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Integrating Social-Ecological and Political-Ecological Models of Agrobiodiversity With Nutrient Management of Keystone Food Spaces to Support SDG 2

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Agrobiodiversity—the biodiversity of food, agriculture, and land use—is essential to U.N. Sustainable Development Goal 2 by providing crucial food and nutritional quality of diets combined with strengthening agroecological sustainability. Focusing on the agrobiodiversity nexus to SDG 2, the current study utilized the interdisciplinary Agrobiodiversity Knowledge Framework (AKF), household-level surveys, and biodiversity sampling of crop fields and home gardens in a case study in Huánuco, Peru, in 2017. Statistical measures estimated agrobiodiversity of crop fields ($n = 268$ households) and home gardens ($n=159$ households) based on species richness (3.7 and 10.2 species/household, in fields and gardens, respectively) and evenness (Shannon diversity index; 0.70 and 1.83 in fields and gardens, respectively). Robust results of Poisson and OLS regression models identified several AKF-guided determinants of agrobiodiversity. Estimated species richness and evenness were significantly associated with 12 social-ecological and political-ecological factors from the four AKF thematic axes: farm characteristics and agroecology; diets and nutrition; markets, governance and sociocultural practices; and global change. This study's AKF approach, agrobiodiversity modeling, agroecological characterization, and field-based case study advanced a series of useful research insights, comparisons, and conceptual innovations to address SDG 2. Characterization of nutrient management through soil- and plant-focused cultural practices and livelihood roles distinguished the "keystone agrobiodiversity-and-food space" of multi-species maize fields (*maizales*) identified in AKF regression and characterization results. This key space furnished crucial food-nutrition and agroecological benefits that can be expanded by overcoming identified barriers. AKF-guided models incorporating key agrobiodiversity-and-food spaces and ecological nutrient management are needed to strengthen SDG 2 strategies.

Keywords: agricultural biodiversity, agroecology, Sustainable Development Goal 2, Agrobiodiversity Knowledge Framework, key agrobiodiversity-and-food spaces, political ecology, social-ecological systems, Peru

INTRODUCTION

Actively addressing global hunger and malnutrition as urged in U.N. Sustainable Development Goal 2 ("Zero Hunger;" hence SDG 2) requires vital, diverse dietary and nutritional inputs derived from the biodiversity of food, agriculture, and land use (agrobiodiversity). This human-managed biodiversity functions in a nexus role between food-nutrition needs and agroecology. Agrobiodiversity bridges both the access to food and nutrition (Foote et al., 2004; Frison et al., 2011; Fanzo et al., 2013; Jones et al., 2018; Lachat et al., 2018; Williams et al., 2018; CIP, 2019; Zimmerer et al., 2020) and the complex of agroecological, ecosystem-service, adaptive, and social- and political-ecological dynamics (Jackson et al., 2007; Jarvis et al., 2007; Pascual et al., 2011; Zimmerer et al., 2019; Gerits et al., 2021; Labeyrie et al., 2021). Focus on the links of agrobiodiversity to SDG 2 is central to socially just, nutritious food systems (Zimmerer and de Haan, 2020) and sustainable development (Gepts et al., 2012; Kremen et al., 2012; Vandermeer et al., 2018; Martin et al., 2019; Willett et al., 2019; Zimmerer et al., 2021). This study uses this focus to prioritize empowering poor and marginalized indigenous and smallholder populations.

The interdisciplinary Agrobiodiversity Knowledge Framework (AKF; Smale et al., 2006; precursors in Smale, 2006; Zimmerer and de Haan, 2019; Zimmerer et al., 2019, 2020) guides this study's focus on the agrobiodiversity nexus with SDG 2 and agroecological nutrient management. As shown (**Figure 1A**), the AKF integrates dynamics of: (1) farms and agroecology; (2) food, nutrition, and diets (food practice, food/nutrition security, health, and SDG2); (3) social/socioeconomic and cultural factors (markets, governance, and cultural practices including livelihood facets and biocultural sub-models); and (4) global changes (climate change, national-international markets, programs, and policies). The AKF model guiding this study thus expands predominant farm-environment approaches.

The four AKF themes (**Figure 1A**) reflect expanding research on agrobiodiversity in relation to dietary, nutrition, and health to address hunger and disease (Foote et al., 2004; Frison et al., 2011; Fanzo et al., 2013; Jones et al., 2018; Lachat et al., 2018; Williams et al., 2018; Downs et al., 2020). The AKF expands emphasis on biodiversity conservation of crop and genetic resources (Brush, 2000; Gepts et al., 2012; Bellon et al., 2015) in conjunction with growing recognition of food and nutrition benefits as well as biocultural dynamics and sustainable development that include human rights and livelihoods (Caillon et al., 2017; Zimmerer and de Haan, 2017, 2019). Additionally, the AKF incorporates agroecological characterization and functions in global-change contexts (e.g., Wood et al., 2015; Zimmerer et al., 2019) including social-ecological and political-ecological transitions (Jackson et al., 2012; Toledo and Barrera-Bassols, 2017; Bottazzi and Boillat, 2021; Goldberg et al., 2021; Labeyrie et al., 2021).

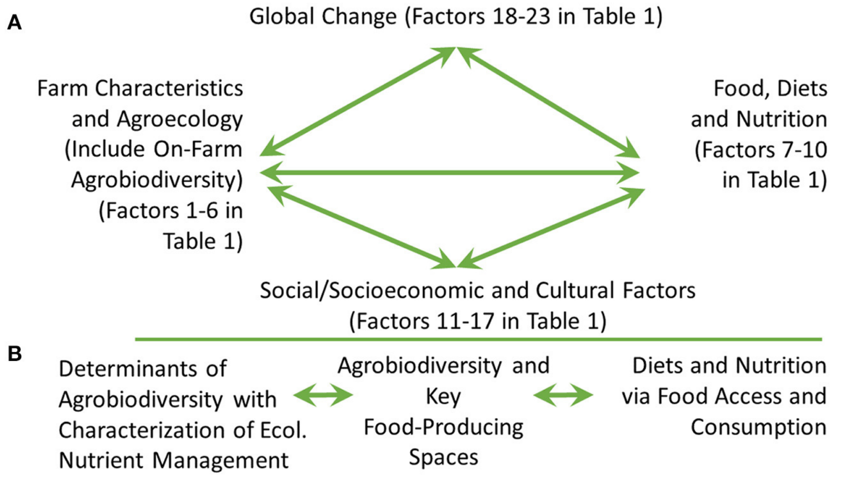

FIGURE 1 | (A) Conceptual model of themes of the Agrobiodiversity Knowledge Framework (AGK) with reference to enumerated factors in **Table 1**. These AKF themes are linked to the specific factors in **Tables 2–4**, with the illustrated AKF themes in this figure and the referenced factors serving as the connecting thread through the tables, text, and analysis. **(B)** Overview of agrobiodiversity-SDG research of this study (left-center) and related project (center-right).

This study addresses questions concerning the nexus roles of agrobiodiversity amid dynamically changing conditions: (1) which AKF-identified factors drawn from social-ecological systems and political ecology (**Figure 1A** and **Table 1**) are associated with the variation of agrobiodiversity? (noting the latter are crucial to nutrition outcomes; Jones et al., 2018; Zimmerer et al., 2020) (2) what keystone food-generating spaces contribute to agrobiodiversity outcomes and what influences their occurrence? (3) what is the preliminary characterization of ecological nutrient management in these key spaces? and (4) how can both comparability of results and new concepts of agrobiodiversity be advanced for SDG 2?

The overarching goal is to strengthen broad, nimble sustainability-enhancing capacities (sensu Petersen-Rockney et al., 2021) that can generate solutions to SDG-2 by integrating the AKF, socio-ecological modeling, and "keystone agrobiodiversity-and-food spaces" with ecological nutrient management. The study's distinct focus (**Figure 1A** and thickened arrow on left center of **Figure 1B**) is integrated with our overarching SDG 2-centered research on dietary diversity and nutrition wellbeing linked to agrobiodiversity (Jones et al., 2018) as well as current food and livelihood struggles (Zimmerer et al., 2020). The relations of this study to overarching research and earlier studies are reflected in the right-center of **Figure 1B**.

This study uses the AKF and existing research to identify potential social- and political-ecological determinants (**Table 1**, 1st column) in each of the four AKF themes (**Table 1**, 2nd column; also **Figure 1A**). Factors are hypothesized to influence agrobiodiversity *via* specific processes (3rd column) and examples of conditional interaction webs (4th column). Each factor is rooted in extensive research utilizing agrobiodiversity regression analyses (5th column).

AKF-based design and testing statistical models of social- and political-ecological predictors, as undertaken here, draw on anticipated influences of economics, development, and policy (Van Dusen and Taylor, 2005; Smale, 2006; Smale et al., 2006; Di Falco et al., 2010; Pascual et al., 2011; Rahman and Kazal, 2015; Garduño and Perrings, 2020; Goldberg et al., 2021). AKF-based consideration of model factors draws also from demonstrated influences of culture and society (Williams and Kramer, 2019), social-ecological systems and political ecology (Williams, 2016), and agroecology (see above). The AKF models developed here seeks to engage and advance these approaches.

This study develops an original approach toward culturally managed "keystone agrobiodiversity-and-food spaces" that can range from crop fields and home gardens to food-generating "wild" spaces (Nabhan, 2012, 2018). Currently, these spaces are being transformed amid intensified livelihood integration with extra-local product and labor markets as well as state- and non-state programs and projects (Zimmerer et al., 2020, 2021). Evolving spatial complexity requires identification and analysis of this dimension of agrobiodiversity's role in SDG 2.

Finally, this study engages expanding agroecological focus on ecological nutrient management (Fonte et al., 2012; Vanek et al., 2020) to offer preliminary results on key agrobiodiversity-and-food spaces. It focuses on field fallow and crop rotation as major management strategies (Arce et al., 2019a,b) as well as principal groups of cultivated and managed plants related to soil-nutrient management (Smil, 1997; Schipanski and Drinkwater, 2012; Pérez-Garcia and del Castillo, 2016; Meena and Lal, 2018). It suggests future linking of agrobiodiversity and agroecological research through integrating the AKF, socio-ecological modeling, and key food spaces with ecological nutrient management.

MATERIALS AND METHODS

Study Area of Huánuco, Peru: Combined "Bright Spot" and "Hot Spot" of Agrobiodiversity

Huánuco, Peru, is marked by complex relations of food, nutrition, and agrobiodiversity (**Figure 2**; Malice et al., 2010; Velásquez-Milla et al., 2011; Jones et al., 2018; Zimmerer et al., 2020). Climate, topography, soils, and environmental diversity of Huánuco are representative of valley-upland regions of the Andes Mountains in Peru (Pulgar Vidal, 1996, p. 225) and western South America. The Huánuco Andes extend to ecotones of the Upper Amazon. This "bright spot" of agrobiodiversity (sensu Gould et al., 2021) is also a "hotspot" subject to dynamic agri-food changes including widespread food and nutrition insecurity (Zimmerer et al., 2020) where policy legacies and land privatization (Mayer, 2009) contribute to the urgent need to address SDG 2. Social-ecological and political-ecological drivers of agrobiodiversity change in Huánuco are characteristic of the Andes, Amazon, and global trends (de Haan et al., 2010; Oyarzun et al., 2013; Skarbø, 2014; Arce et al., 2019b; de Haan, 2021; Zimmerer et al., 2021).

This study was sited in three Huánuco landscapes (Quishqui, Amarilis-Malconga, and Molinos-Umari; **Figure 2**) that are environmentally and socially distinct. Census and municipal-level data guided the structured-random selection of 10 communities with similar elevation-range characteristics in each landscape. 20 households were then randomly selected to participate out of the 25–40 households in study communities. Eligible households met the following inclusion criteria: (1) members were permanent residents of the household, (2) a woman aged 15–49 years was a household member, and (3) field and/or garden crops had been cultivated by one or more members in 2016–17. For the household survey, we sampled 20 households per community. The selected communities had 25–40 households while extremely small communities were excluded. Institutional human subject approvals (IIN in Lima, Peru, and University of Michigan) guided informed consent and research ethics protocols.

Household Survey

We administered a multi-module household survey to the 600 participating households (April–June 2017) that collected data on potential co-variates with agrobiodiversity. It included

TABLE 1 | Hypothesized social-ecological and political-ecological determinants of agrobiodiversity based on the Agrobiodiversity Knowledge Framework (AKF); data sources for variables refer to survey as "S" and agrobiodiversity sampling as "AS" (descriptions in text).

Variable (with measure) and data source	AGK concept category and added details of variable (if needed)	Hypothesized immediate influence	Interacting factors in potential pathways AND Webs	Supporting research (regression models of agrobiodiversity and select non-regression studies)
1) Areas of total cultivated area and fields only (hectares) (AS)	Farm Chars. and Agroecol.	Households with more planting area (both overall and field space only) are enabled to produce higher levels of agrobiodiversity (+)	Demographic change and influences of population and land-access reforms of the Peruvian state including policies and political economy	Ban and Coomes, 2004; Abay et al., 2009; Di Falco et al., 2010; Velásquez-Milla et al., 2011; Oyarzun et al., 2013; Skarbø, 2014; McCord et al., 2015; Obayelu et al., 2015; Arce et al., 2019a,b; Dessie et al., 2019; Williams and Kramer, 2019; Goldberg et al., 2021; Li et al., 2021
2) Field number (count) (AS)	Farm Chars. and Agroecol.	More fields enable households to produce higher agrobiodiversity (+)	See above	Benin et al., 2004; Coomes and Ban, 2004; Van Dusen and Taylor, 2005; Dessie et al., 2019
3) Elevation and Elevation Range (masl) (AS)	Farm Chars. and Agroecol.	Elevations of residence and/or across range of fields can enable higher agrobiodiversity (+)	See above	Van Dusen and Taylor, 2005; Abay et al., 2009; Mercer and Perales, 2010; Arce et al., 2019a,b
4) Legume crop rotation (LCR index[a]) (AS)	Farm Chars. and Agroecol.	Enhances soil fertility and nutrient availability for agrobiodiverse plants (+)	Multi-factor decision-making about crop choice; agroecological awareness and support	Smil, 1997; Benin et al., 2004; Di Falco et al., 2010; Meena and Lal, 2018
5) Garden Presence/Absence and Area (hectares) (AS)	Farm Chars. and Agroecol.	Enables household to maintain seeds and production knowledge for agrobiodiversity(+)	Space and resources (time, growing environment) near house	Ban and Coomes, 2004; Wezel and Ohl, 2005; Perrault-Archambault and Coomes, 2008; Williams and Kramer, 2019
6) Multi-Species Maize Field (pres./abs.) (AS)	Farm Chars. and Agroecol.	Enables household to maintain seeds and production knowledge for agrobiodiversity (+)	Space and resources (time, growing environment) near house	Velásquez-Milla et al., 2011; Skarbø, 2014; Novotny et al., 2021
7) Self-Produced Food in Diet (calories) (S)	Food; Refers to diet of adult woman individual (see text)	A household's greater reliance on self-produced food increases agrobiodiversity (+)	Influenced by combined self-production and marketing rationales	Velásquez-Milla et al., 2011; Oyarzun et al., 2013; Nordhagen et al., 2017; Williams and Kramer, 2019; Li et al., 2021
8) Traditional- Foods (S)	Food; Calories of traditional foods in diet of adult woman individual	Greater reliance on traditional foods in diet leads to higher agrobiodiversity (+)	Influenced by choices and capacity to utilize traditional food	Oyarzun et al., 2013; Skarbø, 2014; Nordhagen et al., 2017; Li et al., 2021
9) Dietary Diversity (MDDW Achieved or Not Achieved) (S)	Food; Refers to diet of adult woman individual (see text)	Greater expectation and familiarity with dietary diverse can increase production of agrobiodiversity (+)	Potential influence on agrobiodiversity production through awareness and valuation	Fanzo et al., 2013; Oyarzun et al., 2013; Nordhagen et al., 2017; Li et al., 2021
10) Food Security (S)	Food; Refers to all household members	Food-secure households access foods associated with higher production agrobiodiversity (+)	Potential influence on agrobiodiversity production through awareness and valuation	Frison et al., 2011; Fanzo et al., 2013; Nordhagen et al., 2017; Zimmerer and de Haan, 2020
11) Age (head of household) (AS)	Social/socio-economic and cultural factors	Older heads of households manage knowledge, food preferences, and production portfolios associated with higher agrobiodiversity (+)	Demographic factors such as migration of young adults can influence the prevalence of elderly in rural communities	Benin et al., 2004; Van Dusen and Taylor, 2005; Perrault-Archambault and Coomes, 2008; Abay et al., 2009; Ng'endo et al., 2015; Williams, 2016; Dessie et al., 2019; Williams and Kramer, 2019; Gauchan et al., 2020; Li et al., 2021
12) Gender (head of household) (AS)	Social/socio-economic and cultural factors	Women heads of households manage identity practices, knowledge, food preferences, and production portfolios associated with higher agrobio-diversity (+)	Demographic factors such as migration of male adults can influence the prevalence of women-headed households in rural communities	Benin et al., 2004; Momsen, 2007; Perrault-Archambault and Coomes, 2008; Abay et al., 2009; Di Falco et al., 2010; Whitney et al., 2018; Dessie et al., 2019
13) Ethnicity and Language (main language Quechua) (S)	Social/socio-economic and cultural factors	Ethnic identity associated with language can co-occur with cultural practices of high agrobiodiversity (+)	Ethnicity and language are active practices influenced by large webs of factors that include politics of indigeneity	Brush and Perales, 2007; Reyes-García et al., 2008; Velásquez-Milla et al., 2011; Labeyrie et al., 2016; Orozco-Ramírez et al., 2016; Williams, 2016; Whitney et al., 2018; Williams and Kramer, 2019

(Continued)

TABLE 1 | Continued

Variable (with measure) and data source	AGK concept category and added details of variable (if needed)	Hypothesized immediate influence	Interacting factors in potential pathways AND Webs	Supporting research (regression models of agrobiodiversity and select non-regression studies)
14) Household income (soles/year) (S)	Social/socio-economic and cultural factors	Greater household income can lead to planting options that either include or exclude agrobiodiversity (+/-)	Household income reflects socioeconomic assets and policy factors acting on market integration	Zimmerer, 1991, 1996; Benin et al., 2004; Coomes and Ban, 2004; McCord et al., 2015; Ng'endo et al., 2015; Obayelu et al., 2015; Williams, 2016; Zimmerer et al., 2020; Goldberg et al., 2021; Li et al., 2021
15) Social capital (see text) (S)	Social/socio-economic and cultural factors	More and stronger networks and other forms of social capital can either include or exclude agrobiodiversity (+/-)	Networks and other social capital reflect economic capacities, social power relations, and combined politics and micro-politics	Obayelu et al., 2015; Labeyrie et al., 2016; Williams, 2016; Wale and Holm-Mueller, 2017
16) Geographic sub-area (place) (see Methods) (AS)	Social/socio-economic and cultural factors	Geographic sub-area (place) exerts influence through place-based configurations of multiple factors (+/-)	Place-based differences affecting agrobiodiversity arise from local and extra-local forces	Zimmerer, 1991, 1996; Smale et al., 2001; Williams and Kramer, 2019
17) Level of Education (S)	Social/socio-economic and cultural factors	Education level can lead to either higher or lower agrobiodiversity (+/-)	Education effects can drive changed valuation of agrobiodiversity	Gauchan et al., 2005; Van Dusen and Taylor, 2005; Abay et al., 2009; Skarbø, 2014
18) Distance to major urban center (kms) (AS)	Global change	Urban centers expected to exert pressures for market integration and other changes reducing agrobiodiversity levels (–)	Interpretation of distance-to-city effects often assume distance decay model of reduced influence	Benin et al., 2004; Wezel and Ohl, 2005; Perrault-Archambault and Coomes, 2008; Di Falco et al., 2010; Williams, 2016; Conrad et al., 2017; Whitney et al., 2018; Dessie et al., 2019
19) Reliance on agrochemical inputs in field cultivation (S)	Global change; household's number fields with chemical fertilizer use	Modern agricultural inputs including chemical fertilizers reduce agrobiodiversity viability (-)	Agricultural modernization reflects diverse socioeconomic and sociocultural influences	Velásquez-Milla et al., 2011; Dedeurwaerdere and Hannachi, 2019
20) Current participation in programs and projects of government agencies and NGOs (S)	Global change; number of extra-local programs in which household participated	Program influences, ranging from agricultural extension, can either reduce or increase agrobiodiversity (+/-)	Presence and role of programs results from diverse state and non-state actors and organizations	Abay et al., 2009; Williams, 2016; Wale and Holm-Mueller, 2017; Mwololo et al., 2019
21) Degree of commercialization (S)	Global change; percent of household's crop harvest sold (2017)	Market integration of agricultural production may reduce or increase agrobiodiversity (+/-)	Integration into agricultural markets reflects multi-factor web of influences	Van Dusen and Taylor, 2005; Skarbø, 2014; Obayelu et al., 2015; Dedeurwaerdere and Hannachi, 2019
22) Climate and climate change (adaptative responses) (S)	Global change; number of household's adaptions	Climate change impacts can reduce or increase agrobiodiversity (+/-)	Climate change pressures to increase agrobiodiversity include adaptations	Abay et al., 2009; Mercer and Perales, 2010; Bhattarai et al., 2015; McCord et al., 2015; Saxena et al., 2016; Arce et al., 2019a,b; Zimmerer et al., 2019
23) Agrobiodiversity loss awareness (household head) (S)	Global change; number of elements indicated by household head	Awareness of agrobiodiversity loss can be associated with familiarity (-) or conservation (+)	Awareness of agrobiodiversity loss can arise in individual, family, community, and extra-community contexts	Smale et al., 2001; Wale and Holm-Mueller, 2017; Dedeurwaerdere and Hannachi, 2019

[a] *Estimated as the sum of the frequencies of legume-containing fields observed in the 2017 sample and recollected in the field-level histories of crop rotation (2013–2017).*

modules on sociodemographic characteristics, livelihood assets, food security, dietary intake, and livelihood activities, among other topics.

In addition, a quantitative 24-h recall of food intake of the young or medium-age woman used the multiple-pass method (Gibson, 2005). One hundred women from this sample were randomly selected for a second food intake recall interview after the first interview. From recall data, a 10-food group diet diversity score was used to calculate the Minimum Dietary Diversity for Women (MDD-W) indicator, defined as 1 if the respondent consumed five or more food groups in the previous 24 h and 0 otherwise (Martin-Prevel et al., 2015; FAO, 2016). A 15 g minimum cut-off defined consumption of a given food group. Information on co-variates obtained through above methods is marked with "S" in **Table 1** (1st column).

Agrobiodiversity Sampling and Diversity Estimations

One half of surveyed households ($n = 300$) were randomly selected to participate in sampling agrobiodiversity. Most households cultivated fields ($n = 268$) and about one half produced gardens ($n = 159$) as sites for combined market production and home food consumption. The household's principal food-producing spaces were visited with members

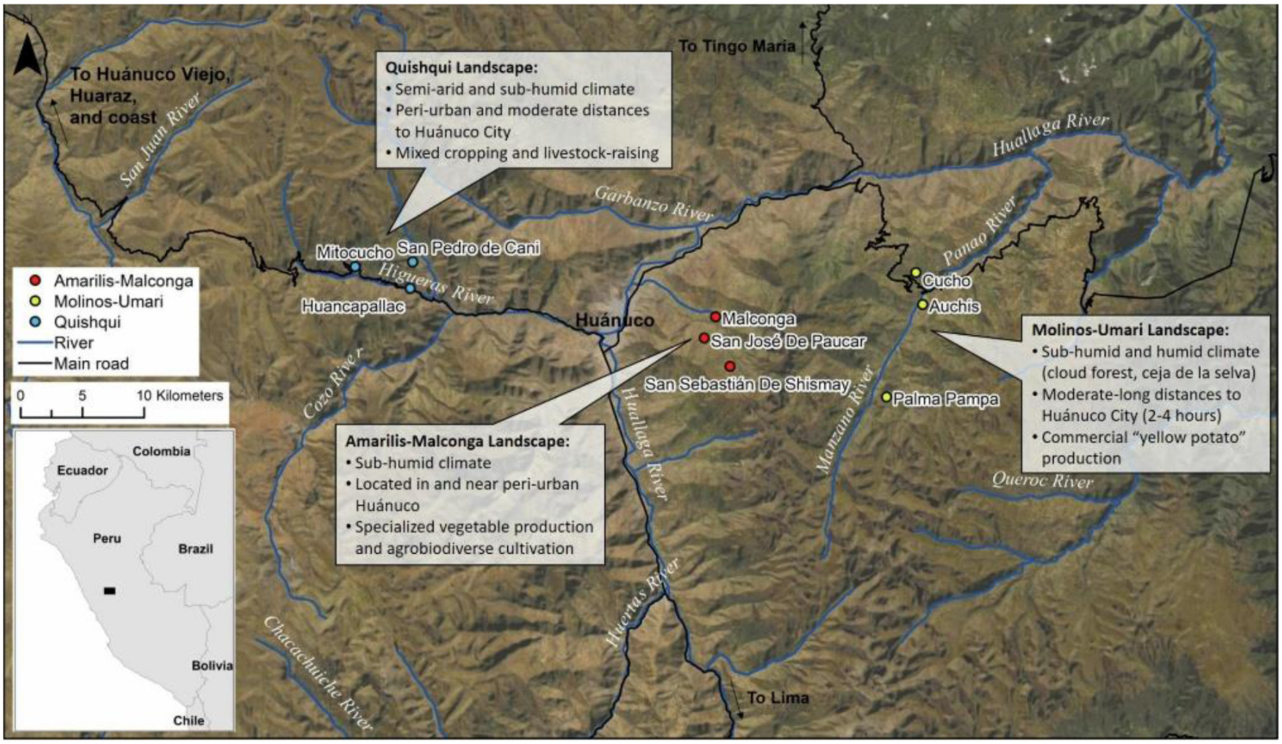

FIGURE 2 | Map of Huánuco study area in Central Peru, with examples of participating study communities in research-focus landscapes (Quishqui, Amarilis-Malconga, Molinos-Umari).

that participated in sampling (Agrobiodiversity Sampling, AS) using local-name identification and spatial sub-areas. Species-level scientific identification of AS taxa was overseen by local agrobiodiversity experts at the Universidad Nacional Hermilio Valdizan in Huánuco. AS incorporated information on the major food-generating spaces of each household (e.g., rotation history, ownership, and type such as field or garden. These co-variate data are marked "AS" in **Table 1** (1st column).

Household-level diversity estimates derived from AS data for fields ($n = 268$ households) and gardens ($n = 159$ households) subsequently were used in regression models described below. Our diversity-estimation approach cites specific works since focus on the species level requires general justification (Colwell, 2009: 258; Magurran, 2013; Williams, 2016; Jones, 2017; Zimmerer et al., 2020; Goldberg et al., 2021) and is used specifically to distinguish key food spaces in this study. This species-level focus complements existing agrobiodiversity estimation of cultivars, varieties, and landraces (Smale et al., 2001; Obayelu et al., 2015; Wale and Holm-Mueller, 2017; Dedeurwaerdere and Hannachi, 2019; Gatto et al., 2021), genetic populations (de Haan et al., 2010; Perronne et al., 2017; Arce et al., 2019a,b), and landscapes (Zimmerer et al., 2020), as well as agroecological functional diversity addressed below.

Richness (a count statistic of the number of cultivated and managed food-producing species) and the Shannon diversity index ($H = - \sum_{s}^{i=1} p_i \ln p_i$) (Colwell, 2009, p. 260)—the latter is an estimate of the relative abundances of species referred to as evenness—were chosen as twin statistical estimates of agrobiodiversity [for statistical formulas, symbols, and rationales see Colwell (2009), Magurran (2013), Smale (2006)]. These diversity measures are widely used individually and in combination for agrobiodiversity research (Benin et al., 2004; Jarvis et al., 2008; Oyarzun et al., 2013; Williams, 2016; Jones et al., 2018; Goslee, 2020; Goldberg et al., 2021) as well as "wild" biodiversity (Colwell, 2009; Hayek and Buzas, 2010). Biodiversity estimates of richness and evenness were visualized on maps and graphs (**Figure 5** in Results).

We calculated additional agrobiodiversity estimates using information statistics of the Margalef and Menhinick indices ($D_{Mg} = (S\text{-}1)/(\ln N)$ and $D_{Mn} = S/\sqrt{N}$, respectively) and alternative evenness measures (modified Shannon diversity index, $H' = e^{H}$ and two forms of the Simpson diversity index, $D = 1 - \sum_{i=1}^{s} p_i^2$ and $D' = (\sum_{i=1}^{s} p_i^2)^{-1}$ (Smale, 2006; Colwell, 2009, p. 260; Magurran, 2013). These additional biodiversity estimates (**Supplementary Tables 1, 2**) were important though less central to this study and less common in existing agrobiodiversity research. Functional diversity, defined as the diversity of species niches or functions (Villéger et al., 2008; Finney and Kaye, 2017; Blesh, 2018), shown elsewhere as complexly related to agroecological multi-functionality (Blesh, 2018), is treated in this study as important general information. Preliminary distinctions of plant functional groups and nutrient management, described methodologically below, suggests a promising area where future research can more fully integrate functional diversity and agroecology as outlined in the Discussion.

TABLE 2 | Estimations of the social-ecological and political-ecological factors of the Agrobiodiversity Knowledge Framework (AGK) in the sample utilized for the regression analysis of fields.

Factor	AKF category	*N* (households)	Mean value	Standard deviation	Range
Crop species richness (fields)	Dependent variable	268	3.7	2.9	1, 24
Crop species evenness (Shannon index) (fields)	Dependent variable	268	0.70	0.52	0, 2.25
Crop species richness (gardens)	Dependent variable	159	10.2	6.3	1, 33
Crop species evenness (Shannon index) (gardens)	Dependent variable	159	1.83	0.65	0, 3.2
Extent of total cultivated area (hectares)	Farm-agroeco	300	0.404	0.036	0.009, 2.45
Extent of total cultivated area of fields (hectares)	Farm-agroeco	268	0.426	0.036	31, 2.39
Extent of total cultivated area of garden (hectares)	Farm-agroeco	159	0.0452	0.0093	0.0086, 0.8367
Number of cultivated fields (count)	Farm-agroeco	300	2.5	1.5	1, 11
Elevation of residence (masl)	Farm-agroeco	300	2650	436	1840, 3885
Elevation range of fields (masl)	Farm-agroeco	300	50	100	0, 625
Legume crop rotation index (defined in **Table 1**)	Farm-agroeco	300	0.60	0.62	0, 2
Garden presence/absence and area (square meters)	Farm-agroeco				
No garden		141	47.0%		
Garden		159	53.0%		
Multi-species maize field (pres./abs.)	Farm-agroeco				
No		154	51.3%		
Yes		146	48.7%		
Self-produced food in diet (% calories self-production)	Food	300	36.5	22.7	0, 100
Traditional foods in diet (% calories from traditional foods)	Food	300	34.2	17.7	0, 89.4
Dietary diversity (MDDW achieved/not-achieved)	Food				
Achieved		137	45.7%		
Not-Achieved		163	54.3%		
Food security	Food				
Food insecure		176	58.7%		
Food secure		124	41.3%		
Age (head of household)	Social/socio-economic and cultural factors	300	49.8	16.7	21, 120
Gender (head of household)	Social/socio-economic and cultural factors				
Male		228	76.0%		
Female		72	24.0%		
Ethnicity and language (primary language Quechua)	Social/socio-economic and cultural factors				
Primary language not Quechua (reference)		100	33.3%		
Primary language Quechua		200	66.7%		
Household income (soles/year)	Social/socio-economic and cultural factors	300	3,571	8,629	0, 128,000
Social capital (sum of indicators)	Social/socio-economic and cultural factors	300	2.8	2.0	0, 13

(Continued)

TABLE 2 | Continued

Factor	AKF category	*N* (households)	Mean value	Standard deviation	Range
Geographic sub-area (place)	Social/socio-economic and cultural factors				
Quisqui		100	33.3%		
Amarilis		100	33.3%		
Molinos		100	33.3%		
Level of education	Social/socio-economic and cultural factors				
No education		34	11.5%		
Incomplete primary		114	38.5%		
Complete primary		64	21.6%		
Incomplete secondary		41	13.9%		
Complete secondary		41	13.9%		
Post-secondary		2	0.68%		
Numbers of fields with chemical fertilizer use	Global change	300	0.64	0.77	0, 4
Degree of commercialization (% marketed)	Global change	267	42.4	36.8	0, 100
Climate and climate change (number adaptations) (0–6)	Global change	300	2.67	1.5	0, 8
Agrobiodiversity loss awareness (1–5)	Global change	300	1.22	1.14	0, 5

Descriptive Statistics and Regression Analysis

Descriptive statistics assessed the hypothesized predictive factors, with calculations of mean, standard deviation and range of each hypothesized determinant and dependent variable (**Table 2** in Results). We then applied multiple regression analysis using Stata statistical software package, version 15.1 (2018; StataCorp) to determine associations of AKF-hypothesized determinants with the four dependent variables (crop species richness of crop fields and home gardens, and Shannon diversity index of crop fields and home gardens).

Poisson regressions were fit to main models regressing covariates on cultivated species richness of crop fields and home gardens (**Tables 3**, **4** in Results). Values are reported as incidence rate ratios (IRR) where a one-unit increase in the independent variable is associated with a percentage increase in the dependent variable based on the IRR (e.g., an IRR of 1.08 equates to an 8% dependent-variable increase). **Table 1** describes each independent variable in these models including its hypothesized process of influence on the dependent variables.

Ordinary least-squares regressions were fit to main models regressing covariates on the Shannon diversity index (**Tables 3**, **4** in Results) in addition to supplementary models using the additional biodiversity indices (**Supplementary Tables 1, 2**). "Distance" and "current participation in programs" were assessed as AKF-guided independent variables although subsequently omitted since they were found to be statistically insignificant and, due to data limitations, would reduce the utilizable sample of households in regression models. Independent variables used in the garden models differed slightly from the models of crop-field agrobiodiversity, with extent of total garden cultivated area substitute for extent of total cultivated field. The variables "presence of a garden" and "fields with chemical fertilizer use" were omitted in the garden-agrobiodiversity regressions.

Associations of predictor factors and diversity indices were considered consistent with random variability at $P > 0.05$ (Fisher, 1950, p. 80), with coefficients, Standard Error (SE) and *P*-values reported in **Tables 3**, **4** in Results. In addition, a supplement of 16 regression sub-models for grouped AKF factors (farm characteristics and agroecology; diets and nutrition; governance; global change) were estimated for crop fields (**Supplementary Tables 3–6**) and home gardens (**Supplementary Tables 7–10**). Breaking out hypothesized factors into sub-models was used to check for possible over-parameterization in the main models. Only factors determined statistically significant in both the main models and supplementary sub-models are reported and discussed below.

Characterization of Keystone Agrobiodiversity-and-Food Spaces

Ecological nutrient management and livelihood roles were estimated for key landscape spaces of agrobiodiversity and food production. Nutrition-focused analysis (Jones et al., 2018; Zimmerer et al., 2020) has signaled the importance of both crop fields (locally *chakras* or *parcelas*) and home gardens (kitchen or dooryard gardens, locally *huertos*). Initial field research involving visits with Huánuco food-growers undertaken in 2017 indicated the potential importance of multi-species maize fields (locally *maizales*) as an additional distinct type specified further in regression results and fieldwork (Results, **Tables 2–4**, **Figure 8**).

Preliminary characterization of ecological nutrient management utilized the AS data to estimate uncultivated fallow (2011–2017), crop rotation (2013–2017), and multi-species

TABLE 3 | Results of multiple regression analyses of the associations of social-ecological and political-ecological factors with crop species agrobiodiversity in fields (*Chakras*, *Parcelas*).

Factor	**Richness incidence rate ratio (standard error)**	***P*-value**	**Shannon evenness coefficient (standard error)**	***P*-value**
Extent of total cultivated area (hectares)	1.00 (0.0000779)	0.48	−0.00004 (0.0000721)	0.583
Extent of total cultivated area of fields (hectares)	0.99 (0.0000795)	0.208	0.00002 (0.0000732)	0.818
Number of cultivated fields (count)	1.26*** (0.0288)	0.000	0.17*** (0.0240)	0.000
Elevation of residence (masl)	1.00 (0.000117)	0.586	0.00008 (0.0000893)	0.382
Elevation range of fields (masl)	1.00 (0.000364)	0.457	−0.0004 (0.000299)	0.155
Legume crop rotation index (**Table 1**)	1.18* (0.0699)	0.019	0.11* (0.0532)	0.037
Garden presence				
Garden not present (reference)				
Garden present	0.64*** (0.0862)	0.000	−0.16* (0.0674)	0.020
Multi-species maize field				
No multi-species maize field				
Multi-species maize field present	1.76*** (0.0830)	0.000	0.45*** (0.0627)	0.000
Self-produced food in diet	0.83 (0.288)	0.521	0.04 (0.228)	0.852
Traditional foods in diet	0.99 (0.00330)	0.398	−0.002 (0.00261)	0.490
Dietary diversity				
MDDW not achieved				
MDDW achieved	0.98 (0.0776)	0.752	0.07 (0.0602)	0.225
Household food security status				
Food insecure (reference)				
Food secure	0.94 (0.0746)	0.433	−0.08 (0.0569)	0.182
Age (head of household)	0.99 (0.00247)	0.973	0.0007 (0.00191)	0.721
Gender (head of household)				
Male (reference)				
Female	0.97 (0.0896)	0.719	−0.04 (0.0706)	0.534
Ethnicity and language				
Primary language not Quechua (reference)				
Primary language Quechua	1.20 (0.0965)	0.060	0.10 (0.0736)	0.169
Household income (soles/year)	0.99 (0.00000483)	0.250	-2.7×10^{-6} (0.00000295)	0.354
Social capital (sum of indicators)	1.04 (0.0182)	0.057	0.002 (0.0144)	0.870
Geographic sub-area (place)				
Quisqui (reference)				
Amarilis	0.89 (0.0920)	0.219	−0.02 (0.0715)	0.818
Molinos	0.87 (0.0971)	0.151	−0.19* (0.0747)	0.013
Level of education (head of household)				
No education (reference)				

(Continued)

TABLE 3 | Continued

Factor	Richness incidence rate ratio (standard error)	*P*-value	Shannon evenness coefficient (standard error)	*P*-value
Incomplete primary	0.91 (0.108)	0.396	−0.08 (0.0903)	0.403
Complete primary	0.90 (0.127)	0.400	−0.10 (0.104)	0.324
Incomplete secondary	0.77 (0.139)	0.066	−0.10 (0.111)	0.384
Complete secondary	0.97 (0.144)	0.833	−0.05 (0.115)	0.644
Post-secondary	3.85^{**} (0.415)	0.001	0.79 (0.440)	0.073
Fields with chemical fertilizer use	1.05 (0.0480)	0.358	−0.04 (0.0379)	0.237
Degree of commercialization (agricultural fields)	0.99 (0.00116)	0.663	0.0007 (0.000905)	0.464
Climate and climate change (number adaptations)	1.01 (0.0261)	0.667	0.02 (0.0195)	0.241
Agrobiodiversity loss awareness	1.00 (0.0339)	0.889	−0.01 (0.0265)	0.617
Pseudo R^2	0.16 R^2			0.45

Values for the model with richness as the dependent variable are incidence rate ratios (IRRs) from Poisson regressions adjusting for the other covariates shown. Values for the model with Shannon Evenness as the dependent variable are partial regression coefficients from OLS regressions adjusting for the other covariates shown. n = 245 for both models. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

plantings (2017). Additionally, AS data enabled categorizing plants in relation to management of soil nutrients and general soil maintenance: (1) nitrogen-fixing legume crops for food and forage; (2) woody vegetation and perennials with generally more extensive root zones; and (3) maize that functions as an extensively rooted annual species. Identification of plant-group categories reflects agroecological, agronomic, and soils research on ecological nutrient management (Smil, 1997; Schipanski and Drinkwater, 2012; Meena and Lal, 2018) as well as research on these plant groups utilized in soil and nutrient management in the Andes (Fonte et al., 2012; Vanek et al., 2020). The total of six above-mentioned agroecological management techniques and plant groups were determined as preliminary estimates feasible using the AS data that had been collected primarily for taxonomic biodiversity estimates. Potential expansion of future social-ecological and political-ecology research on agrobiodiversity to include agroecological methods is described in the Discussion.

Additionally, food and income, which serve major livelihood roles (Arce et al., 2019b; Zimmerer et al., 2020), were characterized based on proportional inputs relative to overall self-produced food and overall farm income, respectively. A group of five key informants knowledgeable about local food, agriculture, and livelihoods rated each farm space from "1 = very important" to "5 = notably unimportant."

RESULTS

Agrobiodiversity and Descriptive Statistics

Agrobiodiversity sampling (AS) and identification resulted in a total of 92 cultivated species in crop fields (**Figure 3**). Most frequent among households were maize (Zea mays, *maíz*; 65.02%), Andean common beans (Phaseolus vulgaris, *frejol*; 34.98%), potatoes (Solanum tuberosum, *papa*; 29.37%), Andean squashes (Cucurbita maxima, *zapallo*, and Cucurbita ficifolia, *calabaza*; 29.04%), and fava beans (Vicia faba, *habas*; 18.81%). Home gardens showed 146 species of agriculturally managed plants (**Figure 4**). Most frequent were onion (Allium cepa, *cebolla*; 46.47%), oregano (Origanum vulgare, *orégano*; 40.59%), cilantro (Coriandrum sativum, *culantro*; 38.24%), peach (Prunus persica, *durazno*; 34.71%), and *chincho* (Tagetes elliptica; 32.94%). The species-frequency curves of both crop fields and home gardens were inverse exponential relationships (**Figures 3**, **4**).

Richness of field crops based on agrobiodiversity sampling (AS) with 268 households (**Table 2**) averaged 3.7 cultivated species/household with the range of 1–24 species. Mean richness of agriculturally management plants in home gardens was 10.2 species per household with a range of 1–33 species (**Table 2**). Results showed the mean of 7.9 species for all households. This estimated total agrobiodiversity richness, as well as field- and garden-level estimates, did not vary significantly among the three study landscapes. Mapping the species-level richness of agrobiodiversity (combined fields and gardens) illustrated the notable occurrence of household-level variation and the lack of geographic patterning or clustering either within or among the study landscapes (**Figure 5**). Mean values of the Shannon diversity index were estimated as 0.70 and 1.83 for the cultivated and managed species of crop fields and home gardens, respectively.

TABLE 4 | Results of multiple regression analyses of the associations of social-ecological and political-ecological factors with managed species agrobiodiversity in gardens (*Huertos*, *Huertas*).

Factor	Richness incidence rate ratio (standard error)	*P*-value	Shannon Evenness coefficient (standard error)	*P*-value
Extent of total cultivated area (hectares)	0.99 (0.0000120)	0.280	7.5×10^{-6} (0.0000245)	0.759
Extent of total cultivated area of garden (hectares)	1.00*** (0.0000240)	0.000	−0.00004 (0.0000677)	0.605
Number of cultivated Fields (count)	1.08** (0.0250)	0.003	0.04 (0.0529)	0.464
Elevation of residence (masl)	1.00 (0.000106)	0.210	0.0002 (0.000214)	0.259
Elevation range of fields (masl)	0.99 (0.000306)	0.781	−0.0002 (0.000599)	0.760
Multi-species maize field				
No multi-species maize field	.	.	.	.
Multi-species maize field present	0.98 (0.0663)	0.707	0.02 (0.135)	0.898
Self-produced food in diet (calories self-production)	0.52* (0.259)	0.011	−1.03 (0.545)	0.062
Traditional foods in diet (fraction of calories from traditional foods)	1.01** (0.00308)	0.002	0.008 (0.00643)	0.233
Dietary diversity (MDDW)				
MDDW not achieved				
MDDW achieved	0.95 (0.0674)	0.425	−0.08 (0.138)	0.547
Household food security status				
Food insecure (reference)				
Food secure	0.95 (0.0628)	0.455	0.04 (0.129)	0.783
Age (head of household)	1.01*** (0.00209)	0.000	0.01** (0.00447)	0.007
Gender (head of household)				
Male (reference)				
Female	1.14 (0.0742)	0.069	0.04 (0.154)	0.809
Ethnicity and language				
Primary language not Quechua (reference)	.	.	.	.
Primary language Quechua	0.77** (0.0817)	0.002	−0.20 (0.166)	0.225
Household income (soles/year)	1.00*** (0.00000203)	0.000	6.6×10^{-6} (0.00000501)	0.195
Social capital (sum of indicators)	0.99 (0.0128)	0.285	−0.02 (0.0274)	0.373
Geographic sub-area (place)				
Quisqui (reference)				
Amarilis	1.08 (0.0802)	0.361	0.007 (0.163)	0.966
Molinos	1.17* (0.0787)	0.044	0.30 (0.160)	0.066
Level of education (head of household)				
No education (reference)				
Incomplete primary	1.10 (0.0948)	0.293	−0.00005 (0.198)	1.000
Complete primary	0.83 (0.123)	0.140	−0.16 (0.241)	0.499

(Continued)

TABLE 4 | Continued

Factor	Richness incidence rate ratio (standard error)	*P*-value	Shannon Evenness coefficient (standard error)	*P*-value
Incomplete secondary	0.90 (0.125)	0.381	−0.26 (0.254)	0.300
Complete secondary	0.89 (0.138)	0.387	−0.36 (0.276)	0.192
Post-secondary	2.72** (0.289)	0.001	1.32 (0.755)	0.084
Degree of commercialization (agricultural fields)	0.99* (0.000964)	0.047	−0.003 (0.00195)	0.100
Climate and climate change (number adaptations)	1.02 (0.0224)	0.372	0.008 (0.0446)	0.853
Agrobiodiversity loss awareness	1.02 (0.0309)	0.474	0.04 (0.0629)	0.567
Pseudo R^2	0.15			
R^2			0.24	

Values for the model with richness as the dependent variable are incidence rate ratios from Poisson regressions adjusting for the other covariates shown. Values for the model with Shannon Evenness as the dependent variable are partial regression coefficients from OLS regressions adjusting for the other covariates shown. n = 130 for both models. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

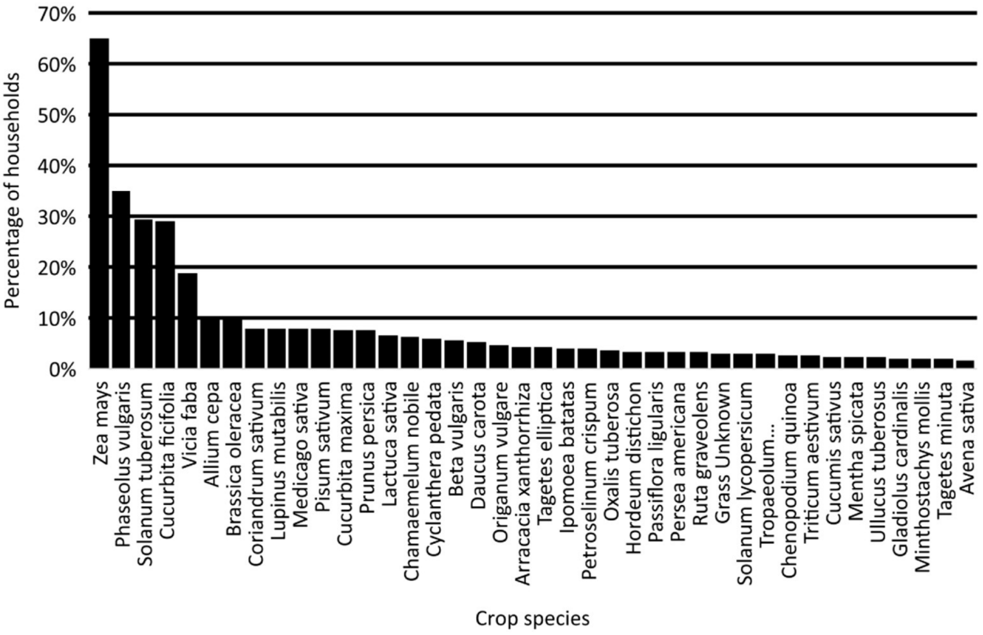

FIGURE 3 | Frequency of cultivated species in crop fields of households ($n = 268$).

Results showed the small extents of total cultivated crop-field and home-garden areas (mean values of 0.361 hectares and 0.0925 hectares, respectively) among sampled households. Similarly, low values were estimated regarding food security (i.e., high food insecurity; 58.7%), income, education, and elevation range (**Table 2**). Estimated household-level capabilities for food production included field numbers (2.5/household), self-produced food in the diet (36.5%), traditional foods in the diet (34.2%), and degree of agricultural commercialization (42.4%) (**Table 2**). These values reflected limited resource access and hybrid traditional-modern food customs including combined non-market/market linkages.

Certain estimated conditions showed large standard deviations. This high variation occurred in legume crop rotations that were defined as leguminous food and forage crops (mean index value 0.60; standard deviation 0.62) and numbers of fields with chemical fertilizer use (mean value 0.64; standard deviation 0.77). Mean climate change adaptations and elements of agrobiodiversity-loss awareness were low-moderate (2.67 and 1.22, respectively). Sample sizes for results estimated in this

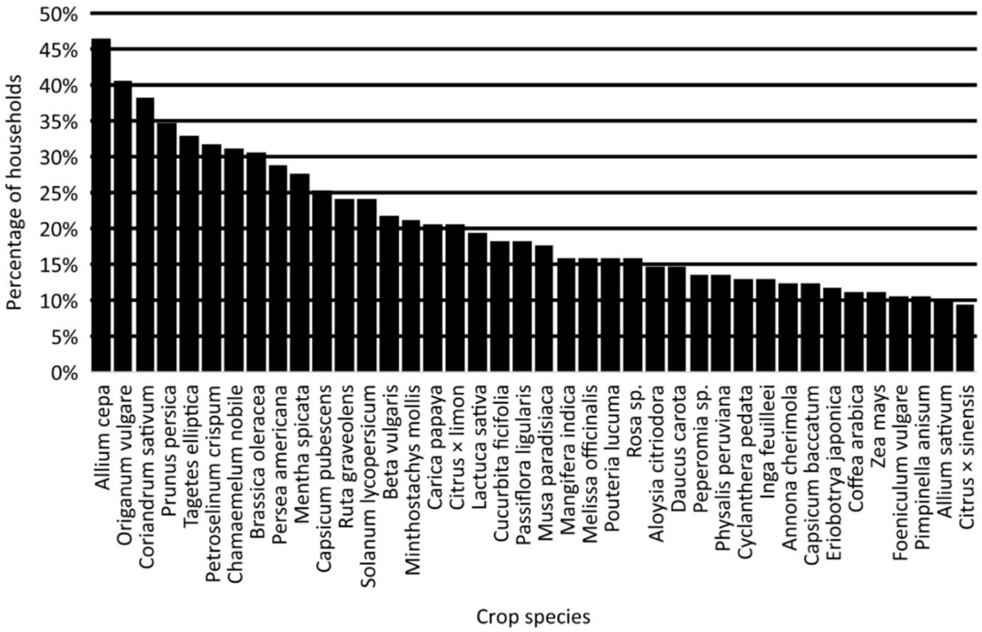

FIGURE 4 | Frequency of agriculturally managed species in home gardens of households (*n* = 159).

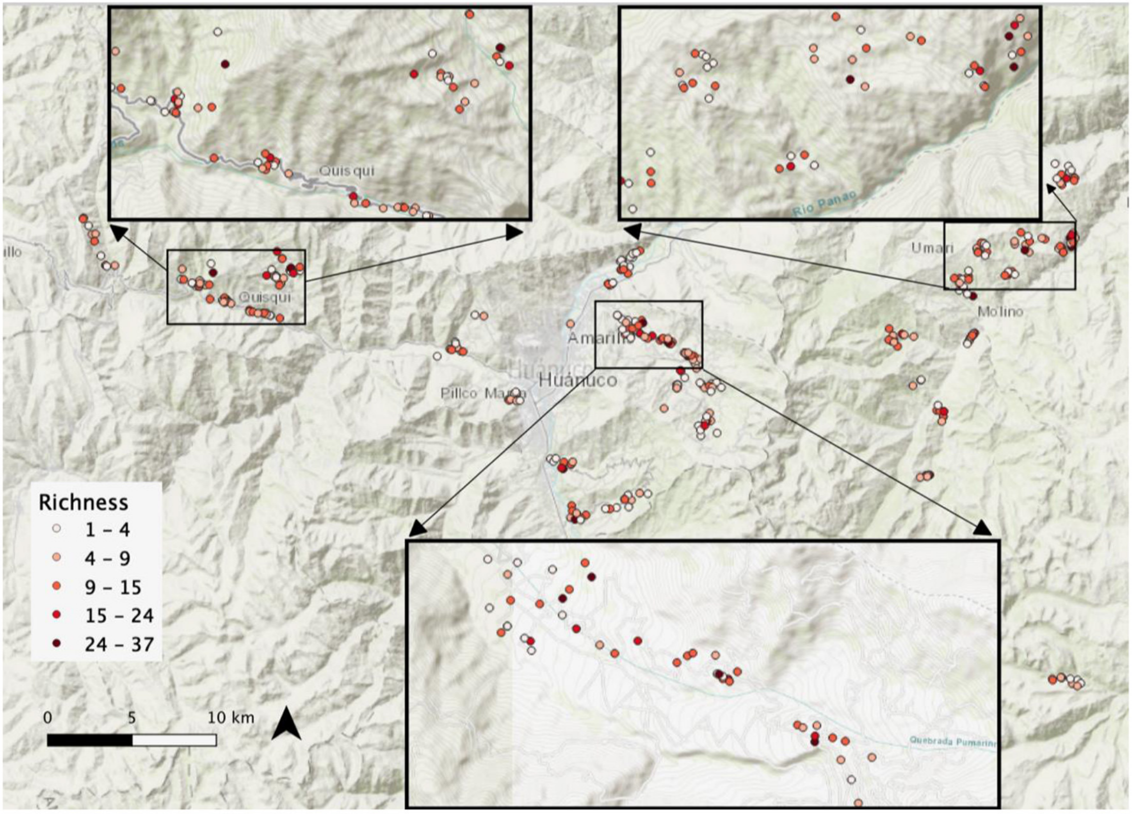

FIGURE 5 | Map of species-level richness of agrobiodiversity (combined richness counts of fields and gardens) among households in Huánuco, Peru.

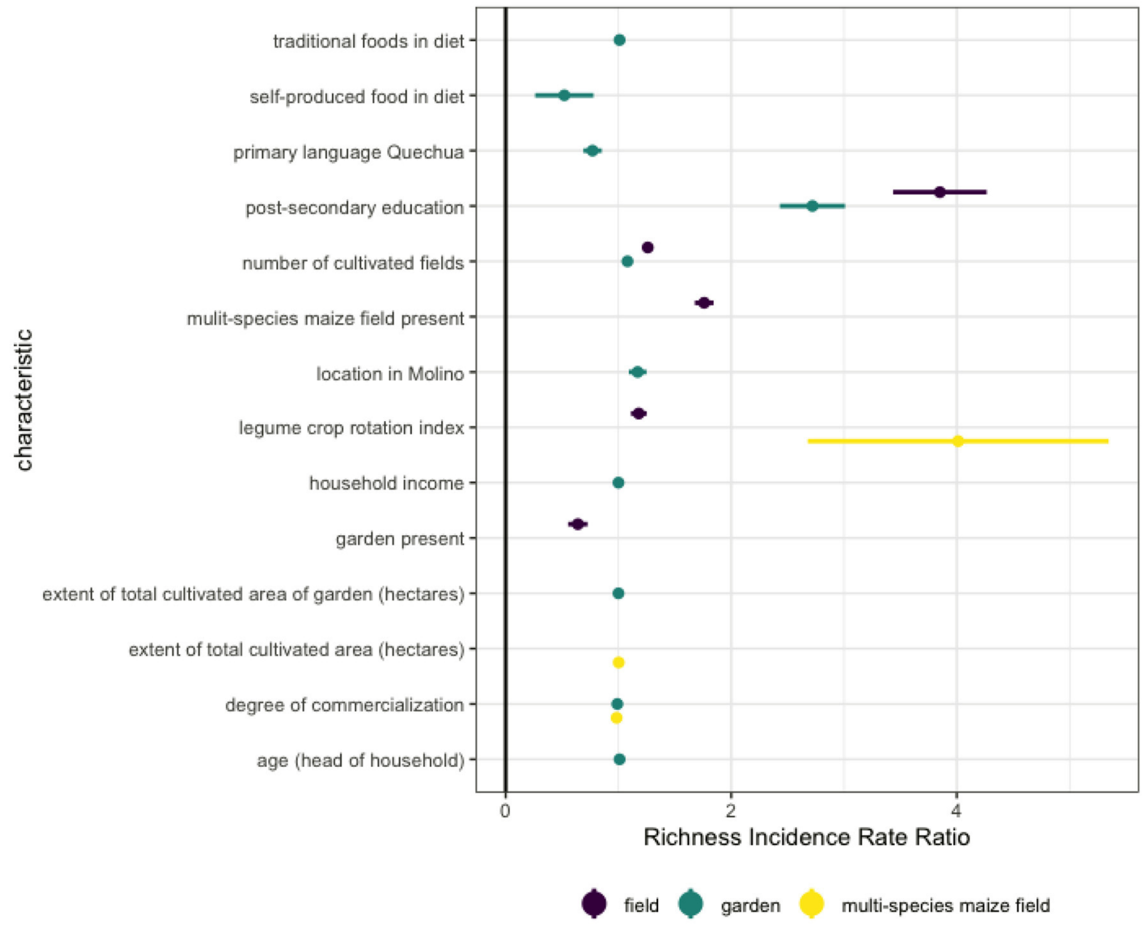

FIGURE 6 | Coefficients and standard errors of significant factors in results of Poisson regression models for richness in agrobiodiversity-and-food spaces (field, garden, multi-species maize fields; each color represents an individual regression model).

paragraph and the preceding varied from 100 to 300 households with most estimates statistically robust. Detailed definitions, data sources, and statistical estimates are given in **Tables 1**, **2**.

Regression Models

Social-ecological and political-ecological factors incorporated in this study's AKF-guided model explained ~16% of variability in the species richness of crop fields (RIRR, Pseudo $R^2 = 0.16$, **Table 3**). These factors accounted for 45% of the variability in the species evenness of these fields (OLS, $R^2 = 0.45$, **Table 3**). In the case of home gardens, social-ecological and political-ecological factors of the AKF-guided model explained ~16% of variability in the species richness of these spaces (RIRR, Pseudo $R^2 = 0.15$, **Table 4**). These factors accounted for 24% of the variability in the species evenness of these fields (OLS, $R^2 = 0.45$, **Table 4**). Social- and political-ecological factors of the AKF-guided models produced similar results to **Tables 3**, **4** using other biodiversity measures as the dependent variables (Materials and Methods; **Supplementary Tables 1, 2**).

Both the species-level richness and evenness of field crops were significantly associated with a set of five factors (**Table 3**). Field number and presence of a multi-species maize field (*maizal*) were most significant in the main model of crop fields ($P < 0.001$; **Table 3**). These highly significant statistical associations occurred across the range of models using the additional agrobiodiversity measures (**Supplementary Tables 1, 2**) as well as the AKF sub-model of farm characteristics (**Supplementary Table 3**).

Field-level richness and Shannon diversity measures showed that legume crop rotation was strongly associated though less significantly ($P < 0.05$; **Table 3**). Additional factors, types of association, and significance levels in the main model of crop fields (**Table 3**) varied among the positive associations of species richness to garden presence ($P < 0.001$) and post-secondary education ($P < 0.01$). Field evenness was negatively associated with the presence of a garden ($P < 0.05$) and the sub-area of the Molinos landscape ($P < 0.05$).

In home gardens, species-level richness was significantly associated with a set of nine factors and the Shannon evenness measure with one (**Table 4**, 2nd and 3rd columns). Age of household head was positively associated at highly significant levels with the species richness ($P < 0.001$) and species evenness of gardens ($P < 0.01$) (**Table 4**). Other factors showing high and positive associations with the species richness of home gardens

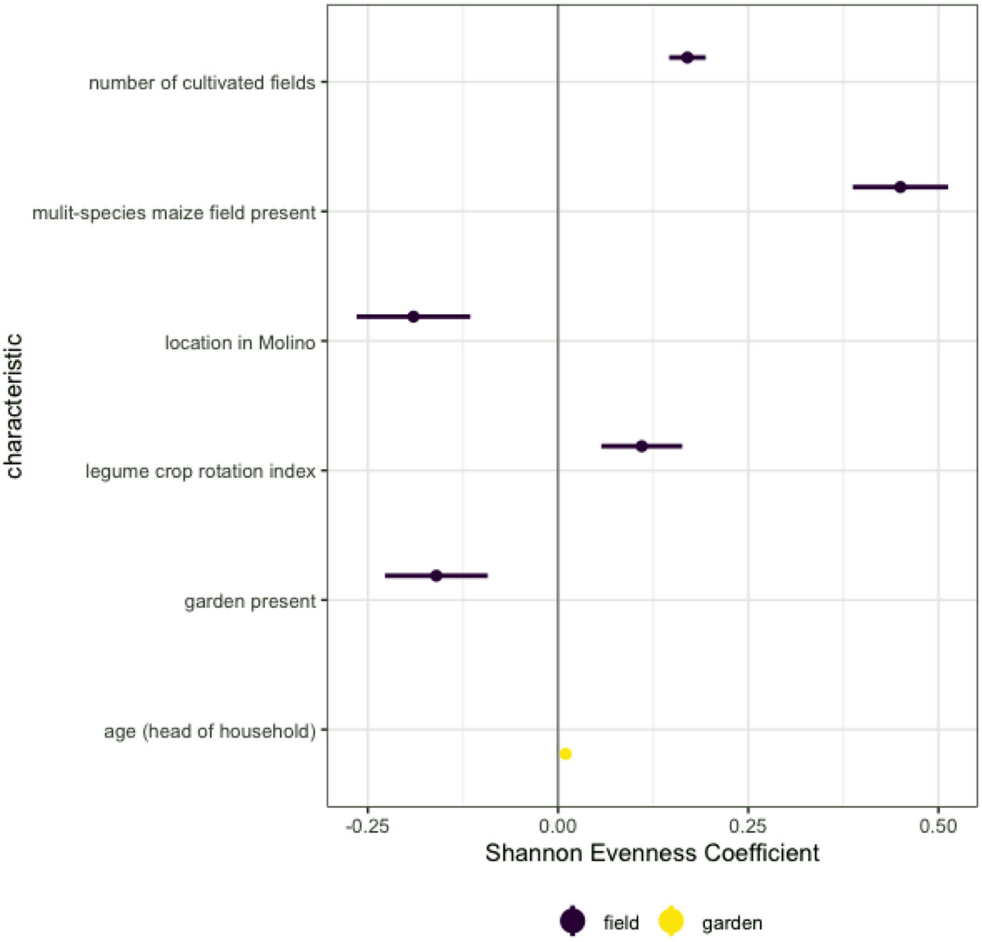

FIGURE 7 | Coefficients and standard errors in regression results on factors in ordinary least squares regression models for Shannon evenness in agrobiodiversity-and-food spaces (field, garden; each color represents an individual regression model).

were garden cultivated area ($P < 0.001$), field number ($P < 0.01$), traditional food in diet ($P < 0.01$), Quechua language ($P < 0.01$), household income ($P < 0.001$), and extent of post-secondary education ($P < 0.01$). Additional factors showed significant positive associations albeit at lower statistical levels. These included the sub-area of the Molinos landscape ($P < 0.05$) and degree of product commercialization ($P < 0.05$).

Individual social- and political-ecological factors identified as statistically significant represented each the four AKF themes (**Figures 6**, **7**) and offered comparisons to previous agrobiodiversity models (last column of **Table 1**) as detailed in the Discussion.

Agroecological and Livelihood Characterization of Keystone Spaces

Agroecological and livelihood characteristics were compared among keystone agrobiodiversity-and-food spaces comprised of multi-species maize fields, other crop-field types, and home gardens. Identification of multi-species maize fields (*maizales*) as an additional keystone space was based on above regression results and fieldwork information (**Figure 8**), including conversations with local people explaining importance. Following above results, further focused analysis of multi-species maize fields as a key space (**Supplementary Table 11** and **Figure 6**) showed the highly positive effect of legume crop rotation ($P < 0.001$), moderate-high correlation with overall field area ($P < 0.01$), and negative association with agricultural commercialization ($P < 0.01$).

Fallow and crop rotation were moderately and highly common in multi-species maize fields (35.2 and 86.2%, respectively) and other field types (32.7 and 76.1%, respectively) (**Table 5**). By contrast, these two practices were applied at low levels in home gardens (1.6 and 4.9%, respectively) (**Table 5**). Intercropped polycultures (planting areas with more than one food species), crop rotation, and legume crops occurred more commonly multi-species maize fields than in other fields. Multi-species mixtures were also moderately common in other crop fields (48.3%). Plant groups with distinct functional roles and traits—legume food and forage crops; the suite of trees, shrubs, and perennials managed in cultivation; and maize—occurred at different levels in the three key agrobiodiversity-and-food spaces (**Table 5**).

FIGURE 8 | Multi-species maize field (maizal) functioning as "key agrobiodiversity-and-food space" in fieldwork visit (February 2017). Photo credit: Karl Zimmerer.

Estimation of the frequency of legume crops and edible managed plants was distinctive among multi-species maize fields, crop fields, and home gardens (71.4, 37.1, 34.6%, respectively; **Table 5**). Leguminous taxa provisioning important foods in the sample consisted of Phaseolus vulgaris (*frijol*, *vainita*, or *numia*), Inga feuilleei (*pacay*), Caesalpinia spinosa (*tara*), Pisum sativum (*arveja*), Vicia faba (*haba*), Lupinus mutabilis (*tarwi*), Arachis hypogaea (*mani*), Inga edulis (*guaba*), Lens culinaris (*lenteja*), and (Medicago sativa *alfalfa*; important as an animal food) as well the widespread ground-covering clover Trifolium spp. (*trebol*). A total of 51 tree species were managed and cultivated, as well as 20 species of perennial herbs.[1]

Estimated relative levels of dietary and income importance varied substantially among the key agrobiodiversity-and-food spaces (**Table 5**). Multi-species maize fields (*maizales*) typically rated intermediate between crop fields (highest levels) and gardens (lower levels yet still important to diet).

DISCUSSION

The Agrobiodiversity Knowledge Framework (AKF) and Comparative Model Results

This study's use of the interdisciplinary Agrobiodiversity Knowledge Framework (AKF) generates reflection on and comparisons with other SDG 2-relevant research. Overall, the AKF framework was thematically comprehensive, theoretically cohesive, and methodologically innovative in predicting agrobiodiversity that is linked to SDG 2-related nutrition security in our overarching design that integrates the agrobiodiversity analysis here with focus on food, nutrition, and diet research (**Figure 1B**; Jones et al., 2018; Zimmerer et al., 2020).

Results showed significant associations across each of the four main themes of AKF predictive factors (**Figure 1A**; agroecology-food/nutrition-governance including sociocultural factors-global change impacts) that provide insights to address SDG 2. First, the AKF-guided models offer a demonstration of agroecological factors (e.g., legume crop rotation; **Table 3**) positively linked to agrobiodiversity. This linkage combines with results on the importance of leguminous food crops to nutrition wellbeing (Jones et al., 2018). Farm-level, resource-access factors were similarly important. For example, access to a garden both determined agrobiodiversity outcomes as shown in this study while it was also associated with favorable nutrition outcomes (Jones et al., 2018). This study's AKF-guided demonstration of well-proven linkages to nutrition build on initial calls (Jarvis et al., 2007; Hajjar et al., 2008) to provide concrete evidence of agrobiodiversity functions that can address SDG 2.

Second, the AKF shows that food and nutrition can operate as significant predictors (**Table 4** and **Supplementary Table 8**). This AKF result is novel since the predominant view is to treat nutrition, food, and other SDG 2-related conditions solely as outcome variables. Instead, it highlights influential bi-directional interactions in which food and diet can serve as model inputs to explain agrobiodiversity, We urge this insight be built into SDG 2 approaches.

Third, AKF-guided analysis of governance predictors, including socioeconomic factors, were significant in the results (e.g., income; **Table 4**). Other significant governance factors were sociocultural factors in the changing spatial strategies of food-growing (multi-species maize fields), agrobiodiversity knowledge (Quechua language), and institutional influences (e.g., school-based education; **Tables 3**, **4**). Each of these factors potentially serves as a strong linkage in addressing SDG 2, including other governance factors (such as the potential major influence of seed systems Arce et al., 2019a) and public-good policies (Graddy-Lovelace, 2021).

Fourth, results showed AKF-SDG linkages involving global-change factors in the significant association of the number of fields with agrobiodiversity (**Table 3**) since the dispersion of fields provides adaptations to weather variation propelled by climate change. At the same time, the resulting higher level of crop diversity has been shown in our related research to predict favorable nutrition outcomes (Jones et al., 2018).

Comparability of model results is needed to advance the use of agrobiodiversity and agroecology to address SDG 2. The AKF supported a much-needed, cohesive approach to interdisciplinary research to enable rigorous cross-case comparisons and policy dimensions ranging from incentives and capacity-building to new initiative such as participatory varietal selection using agrobiodiversity to address SDG 2 (Scurrah et al., 2019). Here we briefly use AKF-guided results to discuss comparisons with other agrobiodiversity studies relevant to SDG 2 approaches and conclude the section by synopsizing this study's model results.

This study's model results show various similarities when compared to related agrobiodiversity studies holding promise for SDG 2 approaches (e.g., Pseudo $R^2 = 0.1883$ of species-level agrobiodiversity in important research linked to food consumption and security in the Northern Ecuadorian Andes;

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[1] Trees and herbs provided important food and nutrition though the legume crops, as a category, were more important as a source of food and demonstrated determinant of healthy diet and nutrition outcomes among local populations in Huánuco and elsewhere (Jones et al., 2018).

TABLE 5 | Characterization of key farm and food-producing spaces according to livelihood importance and the frequencies of soil and soil-nutrient management (Huánuco, Peru).

Livelihood and agroecological components (2017, unless specified otherwise)	Fields (*chakras*, *parcelas*)[a]	Multi-species maize fields (locally *maizales*)	Gardens (locally *huertos*)
Dietary input to self-produced food (37% of average food consumed; 1.0 = highest; see text for methods)	1.8	2.2	2.4
Income input to farm income (1.0 = highest; see text for methods)	1.6	2.8	4.0
Sample size (numbers of units)	742	196	182
Field fallow (2011–2017)	32.7%	35.2%	1.6%
Crop rotation (2013–2017)	76.1%	86.2%	4.9%
Multi-species fields	48.3%	100.0%	100.0%
Legume food and forage crops	37.1%	71.4%	34.6%
Trees, shrubs, and perennials	15.2%	13.8%	67.0%
Maize	41.4%	100.0%	10.4%

[a] *Does not include multi-species maize fields (maizales).*

Skarbø, 2014, p. 723). In addition, our results found similar factors to be significance (e.g., field number and education level). Comparisons are partly limited, however, since the other research did not model determinants of evenness or garden-specific agrobiodiversity [see also Velásquez-Milla et al. (2011) on Huánuco agrobiodiversity custodian farmers that identifies similar statistically significant factors but does not report model-level results; Skarbø, 2014]. As a result, this study recommends comparisons to thematically related social- and political-ecological modeling of agrobiodiversity evenness, such as species-level agrobiodiversity in coastal Nicaragua ($R^2 = 0.34$; Williams, 2016, p. 234) whose general similarity suggests SDG 2 promise.

Our model-level results on the social- and political-ecological determination of home garden agrobiodiversity in Huánuco suggest extended geographic comparison to SDG 2-relevant research in the neighboring Amazon region (e.g., Ban and Coomes, 2004, p. 353). Individual factors identified as highly significant in this study (e.g., garden area and gardener experience) were similar (Ban and Coomes, 2004, p. 353), though different statistical techniques and lack of model-level estimation and evenness estimates limit further direct comparison.

Finally, this study's results from regression models account for species richness to a similar degree in both crop-field and home-garden analysis (Pseudo R^2 values of 0.16 and 0.15, respectively) while evenness, as measured by the Shannon diversity index, differs substantially among crop fields ($R^2 = 0.45$) and home gardens ($R^2 = 0.24$). Relative species abundance in home gardens is known to vary depending on the complex characteristics of individual households (Ban and Coomes, 2004; Coomes and Ban, 2004; Wezel and Ohl, 2005; Perrault-Archambault and Coomes, 2008; Whitney et al., 2018), which may contribute to the lower results of the evenness model.

Biodiversity Estimations and the Social- and Political-Ecological Factors

This study's estimations of agrobiodiversity levels and specific social- and political-ecological factors offer valuable specific comparisons to SDG 2-related research as well as general research advances. Our result on the species-level richness of crop fields (mean 3.7 species/household) was similar though less than findings in the Ecuadorian Andes (7.22 species/household; Skarbø, 2014, p. 714) whose fields traversed a significantly larger elevation gradient (1,000 meters). This study's results on specifies-level richness of home gardens (mean 10.2 species/household) resembled the richness of cultivated species of fruits, vegetables, and herbs (10.2 species/household) that were grown the Ecuadorian Andes (Skarbø, 2014, p. 714). Furthermore, this study's results on total agrobiodiversity species richness in Huánuco, when summed across the households' crop fields and home gardens, resembled an additional study of the Ecuadorian Andes (Oyarzun et al., 2013, p. 525).

Another useful comparison is to local high-agrobiodiversity custodian farmers in Huánuco (Velásquez-Milla et al., 2011) and high-level agrobiodiversity hotspots elsewhere in the Peruvian Andes (Arce et al., 2019a). The current study complements these others, while our sample design and methods were distinct since we integrated focus on agrobiodiversity's roles in SDG-related diets and nutrition that included the randomized sampling of households (see also Jones et al., 2018; Zimmerer et al., 2020).

Important to highlight as a research advance is this study's demonstration that combined biodiversity richness and evenness estimates are needed to understand agrobiodiversity's nexus role connecting to both food-nutrition, such as SDG 2, and agroecology.

Finally, individual factors determined to be significantly associated with agrobiodiversity in this study (see previous sub-section) conform hypotheses in **Table 1** and need to information expanding SDG 2 research globally. Overcoming barriers to link or couple agrobiodiversity access and related SDG 2 benefits for food sovereignty (Zimmerer et al., 2020) will require promoting agroecological management, garden cultivation, and livelihood improvement in addition to income and education as parts of the agendas of social justice and food and nutrition security.

Select factors not showing statistical significance in this study's model results, such as field size and elevation range (**Tables 3**, **4**), help to explain contextual influences. Extremely limited size of cultivated areas in this study (0.404 hectares/household; **Table 2**) is typical of many places in the Andes (e.g., 0.5-hectare farms are common in the central highlands of Ecuador; Oyarzun et al., 2013, p. 523) and smallholder farming globally (van Vliet et al., 2015). Likewise, this study's result on the limited elevation range among fields (**Table 2**) did not result in a significant model result though it is consistent with fieldwork observations of the clustering of small-size fields and gardens near residences. Additionally, this study's findings showed the high frequency of global change factors among surveyed households (e.g., climate change adjustments and elements of agrobiodiversity-loss awareness; **Table 2**), though this study's regression results did not reveal specific statistical associations to these variables.

A Keystone Agrobiodiversity-and-Food Space: Multi-Species Maize Fields

This study's focus on new descriptive, statistical, and conceptual understandings of the role of multi-species maize fields (*maizales*) as a Keystone agrobiodiversity-and-food space is designed to offer a novel contribution and to build on previously hypothesized functions (see multi-species maize fields, **Table 1**). Model results demonstrate that multi-species maize fields, which are distinct due to the types and extent of intercropping (see Results, Agroecological and Livelihood Characterization of Key Spaces), hold a high level of significance in agrobiodiversity relationships (**Tables 3**, **4**). Multi-species maize fields comprise a key space of broad significance to the nexus of agrobiodiversity-agroecology-SDG 2.

We propose the concept of "Keystone agrobiodiversity-and-food space" to describe multi-species maize fields (*maizales*) owing to multi-faceted functions. These fields of Huánuco incorporate widespread inter-plantings of Andean common beans (*frejol*, Phaseolus vulgaris), Andean squash (most commonly *zapallo*, Cucurbita maxima), and *arracacha* (giant Andean carrot or parsnip, Aracacia xanthorrhiza), among other species. Agrobiodiverse *maizal* assemblages, which are extensive in western South America, are distinct while partly resembling the well-known *milpa* system of Mexico and Central America that is agrobiodiverse and nutritionally important (Toledo and Barrera-Bassols, 2017; Novotny et al., 2021).

Notable nutrient management techniques characterize the agroecological functions of the multi-species maize field as a "keystone agrobiodiversity-and-food space" with extensive rotation of crops (86.2% of *maizales* incorporate crop rotation; **Table 5**). Various agrobiodiverse species depend on seed flows and rotated planting sites that link the *maizal* system to other fields. For example, Huánuco households undertaking the non-*maizal* field cropping of Andean maize, Andean common beans and Andean squash species frequently depend on *maizal*-based seed sources and rotated planting sites, and vice versa. A second major function is continued utilization and development of agrobiodiversity management knowledge. This role is crucial since cultivated area and field number are extremely limited among Huánuco households (**Table 2**). In this context, the multi-species maize field (*maizal*) enables the crucial continuation of knowledge and practices of production as well as food processing and consumption that are vital to agrobiodiversity-SDG 2 linkages.

Another key agrobiodiversity-support function of the Andean multi-species maize field is the concentration of livestock grazing on above-ground plant residues following harvest. This emphasis is crucial to the functioning of ecological nutrient management of agrobiodiversity-containing *maizales* as well as nearby fields. Home gardens (locally *huertos*), which are distinct from multi-species maize fields, are also "keystone agrobiodiversity-and-food spaces" though they contain lesser degrees of the linkage functions described above.

Concepts and Barriers for "keystone Agrobiodiversity-and-Food Spaces"

This study's concept of "keystone agrobiodiversity-and-food spaces" is supported by advances in ecological theory extending the keystone species idea from an original food-web focus to other connectivity (e.g., Davic, 2003). An analogous development has occurred in the concept of "cultural keystone species" (Coe and Gaoue, 2020) being expanded to agroecological applications (Nabhan, 2018; Zapico et al., 2020). Use of "keystone" here signifies that addition or loss leads to major changes in occurrence or abundance of other species.

The "keystone agrobiodiversity-and-food spaces" concept is designed to rework the single-taxon definition of a keystone species to one centered on the vital and distinct roles of spatially, culturally, and agroecologically distinct suites of interacting species. Spatial dynamics and influence of food-generating units is traditional in farming and land use (Brookfield, 2001; Mayer, 2018). Changing spatial dynamics of agrobiodiversity pose new challenges and opportunities regarding agroecological sustainability (De Molina et al., 2019). Supporting the positive factors enabling multi-species maize fields (**Supplementary Table 11** and **Figure 6**), such as legume crop rotation, will need to overcome access barriers (e.g., currently multi-species maize fields are linked to larger, less resource-poor farms among indigenous Huánuco smallholders; **Supplementary Table 11**; Zimmerer et al., 2020).

In sum, the multi-species fields or *maizales* of Huánuco function as a distinct, locally recognized, and valued agrobiodiversity-and-food space with widespread intercropping, associated agrobiodiversity, and nutrient management. The latter's characterization (**Table 5**) is preliminary in scope and is intended to stimulate research. We anticipate other "keystone agrobiodiversity-and-food spaces" to include the multi-species, high-agrobiodiversity fields of Andean tuber crops in sectoral fallow management (also known as common field agriculture; Arce et al., 2019b; Vanek et al., 2020). *Milpa* agriculture of Mexico and Central America is another vital space occurring in highly dynamic contexts (Tamariz, 2022) with key linkages and agroecological functions of agrobiodiversity anticipated to be changing rapidly.

Further Links to Future Research

Finally, this study suggests future research avenues centered on AKF-guided approaches to addressing SDG 2 through agrobiodiversity models integrating one or more emphases of agroecology, biodiversity science, and comparisons with existing studies. It indicates the promising role of "keystone agrobiodiversity-and-food spaces" well-suited to expanded integration with these areas of emphasis. Further new research is needed on functional diversity and multi-functionality in agroecology (Blesh, 2018) suited to SDG 2 goals. New AKF-guided modeling approaches related to SDG 2 goals could involve alternative sampling and statistical methods such as Principal Components Analysis, path analysis, constrained ordination, permanova, systems modeling, and reduced-variable parsimonious models.

CONCLUSION

Modeling of social- and political-ecological factors using the interdisciplinary Agrobiodiversity Knowledge Framework (AKF, **Figure 1A**, **Table 1**) was combined with nutrient management characterization of keystone agrobiodiversity-and-food spaces that linked to our project on improving nutrition, diets, and SDG 2 (Zero Hunger). Focused on a continued case study in Huánuco, Peru, the AKF guided the selection, design, analysis, and interpretation of determinants of agrobiodiversity. The latter was estimated using the biodiversity statistics of species-level richness and Shannon diversity index (as well as five additional biodiversity indices) applied both to crop fields and home gardens.

Model results showed significant associations of the farm and agroecological characteristics of field number, garden area, and legume crop rotation. Other factors identified as significant in agrobiodiversity modeling corresponded to the AKF categories of diet and nutrition; social/socioeconomic and cultural factors (governance); and global change. The AKF model was shown to be thematically comprehensive, conceptually cohesive, and timely in focusing on agrobiodiversity-SDG 2 synergies and communicating new research on dynamic, change-prone agrobiodiversity interactions that are increasingly influential (Zimmerer, 2010; Dwivedi et al., 2013; Baumann, 2022; Tamariz, 2022; Tamariz and Baumann, 2022; Zimmerer et al., 2022).

The study's design enabled comparison to other models and estimation that is crucial to advancing agrobiodiversity knowledge, policy, and initiatives to promote SDG 2. Effectively integrating AKF-guided agrobiodiversity modeling and estimation with SDG 2 research relied on incorporating characterization of ecological nutrient management using the concept of "key agrobiodiversity-and-food spaces." Characterization focused on soil- and plant-based elements of nutrient management, with results demonstrating the extensive utilization of field fallow, crop rotation, multi-species fields, legume crops, and managed plantings of trees, shrubs, and perennials as well as maize.

The concept of "keystone agrobiodiversity-and-food spaces" is proposed and developed to account for the combined prevalence and functions of crop fields, home gardens, and multi-species maize fields (*maizales*) in the changing agri-food systems of indigenous smallholders in Peru. Results demonstrated the strong agrobiodiversity associations and ecological nutrient management of each key space with focus on multi-species maize fields. As a key agrobiodiversity-and-food space, the multi-species maize fields are beneficially linked to agrobiodiversity, ecological nutrient management, and food and market capacities, thus offering vital contributions to SDG 2.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Instituto de Investigacion Nutricional, Lima, Peru. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KZ: conceptualization and writing—original draft. HC-K, SH, AJ, KZ, and FP: methodology and supervision. HC-K, SH, AJ, KZ, FP, and MT: investigation. KZ, AJ, SH, RT, CH, and KN: data and analysis. KZ, SH, AJ, and HC-K: writing—review and editing and funding acquisition. RT and CH: visualization. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.734943/full#supplementary-material

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