Understanding Relationships between Diversified Farming Systems and Food and Nutritional Security in Bolivia

by

Jourdan E. Clements

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Thesis Committee:
Associate Professor Jennifer Blesh
Associate Professor Andy Jones

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I Abstract

Small farms are vital to global food systems and supply the majority of nutrients consumed in low- and middle-income countries. Family farms in the Global South vary widely in their management characteristics and socioeconomic conditions, which affect the sustainability of their livelihoods. Managing high levels of crop and livestock diversity sustains key ecosystem functions that can improve farm productivity, and, in turn, shape household livelihoods through multiple pathways. For instance, diversified farming systems can contribute directly to food security and dietary diversity through consumption of foods produced on the farm, and indirectly through factors such as increasing income. However, there are critical gaps in our understanding of the complex relationships through which farm diversity, and its associated ecosystem functions, shape livelihoods.

To address this gap, we conducted an analysis of data from an in-depth survey on farm management and household food consumption conducted with households across two rural-urban continuums in El Alto and Montero, Bolivia. Using these data, we created a diversified farming systems index based on indicators including crop and livestock diversity, soil management practices, and use of external agricultural inputs at the household level. We then tested for relationships between the index and crop yield, food security, and dietary diversity (as an indicator of the nutritional quality of diets), while controlling for key covariates such as wealth quintile and educational attainment. Results of this analysis indicate unique differences in outcomes for our two regions of interest, which highlights the significance of diversified farming practices on shaping food security and diet diversity across regions with differing environmental and socio-political contexts. Diversified farming systems were significantly

associated with higher dietary diversity and lower food insecurity in El Alto, a region with relatively greater household farm production, which supports the importance of farm-scale diversity in populations more reliant on agriculture. These findings advance our understanding of the relationships between agrobiodiversity, agricultural management practices, and household livelihoods, which can inform improved policies to promote more sustainable and multifunctional agricultural systems.

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III Introduction

Food security is a major global challenge, especially with the growing impact of climate change on food production (Baulcombe et al. 2009). Climate change is projected to increase crop loss at the global scale due to more frequent extreme events such as droughts and floods as well as greater variability in precipitation and temperature (Adams et al. 1998). Additionally, crop production in developing low- and middle-income countries is predicted to suffer disproportionately due to a combination of adverse agroclimatic, socioeconomic, and technological conditions (Rosenzweig & Hillel 2008). Furthermore, highly simplified industrial monocultures are becoming increasingly common in the Global South (DeFries et al. 2010). Industrial management practices such as excessive use of fertilizer and other chemical inputs, and simplified rotations with low crop diversity, cause environmental pollution and soil erosion (Maikhuri & Rao 2012). Soil erosion, specifically, is recognized as one of the most widespread problems in agriculture in developing countries (Ananda & Herath 2003).

The majority of nutrients consumed in developing countries are supplied by small farms (Herrero et al. 2017), defined as family-operated farms up to 40 acres in size that gross less than $250,000, significantly contributing to global food supplies and economies (Dixon et al. 2003, Hong 2015). Family farms therefore play a crucial role in sustainable systems through greatly influencing farming and business practices, costs, prices, and consumer choice (Martinez & Davis 2002). As the impact of climate change on small farms continues to grow in severity, there is a greater need for sustainable agriculture that provides sufficient and nutritious food and income to developing countries, while minimizing environmental impact (Eyhorn et al. 2019). However, family farms in the Global South vary widely in their management characteristics and socioeconomic conditions, which affect the sustainability of their livelihoods (Altieri 2008). Transitioning to more sustainable agricultural production systems requires family farmers to develop more productive, profitable, resource efficient, and environmentally friendly practices (Dogliotti et al. 2014). Diversified farming systems (DFS) are a potential solution to these challenges faced by small farms, because they can help mitigate global change while producing diverse food products and generating income for households.

Diversified farming systems integrate functional biodiversity from farm to landscape scales to provide vital ecosystem services that increase the sustainability of crop production (Zhang et al. 2007). As a result, DFS have the potential to provide greater food security, conserve biodiversity, improve access to a diversity of foods, and increase household income (Gangwar & Ravisankar 2016, Mekuria & Mekonnen 2018). Diversification practices can be integrated into farming systems at the plot and field scale through, for example, genetic/cultivar diversity, growing multiple crops together as polycultures, or including cover crops or perennial crops in rotation, and addition of compost or manure can provide additional benefits to soil health and fertility (Kremen et al. 2012). At the landscape scale, DFS may involve crop-livestock integration, including well-managed grazing, silvopasture, use of fallowing, and riparian buffers (Kremen & Miles 2012). In particular, DFS in which households practice mixed farming through coupling crop and livestock production, have the potential to provide greater benefits through positive ecological interactions between multiple farm components resulting in higher soil quality, more efficient nutrient recycling and uptake by crops, and more resilient agroecosystems (Mekuria & Mekonnen 2018, Salton et al. 2014).

By providing multiple ecosystem services to agriculture, DFS reduce environmental externalities and the need for off-farm inputs (Altieri 1999, Kremen & Miles 2012, Tamburini et al. 2020). Specifically, managed biodiversity through DFS interacts with the physical environment to support key ecosystem functions (e.g., nutrient cycling, pest control, water infiltration and storage) that support crop production, thereby increasing agricultural sustainability by relying on ecological processes rather than non-renewable inputs (Pearson 2007, Tamburini et al. 2020). The production of these ecosystem services (e.g., soil fertility, pest control, pollination) is critically dependent on the maintenance of biodiversity and associated interactions (Shennan 2008, Jackson et al. 2009). A recent, comprehensive meta-analysis of agricultural diversification strategies, such as DFS, demonstrated positive impacts on crop production and the environment through the enhancement and maintenance of biodiversity and resulting ecosystem services in varying regions across the globe (Beillouin et al. 2019).

Promoting and monitoring the effects of DFS on soil quality is vital to sustainable land use for mitigating climate change, conserving biodiversity, and achieving food and income security (da Luz et al. 2019). A variety of DFS practices can build soil fertility, including use of cover crops, erosion control, manure or compost, managing crop residues, and leaving the field in fallow (Rosa-Schleich et al. 2019). For example, compost and manure amendments can support diverse microbial and invertebrate communities, which in turn promote nutrient cycling (Rosa-Schleich et al. 2019). Overall, DFS practices that maintain soil fertility and productivity over time contribute to the resilience and sustainability of farm production, which will be of increasing importance in the face of climate disturbances such as drought, flooding, or pest infestations (Tengo and Belfrage 2004, Lin 2011, da Luz et al. 2019, Stratton et al. 2020).

DFS produce not only ecological but also social and nutritional benefits for sustainable agriculture (Rosa-Schleich et al. 2019). For instance, by increasing crop diversity to build ecological functions on farms, DFS can also increase the diversity of nutrients provided by crops on a farm (Stratton et al. 2020). Further understanding and expanding the use of DFS practices also has the potential to benefit farmers and individuals dependent on crop production by contributing to the creation of more sustainable, socially just, and secure food systems through mechanisms such as improving the resilience of agricultural production via sustainable land management (Oyarzun et al. 2013, Rosa-Schleich et al. 2019). Additionally, community engagement from farmers, researchers, and health staff supporting the implementation of DFS is linked to increased awareness of topics including farmer empowerment, equity, and nutritional education (Hunter & Fanzo 2013, Blesh et al. 2023). As a result, DFS and associated community-based education have resulted in improved health outcomes, well-being, income gains, and broadening of dietary diversity (Kerr et al. 2019, Madsen et al. 2021). In total, DFS have the potential to better household livelihoods through multiple mechanisms, including farm production and resilience, and household social well-being and nutritional security (Sekaran et al. 2021).

An important goal of agricultural and food systems is to provide an adequate diversity of the nutrients necessary for a healthy life (Remans et al. 2014). However, despite improvements in crop production and associated nutritional outcomes over the last few decades, the prevalence of undernutrition remains high (Sibhatu et al. 2015). Nutritional deficiencies as a result of poor diet diversity and quality are responsible for population health burdens including impaired physical and mental development, susceptibility to various diseases, and premature death (Lim at al. 2012, Sibhatu et al. 2015). Consumption of nutritionally diverse food therefore serves as an important mechanism to improve food security, nutritional intake, and overall health, especially for food-insecure families (Oyarzun et al. 2013, Sibhatu et al. 2015). In order to shift to more diverse diets, agricultural production also needs to be diversified to provide access to a broader range of different types and varieties of foods, especially in low-income populations (Pingali 2015, Jones 2017). DFS can promote diet diversity through multiple mechanisms, especially greater consumption of farm diversity, or through sale of on-farm diversity (Zanello et al. 2019). However, to-date no studies have tested how DFS, and their comprehensive suite of management practices, influence dietary diversity through increases in on-farm ecosystem functioning and sustainability. Our study therefore seeks to understand this relationship and the potential benefits of DFS on increasing dietary diversity to best inform future planning and assessments of agricultural and food systems policies (Remans et al. 2014).

Bolivia is a developing country in the Global South with a wide range of agricultural management strategies that is particularly impacted by the agricultural, social, and nutritional challenges discussed (Zimmer 2013, Caulfield et al. 2021). Two regions in Bolivia that span a wide range of farm management strategies as well as distinct food environments and infrastructure are El Alto and Montero (Jones et al. 2018). El Alto is a highland city located at 4,150 meters above sea level near La Paz in western Bolivia with production centered around subsistence farming and commercial quinoa and potato production (Jones et al. 2018). Conversely, Montero is a satellite city of Santa Cruz located in the Amazonian region of eastern Bolivia with production centered around commercial agriculture and livestock production (Jones et al. 2018). Differences in the agroecological, political, economic, and sociocultural environments of these regions are comparable to those reflected between the highlands and Amazonian basins of the larger Andean region (Steel & Zoomers 2009).

In this analysis, we addressed the following research questions: 1) How do diet diversity and food security vary on family farms in two regions of Bolivia? 2) How does farming system diversification influence crop yield, food security, and household dietary diversity? For the distinctive regions of El Alto and Montero Bolivia, we assessed the performance of DFS as compared with conventional systems using four agricultural sustainability indicators that represent crop diversity (e.g., use of cover crops), soil management (e.g., use of manure or compost), external inputs to farming (e.g., use of inorganic fertilizers), and livestock management (e.g., livestock species diversity). To advance knowledge of the integrated outcomes of DFS in distinct environmental and social contexts, we sought to understand the complex relationships through which farm diversity, and its associated ecosystem functions, shape livelihoods in differing regions. We expected to find regional differences in food security and diet diversity due to key differences in agricultural practices, and food and built environments between El Alto and Montero. Additionally, we hypothesized that there would be a positive association between farming system diversification and food security and diet diversity.

IV Methods

IV.1 Data collection

We analyzed data from a survey of 3,946 households that was conducted as a baseline assessment of a longitudinal study that captured agricultural, economic, and nutritional data of Bolivian communities. The survey was implemented from August to December 2015 in and around 2 cities: 1) El Alto, a highland city located at 4,150 meters above sea level (masl) near La Paz in western Bolivia; and 2) Montero, a satellite city of the larger metropolitan region of Santa Cruz located in the Amazonian region of eastern Bolivia (350 masl) (Jones et al. 2018). Both of these regions have experienced growth in recent decades from urban migration that has contributed to increasing heterogeneity in the populations and environments that constitute the urban, peri-urban, and rural areas examined in this study (Álvarez-Berríos et al. 2013). Additionally, these two regions have different agroecological, political, economic, and sociocultural contexts (Steel & Zoomers 2009). Agricultural production in El Alto is centered around subsistence farming and commercial quinoa and potato production, while production in Montero is centered around commercial agriculture and livestock production (Jones et al. 2018). The differences in these regions are comparable to those reflected between the highlands and Amazonian basins of the larger Andean region (Steel & Zoomers 2009).

Households were eligible to participate in the survey if the female spouse of the male head of household, or female head of household was a woman of reproductive age (15–49 years). Additionally, the inhabitants of the surveyed home or apartment needed to be the primary residents. All interviews were conducted in Spanish and in-person by trained enumerators. Data were collected from the household member most knowledgeable about each survey module topic. Data on recent diet and health behaviors were collected from an index woman in each household, identified as either the female spouse of the male head of household or the female head of household. This included a qualitative food frequency questionnaire administered to the index woman on behalf of the entire household.

Survey modules also included data on households' agricultural production. This included production of crops, livestock, and inclusion of gardens. Agricultural crop production questions focused on the 2014/15 agricultural season, specifically relating to a farmer's 'best field' – defined as the land or plot that normally has the best harvest of all land or plots used for crop production. Detailed management information for the 'best field' was collected, including questions related to crops grown, crop rotations, external inputs applied (e.g. pesticides and inorganic fertilizers) and any organic fertility sources (e.g. manure). Livestock production was collected as number and types of livestock owned.

IV.2 Variable calculations

IV.2.A An Agroecosystem Function Index

Households in our study with agricultural production spanned a wide diversity of management practices. To characterize the degree of diversification across agricultural, livestock, and garden management of households, we developed an "Agroecosystem Function Index" comprised of four sub-indices focused on key dimensions of diversified farm system management: (1) a crop diversity index (CDI) (Kremen et al. 2012), (2) a soil management index (SMI) (Kremen & Miles 2012, Rosa-Schleich et al. 2019), (3) an external input index (EII) (Maikhuri & Rao 2012), and (4) a livestock index (LI) (Kremen & Miles 2012) (Table 1). The CDI accounted for crop diversity of the 'best field' and presence of a garden within the household, while also considering the functional diversity of cropping systems, which is known to drive key ecosystem functions (Martin & Isaac 2015). Crop diversity of the 'best field' included the sum of the number of crops grown on the field (ranging from a minimum of one crop to a maximum of six crops grown), with an extra point added if a crop was a perennial (weighted by area perennial occupied on the field), as well as an extra 0.5 point if crops were intercropped and an extra 0.5 point if there was a history of cover crops grown in the last five years. If a household also reported having a garden, one point was added to the CDI score. The SMI included management practices reported on the 'best field' that influence soil health, either positively or negatively. This included practices related to erosion control, addition of manure or compost, crop residue management, and periodic use of fallow. Erosion control, manure or compost use, crop residue retention at farm level, and fallow practices were considered practices that would build soil organic matter and thus were assigned positive values (Rosa-Schleich et al. 2019). For each of these indicated practices, households received one point towards their SMI score. Conversely, removal or burning of crop residues were considered soil degrading practices and were assigned negative values. If a household utilized either of these crop residue management practices, one point was subtracted from their SMI score. Application of external inputs, specifically inorganic fertilizer and pesticides, were considered to have negative effects to overall agroecosystem functions, and therefore were assigned negative values in the EII (Maikhuri & Rao 2012). One point was subtracted from a household's EII score if they used inorganic fertilizers and one point was subtracted if they applied pesticides. The LI included the sum of the total number of livestock across all species owned by the household with the number of livestock species reported. Total number of livestock were converted to tropical livestock units (TLU), a measure that standardizes livestock weights based on a 250 kg live weight. Conversion factors used for the livestock reported in this survey included cattle (0.70), sheep and goats (0.1), donkey (0.5), mule (0.7), pig (0.25), poultry (0.01), llama (0.6), alpaca (0.2) and cuy (0.005). TLU were then calculated as the sum of the number of each livestock species multiplied by the respective conversion factor. An overall agroecosystem function index (AFI) was derived by summing all values for the four indices for a given household, resulting in a cumulative positive, negative, or zero (neutral) value. Index values were used as predictor variables in our study. Values closer to extreme values indicated stronger positive or negative functional states on farms.

Table 1. Descriptions of index calculations used to assess agroecosystem function of household farming systems.

Indicator	Metric calculation	Interview question (translated)
Crop Diversity Index (CDI)		
Number of crops grown on field	"+1" for every crop name listed for reported crops (Range: 1-6).	What was one of the crops that you or someone in your household planted on this [LAND OR PLOT] during the agricultural year 2014-2015? Also take into account trees or crops that last more than a year, even if they were planted in the [LAND OR PLOT] before the agricultural year 2014-2015.
Use of cover crop in past 5 years	"+0.5" if answered 'yes' to "Have you grown any cover crops in the last 5 years?"	Have you or any member of your household used any "cover crop" on this [LAND OR PLOT] in the last 5 years, i.e. since the agricultural year 2010-2011? A "cover crop" is an unharvested crop, which is planted between agricultural years, and is sown to improve the soil.
Growing perennial on field	Weighted by relative area perennial occupies on field. "+1 to 0.2" for every perennial grown on field. +1 if whole field planted in perennial, +0.8 if between 3/4 but less than whole area planted in perennial, +0.6 if 1/2 to 3/4 of area planted to perennial, +0.4 if 1/4 to 1/2 of area planted to perennial, +0.2 if less than 1/4 of area planted to perennial.	Is this [CROP] crop a tree or perennial crop? How many trees or perennials (crops of cycle greater than one year) of [CULTIVATION] are there in this [LAND OR PLOT]?
Use of intercropping	"+0.5" if any field crop was reported as being intercropped.	Was this [CROP] crop interspersed with other crops on this [LAND Or PLOT] in the agricultural year 2014-2015? that is, was the [CROP] crop planted at the same time with other crops on this [LAND OR PLOT]?
Presence of garden	"+1" if reported having a garden.	Do you or does any member of your household have a family vegetable or fruit garden? A "family garden" is a part of the land in the house, sayana, chaco in the plot or garden, which can be enabled for the planting of vegetables for daily consumption for the family.
Soil Management Index (SMI)		
Erosion control	"+1" if respondent reported using any erosion control measure on field.	Do you or any member of your household perform any erosion control (soil loss) on this [LAND OR PLOT]?
Use of manure or compost	"+1" if respondent reported using manure or compost on any crop in the field.	Was any type of manure or composting used as organic fertilizer in the cultivation of [CROP] in this [LAND OR PLOT] during the 2014-2015 agricultural year?
Crop residue management	Crop residue management was assessed for the crop that was reported as grown on the greatest area of field (i.e., the main field crop). For crops grown on equal areas, crop residue was determined by the sum of crop residue practices. "-1" if crop residue harvested, removed, or burned. "+1" if residue left on land or used to feed livestock.	What was done with the "stubble or debris" of [CROP] on this [LAND OR PLOT] during the agricultural year 2014-2015? The "residues" are the green or vegetative part of the crop that remains after harvest.
Field in fallow last 5 years	"+1" if last year field was reported as fallow was 2010 or later.	What was the last year that this [LAND OR PLOT] was left on fallow/rest? If the respondent has already responded that the land was fallow during one of the previous agricultural years between 2011-2012 and 2014-2105, enter the appropriate year of your previous answer.
External Input Index (EII)		
Use of inorganic fertilizer	"-1" if inorganic fertilizer applied to any crop in the field	Were any inorganic fertilizers used in this [CROP] in this [LAND OR PLOT] during the 2014-2015 agricultural year?
Use of pesticides	"-1" if pesticide applied to any crop in the field	Was any type of pesticide used on this [LAND OR PLOT] during the 2014-2015 crop year?
Livestock Index (LI)		
Total livestock production	Total tropical livestock unit (TLU) calculated as the number of each livestock species weighted by livestock weight. Values were winsorized to truncate TLU for large numbers of animals.	How many [LIVESTOCK] do you or any member of your household have now?
Number of livestock species	Number of livestock species owned by household	How many [LIVESTOCK] do you or any member of your household have now?
Agroecosystem Function Index (AFI)	Summed value of CDI, SMI, EII, and LI	

IV.2.B Grouping of households

To assess agricultural livelihood strategies, we grouped households into one of eight categories: (1) no crops, gardens, or livestock production, (2) crop production only, (3) garden production only, (4) livestock production only, (5) crop and garden production, (6) crop and livestock production, (7) garden and livestock production, and (8) crop, garden, and livestock production. Of the households surveyed, 1,513 fell into categories 2-8 and were included in our analysis.

Table 2. Descriptions of outcome variables used to assess crop production and household nutritional status.

Indicator	Metric calculation	Interview question(s) (translated)
Crop Yield z-score	Amount of crop harvested standardized per hectare. Transformed to z scores to standardize by mean value for El Alto. For fields with multiple crops, z scores represent the sum for all crops grown on household's representative field.	How much did you harvest in the last 12 months of this [LAND OR PLOT]? If more than one variety of the crop was harvested, calculate the total harvested amount of all varieties. What area of this [LAND OR PLOT] was planted with this [CROP]?
Latin America and Caribbean Household Food Security Measurement Scale (ELCSA)	Determined categorization of household food insecurity via a fifteen-item questionnaire that assesses anxiety and uncertainty about food access, insufficient food quality, and insufficient food intake.	[Example 2 of 15 questions asked:] During the last 3 months, due to lack of money or other economic factors, have you ever worried that your home would run out of food? During the last 3 months, due to lack of money or other economic factors, did you run out of food in your home? [...]
Dietary Diversity Index (DDI)	Representative woman of child bearing age, chosen as either female head of household or spouse of head of household. Modified MDD-W reported as summed value from food groups (1 - 10).	In the last 30 days, from [DAY/MONTH] to now, how often, on average, have you consumed... [FOOD ITEM(S)]

IV.2.C Outcome variables

Measures of crop yield, household food security, and household dietary diversity were the primary outcomes for this study (Table 2).

We measured crop yield by determining the amount of crop harvested (standardized per hectare) from the reported ‘best field’ in the city of El Alto, as this region had the vast majority of data for crop production. Yield values per crop were transformed into a z-score, representing a crop’s score relative to average yield of each crop type reported in the survey. If the field had multiple crops with yield values recorded, z-scores were summed for all crops grown on the household’s ‘best field’.

The Latin America and Caribbean Household Food Security Measurement Scale (ELCSA) was used to assess food access. The ELSCA is a fifteen-item questionnaire that assesses anxiety and uncertainty about food access, insufficient food quality, and insufficient food intake (FAO 2007). The ELCSA survey instrument is both internally and externally valid, comparable across countries in Latin America, and has been used for research purposes throughout the region (Pérez-Escamilla et al. 2009, Bermudez et al. 2010). Additionally, the scale has been validated for use in Bolivia (Kopp et al. 2014). Surveyed households were grouped into one of four ELCSA categories: (1) food secure, (2) mildly food insecure, (3) moderately food insecure, and (4) severely food insecure.

Vulnerabilities and gaps in diet quality have been largely recognized as a pervasive issue, especially for women who are often nutritionally vulnerable due to the physiological demands of pregnancy and lactation (FAO & FHI 2016). We created a dietary diversity index (DDI) modified from the FAO’s Minimum Dietary Diversity for Women (MDD-W) approach and adjusted it to our survey data. Within our survey, the frequency of consumption of 50 food items and food groups in the previous 30 days by each household's index woman was assessed using a qualitative food-frequency questionnaire. For the DDI, we included surveyed food items that fell into one of the ten food groups noted as nutritionally diverse in the MDD-W indicator, which is a food group diversity indicator for women of reproductive age that has been shown to reflect one aspect of diet quality, namely, micronutrient adequacy (FAO & FHI 2016). The ten food groups in the indicator are useful for assessing food group diversity in households, and are also similar to those included in previously developed household-level diet diversity indicators (Hoddinott & Yohannes 2002, FAO & FHI 2016). This DDI (Table 3) captures only 'healthy' food groups (i.e., we excluded 'unhealthy' food groups such as sugars, oils, etc. in alignment

Table 3. Categorization of surveyed food items into DDI food groups [adapted from MDD-W].

Dietary Index Food Groups	**Survey Responses**
1) Grains, white roots and tubers, and plantains	(1) rice, (2) potato, (3) chuno/tunta, (4) instant soup noodles, (5) other noodles, (6) white bread, (7) wheat bread, (8) barley, (9) oats, (10) corn, (11) wheat, (12) amaranth/canahua, (13) oca/papalisa/other, (14) yuca
2) Pulses (beans, peas and lentils)	(1) soy, (2) quinoa, (3) tarwi, (4) beans/peas, (5) lentils
3) Nuts and seeds	(1) sesame, (2) chia
4) Dairy	(1) milk, (2) other dairy
5) Meat, poultry, and fish	(1) hamburger, (2) other beef, (3) pork, (4) cuy/duck/llama, (5) fried chicken, (6) chicken other, (7) organ meat/offal, (8) fish
6) Eggs	(1) eggs
7) Dark green leafy vegetables	(1) leafy greens
8) Other vitamin A-rich fruits and vegetables	(1) sweet potato, (2) carrot, (3) squash/pumpkin, (4) mango/papaya
9) Other vegetables	(1) tomato, (2) onion, (3) other vegetables
10) Other fruits	(1) other fruits

with the MDD-W index). Intake diet data were weighed to determine and capture a monthly consumption frequency value. Data from the 30 day recall survey were standardized to a “per day per month” value, where “1” indicates consumption at least once a day per month and smaller values indicate less frequent consumption per day within the month. Values for each of the 10 food groups in MDD-W were summed to get an overall consumption frequency value per DDI category grouping. Therefore, a summed value of at least 1 for each food group category indicates that a household is consuming food from a healthy food group at least once a day on a monthly basis. Household values were summed from each food group category and dietary diversity was scored from a scale of 0-10 using these summed values. Values closer to 0 indicate a lower dietary diversity and values closer to 10 indicate a higher dietary diversity.

IV.2.D Covariates

The following sociodemographic covariates were included in analyses to adjust for potential confounding factors: number of total household members, highest achieved education level of head of household, and quintiles of an asset-based index of household wealth. The household wealth index was developed using assigned asset weights generated from a principal components analysis that created standardized asset scores (Rutstein and Johnson 2004).

IV.3 Statistical analysis

All analyses were carried out using the R 4.1.3 binary package for macOS 11 and higher (2022; R, Bell Laboratories, NJ) as well as the Stata statistical software package version 14.2 (2017; StataCorp, College Station, TX). We calculated means, standard deviations, and proportions of characteristics of households for both El Alto and Montero. We also calculated means and standard deviations for our four predictor indices, as well as the overall AFI, and all outcome variables by region.

For agricultural analyses, outliers were removed using the 3(IQR) criterion method. For dietary analyses, all women with complete outcome data for relevant nutrition outcomes were included. To address outliers in TLU used to calculate the LI, TLU values for cows were winsorized at the 98th percentiles, to account for the few households that had large amounts of cattle production (Gosh & Vogt, 2012).

We used several types of regression analyses, adjusting for the covariates described previously, to model the associations between predictor and outcome variables by region. Multiple linear regressions were used to model associations between the AFI sub-indices (e.g., CDI, SMI, EII, and LI) and crop yield in El Alto. A Poisson regression was used to analyze the associations between AFI sub-indices and DDI. A multiple logistic regression was used to model the association between the AFI and the ELCSA. The statistical significance of associations was identified at the $p < 0.05$ level.

IV.4 Ethical approval

The study protocol was approved by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board and the National Bioethics Committee of Bolivia (Comité Nacional de Bioética). Comprehensive written informed consent was obtained from all study participants ≥18 y old and written informed assent was obtained for individuals aged 15–17 y.

V Results

Household samples in both Montero and El Alto were relatively evenly distributed among wealth quintiles, and also across a rural to urban gradient (Table 4). The majority of households surveyed were headed by an individual who had completed primary education or higher and were relatively food secure (i.e., mildly food insecure or food secure) (Table 1). Women from households in Montero and El Alto had an average dietary diversity score of 6.78 and 7.16, respectively (Table 4) (FAO). Mean DDI score was not significantly different between Montero and El Alto (Figure 1, Table 4).

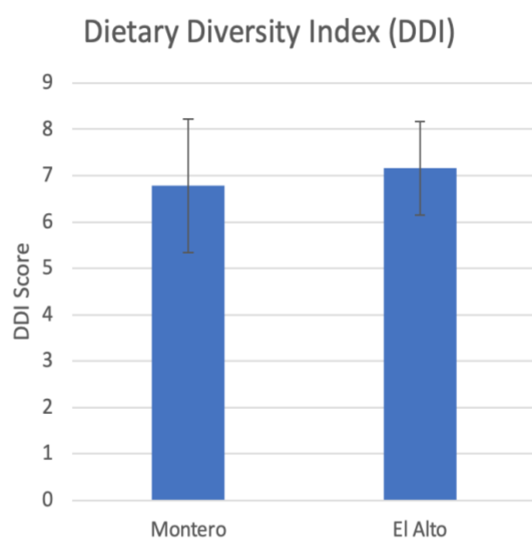

Figure 1. Average DDI score for women in households from Montero and El Alto.

The main agricultural livelihood strategies in the two regions differed widely. Of households analyzed, the agricultural livelihood strategies in Montero were dominated by garden production (37.37%), livestock production (29.90%), and garden and livestock production (23.92%) (Table 4, Figure 2). Conversely, in El Alto agricultural livelihood strategies were dominated by field crop production (30.92%) and integrated crop and livestock production (29.98%) (Table 4, Figure 2). Additionally, El Alto was composed of more small

Table 4. Differences in means and proportions for characteristics among households in Montero and El Alto.

Region	Montero		El Alto	
	n	Value	n	Value
Households	1889		1959	
Household size	1873	4.86 +/- 1.83	1914	4.53 +/- 1.66
Highest attained education level (head of household), %				
No education	60	3.36	11	0.60
Some primary (incomplete)	158	8.84	21	1.14
Complete primary	867	48.49	609	33.12
Complete secondary	497	27.80	930	50.57
Education beyond secondary	206	11.52	268	14.57
Wealth quintiles, %				
Lowest	376	20.07	371	19.38
Low	430	22.96	338	17.66
Middle	393	20.98	359	18.76
High	326	17.41	428	22.36
Highest	348	18.58	418	21.84
Household food insecurity, %; Latin American and Caribbean Food Security Scale (ELCSA)				
Food secure	810	43.50	629	33.23
Mildly food insecure	627	33.67	649	34.28
Moderately food insecure	263	14.12	442	23.35
Severely food insecure	162	8.70	173	9.14
Urban gradient, %				
Rural	561	29.75	608	31.26
Peri-urban	756	40.08	741	38.10
Urban	569	30.17	596	30.64
Household agricultural livelihood strategies, %				
No crops, gardens or livestock	1220		1115	
Crops only	37	5.53	261	30.92
Garden only	250	37.37	29	3.44
Livestock only	200	29.90	124	14.69
Crops & Garden	7	1.05	35	4.15
Crops & Livestock	11	1.64	253	29.98
Garden & Livestock	160	23.92	43	5.09
Crops, garden & Livestock	4	0.60	99	11.73
Crop Yield z-score	25	-0.15 +/- 0.89	482	0.01 +/- 1.20
Dietary Diversity Index (DDI)	1531	6.78 +/- 1.44	1715	7.16 +/- 1.01
Avg field size (ha)	49	17.6 +/- 17.5 (0.5 - 85)	630	0.85 +/- 5.89 (.0001 - 70)

farming systems, with an average field size more than twenty times smaller than the average field size in Montero. El Alto also had 1.3 times the number of households in Montero with agricultural production, and almost twenty times the number of households in Montero with field crop production (Table 4).

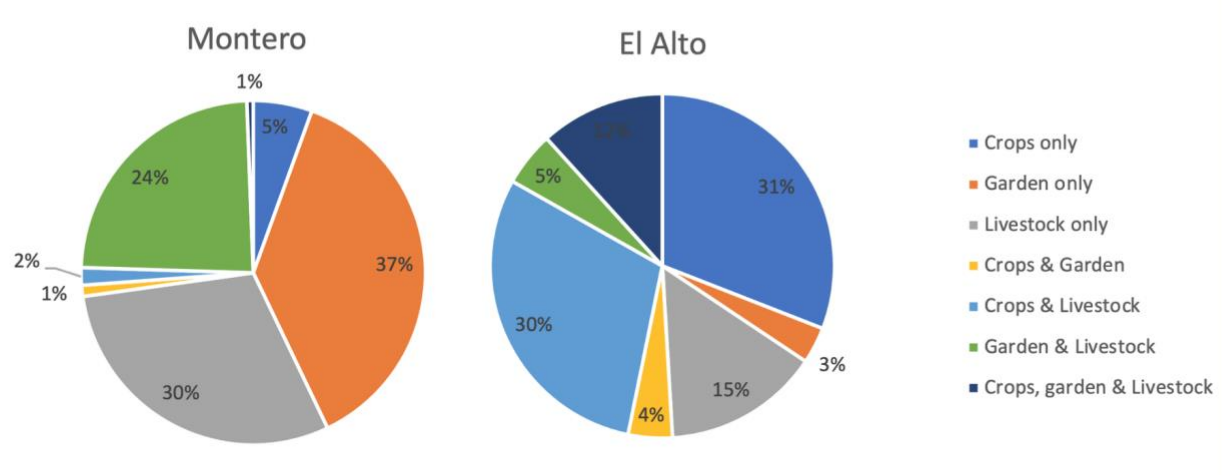

Figure 2. Breakdown of agricultural livelihood strategies by region.

The two regions also had contrasting crop and livestock production systems. Crop production on fields analyzed in Montero was dominated by soybean (32%), rice (22%), and corn (16%) – all of which are characteristic crop types grown in the Amazonian region. Fields in El Alto were dominated by potato (45%), pea (12%), bean (12%), and turnip (10%) production – which are also typical crops grown in the highland region of Bolivia. Livestock production in Montero was highly dependent on raising chickens (96%) and pigs (7%), whereas livestock species were much more diverse in El Alto, with livestock production composed of sheep (49%), chickens (42%), cuy (40%), pigs (31%), and cow (20%).

Overall, the average AFI score for households in El Alto was almost three times greater than that of households in Montero (Table 5), with higher scores for all four sub-indices. Given these observed differences in mean values, regression analyses were conducted separately for each region to identify associations between the AFI and the outcome variables of interest.

Table 5. Differences in means for AFI and sub-indices across households in Montero and El Alto.

	Region			
	n	**Montero**	**n**	**El Alto**
Crop Diversity Index (CDI)	467	1.07 +/- 0.34	713	1.76 +/- 0.99
Soil Management Index (SMI)	52	1.13 +/- 1.21	632	1.97 +/- 0.98
External Input Index (EII)	43	-1.26 +/- 0.44	213	-1.16 +/- 0.37
Livestock Index (LI)	370	1.80 +/- 3.14	506	3.49 +/- 2.77
Agroecosystem Function Index (AFI)	658	1.66 +/- 1.42	826	4.84 +/- 3.36

In a multiple linear regression analysis examining associations in El Alto between crop yield and AFI sub-indices, while controlling for differences in sociodemographic characteristics, two significant associations were observed ($p < 0.05$) (Figure 3). Increased crop diversity, indicated by a higher CDI score, was negatively associated with crop yield z score for the main field crop(s) grown (Figure 3). In other words, higher crop diversity was associated with lower crop yields, on average. Conversely, households with an SMI of 2 had significantly higher crop yield z scores compared to those with an SMI value of -1, indicating that sustainable soil management practices are associated with greater crop yields in El Alto (Figure 3).

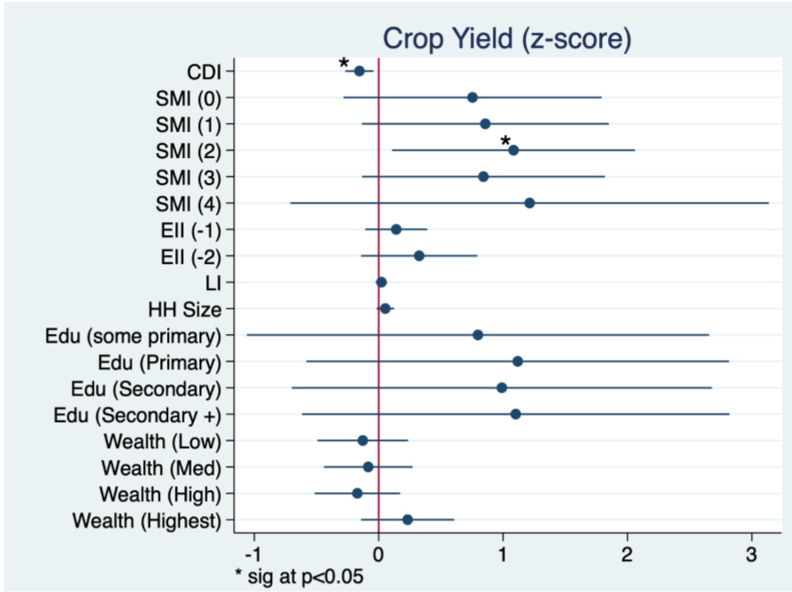

Figure 3. Multiple linear regression results for crop yield z score and AFI sub-indices in El Alto. Each point represents regression coefficient and lines showing 95% confidence intervals.

We used Poisson regression analyses to test for associations in El Alto and Montero between ELCSA and AFI score, while controlling for differences in sociodemographic characteristics ($p < 0.05$) (Figure 4). In El Alto, the AFI had a significant negative association with ELCSA (Figure 4), indicating that households with more diversified farming systems had greater food security. In terms of covariates, household size was significantly associated with greater food insecurity and households in higher wealth quintiles had a significant negative association with ELCSA as compared to households in the lowest wealth quintile (Figure 4). In other words, higher wealth quintiles were associated with lower household food insecurity. Interestingly, these same trends were not observed in Montero. In Montero, households headed by an individual with higher education had a significant negative association with ELCSA, as compared to households headed by an individual with no education (Figure 4). This association signified that lower household food insecurity was associated with higher household head educational attainment in Montero.

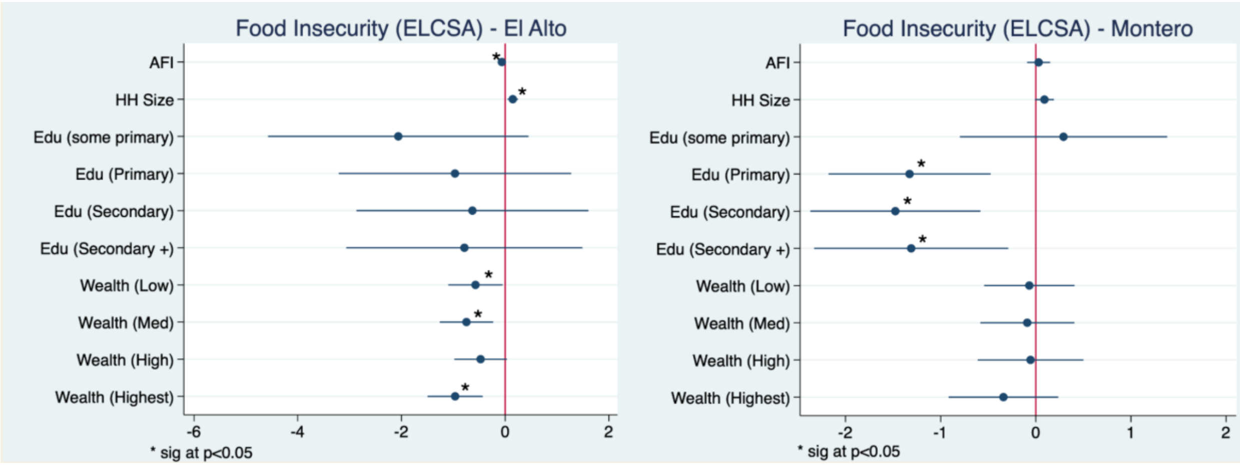

Figure 4. Poisson regression results for ELCSA and AFI in El Alto and Montero. Each point represents regression coefficient and lines showing 95% confidence intervals.

Regional differences were also found for logistic regression analyses examining associations between AFI sub-indices and the DDI score, while controlling for differences in sociodemographic characteristics ($p < 0.05$) (Figure 5). In El Alto, DDI had a significant positive relationship with CDI, indicating that households with higher crop diversity had greater dietary diversity (Figure 5). Additionally, households in the high and highest wealth quintiles were significantly associated with higher DDI scores as compared to households in the lowest wealth quintile (Figure 5). In Montero, DDI had a significant negative relationship with EII (Figure 5). In other words, households that used either pesticides or fertilizers on their main crop field had lower dietary diversity as compared to households that did not use pesticides and fertilizers. Similarly to El Alto, Montero households in higher wealth quintiles had a significant positive relationship with DDI as compared to households in the lowest wealth quintile (Figure 5). Households in Montero in which the head of household achieved primary or secondary education had a significant negative relationship with DDI (Figure 5).

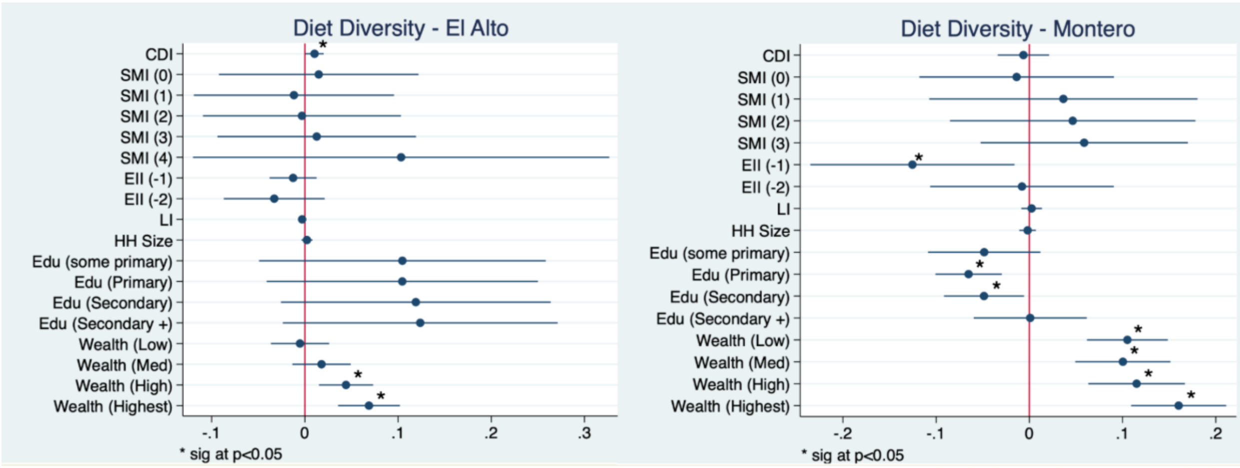

Figure 5. Logistic regression results for DDI and AFI sub-indices in El Alto and Montero. Each point represents regression coefficient and lines showing 95% confidence intervals.

VI Discussion

Improved dietary quality and variety are central to the nutrition and health outcomes of developing nations, especially with the increasing impact of climate change on food production (Baulcombe et al. 2009). The agricultural sector has a significant role to play in alleviating undernutrition for these populations (Dixon et al. 2003). Specifically, small family farms are an important purveyor in rectifying these issues, given their large contribution to developing nation food supplies, but these farms are also projected to be more vulnerable to climate change (Rosenzweig & Hillel 2008, Hong 2015). With the growing need for family farms to provide sufficient and nutritious foods while adapting to a changing climate, DFS may serve as a solution to increase both the sustainability and dietary diversity of smallholder households (Kremen & Miles 2012). Research has demonstrated that the effects of DFS can contribute to ensuring sustainable crop production and a nutritionally diverse diet, however, the benefits of DFS management practices may differ by region due to distinct agroecological, political, economic, and sociocultural environments (Kremen et al. 2012). Our study setting of Bolivia is a heterogeneous developing nation, composed of unique regions with small farm agricultural production and therefore was well suited for addressing our research questions. Using data from a large observational study conducted in two distinct regions of Bolivia, we observed regional differences in agricultural production, food insecurity, and dietary diversity.

We found that the overall relationship between DFS and diet diversity differed between El Alto and Montero. In El Alto, DFS were positively associated with diet quality and food security. In our sample, this region contained more farming households than the Montero region. It is possible that these households may be more reliant on agricultural production for dietary intake or may sell much of their production and use this income to diversify their diets through market-purchased items. These explanations are consistent with prior research on analyses of agricultural practices and dietary diversity in other developing regions that are reliant on agriculture, such as India and sub-Saharan Africa, but more research should be conducted to further understand these relationships in Bolivia (Pradhan et al. 2021, Rajendran et al. 2017). El Alto households with agricultural production were primarily focused on crop production or crop and livestock production. This emphasis on crop production aligns with our regression results showing that CDI was significantly associated with less food insecurity and greater dietary diversity for El Alto households. Conversely, dietary diversity in Montero households, on average, may be less dependent on agricultural production because our index of agricultural sustainability and diversity did not significantly influence diet diversity in this region. This supports our hypothesis (H1) that we would find regional differences in food security and diet diversity because the regions have key differences in agricultural practices, and food and built environments. In the heterogeneous environments of developing regions, which are also experiencing rapid urbanization, our results can help guide future research to best inform the degree to which diversified farming system strategies positively impact dietary diversity in particular environmental and social contexts.

We found that farming system diversification was positively associated with food security and diet diversity in El Alto, but there were some tradeoffs. Specifically, a key tradeoff was observed between overall crop diversity and the yield of field crops, with regression results indicating that more diverse crop systems were associated with lower crop yields. Other studies have found similar tradeoffs, but current research on DFS have also found that while farmers may experience lower yields in DFS as opposed to conventional systems, DFS may provide higher ecological benefits and higher net revenues on the farm due to reduced machinery and labor costs (Rosa-Schleich et al. 2019). In El Alto we also found that practices that build soil health were associated with higher crop yield compared to practices that degrade soil quality. This finding adds to the body of research on the positive relationship between soil health and crop yields due to the generation and maintenance of beneficial ecosystem services (Kremen & Miles 2012, van Es et al. 2019). Additionally, for farming households in Montero, we observed a negative association between diet diversity and the use of fertilizers and pesticides. It is likely that we did not observe this same relationship for households that used both fertilizer and pesticide inputs on their fields due to a small sample size in this category, as the majority of Montero households with external input data in our survey used one or the other. Use of these external inputs are more common practices in larger-scale, less diversified systems (Davis et al. 2012), adding to our evidence that more diversified farm systems are associated with higher diet diversity. Taken together, these results largely support our hypothesis (H2) that there would be a positive association between agricultural diversification and food and nutritional outcomes.

While our study offers new insights into how diversified farming practices impact household livelihoods and crop production in differing regions, our research is not without its limitations. As an inherent limitation of survey studies, our ability to draw causal inferences from observed correlations is limited. Though we captured agriculture data from surveyed households, our survey was administered by individuals who specialize in nutrition rather than agriculture, thereby limiting the number of questions we could ask about the agricultural production systems and the level of detail of the data. Despite including covariates of wealth, education, and household size, we cannot rule out residual confounding factors as an explanation for our findings. Finally, though we implemented standardized protocols for diet assessment, underreporting of dietary intake data by women for their own diet is another potential limitation of the study (Gibson 2005). Despite these limitations, this research advanced knowledge of the complex relationships between DFS, crop production, nutritional security, and dietary diversity in developing nations such as Bolivia.

VII Conclusion

Agricultural practices must transition to emphasize sustainability and resilience in the face of climatic variability and global undernutrition (Baulcombe et al. 2009, Rosa-Schleich et al. 2019). Production from small family farms in developing nations will be particularly impactful in this transition as they significantly contribute to global food supplies and economies (Dixon et al. 2003, Hong 2015). Our study contributes to better understanding the impact of DFS on nutritional outcomes and crop production for small farming households in two contrasting regions of Bolivia, a developing nation. Overall, our research highlights the importance of DFS practices on food security and diet diversity across regions with differing environmental and socio-political contexts. Based on these results we can conclude that DFS were positively associated with household dietary diversity and food security in one, but not both, regions of Bolivia assessed. The diversification strategies that may contribute to increased household diet diversity may differ by region. These novel findings suggest that examining the complex interrelationships between distinct regional contexts and household dependence on agricultural production is important for understanding the multi-scale factors that contribute to dietary diversity, and for targeting agricultural diversification strategies to best improve diet diversity and crop production. In conclusion, implementing and maintaining DFS practices is critical for developing sustainable farming systems and improving livelihoods through nutritional outcomes in developing countries.

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