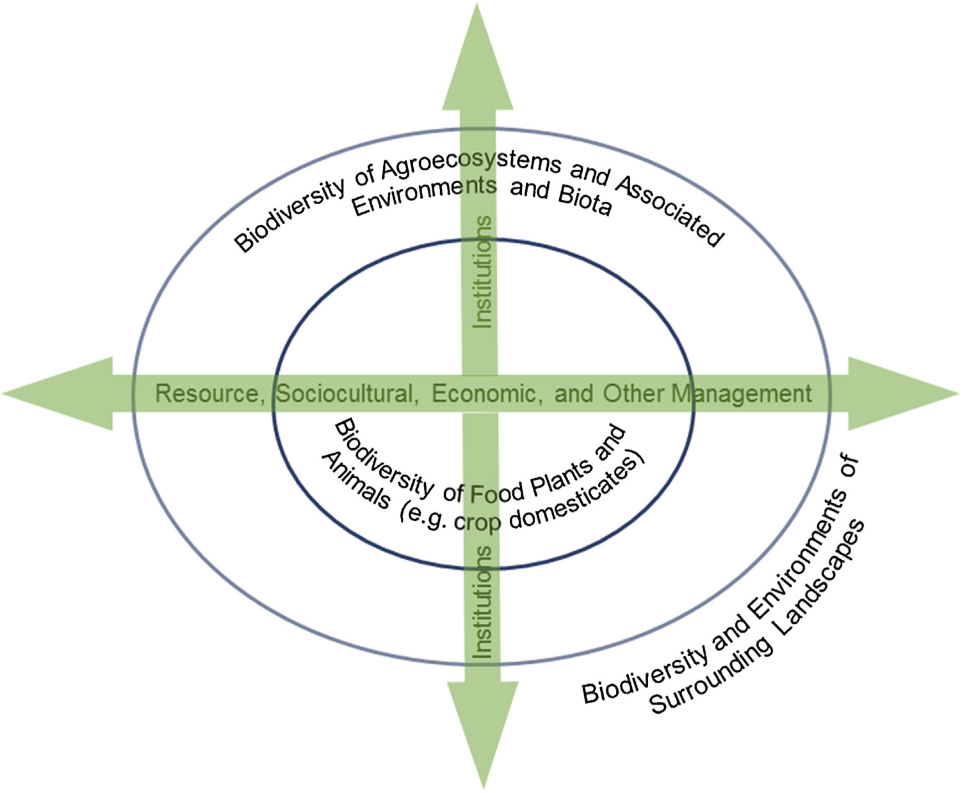

Fig. 1. Visualization of the Expanded Definition of Agrobiodiversity.

world's poor, are now among those most active in promoting the use and conservation of agrobiodiversity (Frison et al., 2011; Jacobsen et al., 2015; Johns and Eyzaguirre, 2006; Johns et al., 2013; Jones, 2017; Khoury et al., 2014; Khoury and Jarvis, 2014). The much-awaited, new report of the high-level, EAT-Lancet Commission on Food, Health, Planet further elaborates this agenda (Willett et al., 2019). Sections 2.4,3.3, 4.1, and 4.3 below address these approaches and the new agrobiodiversity-related advances in nutrition and health.

Complex human dimensions undergird agrobiodiversity dynamics and make it well suited to the general "anthropocene" term (Sections 1.1 and 4.6). Global concentrations of this biodiversity are deeply embedded in the agriculture and food systems of indigenous and smallholder communities worldwide (Brush, 1995; Jarvis et al., 2007; Zimmerer and de Haan, 2017). We incorporate a biocultural approach (Bavikatt, 2015; Sajeva, 2018) to examine diverse community-based management and policy involving agrobiodiversity. It addresses cultural and social identities and movements, stakeholder groups, and social- and political-ecological issues such as biocultural diversity, biocultural heritage, and social power, equity, and justice. Agrobiodiversity analysis, including the biocultural approach, therefore broadens the scope and framing of human-biodiversity interactions in domesticated nature and the anthropogenic biosphere that distinguish Anthropocene ecological investigation (Ellis, 2015; Ellis et al., 2012; Kareiva et al., 2007).

This paper highlights the agrobiodiversity trends of modern, global industrial agri-food systems and such related processes as planetary urbanization. Together with the points introduced in Section 1.1, the expansion of agrobiodiversity concern is reflected in various global institutions, research activities, and initiatives that connect science and scholarship to policy and management (Table 2). Their international scope underscores the global importance and diverse valuation of agrobiodiversity. These interests and works also evidence and argue for the roles of agrobiodiversity as *both* a human-modified, global Earth environmental system (similar to general biodiversity, climate, or water resources) *and* as integral to human dimensions (*sensu* Liverman et al., 2003). The latter demonstrate that the social- and political-ecological dynamics of agrobiodiversity (e.g., transformation, adaptation, resilience, and vulnerability; Sections 2.3, 2.3.1, 2.3.2, 2.3.3, 3.4, 4.2.1, 4.5) are vital to the human dimensions of global agrobiodiversity change and to the issues of equity and justice.

1.3. Overview: developing the Agrobiodiversity Knowledge Framework

The review of representative research in Sections 2.1-2.5.3 characterizes four knowledge themes that function as hubs or nodes of highly active networks. These are: (1) ecology and evolution; (2) governance (including biocultural approaches); (3) food, nutrition, and health; and (4) global environmental and socioeconomic change and transformations (Table 3, Fig. 2). Each theme has distinct knowledge assemblages (disciplinary, interdisciplinary, and transdisciplinary modes) and corresponding valuation as well as associated management and policy (columns in Table 3). Escalating interest in agrobiodiversity among diverse social and scientific sectors (DeClerck et al., 2011; Delaquis et al., 2018) leads us to examine the potential compatibility of diverse valuations as well as conflicts and frequent contestation. We assemble these themes to construct the proposed Agrobiodiversity Knowledge Framework. The framework highlights the distinct themes and networks (Fig. 2) whose overlap enables cross-theme integration (see below). We then report new results from the Agrobiodiversity, Food, and Nutrition Project in Peru (Section III) to develop future research directions (Section IV) and conclusions (Section V).

Reviews to-date have examined the individual themes or sub-themes of agrobiodiversity knowledge but not the fuller scope of both within-theme specialization and cross-thematic integration. Advancing agrobiodiversity science and scholarship as well as policy and management requires meeting the challenges and opportunities posed by these knowledge configurations (illustrated in Fig. 1).

2. Review

2.1. Methods

We conducted a guided, systematic analysis of representative publications (Sections 2.1-2.5.3) including the chronology of agrobiodiversity knowledge (Sections 2.1-2.3.3) and the bibliometric categorization and estimation of research (Fig. 3). This methodology led to the identification of a small group of principal knowledge themes. The four themes are: ecology and evolution (2.2) governance (2.3), food, nutrition, and health (2.4), and global environmental and socioeconomic changes (2.5). We define "knowledge" broadly to include scientific, scholarly, management, policy, and stakeholder forms of know-how, including biocultural and indigenous knowledge systems.

2.2. Ecology and evolution

Biological, ecosystem, and evolutionary values (and associated economic purposes) that range from genetic resources to agro-ecosystem goods and services motivate this theme (Table 3). Major early works on crop and livestock evolution, plant geography and genetic resources owed to Darwin, de Candolle, Vavilov and others (e.g., Vavilov, 1992). By the 1970s, research was further pioneered in the far-sighted works of biologically trained specialists such as Bennett, Frankel, Harlan, Hawkes, Heiser, Iltis, and numerous others whose works continue to exert influence (e.g., Frankel and Bennett, 1970; Nabhan, 2012). They championed the value of the continued co-evolution of extant crop and livestock diversity as genetic resources amid concerns over global decline ("genetic erosion"). Their works and many others advanced evolutionary and ecological insights that have also encompassed genetics, taxonomy, and biodiversity science.

Table 2
Institutional Interest (Examples) and Research Monographs (Examples) With Major Focus on Agrobiodiversity.

Institutional Interests in Agrobiodiversity (2010-persent)	Research Monographs on Agrobiodiversity
Agrobiodiversity as genetic resources (FAO, 2010), multi-function knowledge platforms (ARCAD, 2010); food and agriculture internatioanlly (FAO and PAR, 2011) and nationally (e.g., NAFRI, 2016), ecosystem services (DIVERSITAS in Jackson et al., 2012; MEA, 2005), food system components and impacts (IOM and NRC, 2015); agroecological and food systems (IPES-Food, 2016); seeds and resilience (GAFF, 2016); mainstreaming and indexing (Bioversity International, 2017), and food security and nutrition (HLPE, 2017).	Agrobiodiversity research analysis (monograph-scope): Andersen, 2013; Brookfield, 2001; Brush, 2000, 2004; Cleveland, 2013; Gepts et al., 2012; Jarvis et al., 2016, 2007; Kontoleon et al., 2008; Lenné and Wood, 2011; Nabhan, 2012, 2016; Richards, 1985; Smale, 2005; Vavilov, 1992; Wood and Lenné, 1999; Zimmerer, 1996; Zimmerer and De Haan, 2019

Table 3
Principal Themes of the Agrobiodiversity Knowledge Framework (AKF).

Principal Categories of Agrobiodiversity Knowledge	General Description of Values	Examples of Relevant Academic Fields and Interdisciplinary and Transdisciplinary Approaches	Current Management and Policy Issues
Ecology and Evolution (related to agrobiodiversity)	Biological Values (broadly evolutionary and ecological, including agroecological)	ecology, agroecology, forest ecology, biology, genetics and genetic resources, human ecology, ethnobiology, ecological anthropology, human-environment geography	ex situ and in situ coordination; evaluating the degree of agrobiodiversity loss or “genetic erosion”
Governance (related to agrobiodiversity)	Biocultural and Socioeconomic Values (wide range of culinary, symbolic, social network, and economic and livelihood values)	biocultural approaches, ethnobiology, policy, law, food systems, food environments, economics, sociology, political ecology, anthropology, geography, indigenous studies, gender studies, urban studies	role of ethnicity in genetic diversity; informal seed system support across multiple scales
Diet, Nutrition, and Health (related to agrobiodiversity)	Well-Being Values (incorporates diet and nutrition into physical well-being as well as mental health)	nutrition, health, public health, food studies, planning, agricultural and development economics, urban studies	nutritional security, market integration with possible inflecting of the U-shape curve
Global Change and Transformation (related to agrobiodiversity)	Adaptive Capacity and Resilience Values (capabilities and vulnerability of responses to global environmental and socioeconomic transformations)	social-ecological systems, political ecology, sustainability studies, global studies, ecology, geography, anthropology, sociology	capacities of food production and consumption systems amid global change (including adaptation, resilience, vulnerability, and transformation)

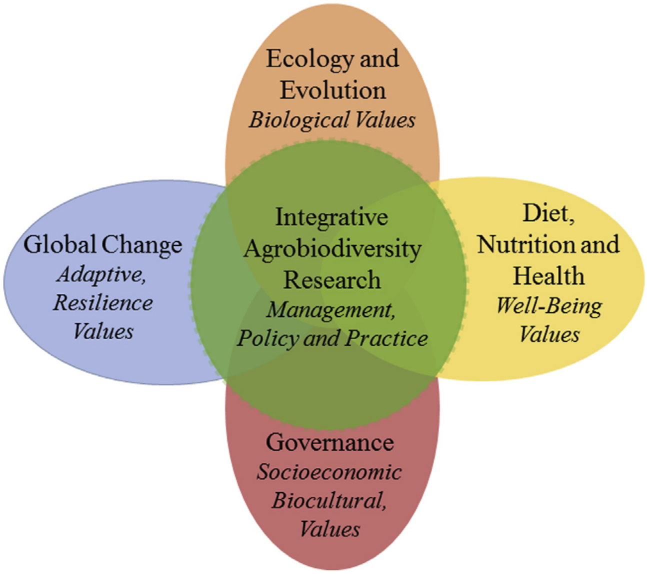

Fig. 2. Agrobiodiversity Knowledge Framework: Themes and Values.

Ecological and evolutionary research on agrobiodiversity has reflected both the long-term human influences on Earth systems and the more recent accelerated impacts. Research has demonstrated the essential values of biodiversity to the ecological, evolutionary, and environmental services of diversified farming in both “traditional” and modern, industrial contexts (Altieri et al., 2015; Bellon et al., 2017; Calvet-Mir et al., 2012a; Davis et al., 2012; Jackson et al., 2007, 2012; Jarvis et al., 2007; Kremen et al., 2012; Letourneau et al., 2011; Liebman and Schulte, 2015; Lipper et al., 2009). Related research has strengthened crop and livestock agrobiodiversity *per se* and sustainability through the design of stakeholder involvement in participatory and evolutionary breeding (e.g., Almekinders and Elings, 2001; Almekinders et al., 2007; Jones et al., 2014a,b; Murphy et al., 2013).

This first knowledge theme requires more robust data on agrobiodiversity occurrence, biogeographic patterns, and population genetics. Systematic comparisons are needed, for example, to design the evolving interplay of *ex situ* conservation in genebanks at the national and global scales and in situ conservation through the continuation of on-farm production, local and regional consumption, and agroecosystem functioning (De Haan et al., 2010a, 2013). Genetic and genomic marker technologies as well as new methods such as gap analysis are supplying new advances (Castañeda-Álvarez et al., 2016). Other advances highlight the characterization, estimation, and monitoring of the status and levels of agrobiodiversity at key spatial scales. These scales range from individual farms and fields to communities, landscapes, countries, regions, and the global (Brush and Perales, 2007; Jackson et al., 2007; Jarvis et al., 2008a,b; Jarvis et al., 2016; Love and Spaner, 2007; Valdivia-Díaz et al., 2015; Zimmerer, 1998). Research on this theme increasingly incorporates spatial and data-intensive approaches (Aguilar et al., 2015; De Haan et al., 2016; Hijmans et al., 2016).

2.3. Governance

Governance of agrobiodiversity refers to policy and legal research as well as wide-ranging biocultural approaches involving initiatives such as seed-system support (Table 3). Legal and policy instruments were already a mainstay of the agrobiodiversity research of Bennett, Frankel, Harlan and others beginning in the mid-twentieth century (Andersen, 2013, 2016). Currently, major legal and policy agreements that formally govern agrobiodiversity include the International Treaty on Plant Genetic Resources for Food and Agriculture, the Convention on Biological Diversity including the 2020 Aichi Targets, the Nagoya Protocol, and the FAO’s Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture (Jarvis et al., 2007; Marques et al., 2014). Requiring institutional linkages worldwide as well as across multiple geographic scales (Andersen, 2013, 2016; see also Young, 1999, 2011), these governance approaches are representative of one of the human dimensions of global agrobiodiversity change (Section 2.5; Table 2).

2.3.1. Biocultural dimensions of governance

Biocultural approaches, defined as integrating the broadly biological and cultural dimensions of human-environment systems, guide the expansion of many local and often community-based initiatives (Brush, 1992; Ellen et al., 2012; Graddy, 2013; Johns and Sthapit, 2004; Plieninger et al., 2018; Richards, 1985; Zimmerer, 1996, 2015). Stemming from varied knowledge practices involving cultural, linguistic, and landscape variation, these approaches have fueled ongoing projects engaging stakeholders and supporting the valuation and use of agrobiodiversity (Bellon et al., 2015; Jarvis et al., 2011). They tend to engage diverse stakeholder groups that include indigenous and smallholder food

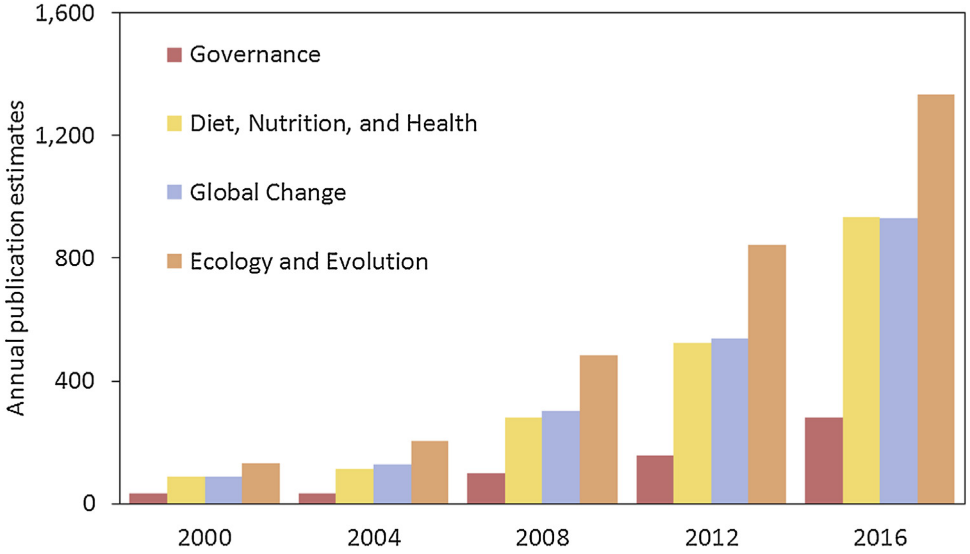

Fig. 3. Estimated Publications in the Principal Themes of Agrobiodiversity Knowledge (Web of Science, 2000–2016).

producers, consumers, and resource managers (Leclerc and Coppens d'Eeckenbrugge, 2011; Orozco-Ramírez et al., 2016; Padoch and Pinedo-Vásquez, 2010; Vigouroux et al., 2011; Voeks, 2004, 2018; Zimmerer et al., 2015). Women are often especially important to agrobiodiversity use and viability (see also Section 4.3).

Biocultural approaches have also focused on the long-term coevolution of agrobiodiversity and incorporated new scientific advances enabling the consideration of the lengthier time spans of human influences on Earth Systems, as detailed below. Combining techniques such as genetic fingerprinting studies, for example, have yielded time depth and spatial resolution elucidating the agency and accomplishments of Africans and African Americans. Their communities have been responsible for the distinctive West African rice, Oryza glaberimma, and other plants transferred via biocultural pathways across the Atlantic to North and South America (e.g., Richards et al., 2008; van Andel et al., 2016; and related works Carney, 1991, 2001, Duvall, 2006). In addition, recent stakeholder initiatives are documenting biocultural knowledge that incorporates monitoring and mapping (Table 3, Section 4.3).

2.3.2. Markets, livelihoods, and governance

Market- and livelihood-based approaches are currently a mainstay of attempts at agrobiodiversity governance. These approaches include the support of economic value chain approaches involving indigenous and smallholder producers, retailing and wholesale outlets for agrobiodiversity across urban and rural spaces, identifying and strengthening crop diversification, social corporate responsibility schemes, and payments for ecosystem services (Kontoleon et al., 2008; Lipper et al., 2009; McCord et al., 2015; Narloch et al., 2013; Nordhagen et al., 2017; Smale, 2005; Tobin et al., 2016). These approaches extend to the role of innovative restaurants ranging from the profusion of farm-to-table venues to the establishments with celebrity chefs. They also encompass the agrobiodiversity impacts of supply chains, food wholesaling, distribution, and retailing that can incorporate agrobiodiversity to varying extents. The "supermarket revolution" is assumed to have negatively impacted biodiversity in farming and food systems (e.g., McMichael, 1994, 2011).

2.3.3. Seed systems and governance

Seed systems, which also include the propagules of vegetatively reproduced plants, are crucial for the generation and distribution of agrobiodiversity through wide-ranging governance mechanisms. Both market and non-market practice, as well as combined traditional and new cultural practices, are evidenced in agrobiodiversity seed fairs, seed banks, seed networks (including the roles of social networks), and seed saving and potential social responsibility agreements (Abizaid et al., 2016; Jansen and Vellema, 2004; Jarvis et al., 2011; Labeyrie et al., 2016; Nazarea, 2006; van Etten, 2011). Seed exchange is vital to agrobiodiversity conservation and smallholder resilience, including in regions of the Global North such as within Spain (Calvet-Mir et al., 2012b). Finally, the surging work on diverse seed systems has shown the complexity of both predominant "informal" or lower-cost grower sourcing and links to the "formal" sector of seed companies and certified production (Louwaars et al., 2013). This expanding research includes reviews and comparative studies (Coomes et al., 2015; Pautasso et al., 2013; Zimmerer, 2010, 2017a).

2.4. Diet, nutrition, and health

This third thematic cornerstone has expanded rapidly as a focus area owing to the potential role of agrobiodiversity in addressing the global epidemic of NCDs and micronutrient deficiencies associated with poor diets and reduced food diversity. Global prioritization of food quality and nutritional security (not *solely* the quantity of food), including the 2030 U.N. Agenda for Sustainable Development, is spurring new interest in agrobiodiversity (Bioversity International, 2017; Dwivedi et al., 2013, 2017; FAO and PAR, 2011; Frison et al., 2011; HLPE, 2017; Khoury et al., 2014; Lachat et al., 2017).

Research has focused on the nutrition transition in particular, characterized by the shift in diet toward more highly-processed foods and higher intakes of animal-source foods, as well as fewer traditional grains (Khoury and Jarvis, 2014; Popkin et al., 2012). Agrobiodiversity may play a key role in buffering the homogenizing consequences of this dietary shift (Johns et al., 2013; Jones, 2017). Varied lines of research demonstrates the importance of the diversity of foods accessed through spatially extensive market systems (Sibhatu et al., 2013) as well as the value of locally sourced agrobiodiversity. The latter includes both locally cultivated foods and semi-domesticates as well as uncultivated and wild plants and animals accessed in the local and regional food environments (Berti, 2015; Davis, 2005; Davis et al., 2004; Jones et al., 2014a,b; Jones, 2015; Powell et al., 2015). Combining this sourcing of nutritious food has proven effective in lessening the negative health outcomes of the nutrition transition in general and such specific impacts as obesogenic consequences.

2.5. Global change

Global changes that range from climate to socioeconomic globalization exert increasing influence on agrobiodiversity. Loosely akin to the pressures on the "wild" biodiversity that is central to Anthropocene research and a well-known scientific and policy emphasis (Johnson et al., 2017), the interaction and fate of agrobiodiversity has emerged as a related yet distinct and significant focus (Fig. 3; Cleveland, 2013; Vandermeer et al., 1998; Zimmerer, 2010, 2013; Zimmerer and De Haan, 2017).

2.5.1. The green revolution and development related to global change

The Green Revolution and its successors globally have incurred impacts on agrobiodiversity that now include newer programs of crop and livestock "improvement," comparative-advantage and export agriculture, and agricultural intensification in the Global South (e.g., AGRA or the Alliance for a Green Revolution in Africa; Pingali, 2012). The programs have marginalized agrobiodiversity in global "improvement" and commodity development of both the major crops (e.g., wheat; Baranski, 2015; Smale 2008) and important regional and local foods including those considered "neglected" or "underutilized" (e.g., millet and sorghum; Baldermann et al., 2016; Bezner Kerr, 2014). Most agricultural research has regarded agrobiodiversity as a genetic resource and its loss as an inevitable consequence of modern productivity (Hoisington et al., 1999). Yet, ongoing adjustments, including among smallholder and indigenous groups, also show the innovative persistence and addition of agrobiodiversity, and reveal its emergent properties in complex social-ecological, livelihood systems (McCord et al., 2015; Zimmerer, 2013). Results demonstrating the geographically uneven persistence amid Green Revolution impacts (Brookfield, 2001; Brush, 1992, 2004; Zimmerer, 1991a, 1991b, 1996) have buffered the earlier projections of a cataclysmic "genetic wipeout."

Research has also demonstrated the partial compatibility of agrobiodiversity with global crop and livestock development during recent decades (Flachs, 2015; Turner and Davidson-Hunt, 2016; Zimmerer, 2013; Zimmerer and Vanek, 2016). Pivotal resource-and culture-based conditions, such as land access and local valuation, can contribute to continued production and consumption of food biodiversity amid increased commodity production. These insights highlight the point that agrobiodiversity is not relegated to relict or vestigial status nor confined to archaic contexts. Instead, it functions and inter-relates in complex current food and agriculture systems as an emergent property across a range of settings and scales that include the global level (Zimmerer, 2010, 2013).

2.5.2. Global climate change

Global climate change both undermines agrobiodiversity and potentially strengthens its usefulness. Direct impacts, such as the reduction or shifts of growing habitats, range extents, and resource inputs, can lead to the loss and extinction of agrobiodiversity and impacts on food systems (e.g., Bellon and van Etten, 2014; Jarvis et al., 2008a,b; Lipper et al., 2014; Saxena et al., 2016; Zimmerer et al., 2018a). One can anticipate the potential loss and extinction of agrobiodiversity through the specialized development and monoculture-based adoption of genetically uniform varieties and breeds that are "climate resistant"—often through pest or disease resistance. Conversely, positive impacts are potentially rooted in the capacities of agrobiodiversity to respond to climate change (Bellon et al., 2011; Bellon and van Etten, 2014; Challinor et al., 2014; FAO, 2015; Hellin et al., 2014; Kotschi, 2007; Mercer and Perales, 2010; Mijatović et al., 2013). Global environmental changes of soil and water resources are similarly expected to exert complex pressures on agrobiodiversity (Jackson et al., 2007). Methodologically, the investigation of agrobiodiversity in the context of climate variation highlights the utilization and continued innovation of such ecological methods as common garden and reciprocal transplant experimental designs (e.g., Mercer and Perales, 2010; Tito et al., 2017; Zimmerer, 1991b).

2.5.3. Global socioeconomic change

Global change also incorporates socioeconomic integration such as urbanization and migration. Research to-date suggests social-ecological processes involving these drivers and their impacts on food and agrobiodiversity that are more complex than initially anticipated (Seto and Ramankutty, 2016; Seto and Reenberg, 2014; Zimmerer and Vanek, 2016). Urbanization, socioeconomic integration, and migration impacts, for example, are often negative owing to such forces as the expanding homogeneity of urban-centered industrial food systems (Khoury et al., 2014; Khoury and Jarvis, 2014). Yet recent research has also shown that agrobiodiversity has been recently adopted in urban and peri-urban areas, as well as in other socioeconomically integrated areas, often through the livelihood strategies of migrant households and their networks (Ávila et al., 2017; Lerner and Appendini, 2011; Poot-Pool et al., 2015; Wezel and Ohl, 2005; Zimmerer, 2014; Zimmerer et al., 2018a,b).

3. New data from the agrobiodiversity, food, and nutrition field project in Peru

3.1. Research overview and methodology

New research results reported here serve to illustrate the four-theme framework of agrobiodiversity (Sections 2.1-2.5.3) and to outline future research (Sections 4.1-4.5.3). The new data derive from the recently concluded fieldwork phase of the Agrobiodiversity, Food, and Nutrition (AFN) Project (2016–2017) in Huánuco in central Peru. Presentation of these new results begins with the agrobiodiversity-related response to global climate change (Section 3.2) in keeping with the emphasis here.

Huánuco, which is located at the juncture of the Andes Mountains and the Upper Amazon, stands out as a widely recognized agrobiodiversity hotspot of western South America and globally (Malice et al., 2010; Velásquez-Milla et al., 2011; Zimmerer et al., 2018a). This distinction owes to the extremely varied range of its tropical climates and ecosystems centered on the inter-Andean valley of the upper Río Huallaga and its uplands and Amazonian tributaries (1700–3800 masl), as well as the current and historical agri-food systems of indigenous smallholders. High-agrobiodiversity foods in current use include the multiple local varieties or landraces of Andean maize that diversified and co-evolved extensively after introduction 4,000–5,000 years ago and earlier domestication in Mexico (Grobman et al., 2012; Perry et al., 2006). Multiple species and landraces of Andean potatoes, beans, squash, quinoa, chile peppers, and grain amaranth in addition to many uncultivated and wild plants are also highly important (Halloy et al., 2005; Rodríguez et al., 2017; Torres Guevara, 2017).

Approximately 75,000 indigenous, Quechua-speaking smallholders cultivate and consume the majority of agrobiodiversity in Huánuco, while the markets, gardens, and population of urban areas and numerous *mestizo* ("mixed-race") smallholders and consumers are also important to agrobiodiversity. In 2017 the AFN Project conducted surveys on food production and diets among the households of indigenous smallholders (n = 600), participatory field- and landscape-level agrobiodiversity sampling with stakeholders (n = 1522 fields), and completed detailed interviews on agrobiodiversity climate change and agrobiodiversity (n = 37). The authors conducted this project in conjunction with the Instituto de Investigación Nutricional (IIN) in Lima. The data presented in Sections 3.2-3.5 derive from each of these methods.

Three representative sub-areas of Huánuco with similar elevational ranges of agriculture (noted as masl or meters above sea level) were chosen for research (Quishqui, 1860–4200 masl; Amarillis/Malconga, 1850–4100; Molinos, 1700–4000 masl). Two hundred agricultural households in each sub-area participated in the in-person multi-module survey questionnaire between April and June 2017. The participatory agrobiodiversity sampling occurred during this same period. Specific design and application of these surveys and agrobiodiversity sampling have been further detailed (Jones et al., 2018: 1626–1627). The interviews on agrobiodiversity and climate change (n = 36) were implemented using a semi-structured format in July 2017. Interviewees were survey participants that cultivated at least one maize field. Equal numbers of households were chosen in each sub-area. The interviews utilized the widely spoken Huánuco dialect of Quechua intermixed with Spanish (Webster et al., 1998). Tabulation techniques were used to estimate basic parameters of the new data (Sections 3.2-3.5; Table 4).

3.2. Global change

Climatic variations in Huánuco in 2016–2017 and preceding years reflect the increasing impact of this global change in the Andes (Tito et al., 2018; Vuille et al., 2003). These trends combine general warming, extended inter-annual drought, and increased intra-annual rainfall variation (Zimmerer et al., 2018a). One potentially common adaptive response to climate change is the upslope shift of maize by 200–300 meters or more that corresponds to increased warming trends at higher elevations in the Andes Mountains (Vuille et al., 2008). This kind of anticipated range shift in response to global climate change is rooted in the adaptation of Andean maize including the cold tolerance and phenology of certain Andean maize types (Hufford et al., 2012; Ross-Ibarra et al., 2017) and maize-growing and consuming indigenous smallholders (Perez et al., 2010; Skarbø and Vander-Molen, 2016).

Andean maize adaption is a potentially valuable response to climate change. It requires widespread evaluation and capacity-building since the upslope expansion of warm-season maize could partly offset the eventual loss of growing environments for Andean potatoes and other cold-season crops as the result of climate change. The new data indicate the widespread presence of maize types with suitable adaptive capacity among many of the indigenous, smallholder maize-growers in Huánuco (Table 4, row 1). Contrary to expectations, however, this shift of maize to higher elevations was uncommonly implemented (Table 4, row 2). Future research on adaption, vulnerability, resilience, and potential transformative change is necessary to clarify this issue (Section 4.1).

3.3. Ecology and evolution

New results from the AFN Project estimate biogeographic patterning and the roles of human management among more than fifty food species. These foods include domesticates, semi-domesticates, and wild foods across field and forest landscapes. The data also incorporate information on the occurrence and frequency of hundreds of food varieties that are mostly local types. Twenty-five distinct maize cultivars occurred in 270 sampled fields. This maize agrobiodiversity was distributed evenly among the three sub-areas: Malconga (12 varieties; a peri-urban area); Molinos (14 varieties; an area dominated by specialized commercial potato production supplying the Lima market with the sought-after farmer variety known as *papa amarilla* or “yellow potato”), and Quishqui (13 varieties, a renowned micro-center of Andean agrobiodiversity within Huánuco; Malice et al., 2010; Velásquez-Milla et al., 2011). This evenness upended our hypothesis of unequal distributions propelled through sub-area differences. Planned ecological and biogeographic analysis in maize and other species is designed to account for the effects of environmental, demographic, livelihood, land use, market, nutrition, and seed-system factors (Sections 4.2,4.4).

3.4. Governance

The new data address agrobiodiversity governance through a major emphasis on the acquisition and provisioning of seed. These data on seed systems place emphasis on socioeconomic, environmental, and geographic components. Since the results vary among crops, the data reported here pertain to Andean maize, which occurred widely in survey and sampling results. The new data demonstrate the reliance on the informal seed system (acquisition through self-provisioning and purchase or barter from other farmers; 92.2%), rather than the formal system (7.8%) (Table 4, row 5). Limits of the latter may include higher seed prices and the provisioning of a subset of varieties that are less useful to the surveyed growers. These new data are significant since they indicate the continued reliance on informal seed systems, which is similar not only to other Andean regions of Peru (considered a middle-income country) but also to regions in Ethiopia and other

Table 4
Results of the Agrobiodiversity, Food, and Nutrition Project (AFN) in Huánuco, Peru (2015–2018).

Variable or Indicator	Result	Data Source
1. Percentage of households with one or more fields of maize; Percentage of maize-growing households growing Andean maize landraces potentially suited to upslope expansion	69.4%; 86.4%	Agricultural production and consumption information in household-level surveys (n = 604 households); Interview on agrobiodiversity climate change (n = 37 households)
2. Percentage of households that reported the upslope expansion or displacement of cropping	4.5% (household survey); 35.1% (interview)	Climate change sub-module in household-level surveys (n = 604 households); Interview on climate change (n = 37 households)
3. Frequency of maize variety types across three study sub-areas	Malconga: 12, Molinos: 14, Quishqui: 13	Participatory field sampling with farmers (n = 270 maize fields)
4. Percentage of use of the informal and formal seed systems for Andean maize (see explanation in text)	Informal seed system (92.2%); Formal seed system (7.8%)	Food production and consumption information in household-level surveys (n = 604 households)
5. Percentage of households experiencing food insecurity (mild, moderate, or severe) and potential relations to agrobiodiversity	86.0%; significant negative correlation significant at P values less than .01 and lower of moderate and severe food security with household agrobiodiversity	Food production and consumption information in household-level surveys (n = 604 households)

low-income countries of sub-Saharan Africa (e.g., Samberg et al., 2013). This persistence is important for future research outlined in Section 4.5.

One additional item of new data concerns the use of biocultural categories among the indigenous smallholders in Huánuco to categorize and manage their maize landraces. The new data indicate that the maize landraces are grouped into two principal biocultural categories based on distinctions of food usage and growing season. These categories are widely recognized locally as *gapya jara* (for parching or toasting into the food known as *kancha*) and *wansa jara* (for preparation as the hominy-type food known as mote). Linguistically, the terms for these biocultural categories of the maize agrobiodiversity of Húanuco are monovalent, meaning they are imbued with the singular meanings mentioned above (Webster et al., 1998: 274, 585). This biocultural distinction may reflect the historical legacy of a pair of distinct indigenous cultural groups in region, referred to as the Serrano and Chupacho peoples. Research has hypothesized that these groups, which are both Quechua-speaking and also significantly distinct, have influenced the evolutionary diversification of Andean maize (Bird, 1966, 1984). This point underlies the development of directions for future integrative biocultural and global change research on agrobiodiversity (Section 4.2).

3.5. Diet, nutrition, and health

Results of the AFN Project emphasize coupled linkages between agrobiodiversity and the diversity of diet, including nutrition-based metrics for demographic and consumer groups (e.g., the Minimum Dietary Diversity for Women (MDD-W) indicator), and metrics of diet quality (e.g., the probability of adequacy of micronutrient intakes) (Jones et al., 2018). In addition, household food insecurity was assessed using the widely used guidelines of the Latin American and Caribbean Food Security Scale (ELCSA) (ELCSA, 2012; Jones et al., 2013, 2018). This module of the AFN's survey incorporated questions about interviewees' experiences of inadequate food access stemming from the lack of resources to purchase or otherwise acquire food through such mechanisms as own production or barter. Three dimensions of inadequate household food access were assessed in the module including: 1) anxiety about acquiring food, 2) access to a sufficient quantity of food; and 3) access to adequate quality of food by both adults and children in the household.

Results determined that household food insecurity is widespread in Huánuco (85.9%; Table 4, row 4). This food insecurity occurred at levels estimated as mild (64.2%), moderate (18.4%) and severe (3.3%). Similarly, high levels were reported regarding consumption entailing “little diversity” of food, both among household adults (43.8%) and children (35.6%). Report of little food diversity in the diets of adults and children, respectively, was associated with lower dietary diversity among women household heads ($P < 0.05$ for reports among adults and $P < 0.001$ for reports among children). Statistically, the different metrics of dietary and nutrient diversity correlated negatively with certain levels of food insecurity. Severe food insecurity negatively associated with *both* the continuous diet diversity score (i.e., count of food groups recently consumed by index woman in the household) ($P < .01$) *and* the MDD-W indicator (i.e., a dichotomous metric indicating if the index woman recently consumed 5 or more food groups) ($P < .1$) (Jones et al., 2018; see also Jones et al., 2013).

One significance of these results is application of the Kuznets Curve to agrobiodiversity. Widely utilized in resource and sustainability research and policy-making (Chowdhury and Moran, 2012), it generalizes the relations of income or resource access (x-axis) to agrobiodiversity (y-axis) (e.g., Narloch et al., 2013; Omer et al., 2010; Zimmerer, 1991a), and also provides potential insight into diet, nutrition, and health. Results here suggest that under extreme poverty and resource deficiency this relationship is inverted with regard to dietary diversity. These results on diet and nutrition, which in turn correspond to agrobiodiversity, offer a concrete example of the relations of biodiversity to both nutrition and health as well as resource-access levels. Modelling these human-system relations of agrobiodiversity is vital to understanding its complex social-ecological interactions (Section 4.2). This modelling promises to advance Anthropocene research relevant to both long-term human interactions with Earth systems and more recent accelerated global change (Section 4.1).

4. Future research directions

4.1. The Agrobiodiversity Knowledge Framework and the anthropocene

A triad of the above results guide development of fruitful directions of future research. First, increased know-how is being situated within each of the thematic cornerstones of the Agrobiodiversity Knowledge Framework as well as integrated across them (visualized in Fig. 2), reflecting the combined roles of disciplinary, interdisciplinary, and transdisciplinary approaches (Table 3). Second, several specific insights (e.g., sections 1.1,1.2, 2.1, 2.3, 2.4, 3.2, 3.5) demonstrate that the understandings of accelerating global environmental and socioeconomic changes must be integrated with the other principal themes of the Agrobiodiversity Knowledge Framework. Third, the future of agrobiodiversity research requires rigorous framing in the distinct time periods relevant to the Anthropocene. As introduced in Section 1.1 and detailed in Table 5, these include: (i) long-term human impacts on Earth (Doolittle, 2015; Fuller et al., 2011; Ruddiman, 2013; Ruddiman and Thomson, 2001; Smith and Zeder, 2013; Zalasiewicz et al., 2017); (ii) the modern industrial period of the past two centuries, including the Great Acceleration (Foley et al., 2013; Steffen et al., 2011; Zalasiewicz et al., 2017); and (iii) the general, informally designated era of the earth's environmental systems dominated by human activities (Bennett et al., 2016; Brondizio et al., 2016; Ruddiman et al., 2015).

4.2. Agrobiodiversity and global change (Adaptive capacity, resilience, vulnerability, and transformation)

Agrobiodiversity research on global change to-date has focused on the adaptive capacity of crop species and varieties (e.g., ACRAD, 2010; FAO, 2015; Jackson et al., 2012; Kotschi, 2007; Perez et al., 2010; Van Etten et al., 2017; Yang et al., 2019). Several studies focus in particular on the adaptive capacity of maize landraces (Bellon et al., 2017; Hellin et al., 2014; Mercer and Perales, 2010; Ross-Ibarra et al., 2017). Significantly less is known about the social- and political-ecological processes of vulnerability, resilience, and transformation. These additional dimensions of global change involving biodiversity in land use and food systems are especially important to indigenous and smallholder peoples and community stakeholder-led initiatives as well as urbanized and industrial agrifood complexes (Bellon et al., 2011; Mijatović et al., 2013; Ticktin et al., 2018; Zimmerer, 2010, 2013). Integral to agrobiodiversity, these added dimensions (vulnerability, resilience, and transformation) require distinction and must be distinguished from adaptive capacities *per se* (Table 6).

Social- and political-ecological vulnerability analysis is central to agrobiodiversity amid global change, particularly in the assemblages of diverse uses and biocultural rights among groups such as indigenous people and smallholders. This focus needs to

Table 5

Examples of Human-Environment Interactions with Agrobiodiversity in Time Periods Relevant to Anthropocene Research (see Section 4.0).

Themes of Agrobiodiversity	Long-Term Human Impacts on Earth (4000 BP – present)	Industrial Era (AD 1800 - present)	General Phenomenon of Human Interactions
Evolution and Ecology	Domestication and co-evolution of plant and animal biodiversity with humans	Development and spread of crop monocultures, including colonial monocrops and agroindustrial market impacts	Human interactions related to food biodiversity, associated agrobiodiversity, and related dimensions
Governance	Co-evolution of biocultural processes (e.g., linguistics) with agrobiodiversity	Legal and policy instruments to address global genetic resources, and markets and political economy for genetic resources that include widespread dispossessions	Social-ecological organization and variation of seed systems
Diet, Nutrition, and Health	Diet, nutrition, and health changes in transitions to early agriculture, both domestication and spread of farming systems	Global Nutritional Transition beginning in the late 1900s, including mass-produced foods as cheap dietary staples; differentiation of agri-food systems	Interactions of diet, nutrition, and health with social-ecological changes (e.g., agricultural intensification and market growth)
Global Change	Agrobiodiversity in relation to transformations and shocks of climate (e.g., El Niño climate events) and socioeconomic organization (e.g., urbanization, state development)	Development and spread of modern industrial food systems, including environmental and socioeconomic transformations, and the Global Nutritional Transition beginning in mid-late 1900s	Agrobiodiversity in relation to widespread social-ecological transformations (e.g., soil degradation)

Table 6

Sustainability-Enhancing Integration of Agrobiodiversity with Global Change (Adaptive Capacity, Vulnerability, Resilience, Transformation).

Concept	General Meaning and Usage	Example of Specific Use with Agrobiodiversity (this research)	Integration of the Agrobiodiversity Knowledge Framework (this research)
Adaptive Capacity	conditions for adaptation	ecological and food functions of landraces among indigenous people	continued co-evolution with biocultural practice and cultural knowledge (e.g. tastes, linguistics)
Vulnerability	precarity owing to marginali-zation	limitation on smallholder farmer access to seed, land, and water; lessening of crop diversification	resource limitation affecting agrobiodiversity through socioeconomic marginalization (e.g. unfavorable trade)
Resilience	capacity to bounce back after shock	seed-system capacities following “global change shocks” (e.g., climate change, market volatility)	movements and flows of people, seed, and information across geographic scales
Transformation	structural changes, big systems	effective, “informal sector” seed-system cooperatives and seed justice governance	social movements’ scaling-up of seed networks and supportive state structures

develop as a complement to the singular emphasis on adaptation traits *per se*. It will enhance predictive models of the range shift of high-agrobiodiversity crops and the scenarios of agricultural transformations in response to global change. Global models of climate change in relation to food and nutritional security require these insights and inputs. In Huánuco, Peru, for example, high-agrobiodiversity landraces possess well-suited adaptive capacities but the social- and political-ecological vulnerabilities of growers constrain the extent of the shift in range of the valuable maize crop in response to climate change (section 3.4; Zimmerer et al., 2018a). Hypothetically, these analyses include limitations not determined solely by crop adaptive traits.

4.2.1. Agrobiodiversity amid the long-term transformations of the anthropocene

Basic insight is needed into the combined diversification and extinction of agrobiodiversity amid major social-ecological transformation in the time periods of the proposed geologic epoch of the Anthropocene. The perspective that human impacts began long ago (Fuller et al., 2011) is vitally important to agrobiodiversity and vice versa due to domestication and early agricultural expansion (4,000–7,000 years ago; Smith and Zeder, 2013). Potential agrobiodiversity research is well suited to concepts such as co-evolution and human-environment coupled systems (McKey et al., 2010a, 2010b). Paleoenvironmental and paleobotanical sources in addition to the archaeological sciences will be paramount to uncovering the past interactions of agrobiodiversity with major climate changes, urbanization, and state formation and development. Focused examination of the diverse components of agrobiodiversity amid such transformations promises important new insight on the capacities, limits, and thresholds of agrobiodiversity in the Anthropocene.

4.2.2. Global technological change (Transgenic, gene-edited, and mega-varieties) and sustainable intensification

The expansion of so-called mega-varieties, including uniform transgenic and genome-edited crops and animal breeds, exerts significant impact on agrobiodiversity. Promoted as global adaptations to respond to biotic stressors and to enhance yields under high-input conditions, their expansion is threatening agrobiodiversity use, environments, and nutrition and diets, especially but not exclusively among smallholders and indigenous people (Krishna et al., 2015; Mercer et al., 2012). Actual cause-effect pathways between the transgenic and genome-edited crops and their impacts on the agrobiodiversity of smallholders and others are complex and defy overly simple generalization (Cleveland, 2013; Flachs, 2015; Krishna et al., 2015). At the same time, alternative approaches to genetic enhancement such as evolutionary breeding and participatory varietal selection have accrued value in certain sectors. The roles of agrobiodiversity need to be investigated amid potentially related global changes such as the debated designs for Sustainable Intensification and Ecological Intensification (Zimmerer, 2013; Zimmerer et al., 2015).

4.2.3. Global food systems and commodity trade

Expanded analysis of modern global systems of industrial agriculture, food, and commodity markets is a sine qua non of the determination of the fate of unique region-scale agrobiodiversity (Johns et al., 2013; Khoury et al., 2014). The value of agrobiodiversity to modern, industrial agriculture and food systems stems principally from its utilization as a genetic resource that often entails dispossession from local indigenous and smallholder peoples and their landscapes and cultural practices (Kloppenburg, 2005; McMichael, 1994, 2011; Montenegro de Wit, 2017). New research is required on the reduced yet hypothetically varied levels of agrobiodiversity in modern, industrial and urban supply chains (e.g., diverse retailing ranging from grocers and supermarkets to prepared food services). Variation and changes in supply chains and retail have potentially profound implications for consumer food environments and agrobiodiversity (Glanz et al., 2005; Herforth and Ahmed, 2015). Commodity-related research is also needed to inquire into the impacts on agrobiodiversity of other global resource and trade booms (e.g., drugs, minerals, energy), especially where production is located in or near indigenous and smallholder populations.

4.3. Global markets, consumer trends, development, gender, nutrition, and well-being

Complex trends involving agrobiodiversity occur as the result of deeply uneven global development and the associated diverse consumer and culinary groups as well as social movements. This complexity is evident in the persistence of agrobiodiversity utilization among various indigenous people and smallholders (Isakson, 2009; Perreault, 2005) that are not geographically isolated but rather engage in long-distance economic and environmental interactions (Zimmerer et al., 2018b). This complexity urges future research to focus on the policy-relevant relations of agrobiodiversity to new sociocultural and economic interactions. The latter include the unanticipated, bifurcated relations of lower resource levels to agrobiodiversity among certain individuals, households, and communities (Section 3.5). Previously overlooked inflections in models resembling the Kuznets Curve need to be re-invigorated in conjunction with widespread urbanization, human migration, and alternative and disrupted development trajectories such as refugee movements (Section 2.5.3).

Relation of nutritional diversity to food security and resource level (or income) need to become a focus of further research since it can be either positive or negative (Bukania et al., 2014). The research in fields such as Feminist Political Ecology will require an emphasis on women who, owing to various rationales, are vital to agrobiodiversity-related processes worldwide (Bezner Kerr 2014; Carney, 1991; FAO, 1999b; Howard, 2003; Zimmerer et al., 2015). Finally, new research examines the role of agrobiodiversity in the expanding cultural formulations of human health and rights related to ecological well-being (Caillon et al., 2017; Sterling et al., 2017), such as the globally influential “Living Well” social movement (Zimmerer, 2017b) and rights to resilience (Walsh-Dilley et al., 2016).

4.3.1. Ecology and evolution: in situ and ex situ conservation

Important research in ecology and evolution illustrates expanded linkages to the themes of global change and biocultural dynamics. The systematic estimation, characterization, and monitoring of biodiversity is expanding through new information and analytical capacities. Major advances are essential to guide agrobiodiversity conservation strategies based on integrated innovations of current systems (in situ conservation) with germplasm collection, banking, and storage (*ex situ* conservation). Current challenges and debate about the methodologies used to measure agrobiodiversity change (e.g., sampling designs; Brush et al., 2015; Dyer et al., 2014, 2015) have led to a “wake up call for crop conservation science.” More rigorous methodologies and innovative estimation techniques are called for, including stakeholder-based observatories and monitoring (e.g., stakeholder atlases of agrobiodiversity and other knowledge approaches).

4.3.2. Functional trait analysis

Second in this set is identifying and characterizing agroecosystem functionalities that incorporate biodiversity. The functionalities and services of agrobiodiversity include food and nutrient provision, yield stability, pest- and disease regulation, and various types of mutualist functions (Cardinale et al., 2012; Reiss and Drinkwater, 2017). Building these functionalities is a priority of research on the temperate-zone, industrial agriculture of the U.S., Europe, Canada, and Australia—for example, examining hypotheses about the functionality and trade-offs of *adding* biodiversity to agroecosystems. Significant work has begun to determine these functionalities across field, landscape, and regional scales (Blesh, 2018; Liebman and Schulte, 2015). In addition, characterizing and utilizing the functional traits of food agrobiodiversity is a promising and important avenue of current and future research (Wood et al., 2015).

4.4. Governance: evolving biocultural dynamics and international frameworks

Third is productive integration with expanding biocultural approaches as a node of governance research (Fig. 3). Potential agrobiodiversity interactions with ethnic group identities in Huánuco, Peru (Section 3.4) echo the powerful influence of cultural practices of indigenous groups (Leclerc and Coppens d’Eeckenbrugge, 2011; Orozco-Ramírez et al., 2016; Vigouroux et al., 2011; Zimmerer et al., 2018a). The agrobiodiversity analysis undertaken by these biocultural approaches promises to be more fully situated in contexts of rapid global and multi-scale changes that are both environmental and socioeconomic. Similarly, the spaces of governance, including territories and landscapes, are bioculturally vital and integral to agrobiodiversity utilization (Cassia et al., 2012;; Plieninger et al., 2018; Zimmerer, 2017a, 2017b), and are poised for management- and policy-relevant research with stakeholders and the international biodiversity community (Díaz et al., 2015).

4.4.1. Future governance: U.N. Sustainable development goals (SDGs)

Goal 2 of the U.N.’s 17 Sustainable Development Goals (SDGs), which is to “End hunger, achieve food security and improved nutrition, and promote sustainable agriculture,” relates closely to agrobiodiversity (Zimmerer, 2017b). This imperative propels new research with stakeholders on sustainable development that is nutritionally sensitive and potentially compatible with transformative global changes (Johns and Eyzaguirre, 2005; Johns et al., 2013; Kahane et al., 2013; Loladze, 2002; Powell et al., 2015; Zimmerer et al., 2018a). These design desiderata suggest that agrobiodiversity for self-provisioning be combined with market specialization. We hypothesize that such combinations can be theoretically and empirically tested to yield policy-relevant insights. The policy strategies such as short and certified supply chains typically advised for advancing socioeconomic development and agrobiodiversity have proven at best only partially effective to-date (Cassia et al., 2012; Mason and Lang, 2017; Tobin et al., 2016).

4.4.2. Future seed systems and agrobiodiversity governance

Understanding seed systems is paramount to strengthening the roles of agrobiodiversity in human societies amid accelerating global change. Integrated stakeholder and scientific knowledge and institutions are needed to guide seed security and sovereignty, refugee and post-conflict seed initiatives among marginalized populations (Sperling and McGuire, 2010), upgrading quality of informal seed across widespread sectors, promotion of accessible technological advancements and food environments, biosecurity and citizen science approaches (Gildemacher et al., 2012; van Etten, 2011; van Etten et al., 2016) (see also Jarvis et al., 2011; McGuire and Sperling, 2013; Sperling et al., 2008; Sperling and McGuire, 2010, 2012). For example, meta-population structure and gene-flow processes are highly varied in these seed systems, (Badstue et al., 2007; Dyer et al., 2011; Mercer et al., 2012; Zimmerer, 1998). We hypothesize that this variation mediates the different levels of vulnerability needed to informed biosecurity and other policies that are scientifically valid and anchored in social analysis.

New research is especially needed on the accessibility of seed flows at multiple geographic scales. The approach of Citizen Science is notably promising (Van Etten et al., 2017). For example, the connectivity of seed systems and related networks (including social networks, Abizaid et al., 2016; Okry et al., 2011), especially extra-local linkages (e.g., Samberg et al., 2013; Zimmerer, 2003, 2017a), suggest the role of intermediate scales that can be hypothesized to enhance resilience and potential food sovereignty amid transformative global change (McGuire and Sperling, 2013). Better understanding is needed of new social and cultural movements for seed and food sovereignty that are responding to anthropocene conditions. Agrobiodiversity is central to such powerful social movements as Via Campesina, Slow Food, Food First, and FIAN-International as well as international agreements such as the new United Nations Declaration on Rights of Peasants and Other People Working in Rural Areas signed in late 2018. Such work must engage the rapidly evolving impacts on agrobiodiversity owing to global and national-level political economies of agriculture, food, industrial, and financial systems (Aistara, 2014; Graddy, 2013; Kloppenburg, 2005; Montenegro de Wit, 2017).

4.5. Applications of the Agrobiodiversity Knowledge Framework in the anthropocene

The Agrobiodiversity Knowledge Framework (Table 3), including the expanded definition (Table 1), are poised for application and refinement to advance scientific understandings, policy, and management. Correspondence to the time periods relevant to the Anthropocene (Table 5) provides results that can be built upon in future research. Moreover, both this framework and the expanded definition (Figs. 1 and 2) reflect increased global connectedness. Agrobiodiversity functions as an institutional boundary object both shared and contested among global organizations and movements (e.g., CGIAR centers, Bioversity International) as well as national agencies and local groups (e.g., NGOs, farmer and food groups) (Zimmerer, 2015; see also Aistara, 2014; Cash, 2001; Cash et al., 2003; Clark et al., 2016; Orlove and Caton, 2010). Many communities engulfed in transformative global changes interact with these global-scale organizations attempting to strengthen sustainability, nutritional security, and agrobiodiversity (Arce et al., 2016; De Haan et al., 2010b; Oyarzun et al., 2013; Sherwood et al., 2013; Willett et al., 2019).

5. Conclusions: the Agrobiodiversity Knowledge Framework and the anthropocene

5.1. Global change, sustainability, and food and nutritional security

The above synthesis of understandings of agrobiodiversity from the perspective of human-environment interactions in the Anthropocene has resulted in the formulation of the Agrobiodiversity Knowledge Framework. Four distinct themes are central and serve as nodes of highly active knowledge networks: (1) ecology and evolution; (2) governance; (3) diet, nutrition, and health; and (4) global change. The framework successfully guided the presentation of new results from the Agrobiodiversity, Food, and Nutrition Field Project in Peru. Subsequently, the Agrobiodiversity Knowledge Framework proved effective in formulating future research directions. Finally, it elucidates a definition of agrobiodiversity that includes interdependence on multiple human factors and that responds to urgent calls for addressing sustainability issues.

Our results demonstrate that agrobiodiversity and closely linked human-environment interactions are complexly related to land use, food, and sociocultural and economic systems amid the global transformation of the Anthropocene. Research demonstrates its viability among changing human systems is partial albeit complex. This viability hinges on the innovative, emergent properties of agrobiodiversity and related human systems amid transformative planetary changes. Many pose major threats and spur agrobiodiversity decline, regional loss, and potential global extinctions. Expanded research on agrobiodiversity interactions with global change has yielded multiple, new insights from both systematic, in-depth analysis as well as integrative approaches.

Integrative approaches to research, management, and policy increasingly recognize the potential compatibility, as well as conflict and contestation, of the knowledge themes of agrobiodiversity. Further analysis of values and practice of knowledge are needed to address high-priority environmental and social of the Anthropocene. Agrobiodiversity is crucial to specific management and policy solutions needed for sustainable development, food and nutritional security, biodiversity conservation, and social equity and justice. Similarly, it undergirds capacities to respond to global challenges of climate change and nutrient pollution. Agrobiodiversity analysis thus evidences special promise in helping to understand and respond to the intensified human interactions with Earth systems and accelerating global changes of the Anthropocene.

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