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Exploring the Potential of Agriculture Diversification as a Pathway to an Improved Smallholder Livelihood Dietary System in Nepal

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Abstract: Agriculture, a cornerstone of Nepal's economy, is dominated by smallholder farmers cultivating staple crops under resource and input constraints, leading to declining productivity amid rapid population growth and urban migration. This study explores the role of agricultural diversification in enhancing dietary diversity and improving smallholder livelihoods using panel data from the Nepal Household Risk and Vulnerability Survey (2016–2018). Analysis through the Simpson diversification index and food consumption scores reveals a strong positive correlation between agricultural diversification and dietary diversity. Key determinants include market access, irrigation systems (rainfed or canal-based), input availability (fertilizers and labor), and land type. Dry season crop diversification was positively associated with dietary diversity, while market access showed a significant negative impact on dietary diversity as distance increased. Upland areas exhibited higher potential for diversification, especially in the dry season, driven by improved access to inputs and irrigation. Policy recommendations highlight the need to enhance infrastructure in upland regions, improve market access, and ensure input availability, particularly fertilizers and labor, to support seasonal diversification. Such measures are essential for strengthening food security, nutritional diversity, and economic resilience among smallholder farmers in Nepal.

Keywords: agriculture diversification; dietary diversity; smallholder farmers; cropping seasonal variation; Nepal

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Citation: Nepali, B.; Jackson, T.; Johns, C. Exploring the Potential of Agriculture Diversification as a Pathway to an Improved Smallholder Livelihood Dietary System in Nepal. *Sustainability* **2024**, *16*, 9384. https://doi.org/10.3390/su16219384

Academic Editors: Jonas Volungevičius and Kristina Amalevičiūtė-Volungė

Received: 21 September 2024
Revised: 20 October 2024
Accepted: 25 October 2024
Published: 29 October 2024

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1. Introduction

Agriculture constitutes a cornerstone of Nepal's economy, accounting for approximately 27.6% of its GDP and engaging 66% of smallholder farmers in agricultural activities, with an emphasis on ensuring national food security [1]. The country's agricultural portfolio is diverse, comprising staples such as rice, maize, wheat, millets, barley, pulses, oilseeds, and sugarcane. Despite substantial investments in agricultural research and extension services, there has been a decline in crop yield growth from 2.3% in the fiscal year 2022 to 2.0% in the fiscal year 2023 [2,3]. Concurrently, the population has been rising at a rate of 1.14% annually, accompanied by a significant expansion in both the number and size of urban areas. This decrease in agricultural productivity is occurring in the context of a 1.14% annual population growth and an expanding urban demographic, intensifying the challenges of food insecurity and hunger.

Globally, hunger and insufficient intake of essential micronutrients afflict 2 billion individuals, which equates to 30% of the world's populace, with 815 million, or one out of every nine people, facing chronic food scarcity daily [4]. Although Nepal has made strides, reducing its Global Hunger Index score from 37.4 in 2000 to 19.5 in 2020, persistent food and nutritional insecurity issues are evident [5]. Research from Tufts University and the Global Dietary Database indicates that in Nepal, the dietary intake of critical foods and nutrients for adults over the age of 20 falls below half of the advised daily consumption levels [6]. A predominant etiological factor for nutritional deficiency is attributed to

inadequate dietary diversity or consumption patterns. This situation is partly due to the prevalence of monocultures producing staple foods with limited nutritional value and a decline in agricultural diversity among rural cultivators, contributing to elevated malnutrition and food insecurity rates [7,8]. Despite the escalation in food production and caloric consumption attributed to monoculture practices, these methods correlate with nutritional imbalances and dietary deficits [9]. In Nepal, the dominance of cereal cultivation, covering three-quarters of the agricultural terrain [10], mirrors the widespread micronutrient scarcity and a uniform diet heavily dependent on staple grains. This pattern of reduced agricultural and food diversity could substantially influence global dietary trends. An estimated half a billion smallholder farms, located primarily in sub-Saharan Africa and parts of Asia, contribute to 80% of the region's food production, according to [11]. Despite this significant output, the potential of agriculture to alleviate malnutrition through the provision of nutrient-dense food remains inadequately tapped. Smallholder farmers often endure protracted phases of food insecurity, consuming less than optimal quantities of their own agricultural produce and facing restricted access to market-sourced foods, which exacerbates dietary deficiencies and undernutrition.

The government's focus on augmenting agricultural output is evident, and agricultural diversification has been identified as a strategic approach to achieve this enhancement. Agricultural diversification represents a tactical method pursued by agricultural stakeholders to augment the robustness, ecological persistence, and economic viability of their cultivation systems. This strategy mitigates the vulnerability associated with monocultural practices by providing a spectrum of advantages, including improved risk mitigation, economic equilibrium, environmental protection, and heightened nutritional sufficiency [12,13]. Global initiatives have deployed agricultural diversification strategies with the dual aim of augmenting household earnings and fostering nutritional adequacy in developing countries [14]. The Agriculture Development Strategy (ADS) for the period 2015–2035, ratified by the Nepalese government, emphasizes the critical importance of diversifying agricultural output by promoting the cultivation of high-value crops and diminishing dependence on traditional agricultural practices [15].

2. Literature Review

Agricultural diversification has been widely considered as a critical approach for improving food security and farm livelihoods, especially in developing nations. It is frequently viewed as a way of mitigating the hazards associated with monoculture farming, increasing climate resilience, and contributing to sustainable agricultural growth [12,14]. Ref. [16] claims that a framework for evaluating diversification in broadacre agriculture can offer information on practical possibilities for diversity, boosting agricultural systems' resilience and sustainability. In the context of smallholder farming, agricultural diversification allows farmers to cultivate a range of crops and raise animals, which not only increases income but also adds to better nutrition by expanding access to varied food groups [9,17].

The idea of agricultural diversification is inextricably linked to dietary variety, which is a major indication of nutritional well-being, particularly in rural regions where market access is limited and subsistence farming prevails [18]. Studies have shown that diverse farms offer a wider selection of food items, thus enhancing the consumption of nutritionally dense diets [19,20]. According to [21], a rural livelihood's capacity to diversify protects against food insecurity. Other factors that affect this capacity include household assets, market accessibility, and educational attainment.

Agricultural diversification plays an even larger role in low-income nations like Nepal, where food insecurity and malnutrition are recurrent problems. Rural communities often face restricted market access, limiting their capacity to acquire diverse crops, making on-farm diversification crucial for improving dietary variety [11,22]. Diversification offers advantages, but in Nepal, it is frequently constrained by problems such as land fragmentation, poor irrigation infrastructure, and a lack of labor and other necessary inputs [23,24].

Existing research indicates that agricultural diversification is extremely context-dependent, with geographical characteristics such as elevation and irrigation infrastructure affecting the extent to which diversity may be successfully implemented [21,25]. For instance, in the upland region, the availability of water resources and adequate cropping patterns during the dry season can have a substantial impact on diversification results [26]. Addressing these geographical inequalities highlights the importance of customized interventions that focus on improving infrastructure and market linkages to promote diversification initiatives [27].

While the benefits of agricultural diversification for revenue creation and environmental sustainability are well known, empirical information on its direct influence on household dietary diversity remains scarce, notably in Nepal [22]. Prior studies have primarily focused on the economic benefits of diversification, frequently disregarding its potential to improve food security by increasing access to a diverse range of nutrient-dense foods [28,29].

While research on the link between agricultural diversification and dietary diversity is expanding, this study aims to fill a knowledge gap regarding the effect of diversification in enhancing nutritional outcomes in Nepal. This study provides a more thorough understanding of how agricultural diversification might enhance food security and nutrition in smallholder farming systems by looking at variables including market accessibility, irrigation systems, and input availability. This is in line with research results that highlight the necessity of integrated strategies to support varied farming, which in turn promotes sustainable agriculture and better livelihoods [21,30].

3. Conceptual and Theoretical Framework

This research posits three hypotheses to elucidate its core concepts: the first posits a substantive correlation between agricultural diversification and dietary diversity during systemic transitions and development; the second suggests that farmers are likely to diversify their agricultural practices by incorporating various commodities into their current systems if it results in an income increase, thereby corroborating the **utility maximization theory** [28,31,32]. Thirdly, uptake by households is also obtained through market purchases and household production, supporting the **entitlement theory** [33,34]. Combining these two theories, a new theory, the **utility–entitlement theory,** suggests that nutritional dietary diversity in a household requires market-oriented agriculture diversification to generate income, which increases the range of food available to satisfy this demand. According to Figure 1, the various factors associated with household resources and characteristics affect agriculture diversification and dietary preferences, which we study further in this research.

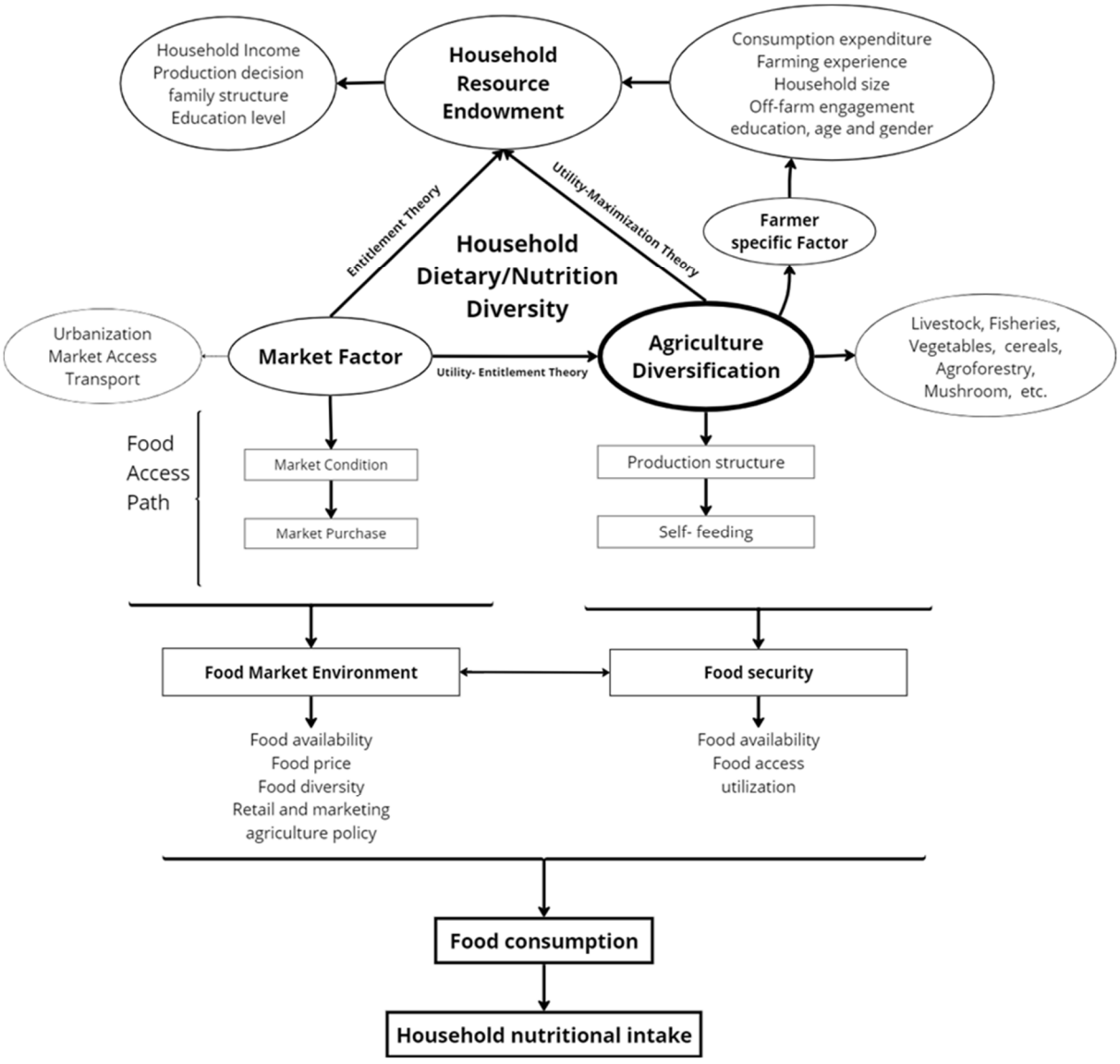


Figure 1. Conceptual and theoretical framework of utility–entitlement theory [28,32,34,35].

4. Material and Methodology

4.1. Data and Software

The research was conducted by using the Nepal Household Risk and Vulnerability (HRVS) Panel Survey data from the World Bank between 2016 and 2018, with funding provided by the UK Department for International Development (DfID). It encompasses 400 settlements and 6000 families in rural and peri-urban locations around the country were included in the study. To enhance the proportion of surveyed households, probability proportional to size (PSU) was used to choose 50 out of 75 districts in Nepal (excluding homes in the districts of Bhaktapur, Lalitpur, and Kathmandu Valley).

Out of the 6000 Wave 1 households, 5654 (94%) took part in all three waves. A total of 6005 homes were questioned as part of Wave 2, among which 5835 (97%) were Wave 1 households and 165 (3%) lacked additional households recruited to replace Wave 1 families that were unreachable. A representative group of 6051 homes were questioned as part of Wave 3. The greater number resulted from certain homes that were contacted again in Wave 3 after being questioned in Wave 1 but not in Wave 2 Presented in Table 1 [36].

Table 1. Household respondent data frame from 2016 and 2018.

Years	Participants No.	Response Rate	Household Added
Wave 1 (2016)	5654	94%	
Wave 2 (2017)	5835	97%	165
Wave 3 (2018)	6051	100.84%	192

All these data were structured district-wise to articulate a national-level study and analysis of the variables accordingly. Data analysis and visualization were performed in RStudio 2024 using the 'vegan' package for ecological diversity analysis and 'ggplot2' for graphical representation, applied to pre-processed and categorized comma-separated values (CSV) data exported from Excel 2016.

4.2. Measurement of Agriculture Diversification and Dietary Diversity Score

4.2.1. Simpson Diversification Index for Agriculture Diversification

In agriculture, adding a wider variety of crop species rather than being specialized in a single crop indicates diversification. The Simpson diversification index (SDI) can be used to measure crop or product diversity within a particular region or farming system. We have categorized agriculture diversification into crop diversification and livestock diversification for this research. Furthermore, based on seasonal cropping in Nepal, the crop diversification was separated into wet (kharif) season crop diversification and dry (Rabi) season crop diversification. SDI is the difference between one and the sum square of a variety of species in a specific area at a particular time. The SDI ranges from 0 to 1, where zero indicates less diversified and one means highly diversified.

The formula below is used to compute the Simpson index:

$$SDI = 1 - \sum_i (ni/N)^2$$

ni = amount of crop species grown in a particular area at a given period of time;
N = denotes the total quantity of individual crop across all crop species.

4.2.2. Food Consumption Score (FCS) or Dietary Diversity Score (DDS)

The frequency of consumption of foods from nine distinct food categories by families during the preceding seven days is taken into consideration by the DDS. The World Food Program served as the inspiration for the mathematical method we used to obtain this score, called the dietary diversity score (DDS) method as mentioned in Table A1 [13,28]. This score functioned as a proxy for the degree (0–21 = Poor; 21.5–35 = Borderline; and >35 = Acceptable.) to which households satisfied their requirements for micronutrients.

The DDS is calculated as follows:

$$DDS = AiXi + A\mathit{in}X\mathit{in}$$

Ai = weight according to the dietary category assigned by WFP for n number of food group.

Xi = the amount of food consumed over seven days concerning each n number of dietary category.

4.3. Econometric Model

We have three years of balance panel data from HRVS, Nepal to understand the effect of the independent variable on the dependent variable. We perform KMO and Bartlett's tests for suitable factorial linear regression analysis. Based on this test, we assign two regression models to analyze the relationship between a dependent variable (Multivariable regression model) and various factors with a dependent variable (OLS regression model).

4.3.1. Multivariable Regression Model

This model is applied to understand the relationship between agriculture diversification as an independent variable and dietary diversity score as a dependent variable.

$$\mathrm{DDS}i = \beta 0 + \beta 1 * (SDI)i + \ldots + \mathrm{E}i$$

DDSi = dietary diversity score for diverse i;
(SDI)i = agriculture diversification by Simpson index for diverse i;
Ei = error term.

4.3.2. Ordinary Least Square (OLS) Regression Model

We used OLS model to estimate the linear relationship between dietary diversity score or agriculture diversification (dependent variable) and one or more household characteristics (independent variable). This OLS model tries to minimize the distance between the observed values and the values predicted by the linear model.

$$(\mathrm{DDS\ or\ SDI})\ i = \beta 0 + \beta 1 * (\mathrm{HC})i + \beta 2 * Xi + \mathrm{E}i$$

(DDS or SDI) i = dietary diversity score or agriculture diversification for diverse i;
(HC)i = household characteristics for household i;
Ei = error term of household i;
and Xi = vector of other characteristics of household i.

5. Result and Discussion

5.1. Result

5.1.1. Bartlett's Test of Sphericity and the KMO Test

In Table 2, the suitability of the data for the utility–entitlement theory analysis was checked using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity. The factor analysis's sample adequacy is modest, as shown by the KMO score of 0.66. Since the correlation matrix does not appear to be an identity matrix and is suited for factor analysis, Bartlett's test has a highly significant *p*-value (0.000). There are 28 degrees of freedom and a chi-square value of 396.2046.

Table 2. Bartlett's test of sphericity and the KMO test.

KMO and Bartlett's Test	
Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy	0.66
Bartlett's test of sphericity	
Approx. chi-square	396.2046
df	28
Sig.	0.000

5.1.2. Estimation of Kernel Density with the Agriculture Diversification Index

Simpson categories for dry crop, wet crop, and livestock are compared on a kernel density estimation plot. The x-axis displays the value of the data, and the y-axis displays the density, visualizing the distribution of data values for each category. In order to establish a binary variable that indicates whether a household varied their agricultural activities, the mean for the Simpson diversification index of agricultural diversification was utilized as the cutoff threshold. A value of zero (not diversified) was given to households below the diversification index's mean, while a value of one (fully diversified) was given to those above it as shown in Figure 2. Our econometric findings, which are detailed subsequently, are based on the selection equation, which uses this binary variable as a sub-dependent variable.

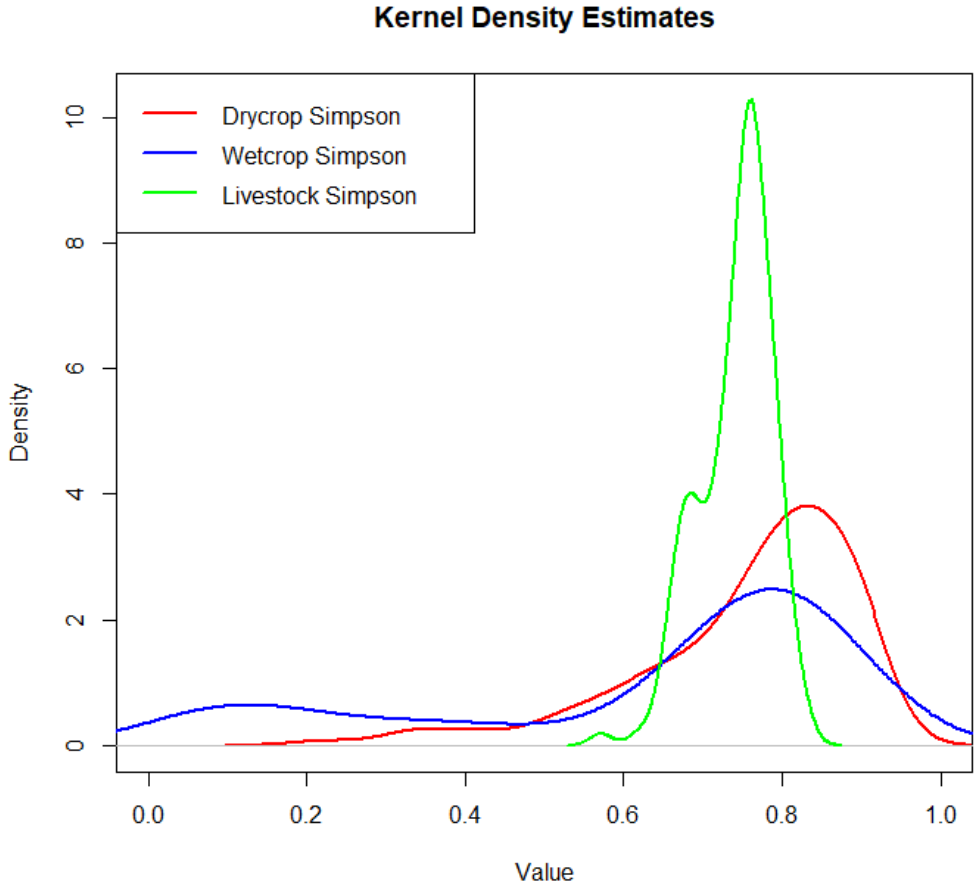


Figure 2. Agriculture diversification distribution flow estimation from 0 to 1.

5.2. Estimation of Correlation Among Diversification and Socioeconomic Variable in a Matrix

The correlation matrix heatmap visualizes the associative magnitudes among variables pertinent to socio-economic status and agricultural diversity. In Figure 3, the coefficients within this matrix oscillate between −1 and 1, symbolizing a spectrum from negative to positive linear relationships, respectively. Notably, a pronounced positive linear relationship is observed between 'drycrop_simpson' and 'wetcrop_simpson', with a correlation coefficient of 0.56, suggesting a concurrent increase in both variables. Conversely, 'wetcrop_simpson' and 'Land_Size' exhibit a notable inverse relationship, with a correlation coefficient of −0.66. The heatmap employs gradations of blue to denote positive correlations and shades of red to denote negative correlations, with the depth of color intensity corresponding to the strength of the correlation.

5.3. Analysis of Agriculture Diversification and Dietary Diversity Score with Socioeconomic Variables

The Table 3, presents the results of a regression analysis exploring the relationship between dietary diversity score and three variables: wet season crop diversification, dry season crop diversification, and livestock diversification. The wet season crop diversification is significantly negatively associated with dietary diversity score (Estimate = −13.008, $p < 0.001$), explaining approximately 21.58% of the variance in the dietary diversity score (R-square = 0.2158). Dry season crop diversification is also significantly positively associated with the dietary diversity score (Estimate = 17.430, $p = 0.00212$). However, there is no significant association between livestock diversification and the dietary diversity score ($p = 0.34618$).

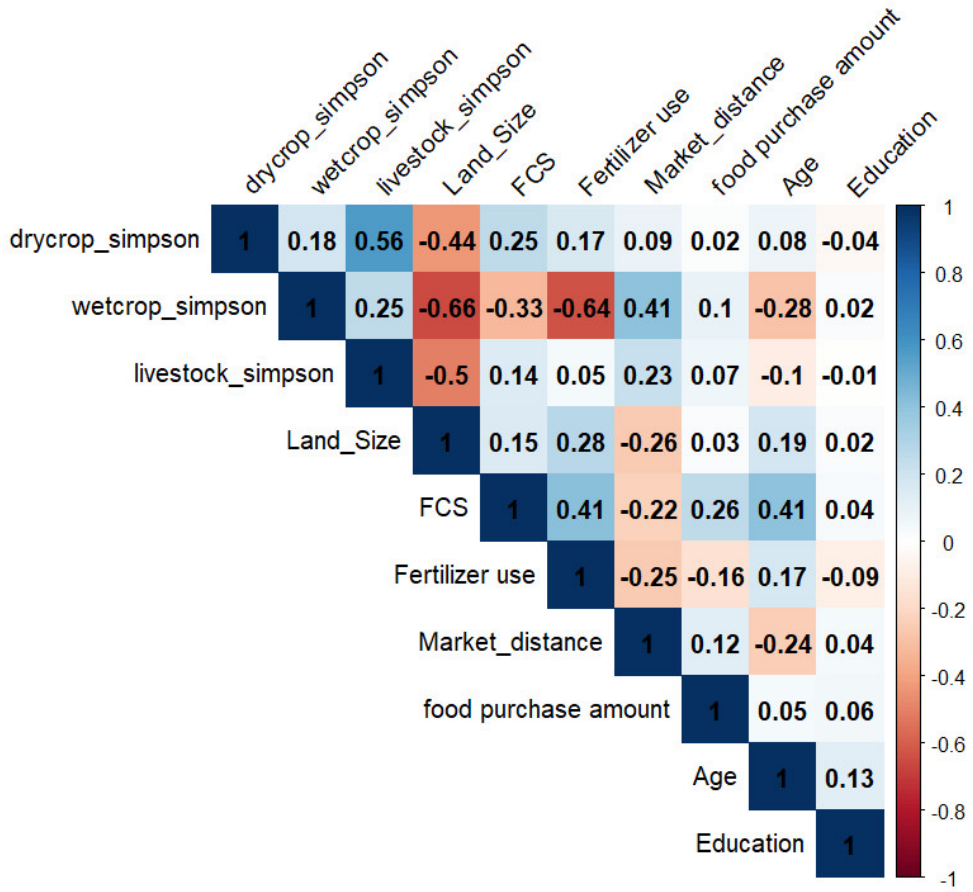


Figure 3. The heatmap depicts a correlation matrix focusing on agricultural diversification, household resources, and market-related factors. Note: Land Size in Sq. Km, Fertilizer use in Kg per hector, Market distance in Km, Education in Count number, Income in Rupees.

Table 3. Relationship between dietary diversity score and agriculture diversification.

		Dietary Diversity Score					
	Median	**Estimate**	**std. Error**	***t*-Value**	***p*-Value**	**R-Square**	**F-Value**
Wet season Crop Diversification	1.120	−13.008	2.449	−5.312	$\mathbf{3.97 \times 10^{-07}}$ ***	0.2158	13.39
Dry season crop Diversification		17.430	5.571	3.129	**0.00212** **		
Livestock Diversification		16.452	17.408	0.945	0.34618		

Note: Significant codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', and 1.

Larger food expenditures, nearby market access, and higher agricultural income are positively connected with DDS, underscoring the significance of economic considerations in dietary variety. Males have a significantly higher estimate than females, as indicated by the *t*-value (2.89) and a significant *p*-value (0.00443 **). Market access (distance KM) has a significant negative relationship with dietary variety score, according to the research (Estimate = −0.4305, $p = 0.00623$). This relationship shows that as market access distance grows, dietary variety declines. Food purchase (NRs.) exhibits a statistically significant positive connection with dietary diversity score (estimate = 0.11179, $p = 0.00163$), indicating that dietary diversity and food spending are correlated. Agriculture-related income has a substantial positive impact on the dietary diversity score as well (estimate = 7.482×10^{-05}, $p = 0.0036$); however, education, crop price, and non-agriculture-related income do not have a significant impact on the dietary score. The R-square values indicate that the model only adequately accounts for a small amount of the variation in the dietary diversity score.

Analyzing Table 4 for dry and wet season crop diversification, it appears that age has a significant negative correlation with wet season crop diversification ($t = -3.61$, $p < 0.001$) but not with dry season. Gender differences in crop diversification are significant in the dry season ($p = 0.688$) and wet season ($p = 0.029$), with males diversifying more in the latter. Land type shows a significant difference in diversification between lowland and upland, with upland showing a strong positive correlation in both seasons. Irrigation mode is significant for rainfed and tube-well/boring with wet season diversification. Fertilizer use is significant in dry season ($p < 0.05$) and very significant in wet season ($p < 0.001$). Labor availability correlates significantly with diversification in both seasons, and market access shows a significant positive correlation with wet season diversification. Education, labor cost, and crop price do not show a significant correlation with crop diversification in either season.

Table 4. Various factor affecting the food consumption patterns or dietary diversity score.

		Dietary Diversity Score					
	Category	**Estimate**	**std. Error**	***t*-Value**	***p*-Value**	**R-Square**	**F-Value**
Gender	**Male**	0.13328	0.04612	2.89	**0.00443** **	0.05342	8.352
	Female	0.03845	0.11318	0.34	**0.735**	0.000779	0.1154
Market access	**Distance KM**	−0.4305	0.1551	−2.775	**0.00623** **	0.04946	7.701
Food purchase	**NRs.**	0.11179	0.03482	3.210	**0.00163** **	0.06511	10.31
Income	**Agriculture**	7.482×10^{-05}	2.529×10^{-05}	2.959	**0.0036** **	0.0562	8.753
	Non-agriculture	7.028×10^{-07}	6.033×10^{-06}	0.116	0.907	9.167×10^{-05}	0.01357
Crop price	**NRs.**	−0.001539	0.001869	−0.824	0.411	0.6785	0.004564
Education	**Yes**	0.001755	0.004060	0.432	0.666	0.00126	0.1867
	No	0.001551	0.008643	0.179	0.858	0.0002175	0.03219

Note: Significant codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', and 1.

The results from Tables 5 and 6 show that both crop and livestock diversification in Nepal are strongly influenced by factors such as gender, land type, irrigation mode, and market access. For crop diversification, males are significantly more involved in wet season diversification ($t = -5.345$, $p < 0.001$), while females contribute more in the dry season ($t = 2.198$, $p = 0.029$). Upland areas positively influence both dry and wet season diversification ($t = 3.502$, $p < 0.001$ and $t = 10.08$, $p < 0.001$, respectively), whereas lowland areas have a negative impact on wet season crops ($t = -14.89$, $p < 0.001$). Irrigation is key, with rainfed systems considerably increasing both wet season ($t = 4.851$, $p < 0.001$) and dry season diversification ($t = 3.49$, $p = 0.0006$), whereas fertilizer usage significantly reduces wet season diversification ($t = -10.12$, $p < 0.001$). Market access is crucial for wet season crop diversity ($t = 5.461$, $p < 0.001$), indicating the favorable impact of closeness to markets on diversification.

Table 5. Influence of various factors on dry season and wet season crop diversification in Nepal.

Variable	**Categories**	**Mean**	**SD**	**Dry Season Crop Diversification**			**Wet Season Crop Diversification**		
				***t*-Value**	***p*-Value**	**F-Value**	***t*-Value**	***p*-Value**	**F-Value**
Age		43.478	3.869	0.930	0.354	0.8657	−3.61	**0.000** ***	13.06
Gender	Male	27.87	15.16	0.402	0.688	0.1615	−5.345	**0.000** ***	28.57
	Female	6.79	6.35	2.198	**0.029** *	4.833	−1.042	0.299	1.085
Land type	Lowland	88.38	63.207	0.318	0.751	0.1011	−14.89	**0.000** ***	221.7
	Upland	100.95	78.047	3.502	**0.0006** ***	12.26	10.08	**0.000** ***	101.6
Irrigation mode	Canal	37.05	24.181	1.908	**0.0583.**	3.641	−1.029	0.305	1.059
	Rainfed	134.74	74.7996	3.49	**0.0006** ***	12.18	4.851	**0.000** ***	23.53
	Well	0.4667	1.45937	1.501	0.136	2.253	0.11	0.912	0.01214
	Pond/Tank	0.5533	1.50853	0.191	0.849	0.03657	1.482	0.14	2.197
	Tube-well/Boring	15.967	30.5171	−0.645	0.52	0.4163	−18.22	**0.000** ***	332.1
Fertilizer	Yes	63.087	52.2349	2.083	**0.039** *	4.337	−10.12	**0.000** ***	102.4
	No	57.04	28.4192	−0.899	0.37	0.8073	−2.524	**0.0127** *	6.37
Fertilizer cost	NRs.	1124.2	1073.92	1.038	0.301	1.078	−11.68	**0.000** ***	136.5
Pesticide	Yes	23.88	31.0548	0.086	0.932	0.0073	−11.56	**0.000** ***	133.6
	No	96.253	45.1027	1.771	0.0786	3.136	−5.225	**0.000** ***	27.3
Pesticide cost	NRs.	153.74	228.699	−0.099	0.922	0.009713	−4.985	**0.000** ***	24.85

Table 5. *Cont.*

Variable	Categories	Mean	SD	Dry Season Crop Diversification			Wet Season Crop Diversification		
				t-Value	*p*-Value	F-Value	*t*-Value	*p*-Value	F-Value
Labor availability	Yes	46.893	33.3517	2.109	**0.037** *	4.45	−6.475	**0.000** ***	41.92
	No	73.24	41.1260	0.301	0.764	0.0907	−8.481	**0.000** ***	71.93
Labor cost	NRs.	1481.0	1127.01	1.518	0.131	2.304	−1.437	0.153	2.065
Crop price	NRs.	228.51	383.856	0.957	0.34	0.9162	0.478	0.634	0.2281
Market access	Distance KM	6.3405	4.51879	1.102	0.272	1.214	5.461	**0.000** ***	29.82
Education	Yes	363.75	176.968	−0.448	0.655	0.2004	0.275	0.783	0.07585
	No	152.45	83.17916	−0.562	0.575	0.3163	0.229	0.819	0.05237

Note: Significant codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', and 1.

Table 6. Various factor associated with livestock diversification in Nepal.

Variable	Categories	Mean	SD	Livestock Diversification			
				Estimate	*t*-Value	*p*-Value	F-Value
Age		43.478	3.869	−0.00114	−1.18	0.237	1.413
Gender	Male	27.87	15.16	−0.0001084	−0.44	0.661	0.1933
	Female	6.79	6.35	0.0011650	2.003	**0.047** *	4.013
Land type	Lowland	88.38	63.207	-6.972×10^{-05}	−1.183	0.239	1.399
	Upland	100.953	78.047	2.019×10^{-04}	4.487	**0.000** ***	20.13
Irrigation mode	Canal	37.05	24.181	0.0003093	2.026	**0.0445** *	4.105
	Rainfed	134.74	74.79964	1.685×10^{-04}	3.504	**0.000** ***	12.28
Labor availability	Yes	46.8933	33.3517	-5.166×10^{-05}	−0.461	0.646	0.2123
	No	73.24	41.1260	-5.530×10^{-05}	−0.608	0.544	0.3702
Labor cost	NRs.	1481.04	1127.01	5.497×10^{-07}	0.166	0.869	0.02741
Market access	Distance KM	6.34048	4.51879	0.0023860	2.965	**0.00353** **	8.792
Education	Yes	363.75	176.968	-2.904×10^{-06}	−0.137	0.891	0.01885
	No	152.45	83.17916	-5.941×10^{-05}	−1.328	0.186	1.764

Note: Significant codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', and 1.

For livestock diversification, females show significantly higher diversity ($t = 2.003$, $p = 0.047$), and upland areas again show a strong positive effect ($t = 4.487$, $p < 0.001$). Rainfed irrigation systems are positively associated with livestock diversification ($t = 3.504$, $p < 0.001$), and market access remains a crucial factor, with proximity to markets significantly increasing livestock diversification ($t = 2.965$, $p = 0.00353$).

5.4. Discussion

5.4.1. Season Crop and Livestock Diversification in Relationship with Dietary Diversity

The adverse correlation from Table 3 may indicate that dietary diversity declines as wet-season crop diversification rises. This could be due to farmers focusing on a limited number of staple crops like rice and maize during the wet season, leading to a reduced assortment of foods being consumed. Also, Figures 3 and A1, A2, A3 and Table 5 suggest that crop diversification during the wet season is lower in the Terai, or lowland areas, compared to the hilly or upland regions of Nepal. This trend is attributed to waterlogging in the Terai region, which compels farmers to predominantly cultivate rice. A decline in the production of some nutrient-rich crops that contribute to nutritional variety might, on the other hand, result from increasing diversification in wet season crops [13,37]. The dry season might allow for the cultivation of alternative and nutritionally diverse crops like legumes, millets, and certain vegetables, which can enhance dietary diversity [38]. In Nepalese communities, cattle and buffalo are frequently considered capital rather than regular food sources [39]. Livestock ownership, particularly in smallholder agricultural systems, is frequently connected with financial stability rather than immediate nutritional advantages. However, livestock-derived goods such as milk, meat, and eggs can help to diversify household diets [19,40]. While livestock diversification does not directly affect dietary variety, studies have demonstrated that access to different livestock products improves nutritional outcomes, particularly in rural and resource-poor settings [41,42].

5.4.2. Factor Associated with Dietary Diversity in Consumption

Aging individuals often become more discerning regarding dietary choices and intake, yet alterations in consumption and variety may escalate the risk of nutrition-related dis-

orders [43], with national-level data indicating a correlation between advancing age and enhanced food consumption scores (FCSs). Market proximity enhances dietary diversity by enabling easier access to assorted nutritious foods, including fresh produce and meats [12]. Nutritional outcomes in smallholder farmers are contingent on market functionality and intra-household income management, as shown in Figure A4. Access to nearby markets and the generation of high-incomes enable smallholder farmers to purchase a diverse array of food products [19], which allows for a shift in consumption from homegrown produce to processed foods, potentially affecting human health. Lower household incomes, typically linked with poorer dietary quality, can inversely affect the diversity of food production and consumption. So, targeting household food expenditures could be a key strategy to enhance diet quality in low-income groups, contingent on the affordability of food items [44]. Besides all this, education and gender aspects have a positive impact on household dietary decisions and food security because female education and empowerment are pivotal in altering household dietary practices, improving nutrition, and thus influencing diet-related health outcomes in developing countries [45].

5.4.3. Effect of Variable in Agriculture Diversification

Geographic (land type) and climatic variations significantly influence agricultural diversity, with the Bari (upland) region's farming in dry and wet seasons, including livestock, showing high diversification due to efficient natural resource use and lower input costs for fertilizers, pesticides, and labor, as Table 5 illustrates. Cropping diversification enhances the economic viability and social acceptability of sustainable upland agriculture, but intensive use of agrochemicals and hybrid seeds is reducing soil fertility and increasing farmer reliance on external inputs, compromising long-term sustainability [26]. In Khet (lowland) regions prone to waterlogging, crop diversity decreases during the wet season due to reliance on tube wells and rainfed irrigation, indicating that water management costs affect crop selection, resulting in farmers achieving only 76% of the maximum rice farming potential [23,46]. The diversification of crops and livestock on farms is largely attributed to female farmers, with evidence showing that over 74% of women actively participate in the decision-making processes related to farming practices [39]. Furthermore, increased labor and farmer experience (older age farmers') enhance dry-season crop variety, whereas labor scarcity hampers diversification in wet seasons. However, few agricultural models consider labor supply as a decisive factor in farming choices, even though labor is crucial for producing many fruits and vegetables [47]. These findings imply that farmers near markets tend to focus on a narrower range of high-demand crops, whereas those farther away choose diversification to mitigate risks. Proximity to markets is key for agricultural diversification; farmers tend to diversify when markets are within easy reach, easing the sale of produce and mitigating market competition risks [12]. Diversification on farms can increase and stabilize income to a threshold, beyond which it may decrease income due to lost specialization advantages [19]. The limited influence of education suggests it may not be a critical factor in crop selection or that other factors outweigh its significance.

5.4.4. Important Correlation Matrix Factor of Agriculture Diversification and Dietary Diversity with Socioeconomic Variables

Access to nearby markets will lead farmers to engage in selling farm produce, which can enhance dietary variety by increasing household income and introducing a broader food selection. This can lead to better nutrition, particularly for women and children in low-income areas who often face restricted food diversity. Enhancing market access and income diversification for smallholder farmers is key to improving dietary quality and food security. Investments in rural infrastructure and market facilities are recommended to facilitate market access, reduce transportation costs, and save time [12]. The fragmentation of agricultural land in Nepal presents a potential avenue for diversifying agriculture, and utilizing a community- or group-based approach is recommended to enhance agricultural performance. Farmland fragmentation is linked to diversified food sources, encompassing

aspects such as food quality, acceptability, accessibility, and local community autonomy at the individual and household levels. Conversely, at broader scales, such as community, region, and country, consolidating farmland often correlates with increased total food production and availability [48]. Furthermore, the enhancement of cropping intensity is influenced by both irrigation facilities and a diverse range of crops cultivated. For instance, shifting from water-intensive crops (e.g., paddy or sugarcane) to pulses in the Rabi (dry) season may not require many irrigation facilities, leading to an inverse relationship between the two [49]. In Nepal's context, diversifying the crop portfolio not only reduces the impact of drought in upland regions but also improves water utilization efficiency and boosts crop yields.

6. Conclusions

The study found a considerable beneficial association between agricultural diversification and dietary variety among Nepalese smallholder farmers, especially in highland areas and during the dry cropping season. The study finds that factors such as market access, irrigation infrastructure, input availability, and labor impact farmers' capacity to diversify their crops, which improves nutritional results. While market access and material availability are important, gender engagement and seasonal crop fluctuation also play a role in increasing dietary diversity. These findings indicate that smallholder farmers' food security and livelihood resilience may be improved by smart investments in infrastructure, resources, and education.

7. Policy Recommendation

7.1. Improve Market Access Through Infrastructure Development

Governments should make investments in rural and upland transportation infrastructure in order to increase agricultural and nutritional diversification. Better roads and rural markets may reduce the time and expense of transporting goods, enabling farmers to more efficiently access markets and buy a variety of items with different nutritional values. The availability of a wider variety of crops and the resulting demand for a wider variety of food items will result from building closer to urban centers, which will have a direct impact on family nutrition.

7.2. Invest in Irrigation Systems and Water Management

The study highlights how important irrigation systems are, especially in the dry seasons when diversity is most useful. In order to enable farmers to grow a variety of crops all year round, governments should give priority to developing rainfed and canal irrigation systems in upland regions. Purchasing water-saving equipment can help ensure sustainability in the face of climate change, boosting smallholder farmers' income and agricultural productivity. Having access to an IoT sensor-based soil moisture device would also empower farmers to make wise decisions about conserving water for crop growth.

7.3. Facilitate Access to Agricultural Inputs

To achieve the best possible crop diversity, human resources and fertilizers must be easily accessible. In order to guarantee prompt access to these inputs, the government had to construct input distribution hubs in rural areas and give subsidies. Policy frameworks should also prioritize improving smallholder farmers' access to reasonably priced finance so they may purchase inputs that will increase their crop diversity and resilience.

7.4. Encourage Gender-Responsive Agricultural Programs

Women play an important role in agricultural decision-making, especially in livestock and crop diversification. Policies ought to support initiatives that are gender-sensitive and assist women in gaining access to leadership opportunities, training, and resources in the agricultural industry. Women are major contributors to dietary diversity in rural regions;

thus, increasing their involvement in agricultural decision-making will empower them and enhance nutrition in the home as a whole.

7.5. Expand Agricultural Extension and Education Services

It is necessary to improve extension services in order to provide smallholder farmers the information and assistance they need to adopt sustainable diversification strategies. To inform farmers about market opportunities, climate-resilient crops, and effective agricultural practices, the government should emphasize growing extension services, especially in upland regions. Extension programs can also improve dietary outcomes by including nutrition education.

7.6. Support Community-Based Farming and Land Consolidation Initiatives

Policies should support community-based agricultural projects, encouraging cooperative farming and shared access to resources like irrigation systems and markets, especially in places where land fragmentation is impeding diversity. With the help of this strategy, smallholder farmers will be able to overcome obstacles caused by their small land sizes and little resources, which will increase their capacity to diversify their crops and raise food security.

8. Limitation and Challenges

Several limits were faced, even though the data had time limitations and gave significant insights for the newly proposed project. First, the dataset showed signs of potential data bias. To address this, imputation techniques such as mean or median imputation were used for missing numerical data to avoid making inaccurate assumptions, such as considering missing values as zero, which might skew the results. Second, crucial variables intimately related to the theoretical framework were overlooked, such as precise household socioeconomic data, access to extension services, and more complex irrigation techniques. Future studies must incorporate these variables to offer a more complete picture of the factors impacting agricultural diversification and nutritional variety. Third, measurement errors were discovered, notably with seasonal food patterns, which were not fully represented due to temporal variability. To address this issue, future research should use a time-series analysis or seasonal decomposition technique to distinguish seasonal impacts from long-term trends. Finally, the use of R statistical software and the vegan package posed new hurdles to ecological diversity research. Collaboration with statistical specialists and the use of alternative software packages intended for longitudinal and panel data analysis can improve the accuracy and efficiency of future studies.

Author Contributions: Writing Original draft, reviewing, editing, visualization, conceptualization, Methodology, result and discussion by B.N., and Supervision by T.J. and C.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Adelaide (protocol code 4339_AGRIBUS_7062B, approved on 24 November 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The World Bank; https://microdata.worldbank.org/index.php/catalog/3705. Household Risk and Vulnerability Survey, Full Panel 2016-2018, accessed on 17 September 2021.

Acknowledgments: Gratitude is extended to the Australian Centre for International Agricultural Research (ACIAR) for providing an internship opportunity, and profound appreciation is directed towards the principal supervisor Craig Johns, mentor Tamara Jackson from the ACIAR project lead, as well as Adam Loch and Di Zeng for their invaluable guidance and mentorship. Data were collected and available in The World Bank; https://microdata.worldbank.org/index.php/catalog/3705.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The World Food Program (WFP) designed the food group frequency weight to measure the dietary diversity Score (DDS) or food consumption score (FCS) by an individual within a week.

S. No.	Food Items	Food Group	Weight
1	Rice; beaten, flattened rice; maize; maize flour; wheat flour; millet; barley	Cereals and field crops	2
2	Lentil (black gram), horse gram, beans (greengram, masyaura)	Beans	3
3	Potatoes, onions, tomatoes, green leafy vegetables, other vegetables	Vegetable	1
4	Fruits, dried fruits and nuts (coconut, cashew, dates, etc.)	Fruit	1
5	Fish, mutton, buffalo meat, chicken, other meats (pig, boar, duck)	Fish and meat	4
6	Eggs, milk, powder milk, curd/whey, other milk products (cheese, paneer)	Egg and milk	4
7	Sugar, gur (sakhar), sweets (mithai), tea (dried leaves)/coffee (ground, instant), other non-alcohoblic (fruit juice, Coca Cola, Pepsi)	Sugar	0.5
8	Ghees, vegetable oil, mustard oil, other oil (soya, sunflower, corn, etc.)	Oils	0.5
9	All types of alcohol, cigarettes, tobacco, jarda, khaini, beetle, misc. other food expenditures, none, salt, other spices and condiments (coriander, nutmeg)	Condiments	0

[28]

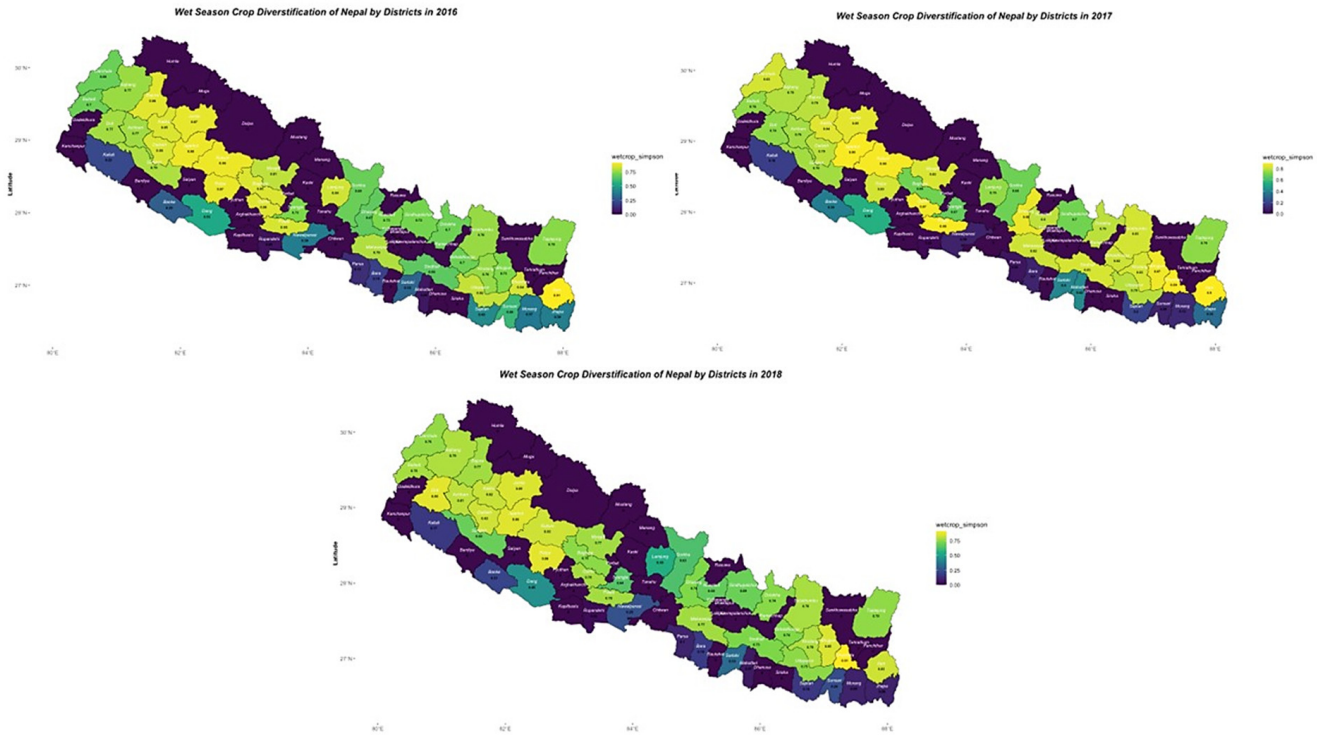


Figure A1. Crop diversification in Nepal during wet season from 2016 to 2018.

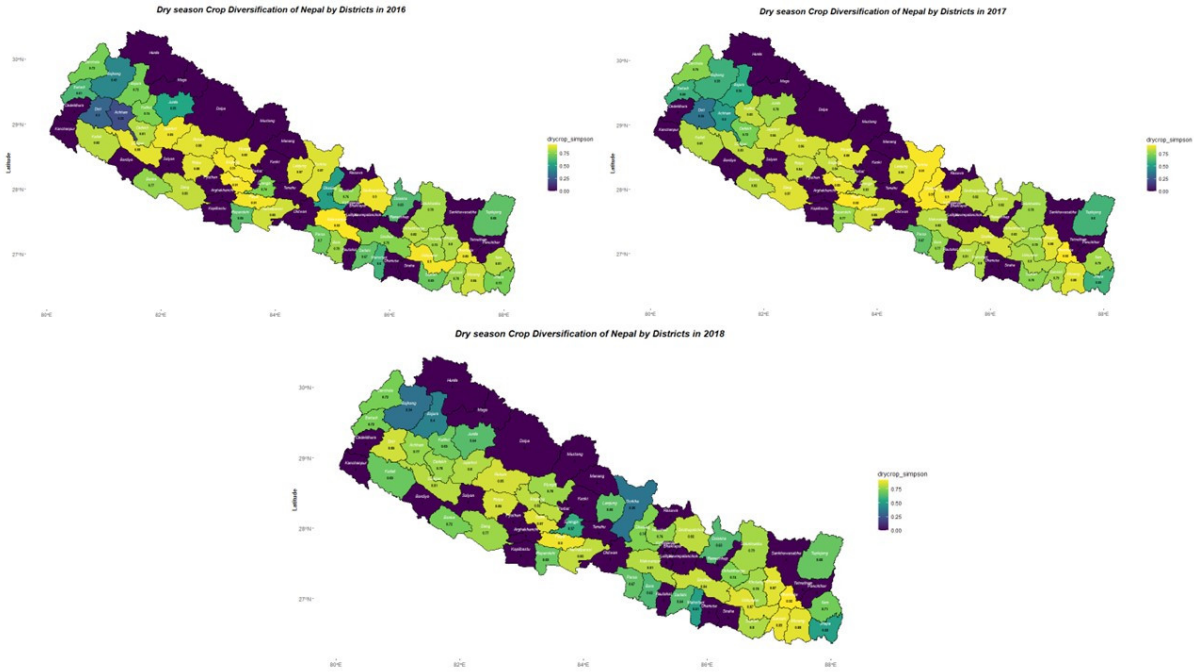


Figure A2. Crop diversification in Nepal during dry season from 2016 to 2018.

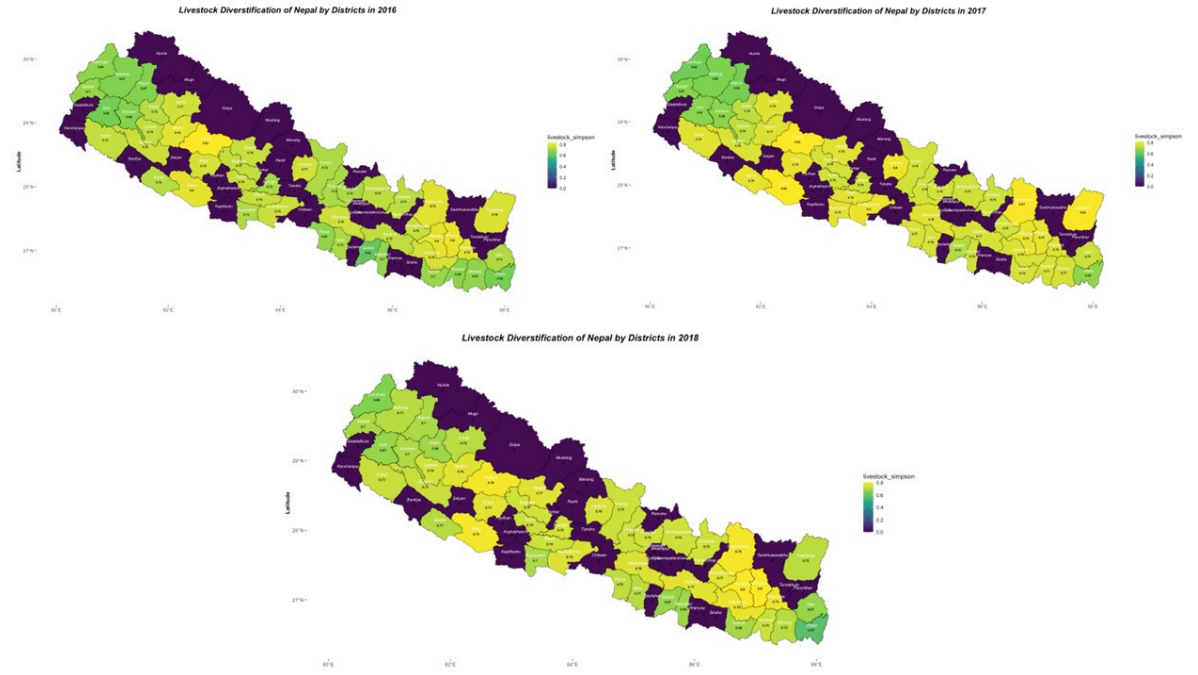


Figure A3. Livestock diversification in Nepal from 2016 to 2018.

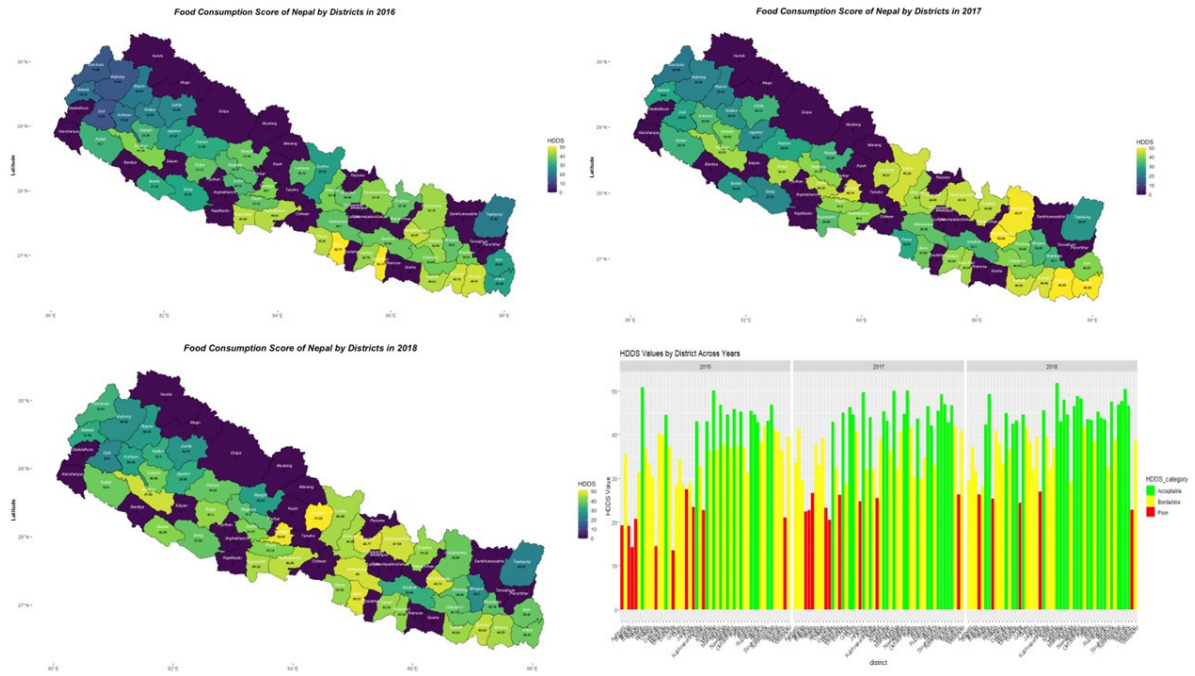


Figure A4. Dietary diversity score pattern in Nepal from 2016 to 2018.

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