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Toward the Integrated Framework Analysis of Linkages among Agrobiodiversity, Livelihood Diversification, Ecological Systems, and Sustainability amid Global Change

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Abstract: Scientific and policy interest in the biological diversity of agriculture (agrobiodiversity) is expanding amid global socioeconomic and environmental changes and sustainability interests. The majority of global agrobiodiversity is produced in smallholder food-growing. We use meta-analyses in an integrated framework to examine the interactions of smallholder agrobiodiversity with: (1) livelihood processes, especially migration, including impacts on agrobiodiversity as well as the interconnected resource systems of soil, water, and uncultivated habitats; and (2) plant-soil ecological systems. We hypothesize these interactions depend on: (1) scope of livelihood diversification and type resource system; and (2) plant residues and above-/belowground component ecological specificity. Findings show: (1) livelihood diversification is linked to varied environmental factors that range from rampant degradation to enhancing sustainability; and (2) significant ecological coupling of aboveground and soil agrobiodiversity (AGSOBIO assemblages). The environmental impacts of livelihood interactions correspond to variation of diversification (migration, on-farm diversification) and resource system (*i.e.*, agrobiodiversity *per se*, soil, water). Our findings also reveal mutually dependent interactions of aboveground and soil agrobiodiversity. Results identify livelihood diversification-induced reduction of environmental resource quality with lagged agrobiodiversity declines as a potentially major avenue of global change. Our contribution re-frames livelihood interactions to include both agrobiodiversity and ecological systems. We discuss this integrated social-environmental re-framing through the proposed spatial geographic schema of regional agri-food spaces with distinctive matrices of livelihood strategies and relations to biodiversity and resources. This re-framing can be used to integrate livelihood, agrobiodiversity, and ecological analysis and to guide policy and scientific approaches for sustainability in agriculture and food-growing.

Keywords: livelihood diversification; migration; environment; development; agrobiodiversity; agroecology; water resources; soil microbial diversity; ecosystem services; global change; meta-analysis; social-ecological systems; ecological intensification

1. Introduction: Integrating the Analysis of Livelihoods, Agrobiodiversity, and Ecological Interactions

Science and policy increasingly recognize biodiversity as central to land-use and agri-food systems amid global-scale changes that are socioeconomic (e.g., trade policy) and environmental (e.g., climate change) [1,2]. Biodiversity is also being appreciated as embedded in the context of human-environment

interactions involving the use of ecological systems comprising agricultural resources such as soil and water [3]. Agrobiodiversity is particularly interdependent on human-environment interactions. It is defined broadly as the biodiversity of food-producing organisms and their landscapes and ecosystems, wild counterparts in natural areas, and the realms of knowledge, skills, management, access, and the related socioeconomic and cultural factors that are integral to these human-environment systems. Previously, agrobiodiversity was considered chiefly as a source of the stocks of genetic resources and corresponding raw material for “improved” crops and livestock [4]. By contrast, we adopt and advance a new understanding of agrobiodiversity that places emphasis on its relations to current livelihoods and human well-being [5–8], including the function of agrobiodiversity in diet quality and health. Ecological interactions [2,9–11] including vegetation, soil biodiversity, water resources, and the diversity of landscape and agroecosystem components are also integral to agrobiodiversity.

The wide-ranging interactions of agrobiodiversity amid global change encompass: (a) the management, quality, and access to livelihood-related resource inputs (e.g., skills, knowledge, and labor engaged directly with agrobiodiversity and supporting resources, such as soils and water) amid the livelihood diversification of food-growers [12–14]; (b) ecosystem services and specifically interactions within agrobiodiversity-supporting ecological systems (plant-soil interactions) [10,15]; (c) crop and food-growing strategies using agrobiodiversity for combined economic, environmental, and cultural rationales [16–21] including agrodiversity, which refers to management of environmental variation in agriculture [5,22]; (d) adaptation, resilience, and mitigation in response to climate change [23–27]; (e) biodiversity use and conservation [9,28–32]; (f) market opportunities [33,34]; and (g) food security and sovereignty together with nutrition and dietary diversity and human well-being [35–39]. Each of the above linkages is receiving increased research and policy interest that includes synthesis treatments of multiple linkage types [40,41].

Our analysis is directed specifically at the linkages of agrobiodiversity to livelihood diversification and the ecological system of plant-soil interactions. These linkages are represented as the first ones in our aforementioned list. Our analysis thus addresses an important gap in current research on global changes since these factors are increasingly influential in sustainability challenges and potential opportunities. Focusing on this pair of core linkages requires a selective integration across thematic and conceptual fields. First, the concept of social-ecological systems highlights causal linkages in global change and the relationship between resources and governance [42–44]. Second, the concept of human-environment interactions draws attention to the complex coupling of these systems [45–49]. Third, political ecology has examined the driving forces as well as the “inner workings” (e.g., gender relations) of rapidly expanding livelihood diversification [50–54]. Political ecology also includes a focus on the impacts of labor migration indicative of the “new rurality” [55,56]. Fourth, the ecology of soil-plant systems is needed to analyze agrobiodiversity interactions and environmental sustainability [9,57–59], in order to include the important non-human interactions of these systems. The selective integration of these four fields is needed to address the multi-faceted issues that arise in the livelihood-environmental interactions of smallholders. Such issues range from poverty alleviation, resilience, and food security [60,61] to sustainability and the intensification of land use [4,52,62–66].

Topically, this study engages with agri-food systems and global socioeconomic and environmental changes of small-scale agri-food producers that are also agricultural workers (smallholder) [52,66–70]. We focus specifically on two types of interactions of agrobiodiversity: (i) with the diversification of smallholder livelihoods whose scope includes migration and cash cropping that reflect global socioeconomic change; and (ii) within the context of the ecological systems of plant-soil biotic interactions that range from the cultivated and managed to the partly “wild” (e.g., forests and woodlands). These ecological systems strongly influence the resilience capacity of food growers and their fields and agricultural landscapes [11,71–73]. We recognize that many works to date in the global change sciences have focused on forest ecosystems and deforestation. Our research intends to incorporate agri-food systems and environments as central to integrated scientific frameworks of global changes. Indeed, the major drivers of global change on forest cover, such as neoliberal

political economy, urbanization, trade liberalization, and climate change, also influence agri-food systems, agrobiodiversity, and livelihood diversification. More broadly, our approach contributes to the scientific and policy analysis of smallholder agrobiodiversity and thereby advances environmental sustainability and social issues of food and equity.

Our conceptual model is focused on the linkages of livelihood diversification to the biodiversity of agriculture and food-growing in particular (Figure 1). This model highlights the direct livelihood linkages to related yet distinct sub-components comprised of above- and belowground agrobiodiversity (lower left of Figure 1) and the components of soil and water resources (lower right of Figure 1). Our model offers a re-framing of livelihood analysis to include the linkages to both food-growing and the ecology of resource systems. The increasingly complex roles of livelihood interactions are pronounced in the agri-food systems of smallholders both locally and globally (Sections 2 and 3).

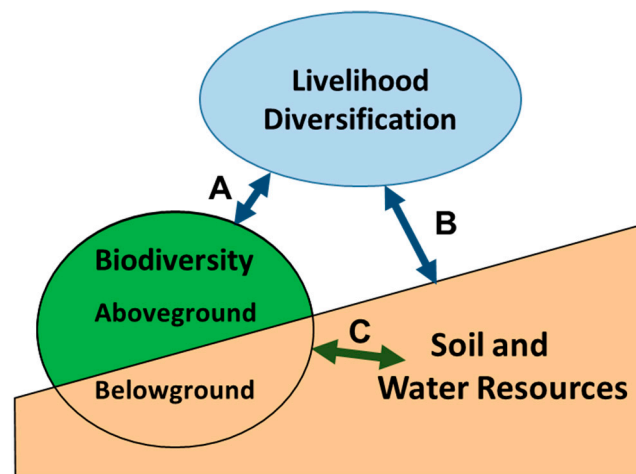


Figure 1. Conceptual diagram of the linkages of livelihood diversification to agrobiodiversity, as both aboveground and belowground sub-components, and to soil and water resources. Arrows A and B represent principal linkages of livelihoods to natural systems; C represents coupling between natural resources and agrobiodiversity.

Current smallholder livelihoods rely on a mix of economic, social, and cultural activities undertaken as individuals and as household groups, as well as in extra-household networks and spaces in their communities and beyond. In the context of expanding globalization and urbanization, migration is increasingly vital to the livelihood diversification of smallholders worldwide. A majority of the world's 500–800 million migrants between 1990 and 2010 belong to smallholder households (see also below, Section 2). Smallholders have thus extensively diversified their off- and non-farm incomes while continuing to derive livelihoods partially from the use of local land and resources. Ecological systems are integral to these changing local agri-food spaces. The local social-ecological systems of large populations of smallholders are also essential to global agrobiodiversity (see current demographic estimate in the next section). Seen in the context of smallholder livelihoods and ecological interactions, agrobiodiversity is recognized as fulfilling a range of functions ranging from agroecosystem dynamics to nutritional and dietary diversity, food supply, and cultural roles.

This paper's methodological goal is to examine the case study-based documentation of the linkages of agrobiodiversity and related resource use to global change consisting of livelihood diversification (Section 3) and ecological systems with an emphasis on soil-plant interactions and biodiversity (Section 4). We employ the methodology of meta-analysis to research these linkages [74–76]. First, we conduct an analysis of the interactions of recent livelihood diversification with agrobiodiversity use and the related management of soils, water, and uncultivated biodiversity (Section 3). We place emphasis on migration and on-farm cash cropping as two common forms of

smallholder livelihood diversification. Second, we analyze the ecological interactions of aboveground biodiversity to belowground, soil-level biotic functions and diversity (Section 4).

Meta-analysis has become significant in research on global change and social-ecological systems in order to synthesize expanded fields of study as well as to advance new understandings and hypotheses [74–76]. Design of this study's meta-analyses draws also on our extensive personal experience in field-based research on the linkages of biodiversity and soil and water management to livelihoods and livelihood changes. This occurs in three ways: (a) our backgrounds as an interdisciplinary environmental scientist and geographer (ksz) focused on human-environment, ecological, and livelihoods research and as a soil scientist and ecologist (sjv) focused on agroecosystems helped to generate the specific ideas about linkages being tested and evaluated in this meta-analysis; (b) our field experiences suggested that the widely spanning human-environmental linkages examined here are scientifically important, policy-relevant, and often escape consideration in the way we formulate them here; and (c) more generally our field experiences motivate our collaboration with one another and other teams to undertake the meta-analysis research and synthesis undertaken in this article.

In keeping with our emphasis on geographic linkages, we have incorporated our meta-analysis findings into a spatially explicit conceptual framework of livelihood-diversification and agricultural intensification regimes that we relate to expected or hypothesized interactions and outcomes with regard to agrobiodiversity (Section 5). Relating agrobiodiversity to regional spaces of agri-food systems with characteristic livelihood-diversification regimes enables us to offer hypotheses for future scientific study and insights for policy analysis. Our discussion of livelihood interactions with agrobiodiversity and ecological systems using this spatial framework reflects the need for sustainability research with a meso-level focus. Focus on meso-level geographic and thematically specified social-ecological systems has gained importance in light of the growing number of high-profile and influential yet general summary-style calls in science and policy for sustainable intensification, ecological intensification, and smallholder sustainability ([3,4,11,62,64,65,77]; see example of related meso-level research in [52,66]).

2. Empirical Focus and Research Methodology: Global Smallholders and Nested Meta-Analysis

Globally, smallholders comprise a population of 2.0–2.5 billion persons whose lands are significantly smaller in areal extent and endowed with fewer capital- and technology-intensive resources than mean-size agricultural enterprises [77]. Livelihoods and socioeconomic capacity demonstrate a high level of heterogeneity within this group. Most smallholders live in geographic areas of Asia, Africa, and Latin America that range from remote rural to intermediate-distance and peri-urban locales [52]. Smallholder livelihood strategies involve production for agri-food systems that are local, national, and global in scope. Non- and off-farm labor, including agricultural work and migration at multiple scales (*i.e.*, local, national, global), are livelihood activities that link to their agri-food spaces and systems. This lived complexity of smallholders is far from an ideal socioeconomic reality since the large majority are poor by local and national standards, and many also suffer food insecurity. In addition, our perspective on global smallholders is non-teleological in the sense of not presupposing either smallholder disappearance or persistence. Most smallholders live a grueling, marginal existence underscoring the importance of livelihood issues. This reality is fused with the economic dominance of corporate, industrial agri-food systems globally as well as land grabs displacing smallholder populations [64,73,78]. These circumstances do not, however, detract from importance of the world's present-day population of 2.0–2.5 billion smallholders and their access to food and resources, combined with non- and off-farm linkages, wrought through livelihoods that include the use of agriculture and ecological systems.

Smallholder agri-food systems are distinguished through the varied use of land, water, and other resources, including agrobiodiversity. Across a wide range of global contexts, smallholders generally manage marginal land that is vulnerable to degradation [5]. Their access to soil and water varies widely, with smallholder resources often threatened through input-intensive agri-food

production. Nonetheless significant global agrobiodiversity is concentrated in the fields and gardens of smallholders in the context of these limitations and constraints [52]. Agrobiodiversity is furnished through locally accessible seed systems and it reduces the risk of crop loss in low-input agroecological conditions [1,17,27], in addition to furnishing locally valued foods. The adequate management of soil and water resources is integral to these functions of agrobiodiversity that, in turn, provides nutritional and health benefits to smallholder populations.

To address the complexity of this human-environment system, we designed a meta-analysis on smallholder livelihoods, migration, agrobiodiversity and environmental resources. We used the Web of Science database to identify relevant publications since 1985. Forty-two research publications were chosen for our analysis in the first area of meta-analysis using the combinations of specific search terms (Table 1). Each of these studies explicitly addresses the household- and local-level mechanisms of livelihood-environment interaction, thus guiding us with regard to the issue of scale. Publications were chosen that provide case studies combining results on *both* livelihood diversification *and* environmental impacts and interactions. Our analysis is focused on studies of the environments (*i.e.*, agrobiodiversity, soils, water, uncultivated biodiversity) of smallholder *home* communities (referred to a “source” in the migration literature), while it recognizes that an important yet quite distinct analysis would focus on environments in migrant *destinations*. (The latter type of analysis would characterize much of migration’s role in environment–development interactions in frontier settings in countries such as Brazil.) The 42 research publications chosen were found to contain 56 descriptions of specific livelihood diversification–environment interactions. Many research works ($n = 32$) are based on case studies undertaken after 1999. Case studies cover examples in Latin America, Africa, Asia, and Europe. Using a coding approach, we created quantitative estimates of: (a) change of agrobiodiversity (decrease, increase, and stasis) typically described at the taxonomic level of species or varieties (often termed landraces in the case of traditional crops); (b) soil quality and degradation (e.g., soil erosion); (c) water quantity and quality; and (d) uncultivated biodiversity. The studies were also stratified by the type of livelihood diversification depending on the predominance of migration or on-farm livelihood diversification. In addition, studies were coded according to changes in the gendered roles of resource use.

Table 1. Search terms and published sources ($N = 42$) in the meta-analysis of the interactions of livelihood diversification and resource and environmental systems (*i.e.*, agrobiodiversity, soils, water, wild biodiversity). Several sources address more than one resource or environmental system.

Search terms consulted (Web of Science database)
(“Livelihood diversification” OR “migration” OR “development”) AND (“agrobiodiversity” OR “crop diversity” OR “soil” OR “water” OR “biodiversity” OR “secondary forest transition”)
Authors and publication year of sources with numbered reference
Aide, and Grau 2004 [79], Batterbury 2001 [80], Bilsborrow 1992 [81], Garcia-Barrio and García-Barrios 1990 [82], Bilsborrow and DeLargy 1990 [83], Carr 2009 [84], Chambers and Momsen 2007 [85], Chen <i>et al.</i> 2012 [86], Collins 1987, 1988 [87,88], Davis and López-Carr 2010, 2014 [89,90], European Commission 2015 [91], Grau and Aide 2007 [92], Gray 2009a [93] Gray and Bilsborrow 2014 [94], Gray 2005 [95], Heartherington 2014 [96], Hecht <i>et al.</i> , 2006 [97], Huijun <i>et al.</i> 2002 [98], Iniesta-Arandia <i>et al.</i> , 2015 [99], Jewitt 2000 [100], Jiménez Olivencia 2010 [101], Jiménez Olivencia <i>et al.</i> , 2015 [102], Jokisch 2002 [103], Lerner <i>et al.</i> , 2013 [104], Li <i>et al.</i> 2014 [105], López 2006 [106], McCord <i>et al.</i> 2015 [27], Mutersbaugh 2006 [107]; Nuijten 2010 [108], Preston, D 1997 [109], Qin 2010 [110], Radel and Schmook 2008 [111], Radel <i>et al.</i> 2012 [112], Reardon <i>et al.</i> 2001 [113], Rudel <i>et al.</i> 2002 [114], Schmook <i>et al.</i> 2013 [115], Turner 1999 [116], Zimmerer 1991 [117], 1993 [118], 1996 [7], 2014 [119].

The second area of meta-analysis focused on the interactions between above- and belowground components of agrobiodiversity. We use the term AGSOBIO (AGricultural and SOil BIOdiversity system) to denominate these coupled environmental components. For the AGSOBIO meta-analysis, 50 research publications (Table 2) were coded. Ecological systems in these publications range

from croplands to perennial landscape components (*i.e.*, agroforestry, managed forests, fallows, and pastures). We gathered quantitative estimates and overall interpretations about the impact of increasing aboveground biodiversity on (a) belowground biotic community structure, regardless of diversity; (b) taxonomic diversity or functional diversity, using the measures of diversity given in the reviewed papers (e.g., the Shannon-Wiener index, or belowground species richness depending on the paper); and (c) changes in ecological function of soils for crop production that characterize the supporting role of soil biota as coupled to aboveground biodiversity, e.g., impacts on mycorrhizal colonization or activities of soil enzymes that catalyze biogeochemical cycling. The studies were also stratified by the type of change in vegetation diversity, between studies that examined land-use level change, e.g., forest conversion, secondary succession, adoption of agroforestry, and those studies that compared plant diversity within only agricultural land uses (e.g., crop rotation, fallow type, and introduction of short-term pasture). We also stratified the studies by functional type of soil biota: whole community metagenomic studies of bacteria, archaea, and fungi; arbuscular mycorrhizal symbioses in land-use systems, for which there were a particularly large number of studies; and macrofauna, which are increasingly valued as a soil quality indicator. The AGSOBIO meta-analysis is conceptualized as the lower-left vertex of our conceptual model (Figure 1) and thus nested within the triad of interactions that includes livelihood diversification.

Table 2. Search terms and published sources ($N = 50$) used to construct the meta-analysis of relationships between above-ground biodiversity and soil biotic communities. Sources are divided according to the domain of soil biota each research paper addressed. In addition to the search terms, backwards and forwards reference searches were used to more fully explore the database.

Search terms consulted (Web of Science database)	
("Land use" OR "crop rotation" OR "crop diversity" OR "cropping system") AND ("microbial diversity" OR "microbial functional diversity" OR "macrofaunal diversity" OR "macrofauna" OR "mycorrhiza" OR "fungal diversity" OR "bacterial diversity")	
Domain of soil biota	Authors and publication year of sources with numbered reference
Whole community: e.g., soil bacteria, archaea, and/or fungal communities	Acosta-Martínez <i>et al.</i> 2010 [120], Alvey <i>et al.</i> 2001 [121], Asgharipour <i>et al.</i> 2011 [122], Bach <i>et al.</i> 2012 [123], Berthrong <i>et al.</i> 2009 [124], Buckley and Schmidt 2003 [125], Duchicela 2013 [126], Garbeva <i>et al.</i> 2006 [127], Garcia <i>et al.</i> 2012 [128], Gomez <i>et al.</i> 2004 [129], Gonzalez-Chavez <i>et al.</i> 2010 [130], Jiang <i>et al.</i> 2014 [131], Johnson <i>et al.</i> 2010 [132], Larkin and Honeycutt 2006 [133], Lienhard <i>et al.</i> 2014 [134], McDaniel <i>et al.</i> 2014 [135], Meriles <i>et al.</i> 2009 [136], Millard and Singh 2010 [137], Nayyar <i>et al.</i> 2009c [138], Nurulita <i>et al.</i> 2015 [139], Shen <i>et al.</i> 2008 [140], Sheng <i>et al.</i> 2013 [141], Vasileiadis 2013 [142], Yao <i>et al.</i> 2006 [143], Yu <i>et al.</i> 2012 [144]
Mycorrhizae	Almacá and Ortas 2010 [145], Bedini <i>et al.</i> 2013 [146], Carpenter <i>et al.</i> 2001 [147], Chaturvedi <i>et al.</i> 2009 [148], Dai <i>et al.</i> 2013 [149], Gavito and Miller 1998 [150], Hendrix <i>et al.</i> 1995 [151], Higo <i>et al.</i> 2014 [152], Hijri <i>et al.</i> 2006 [153], Lehman <i>et al.</i> 2012 [154], Lekberg <i>et al.</i> 2008 [155], Melo <i>et al.</i> 2014 [156], Muchane 2012 [157], Oehl <i>et al.</i> 2003 [158], Rao <i>et al.</i> 1995 [159], Säle <i>et al.</i> 2015 [160], Sturmer <i>et al.</i> 2011 [161], Tchabi <i>et al.</i> 2008 [162], Tian <i>et al.</i> 2013 [163], Verbruggen <i>et al.</i> 2010 [164], Vestberg <i>et al.</i> 2011 [165]
Macrofauna	Dominguez <i>et al.</i> 2010 [166], Hulugalle <i>et al.</i> 1997 [167], Maria De Aquino <i>et al.</i> 2008 [168], Sileshi <i>et al.</i> 2008 [169]

3. Results: Livelihood Diversification and Environmental Linkages

The linkages among smallholder livelihood diversification and environmental impacts are increasingly known to be complex [170]. Nonetheless, our findings demonstrate there is ample evidence to identify and assess the role of specific linkage mechanisms and, more generally, to advance the understanding of these impacts (Table 3). The studies surveyed here and the perspective of our research urge that the increased amount of attention to livelihood-diversification processes view these phenomena as both cause and effect in relation to environmental change. Likewise, they reveal complex links to socioeconomic changes, such as globalization in the form of international labor market integration that is, in turn, an important driver of migration. At least three hypothesized mechanisms underlie the linkages of livelihood diversification to environmental

impacts (Figure 2a). First, conventional understanding asserts the reasonable expectation that migration lessens environmental pressures in the home communities since livelihoods are expected to become less dependent on cropping and other land use including grazing and forestry [93,171]. Second and by contrast, various studies beginning in the late 1980s and early 1990s suggest that livelihood diversification reduces the supply of labor needed for the sustainable management of agroecosystems, including terracing of agricultural fields on sloped soils [87,88] and the cultivation of high-agrobiodiversity crops with staggered or extended growing seasons [117]. Third, the role of migration remittances is complex and may be either detrimental or beneficial with regard to environmental impacts in sending communities [89,90], which has seemed to motivate the growing number of case studies of livelihood diversification and environmental impacts in development. Gendered social relations and their role in agriculture and land use are an increasingly important focus of these studies [112,172–178]. Yet research has not focused as systematically as we do here across the geographic and interdisciplinary integration of multiple forms of livelihood diversification (e.g., migration, on-farm diversification), environmental resource- and environment-specific systems (e.g., agrobiodiversity, soil, water, uncultivated biodiversity), and related gender relations.

Results of our first meta-analysis demonstrate significant variation in the interactions of smallholder livelihood diversification with agrobiodiversity levels (Table 3). Agrobiodiversity increase, decline, and stasis are all demonstrated. Decreases in agrobiodiversity with livelihood diversification are significant in these results (33%) and exceed the cases of increased agrobiodiversity (8%) (Table 3.2). Overall, studies showing no change or mixed outcomes, combining increases and decreases of agrobiodiversity that were locally or regionally differentiated, are predominant (58%). These latter results are significant since they evidence the partial conservation of agrobiodiversity. They support calls for on-farm, *in situ* conservation in the context of current smallholder livelihoods and diversification trends. The meta-analysis also shows that livelihood diversification via migration is more favorable to agrobiodiversity than diversification using non-migration portfolios (Table 3). A key factor influencing these outcomes is whether smallholders had the inclination and capacity to commit resources (e.g., labor, land, water) to agrobiodiversity amid other demands. Such capacity can be increased non-traditionally (e.g., high levels of internal migration combined with local in-migration; 119) so that flexible household-level land use and the corresponding versatility of resource allocation enables the use of agrobiodiversity more effectively than in the high-intensity agriculture of prime areas of commercial cropping [2,5,52,104,119]. These findings illustrate so-called emergent social-ecological properties of smallholder agrobiodiversity, illustrating through either its disappearance or continued production the increase of linkages to global change.

Livelihood diversification frequently results in a decline in the quality of smallholder soil resources (59%) and water resources (53%) (Table 3.2). At the same time, occurrence of quality increases is shown to be significant albeit less common (26% and 35%, respectively). In general, a greater level of research has been focused on the interactions of livelihood diversification with soils ($n = 27$ studies) and water ($n = 17$ studies) compared to agrobiodiversity. This research emphasis owes to the immediate impacts of soil and water management on human well-being as well as the potential reverse causation, namely, that soil or water degradation, or “agro-ecological drivers” more generally, contribute to the migration decisions of individuals and households [93,176–179]. The importance of soil degradation in smallholder land use, for example, can be symptomatic of resource-poverty traps associated with livelihood diversification that is detrimental to both the environment and human well-being [61,173,174]. Water resources and management show a discernible trend toward increased quality (60%) under changes associated with on-farm livelihood diversification in contrast to migration, since the former often incorporates small-scale irrigation systems (Table 3.3b). Variation in outcomes with regard to smallholder soil and water resources depends principally on the viability of investing labor, capital, and land and the availability of these factors. This viability hinges on household capacities and endowments amid livelihood diversification that occasionally incorporates their access to the inputs of institutions working in the realm of environment and development [180].

Table 3. Results of the meta-analysis of research studies ($N = 42$) on the interactions of livelihood diversification with resource and ecological systems. This analysis drew from 42 published research papers that related the diversification of livelihood activities, with emphasis on migration, non-migration diversification of livelihoods, and the conditions of agrobiodiversity, soil and water resources, and uncultivated biodiversity.

3.1. All studies: association of livelihood diversification with change <i>vs.</i> no change in agrobiodiversity, soil, and water resource factors					
	N (Studies Reporting)	Change in One or More Factors		No Change (in Any Factor)	
	42	93%		7%	
3.2. All studies: changes in food plant agrobiodiversity richness (species or varieties) and the environmental quality of soil and water resources					
	N (Number of Comparisons)	Increase	No Change or Mixed	Decrease	Observations and Main Tendencies
Changes in agrobiodiversity	$N = 12$	8%	58%	33%	Change interpreted as a mixed outcome shows both increase and decrease occurring as local variation among households and local places as well as regionally.
Changes in soil quality	$N = 27$	26%	15%	59%	
Changes in water quality	$N = 17$	35%	12%	53%	
Changes in wild biodiversity	$N = 18$	39%	22%	39%	
3.3. Studies grouped by predominant type of livelihood diversification					
(a) Studies that focus primarily on migration as the major form of livelihood diversification					
Changes in agrobiodiversity	$N = 6$	17%	50%	33%	Livelihood diversification studies with a migration emphasis tend to incorporate a focus on the abandonment of soil and water infrastructure (e.g., historic irrigation systems)
Changes in soil quality	$N = 20$	25%	15%	65%	
Changes in water quality	$N = 12$	25%	8%	67%	
Changes in wild biodiversity	$N = 12$	42%	25%	33%	
(b) Studies with emphasis primarily on-farm livelihood diversification (without migration emphasis)					
Changes in agrobiodiversity	$N = 6$	0%	67%	33%	Livelihood diversification studies (without migration emphasis) tend to focus on local land-use capacity, including increased infrastructure for soil and water management (e.g., irrigation)
Changes in soil quality	$N = 7$	33%	17%	50%	
Changes in water quality	$N = 5$	60%	20%	20%	
Changes in wild biodiversity	$N = 6$	33%	16%	50%	
3.4. All studies: gender analysis in diversified livelihood interactions with food plant agrobiodiversity, soil, and water resources					
	N (Number of Comparisons)	Frequency			
Contains analysis of gendering	$N = 23$	55%		Level of gender analysis varies widely in these studies	
Women's increased role in resource use	$N = 22$	96%			
Men's increased role in resource use	$N = 8$	35%		Associated principally with livelihood diversification and relatively minor role of migration and, in some cases, recent increased migration among rural women (e.g., Spain and Andean countries)	

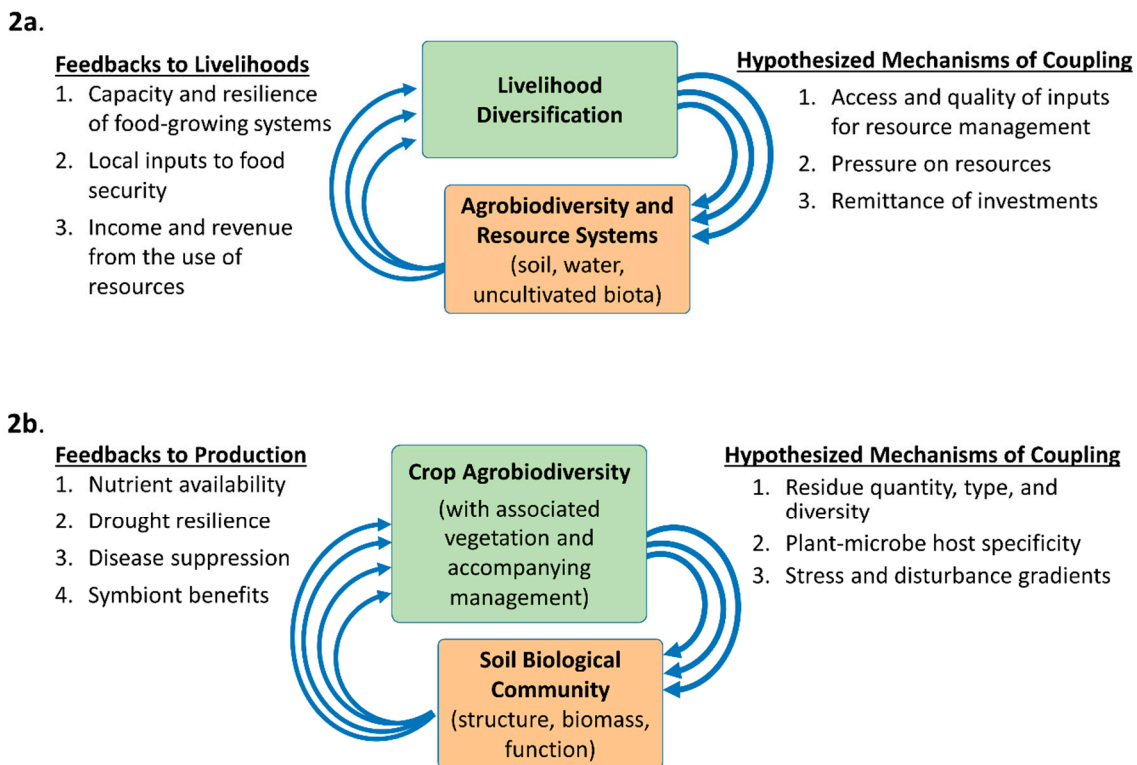


Figure 2. (a) Coupling of the interactions of livelihood diversification and agrodiversity and (b) the above- and belowground components of agrodiversity.

Uncultivated or “wild” biodiversity associated with forest cover is incorporated as a focus in several studies related to livelihood diversification ($n = 18$; Table 3). A significant portion of these studies (39%) report favorable interactions with forest and woodland biodiversity resulting from forest regrowth, or so-called secondary forest transitions, occurring through the disintensification of agriculture linked to household-level livelihood diversification (in addition to the case studies in Table 1, see also [181,182]). These findings of favorable impacts on uncultivated biodiversity through forest regrowth resulting from livelihood diversification are found more often in conjunction with predominant migration (42%) than on-farm activities (33%) (Table 3.3a,b). Conversely, livelihood diversification can be a significant driver of deforestation and resulting loss of wild biodiversity through land use (39%), with the remainder reporting mixed outcomes or no change (22%) (Table 3.2). These declines of forest and woodland biodiversity reflect outcomes discernible within the group of studies characterized as indicating the prominence of migration (33%) and within the contexts of predominantly on-farm activities (50%) (see also [183]). Whether forest and woodland biodiversity is increased or decreased depends on such factors as household-level decision-making with regard to the expansion of agriculture and land use, including the grazing of livestock, and feasibility of access to forested lands. In sum, our meta-analysis of case studies shows that the impacts of livelihood diversification on wild biodiversity are mixed and dependent on factors in the local milieu of smallholder and, in the case of migration, in the destination context. These findings resemble the findings of our analysis with regard to agrodiversity, soils, and water resources.

Dynamics of gendering and land-use intensification are two additional themes increasingly common within the suite of research dealing with livelihood diversification and migration related to the environment. Interests in and the analysis of gendering in livelihood diversification are expanding significantly and build upon vibrant existing research traditions in household-level analysis in agricultural, resource, and development economics and sociology and also in such fields as geography and anthropology (e.g., [172,184–192]), as well as interdisciplinary approaches such as feminist political

ecology (FPE; [53,54,193]). Gendered resource access and knowledge systems are integral to the resource use and agri-food systems of smallholders amid livelihood diversification and global changes. These interactions may include unanticipated outcomes. For example, gendered changes have been found to be influential in soil management and the potential of resource-poverty traps [194]. The gendered livelihood changes associated with purportedly beneficial land use, such as conservation agriculture (CA) in African smallholder systems, have been found to undermine nutrient-management goals due to an inequitable shift of labor requirements to women [195]. Our meta-analysis results show the gendering of work activities related to livelihood diversification and resources to involve an expanded role of women's efforts in nearly all studies (96%; Table 3.4). Men's work activities were expanded less commonly in resource use (35%), which owes partly to the expansion of off- and non-farm livelihood activities.

Environmental impacts of the intensification or disintensification of land use vary significantly as a result of livelihood diversification. Since these impacts are often not measured in these studies, we noted only qualitative information in our meta-analysis. Generally, the process of disintensification is associated with livelihood diversification, although several studies mention it, and a few are able to demonstrate the increase of intensification, while others suggest the occurrence of no change in intensification level. Gender dynamics are critical to these trends, since in many cases women become the main farm managers, and this "feminization" of resource use exerts a major influence on the specifics of agricultural change (e.g., crop choice) and general outcomes (e.g., intensification or disintensification) [14,48,51,89,90,97,172–177,196–198]. For example, the decline of chili pepper markets led to disintensification in the southern Yucatán region of Mexico through processes of livelihood diversification based on international migration and the influence of women's role in subsequent resource use [173,196,197]. In other cases, where women have migrated significantly, such as the case of remote-rural regions of Spain and elsewhere in Europe, including the former German Democratic Republic [99,198], new arrangements combine the "masculinization" of continued land use with social innovations in women's continued albeit reduced involvement.

In summary, our results combine with other new findings to build upon earlier demographic approaches [199]. These findings demonstrate how the influences of livelihood diversification on agricultural intensification vary significantly and are conditioned on the existence of geographically specific opportunities and constraints in both sending areas and receiving areas.

4. Results: Ecological Linkages within Agrobiodiversity Systems

We turn now to the results of meta-analysis of the ecological linkages within agrobiodiversity systems (Table 4). Our analysis focuses on the interactions between soil biotic diversity and the biodiversity of crop species, including local varieties of food crops known as landraces, along with associated management as well as managed wild species (bottom of Figure 1). The component of soil biota is a key form of "associated biodiversity" [1,11] that provides supporting ecosystem services key to food production [200–203]. Considering AGSOBIOs as coupled above- and belowground agrobiodiversity components provides the explicitly ecological framing to complement our recognition that each of these components may be impacted through livelihood diversification, as discussed above (Section 3) and illustrated graphically (Figure 1). Livelihood changes that affect either the above- or belowground component will also potentially impact the other component. The ecology of these plant-soil interactions is the focus of meta-analysis in this section.

Table 4. AGSOBIO meta-analysis. This analysis drew from 50 published research papers with 53 land-use and crop rotation comparisons of community composition, total biomass of target biota in the study, and soil ecological function under increasing levels of aboveground plant diversity. Sections 4.1 and 4.2 show the change of community structure, and any increase, lack of change, or decrease in soil biological diversity with increases in aboveground diversity. Section 4.3 divides the analysis into studies that assessed increasing diversity via land use change (e.g., forest conversion to crops, secondary succession from crops, and adoption of agroforestry) *versus* those that assessed increasing diversity in comparisons of crop rotations and associated short-term pasture or fallow management. Section 4.4 groups the studies by soil biota functional type for which there were sufficient research papers.

4.1. All studies: changes in soil biotic community structure					
	N (Number of Comparisons)	Change	No change		
	N = 53	92%	8%		
4.2. All studies: changes in soil biological diversity, abundance, and biological function under increasing aboveground biodiversity					
	N (Number of Comparisons)	Increase	No Change	Decrease	Observations and Main Tendencies
Changes in soil biotic diversity	N = 53	55%	34%	9%	
Changes in biotic abundance or biomass	N = 26	69%	23%	4%	
Changes in soil biological function (e.g., enzyme activity, mycorrhizal colonization)	N = 28	79%	14%	7%	
4.3. Studies grouped by land management types that alter aboveground biodiversity:					
Studies that examined changes in land use (forest conversion, succession, agroforestry <i>vs.</i> cropping)					
Changes in soil biotic diversity	N = 25	64%	28%	8%	Differences in soil organic matter accumulation, disturbance, and species type that drive soil biotic differences are especially strong between long-term perennial uses as a group (e.g., forest) versus cropping systems as a group.
Changes in biotic abundance or biomass	N = 9	78%	11%	11%	
Changes in soil biological function	N = 8	100%	0%	0%	
Studies that examined changes in agricultural and livestock management within agricultural land uses (among crop rotations, fallows, pastures)					
Changes in soil biotic diversity	N = 34	41%	47%	9%	Management accompanying crop diversity is important, e.g., increased tillage under continuous monoculture <i>vs.</i> diverse rotations with fallows and variation in tillage regimes.
Changes in biotic abundance or biomass	N = 16	69%	31%	0%	
Changes in soil biological function	N = 17	65%	24%	12%	

Table 4. Cont.

4.4. Studies grouped by soil biota type impacted by increasing aboveground biodiversity:					
	<i>N</i> (Number of Comparisons)	Increase	No Change	Decrease	Observations and Main Tendencies
Analyses of soil whole microbial communities (using e.g., bacteria, archaea, fungi using whole metagenome analysis)					
Increases in soil biotic diversity	<i>N</i> = 20	50%	40%	10%	Long lag times: decadal “imprint” of management based on previous land use. High degree of functional diversity and redundancy in bacterial and archaeal communities that creates temporal stability/hysteresis in community composition. Less well-understood aboveground/belowground relationships than for symbiont communities or macrofauna. In addition the fungal: bacterial ratio of various biomass measures (e.g., PLFA) often increases with the amount of recalcitrant residues in systems and decreases under soil disturbance (e.g., grassland has a higher fungal: bacterial ratio than an intensified vegetable rotation.)
Increases in biotic abundance or biomass	<i>N</i> = 9	78%	22%	0%	
Analyses of arbuscular mycorrhizal communities (using spore classification and counts and fingerprinting using mycorrhizal DNA primers)					
Increases in soil biotic diversity	<i>N</i> = 34	59%	35%	6%	Strong influence of whether aboveground species that add biodiversity are mycorrhizal or non-mycorrhizal, and specialist vs. generalist mycorrhizal fungal species.
Increases in biotic abundance or biomass	<i>N</i> = 12	67%	25%	8%	
Analyses of macrofaunal communities (using field methods and visual classification of macrofauna)					
Increases in soil biotic diversity	<i>N</i> = 4	75%	25%	0%	Mediation by plant residue quantity and quality accompanying aboveground species diversity and associated management is especially strong.
Increases in biotic abundance or biomass	<i>N</i> = 3	100%	0%	0%	

Several hypothesized mechanisms underlie the coupling of above- and belowground biodiversity in AGSOBIOs (Figure 2b). First, various research studies suggest that soil biodiversity responds to niche differentiation corresponding to plant diversity as proposed by Reynolds *et al.* [204]. In particular, soil biotic diversity could arise from different amounts and temporal dynamics of nutrients and labile carbon for microbes in the root systems of different species [205], or based on plant species-dependent quality and quantity of residues from dead above- and belowground biomass (e.g., [137,206]). Second, plants often host symbiotic microbes such as mycorrhizal fungi and N-fixing rhizobia and associative bacteria. Host-specificity of these symbioses may affect the microbial community that inhabits plant root systems. Third, the agricultural management associated with crop and associated plant communities, such as tillage, fertilization, irrigation, and weed management, create different levels of nutrient and water stress and physical disturbance (e.g., tillage, harvest) for soil biotic communities that favor higher or lower diversity and the ecological function of microbes, with the highest levels of diversity theorized to occur at intermediate levels of stress and disturbance [141,207].

These varied potential mechanisms illustrate that the linkages between the aboveground and belowground components of biodiversity are undoubtedly complex [59]. Furthermore, there are differences in magnitude between above- and belowground biodiversity: Aboveground agrobiodiversity incorporates crop varietal differences in phenology and growth habit as well as suites of perennial and annual species that embody plant family and functional type differences. By contrast, the soil component of this biodiversity is far more varied, ranging from thousands of species of soil bacteria and archaea that mediate nutrient cycling and interact with plant roots, to fungal symbionts and pathogens, to fauna including macrofauna that serve as so-called soil ecosystem engineers and provide the physico-chemical scaffolding for both root and microbial activities that support food production [200,208].

In spite of this complexity, our meta-analysis yielded sufficient evidence to contribute to understanding how and under what conditions aboveground plant agrobiodiversity influences soil biological communities (Table 4). Over 90% of the 53 comparisons included in the analysis found that changes in plant biodiversity changed the microbial or faunal community structure of soils, including cases when some measure of community structuring was found to change even if diversity indices (e.g., richness, Shannon-Wiener index, functional diversity) of the soil communities did not change.

In addition, just over half of studies show increasing soil biodiversity with aboveground diversity, while only 9% showed declines in soil agrobiodiversity. Moreover, the plausibility of feedback effects of soil biota for contributing to food production is verified: For studies that measured aspects of soil biological function that contribute to aboveground productivity, a majority (79%) show that these functions were improved under higher diversity plantings (e.g., more complex crop rotations with legumes, or reforested areas compare to intensive agriculture). Increased soil biodiversity and improved soil properties relate to aboveground biodiversity were relatively common when comparisons were made between non-agricultural land uses and agriculture (Table 4.3). Nevertheless, comparisons of vegetation diversity made only within agriculture and pasture land uses also showed a preponderance of increases over decreases in soil biotic diversity and biological soil function as plant communities became more diverse. Very few studies tested the impact of varietal diversity within a crop species on soil biological communities. However, a few studies demonstrated that crop varietal interactions with soil biota were plausible, for example, those that found higher response of local maize landraces and older varieties to mycorrhizal symbionts than from modern varieties [209–211].

5. Discussion: Hypothesizing Pathways and the Spatial-Geographic Dynamics of Livelihoods and Agrobiodiversity amid Global Change

These results offer a new framing of the study of the interactions of livelihoods (Figure 1, top) with agrobiodiversity (Figure 1, lower left) and closely related resource systems (Figure 1, lower right). This framing is focused on globally predominant modes of diversification that include off-farm activities (migration) and on-farm shifts (toward more mixed portfolios), gender dimensions, and land-use

intensification or disintensification. Focus of our framing also encompasses the elements of biodiversity in agriculture (agrobiodiversity), resource use, and the large global population of socioeconomically vulnerable smallholders (Section 2). Our framing needs to be understood as contributing to the interdisciplinary analysis of global change that links major trends, such as migration, urbanization, and commodity trade, with the environment [212–214]. Finally, our framing engages and contributes to growing interdisciplinary research on migration-dependent livelihoods and the environment [215,216]. Here our intent is also to offer explicit re-framing that integrates multiple ecological components rather than treating the environment as a simple, single sub-system.

This re-framing is evident in the design and results of our meta-analysis to encompass multiple, related environmental resources (e.g., agrobiodiversity, water, soils): the increased links of livelihood diversification to agrobiodiversity are associated with minor or mixed changes while this increase shows pronounced negative impacts on the environmental quality of soils and water, albeit with some exceptions (Section 3). The noted absence of significant change in agrobiodiversity systems may be influenced by observational challenges. For example, agrobiodiversity loss tends to be less visually apparent than erosion or other prevalent forms of soil degradation. Noteworthy too is that primarily negative consequences for soil systems, in particular soil biotic functioning and diversity, may subsequently incur deleterious impacts on biodiversity of crops as well as uncultivated vegetation.

The results of our AGSOBIO meta-analysis (Section 4) demonstrate the mutually dependent interactions between aboveground and soil biodiversity in agricultural landscapes, and suggest that crop/land-use diversity and soil biodiversity act in a coupled way to support local food production. Understanding the linkages between vegetation and soil biodiversity in a way that is more sensitive to both biophysical context and the management techniques driven by types of livelihood diversification will help to better understand sustainability linkages to livelihoods. Methodologically the coupling of soil and crop diversity suggests that remote sensing could in the future be helpful in first characterizing aboveground biodiversity and then stratifying and orienting subsequent ground-based research to understand AGSOBIOs. Crop-level distinctions will require the use of medium- to high-resolution imagery to allow distinguishing crops, pasture, and fallow areas within rotations. Lower resolution phenology-based greenness data (e.g., MODIS) with high repeat acquisition rates may be useful if periods of greenness and seasonality of productivity can be associated with the phenologies of different crop varieties and species or perennial landscape components.

The interactions between above- and belowground components may potentially serve as a conduit transferring impacts from deteriorating soil and water systems to biodiversity. Without an explicit ecological framework, as detailed in the results of Sections 3 and 4 the consideration of livelihood impacts tends to be directed at separate, isolated environmental elements. By designing a framework of the interactions of livelihoods with above- and belowground biodiversity components, rather than either one in dyadic isolation with livelihood diversification, our research is able to identify and distinguish these crucial functional interdependencies.

Delimitation of the principal interactions of livelihood diversification are highlighted throughout this study (Interaction A and Interaction B in Figure 1). These bi-directional interactions represent the coupling of human-environment systems of resource use. These systems are also social-ecological in the sense that spatial units of agroecosystems, their governance, and resource properties are all considered (for human-environment and social-ecological approaches see Section 1). In order to both expand and strengthen our analysis of livelihood-agrobiodiversity interactions in our first meta-analysis (Section 3), we focused our second meta-analysis on the ecological coupling of above- and belowground agrobiodiversity assemblages, referred to as AGSOBIOs (Section 4). Results from the studies we analyzed suggest the functional interdependence of above- and belowground AGSOBIO components, with plant-host microbe specificity and primary production of residues as major coupling drivers and the ecological services of soil biota as dominant feedbacks. In addition, responses of whole soil microbial communities to management in these systems are characterized by significant lag times. This finding, combined with other results, suggests the potentially influential yet indirect pathway of

agrobiodiversity change through degrading soil and water resources that influence plant productivity. In the case of soil degradation, which is probably most common, the linkages are mediated by processes such as erosion and nutrient depletion and resulting changes in the amount, quality, and diversity of crop residue (Figure 2). Current and future decline of agrobiodiversity—also referred to as genetic erosion—may thus be widely, albeit partially, linked to soil degradation [2].

The comprehensive framing and careful analysis of ecological interactions within agrobiodiversity systems is an important and novel addition to understandings of livelihood—environment interactions. It promises new insights well-suited to integration with livelihood analysis that together provide a significantly fuller perspective on the suite of agrobiodiversity interactions with human-social and ecological factors. Here, our findings highlight the importance and interconnectedness of the interactions specified in the framework we have developed and implemented in this research (Interactions A, B, and C in Figure 1).

We propose that a productive way to integrate further the above results into a new spatial analytic approach is through the concept of large-area regional spaces comprised of characteristic agri-food systems with corresponding livelihood diversification strategies and agrobiodiversity. Here, our discussion uses the hypothesized role of distinct Regional Agri-Food and Livelihood Diversification Spaces (RALDS) (Table 5, left column). Factors determining these RALDS include distance to markets and resource functions (e.g., access, availability, quality). While suggesting the possible influence of a distance-based model, we emphasize the predicted patterning of RALDS and agrobiodiversity outcomes as spatial mosaics with the occurrence of non-linear and even irregular relations to distance rather than linear or regular gradients [52,104,119]. Proposed examples in the United States and Peru (Table 5) reflect the non-linear, mosaic patterning of RALDS [217].

Globally, the land use of smallholders is relatively common in two of the four RALDS (Table 5, second column). Elsewhere, we have used the recent estimate of global smallholder population as 2.0–2.5 billion to offer the conceptual model of these geographic spaces [52]. It focuses on the hypothesized roles of gender and agrobiodiversity in the context of agricultural intensification and disintensification. Here, we are able to use the results of the above section to extend this model (Table 5). We focus on how each of the RALDS is anticipated to correspond not only to an anticipated agricultural intensity level (third column) but also environmental change pathway (fifth column) and agrobiodiversity (sixth and seventh columns). The latter is hypothesized to incorporate distinct agrobiodiversity in the aboveground and belowground components.

This type of conceptual categorization is well suited to elevated policy interest in the intensification and sustainability of food-growing [3,4,52,62,65]. For example, it predicts how RALDS with less significant livelihood diversification may turn out to be associated with either low or high agrobiodiversity levels (Table 5). Similar potential of bimodal outcomes is predicted in spaces of high livelihood diversification. In sum, the features of each of the RALDS are hypothesized to reflect the intersection of agri-food system properties, livelihood diversification strategies, and distinct agrobiodiversity interactions. These delineations are predicted in advance of rigorous empirical study, models, and testing.

Table 5. Predicted spatial-geographic patterning and the predominant processes of agrobiodiversity and Regional Agri-Food and Livelihood Diversification Spaces (RALDS is discussed in Section 5. Impacts in this table refer to both above- and belowground agrobiodiversity per Section 4.)

Regional Agri-Food and Livelihood Diversification Space	Predicted Social-Ecological Characterization	Predicted Agricultural Intensification Level	Predicted Livelihood Diversification Level	Anticipated Environmental Change Pathway ¹	Above-ground Agrobiodiversity	Belowground Agrobiodiversity	Examples (United States and Peru)
Prime Agricultural	Productivist, corporate industrial; smallholders nominal	High	Low	Predominant agrochemical substitution (LR)	Low, non-local seed and breed systems	Low, limited by low soil organic matter and residue returns	Central Valley, California, US; major valleys, Peru
Marginal-Land and Remote Rural Food Growing	Low-input land use for local and regional food; smallholder significance high	Low-Medium	Low	Locally varied; includes ecological disintensification (UL) and intensification (UR)	High, labor-saving local seed and breed systems	High/varied, both crop and “wild” managed ecosystem components	California coastal range, US; Andean uplands
Remote Rural Specialized Livestock or Cropping	Transition from food-growing; smallholder significance medium	Low-Medium	Low	Specialized intensification (LR) and disintensification (LL)	Low, non-local seed and breed systems	Medium/varied, limited by low residue inputs.	Great Plains, US; Altiplano, Peru ²
Peri-Urban, Ex-Urban	Multi-purpose; smallholder significance medium	Medium	Low	Locally varied; includes ecological intensification (UR)	High, local seed and breed systems	High, managed to foster agroecosystem services	Bay Area, US; Huancayo, Peru

¹ Summaries provided in the column on Anticipated Environmental Change Pathway combine a first descriptor associated with disintensification vs. intensification and a second descriptor associated with ecological vs. specialized agrochemical management (Additional information that appears parenthetically in this column refers to the quadrants of Figure 3 found on page 52 of Reference [52]: LR = lower-right; UL = upper-left; LL = lower-left; UR = upper-right). ² Includes processes of landscape polarization. (See also Reference [52], including Figure 2 on page 51).

Finally, by focusing on AGSOBIOs, this study highlights the importance of the interactions among non-human components as being advanced in sociocultural anthropology, human geography, and related fields of the social sciences and humanities [218,219]. Similarly, this incorporation of ecological analysis contributes to understanding other dimensions of livelihood diversification (Figure 3). For example, influential interactions occur within the human system influencing livelihood diversification. These include the interactions of macro-scale neoliberal political economy with important demographic and social factors (Figure 3). The latter especially include the productive analysis of gender in these interactions as discussed in Section 3. We hasten to underscore that the literature consulted in Sections 1–4 is comprehensive to the best of our knowledge and could be made even more extensive if we were to broaden further our research goals. In addition, while interdisciplinary to a considerable extent, the literature here is not exhaustive across all possible points of reference with regard to the other factors of both the social-ecological and ecological systems of agrobiodiversity.

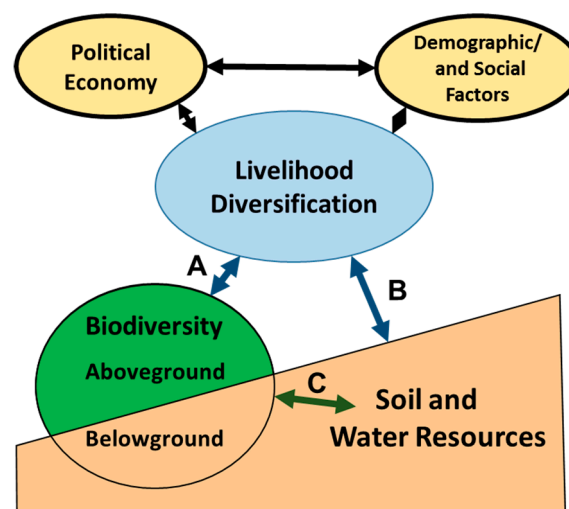


Figure 3. Expanded conceptual diagram of the linkages of livelihood diversification to human-social factors and environmental factors. Arrows A and B represent principal linkages of livelihoods to natural systems; C represents coupling between natural resources and agrobiodiversity.

6. Conclusion: Interactions of Agrobiodiversity and Smallholder Livelihood Diversification in the Context of Global Change

Analysis of the interactions of smallholder livelihoods with agrobiodiversity and interactions (including the ecological inner-actions within AGSOBIO assemblages) yield a total of more than ten synthesis-based statistical summaries. The meta-analysis of empirical studies contributes scientific research and policy insights. The past 25 years have witnessed a significant evolution from the view of smallholder or peasant livelihoods and their environments as significantly separate from global systems, such as the once common concept of disarticulated economies ([220]; pp. 32–40). Currently, concepts and conditions highlight the relevance of smallholder connectedness with national and global systems including so-called planetary urbanism. Correspondingly, these interactions of smallholder livelihoods are producing emergent qualities in agrobiodiversity and other land, water, and biotic resource systems. This perspective highlighting the potential social-ecological emergence of agrobiodiversity [8,14,52,119] is replacing the earlier blanket assumption of purely traditional resource management and, therefore, the inference of agrobiodiversity as a vestige or relict.

Our study’s meta-analysis demonstrates how expanding research on livelihood diversification is evidencing causal influences along with noticeable variation in regard to local outcomes and, additionally, in regard to the type of resource or environmental system (agrobiodiversity, soil resources, water resources, uncultivated biodiversity). This finding can be used to nest our interpretation of

interactions in agrobiodiversity systems. Combined in this way, the two meta-analyses confirm the conceptual importance and empirical validity of interactions among and within the dynamics of agrobiodiversity, livelihood diversification, and environmental resources.

The meta-analysis of agrobiodiversity components furnishes an important additional dimension to existing livelihood-environment frameworks. Our approach re-frames the predominantly dyadic concepts used to understand the linkages of livelihoods to the environment where the latter are single elements or environmental sub-systems isolated from ecological interactions. The expanded conceptual framework and analysis is essential to understanding the interactions of agrobiodiversity. Livelihood diversification commonly exerts immediate impacts on either the above- or belowground components of agrobiodiversity, thus leading to the need for the framework developed here. The interactions of above- and belowground components must be seen as critical to the health and vitality of agrobiodiversity in the context of smallholder livelihoods and diversification.

This research offers insights and contributions to the major scientific and policy approaches of Sustainable Intensification and Ecological Intensification. It potentially strengthens the bridging of this pair of approaches—two goals that are among the highest priority issues of global change facing societies and science worldwide. The foundations of Sustainable Intensification and Ecological Intensification suggest a productive tension [65] insofar as the former is focused on such issues as social equity and food security [3,4] while the latter prioritizes ecosystem services and ecological sustainability [62]. Our framework of livelihood diversification—environment interactions and the coupled system of AGSOBIO interactions can contribute to the expanded integration of the goals associated with both Sustainable Intensification and Ecological Intensification. It illustrates an integration of themes by carefully combining the concerns of livelihood sustainability (prioritized in Sustainable Intensification) with the analysis of agrobiodiversity and ecological functions *per se* (prioritized in Ecological Intensification). The potential for this selective fusion using the re-framing of livelihood-environment interactions we have developed here can aid in the practical application of combined Sustainable Intensification and Ecological Intensification in future scientific research and policy formulations.

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