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DRIVERS OF SMALLHOLDER FARMERS' CROP DIVERSIFICATION: EVIDENCE FROM THE RICE-DOMINATED FARMING SYSTEM OF FOGERA PLAIN, NORTHWEST ETHIOPIA

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ABSTRACT

Crop diversification has long been a key strategy for smallholder farmers in Ethiopia to mitigate climatic and market-related risks, and it is actively promoted in the country's agricultural policy as a pathway to resilient cropping systems. Beyond reducing risks, diversification provides multiple benefits, including increased farm income, employment generation, natural resource conservation, reduced pest and disease pressure, and improved soil fertility. Given its importance, this study examined the level and drivers of crop diversification among 397 systematically sampled households in Fogera plain northwest Ethiopia, using descriptive and inferential statistics, including the double-hurdle model. Results indicate an average Simpson Diversification Index (SDI) of 0.48 (SD = 0.27), with values ranging from 0 to 0.82, and 47.61% of households exhibiting a moderate level of diversification. Most diversified households cultivated at least one crop from three major categories, cereals, legumes and vegetables, highlighting its role in enhancing food security and income stability. Econometric analysis identified key factors influencing both the decision to diversify and the intensity of diversification. Participation in crop diversification was significantly affected by occupation, number of plots, proportion of fertile land, access to irrigation, and use of improved seeds, reflecting both resource availability and institutional support. Meanwhile, the intensity of diversification was shaped by factors such as age, number of plots, oxen ownership, and access to credit, with older (experienced) farmers and those with higher number of plots and better financial access demonstrating higher diversification level. These findings underscore the importance of both household-level factors and financial enablers in shaping diversification decisions among smallholder farmers. To enhance crop diversification and build more resilient farming systems, several policy measures are recommended. These include providing improved seeds suited to diverse agro-ecological conditions, expanding irrigation infrastructure, enforcing effective water user association regulations, improving access to credit, strengthening livestock health services, and promoting alternative tillage technologies. Implementing these strategies will help farmers diversify their cropping systems more effectively, contributing to Ethiopia's broader policy goals of food security, income diversification and environmental sustainability.

Key words: diversification, double-hurdle, Ethiopia, Fogera Plain, rice, risks, SDI, smallholder farmers

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INTRODUCTION

Ethiopia is blessed with enormous and diversified natural resources that are favorable for agricultural development. It is endowed with 74.3 and 4.3 million hectares of land apposite for rain-fed and irrigation-based crop production, respectively [1]. In addition, the availability of different agro ecological zones provides an opportunity to cultivate diverse crops [2]. Efforts have been made by different actors to exploit these potentials, thereby attaining the major objective of a nation, which is improving farmers' incomes and livelihoods to end poverty by making agriculture more productive and competitive [3].

Ethiopia's agricultural sector is smallholder-dominated and characterized by low-productivity [4]. Smallholder farmers, who account for over 15 million, plow approximately 96% of the 18 million hectares of land and produce 95% of the national crop supply [5]. Contrary to their significant contribution, they are commonly identified as subsistence-oriented; they mainly own fragmented land, produce mostly for their consumption, generate only a small market surplus, are lower-income earners, and cannot invest well in their farms [6,7]. The second characteristic of the sector, low productivity, mainly emanates from structural, institutional and climate change factors [6,8].

Crop diversification is assumed to be a mitigation and adaptation strategy for limiting the damage caused by climate change. Farmers are able to spread production and financial risk among a number of crops by diversifying their crop portfolios. Farmers who diversify their farms can have the benefits of enhancing resilience to highly variable weather conditions, increase income on small farm holdings, help to withstand fluctuations in commodity prices, maximize income by expanding the market potential, increase profits by minimizing production costs and increase employment opportunities [9]. It could also provide nutritionally diversified and healthy food, decrease pest pressure by disturbing the full cycles of insects and diseases, enhance beneficial pollinator populations, improve soil quality and increase crop yields [10].

The debate on crop diversification versus specialization revolves around balancing productivity, risk management and long-term sustainability. Specialization allows farmers to focus on a single high-demand crop, maximizing efficiency, optimizing resources and increasing profitability. However, this approach carries significant risks, such as vulnerability to market fluctuations, pests, diseases and soil depletion, which can threaten livelihoods if a single crop fails. In contrast, diversification spreads risk across multiple crops, improving resilience against climate variability and market instability while enhancing soil health and ecological balance. However, managing multiple crops can be complex, requiring additional technical skills,

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resources and labor, which may reduce overall efficiency. A middle-ground strategy, market-based diversification, seeks to combine the advantages of both approaches by selecting complementary crops that meet market demand while supporting soil fertility and pest control. Ultimately, the choice between diversification and specialization depends on factors such as climate conditions, infrastructure, market access, and a farmer's ability to manage risks effectively.

Optimizing the benefits of crop diversification requires a thorough understanding of the factors that drive or hinder its adoption. Farmers are motivated by economic incentives, risk management strategies, soil health improvement and market opportunities. However, challenges such as limited knowledge, financial constraints, policy barriers and climate variability can discourage diversification [10, 11]. Based on theoretical frameworks, empirical literature and researcher observations, key drivers of crop diversification have been identified to address major research questions. These include understanding the socio-economic factors that influence crop diversification, examining how biophysical factors such as soil fertility and land fragmentation, along with institutional factors like access to extension services and credit, impact farmers' decisions, and exploring the role of technological innovations such as improved seed varieties and irrigation systems in the adoption of diversification practices. By analyzing these aspects, this study aimed to provide insights into the enablers and barriers to crop diversification, offering a foundation for targeted interventions and policy recommendations.

This study was, therefore, motivated by two key issues. First, in empirical research analyzing the drivers of farmers' crop diversification, the theoretical background is often the primary justification for selecting a model. However, relying solely on the theoretical background is insufficient because the nature of the data (its fit to the model) also plays a crucial role in ensuring consistent, unbiased, and valid results. Second, to the best of the researchers' knowledge, no similar research has been conducted in the study area. To address these gaps, this study will apply a model-specification test to achieve its objective.

MATERIALS AND METHODS

Study area description

South Gonder Zone is located at the center of the Amhara region and is bordered by six zones along with Lake Tana, the largest lake in Ethiopia, which is recognized as a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage and Biosphere Reserve Site due to its ecological and cultural significance [12]. The zone lies at 11° 50' 19" latitude and 38° 5' 58" longitude, covering an area of 14,095.19 square kilometers (see Figure 1). Within this zone, the study area comprises three districts, Fogera, Dera and Libokemkem, collectively known as the Fogera Plain. In the past, the Fogera Plain was characterized by extensive swamps during the rainy season, making it unsuitable for crop cultivation. As a result, the land was primarily used for grazing by the indigenous Fogera cattle breed, which is well adapted to waterlogged conditions [13]. To some extent, farmers cultivated tef and niger seed once the wetlands dried after the rainy season [14]. The subsequent introduction of rice shifted the dominant land use from cattle grazing to cultivation of multiple crops [13]. As rice farming expanded, grass pea production also emerged and became a popular successor crop to rice due to its ability to support double- or triple-cropping while also improving soil fertility. Additionally, new crops such as vegetables like onion and tomato and maize were introduced to the wetlands [14]. The increasing trend of cultivating multiple crops is attributed to several factors, including favorable and diverse agro-ecological conditions, relatively larger landholdings, expansion of irrigation using abundant water sources, and support from agricultural institutions.

The three districts of the Fogera Plain are endowed with diverse natural resources that support a large number of smallholder farmers, whose livelihoods primarily depend on agriculture. The area's favorable agro-ecological conditions make it highly suitable for cultivating a variety of crops. Fogera, with an altitude ranging from 1,774 to 2,410 meters above sea level (masl), receives an average annual rainfall of 1,216 mm and has a mean temperature of 19°C, with a temperature range of 10.7°C to 27.3°C [15]. Libokemkem, situated at an altitude of 1,800 to 2,850 masl, experiences annual rainfall between 900 mm and 1,200 mm, with temperatures ranging from 12°C to 26°C [16]. Dera, at an altitude of 1,500 to 2,600 masl, receives 1,000 mm to 1,500 mm of annual rainfall, with temperature varying between 15°C and 32°C [16]. In addition to these favorable environmental conditions, the study area offers relatively large farmlands. On average, farmers own one hectare of land, which is higher than the Amhara region's average landholding of approximately 0.75 hectares [17]. Moreover, the area is blessed with abundant water resources, including Lake Tana and two major rivers, Gumara and Rib. These water bodies provide irrigation opportunities during the dry season, enabling farmers to cultivate multiple crops beyond the rainy season. Access to reliable water sources has significantly contributed to the expansion of diversified farming practices in the area.

Moreover, the availability of several institutions in the study area plays a vital role in facilitating crop diversification. Institutions such as the Fogera National Rice Research Training Center (FNRRTC), Agricultural Technical and Vocational Education and Training (ATVET), and the Amhara Credit and Saving Institution (ACSI) and unions and cooperatives provide essential services to farmers. These institutions support farmers by supplying well-adapted agricultural technologies, offering high-quality extension services, improving access to agricultural inputs and

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alleviating financial constraints faced by smallholder farmers. By improving access to credit and modern farming techniques, they enable farmers to invest in agricultural intensification, a key driver of crop diversification. As a result of these combined factors, on a national scale, the study area is recognized as a key hub for horticulture and cereal commercialization [18]. Additionally, it has emerged as a promising location for rice cultivation, a newly introduced crop in Ethiopia, often referred to as the country's "white gold" and "millennium crop" [19].

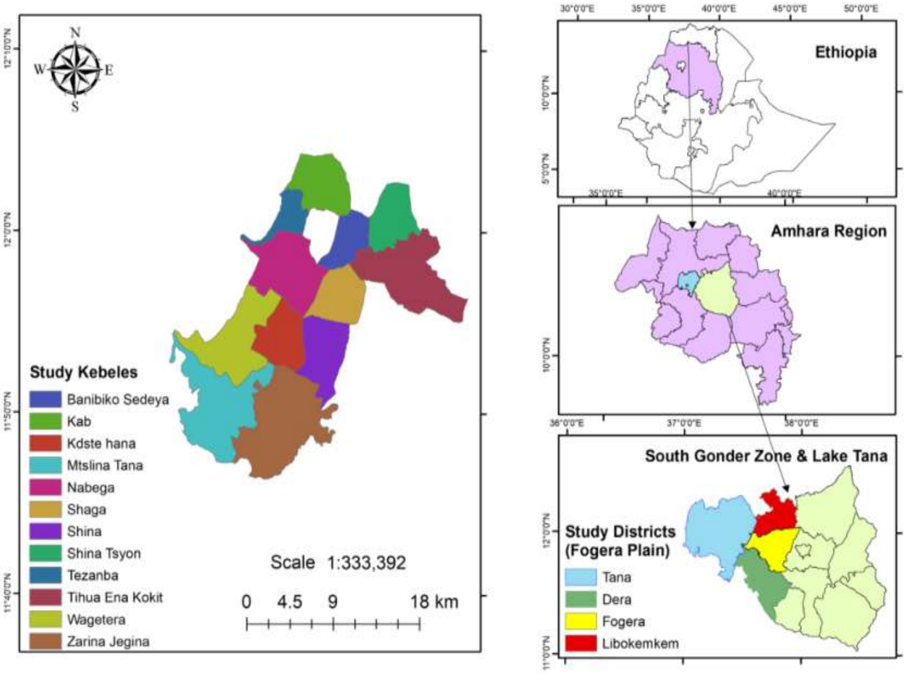

Figure 1: Geographical location map of the study area
Source: Ethio-Geospatial data (2021)

Methods of sampling and sample size determination

A multistage sampling procedure was employed to draw districts, *kebeles*[1] and farm households to be considered in the study. In the first stage, the Fogera, Libokemkem, and Dera districts were randomly selected as the primary sampling units. In the second stage, 13 *kebeles* were randomly selected with a distribution of six, four and three *kebeles* from the Fogera, Libokemkem, and Dera districts, respectively. In the third stage, the ultimate sampling units, sample farm households, were selected with a probability proportional to the population size using a systematic random sampling technique. The study used sampling frames developed by the agricultural offices of the respective districts. The study applied Yamane's [20] sample size determination formula to calculate the minimum sample size. Its

[1] *Kebele* is the lowest administrative unit in the Federal Democratic Republic of Ethiopia.

merits over Cochran 's is that it uses the population size to determine the sample size. It also provides a relatively larger sample size than Kotari and Chochran.

Yamane's formula is expressed as follows:

$$n = \frac{N}{1+N(e^2)} \qquad (1)$$

where n represents the sample size, and N and e denote population size and precision, respectively.

Hence, using Yamane's formula with a precision level of 0.05 and a total population of 22,424 farm households, the minimum required sample size was 393. The study included four samples and used 397 sample households.

Data sources and collection methods

In this study, only primary data were collected directly from farmers and agricultural experts. Semi-structured questionnaires and checklists were used for individual interviews and focus group discussions (FGDs) with the farmers and agricultural experts, respectively. The questionnaire was created using CSPro version 7.2 software to facilitate data collection using Information Communication Technology (ICT). Pre-testing of the questionnaire was undertaken in May 2021 ahead of practicing full-flagged data collection, which was undertaken in May and June 2021. In addition, five FGDs with farmers and six key informant interviews with crop experts and office heads of the respective districts were undertaken by the researchers. The FGDs were executed in September 2021, after the generation of results from econometric model estimation, to gain a better insight into why and how the statistically significant variables influenced smallholder farmers' decision to diversify and intensity of diversification.

Data analysis

Data analysis was performed using descriptive statistics and econometric model, accompanied by the STATA 15 software package. Descriptive statistical tools such as the mean, standard deviation, frequency, and percentage were used to describe the characteristics of the respondent households. The independent t-test was used to compare the mean difference of independent variables while the chi-squared test was used to test relationship or interdependency of dummy explanatory variables between crop diversification decision categories. Moreover, a double-hurdle econometric model was used to identify the drivers of smallholder farmers' crop diversification. The model separates crop diversification decisions into two distinct stages. The first decision is whether or not to diversify, influenced by factors like risk preferences, profitability, and available resources. If the farmer chooses to diversify, the second decision concerns the extent or intensity of diversification, determining how much land, labor, or capital to allocate to new crops (diversification intensification), which is influenced by factors such as expected returns, resource constraints, and market conditions.

Crop diversification analysis

The level of crop diversification can be examined using several indices. This study used the Simpson Diversification Index (SDI), which is computed based on the Herfindahl Diversification Index (HDI). The HDI is calculated as the sum of squares of the area proportion of each crop in the total cropped area [21]. The formula used is as follows:

$$HDI = \sum_{1}^{N} Pi^2 \qquad (2)$$

where N represents the aggregated number of crops cultivated, and Pi measures the farmland share of the individual i^{th} crop in the total cultivated area. It takes the value of 1 when there is a total concentration, and tends to zero as the level of diversification increases. The SDI was calculated by subtracting the HDI from 1. The formula used is as follows:

$$SDI = 1 - \sum_{1}^{N} Pi^2 \qquad (3)$$

In this formula, Pi represents the comparable acreage of the i^{th} crop in the total cultivated acreage, and n represents the sum of the crops cultivated by the farm household. In such a case, when the value is closer to 1, there is higher diversification, while a value closer to 0 means cultivating one crop, which is specialization. The level of crop diversification can be categorized into three groups. For instance, in a study conducted by Gebiso *et al.* [22], the farm household with crop diversification index value of below 0.38 ($0 \leq SDI \leq 0.38$) is categorized in low, in between 0.39 and 0.63, ($0.39 \leq SDI \leq 0.63$) in medium, and above 0.64, ($SDI \geq 0.64$) in high level of crop diversification. This study also used similar cut-points to categorize level of crop diversification measured in SDI.

Data diagnostics

This study undertook multicollinearity, heteroscedasticity and omitted variable tests, and adopted a remedy for the admitted heteroscedasticity problem. The multicollinearity problem was tested for continuous and dummy variables using the Variance Inflation Factor (VIF) and Contingency Coefficient (CC), respectively [23]. The maximum and mean VIF values were 1.32 and 1.13, respectively. As all the VIF values were below 10, which is a cut-off point to assess whether multicollinearity exists, this result indicated the lack of a multicollinearity problem. Additionally, pairwise correlation analysis revealed that the maximum CC value was -0.58, which was less than the cut-off point value of 0.75. This finding revealed no significant correlation between or among the variables, indicating that multicollinearity was not a significant problem in the estimated model.

The presence of heteroscedasticity was determined using the Breusch-Pagan/Cook-Weisberg test. The test's findings showed that the chi-square value was 48.07, and its probability value was 0.0000. The probability value was significant in the data diagnosis procedure at the 1% level of significance, indicating the presence of heteroscedasticity problem. To address the issue, measures have been implemented to estimate models utilizing robust standard errors. Furthermore, the Ramsey RESET test was used to diagnose the omitted variables. The results of the omitted variable test (ovtest) (Prob > chi2 = 0.2315), was insignificant, indicating no omitted variables in the estimated models. In general, the diagnostic test of econometric problem with remedy mechanism for heteroscedasticity indicated no misspecification of the estimated econometric models.

Model specification

In empirical studies aiming to analyze drivers of farmers' decisions in crop diversification, the possible estimation models used included logit [24, 25], OLS [26, 27], Tobit [28, 29, 30, 31], Heckman two-stage [32, 33, 34, 35], and double-hurdle [36, 37, 38].

In this study, a hypothesis test was undertaken among the Tobit, Heckman two-stage, and double-hurdle models to select the appropriate model for the existing data and obtain a good estimation result. The point estimation method is one way of testing the null hypothesis via a test statistic that can be computed from the estimate (bk) and its standard error se(bk). Hence, the ratio of bk to se (bk) is the value of the statistic t or the t-ratio [23, 39, 40]. Following this, the t-ratio was compared with the tabulated value (t-tabulated) at a given degree of freedom and significance level using the chi-squared table distribution. If the t-ratio (t-calculated) is greater than the t-tabulated, it is evidence to reject the null hypothesis.

In comparing the Tobit and double-hurdle models, the null hypothesis posits that the Tobit model is the appropriate specification. The model test result indicated that the t-ratio for the diversification variable was 542.95, which exceeds the tabulated chi-square value of 28.86 at 18 degrees of freedom and a 5% significance level (see Table 1). This result provided sufficient evidence to reject the Tobit model in favor of the double-hurdle model. The result suggested that the decision-making process regarding crop diversification involves two distinct stages: first, the decision to diversify, and second, the intensity of diversification. These two decisions appear to be made independently by individuals, justifying the use of the double-hurdle model.

The presence or absence of selection bias is used to select the appropriate model between the Heckman and the double-hurdle. Selection bias is tested in two error terms for the two separate decisions. The results showed that the likelihood ratio of Heckman's two-stage selection was insignificant (Prob > chi2 = 0.8167) (see Table 1). This result showed that there is no correlation between the two error terms of farmers' decisions to diversify and intensity of diversification. It implied that there is no selection bias in the sample. Hence, the double-hurdle model is selected as the appropriate model for the existing data to obtain a good estimation result.

Therefore, based on the model specification test results, a double-hurdle model was selected to address the research objective. It combines the truncated regression and probit models. The probit model was used to identify the drivers of smallholder farmers' participation in crop diversification, and the truncated regression model was used to identify the drivers of intensity of crop diversification. Below is an estimate:

The first hurdle decision: (probit model)

$$\left.\begin{aligned} \mathrm{yi}^* &= \mathrm{Xi}\alpha\mathrm{i} + \mathrm{Ui} \\ yi &= 1, if\ yi^* > 0 \\ \mathrm{yi} &= 0, \mathrm{if}\ \mathrm{yi}^* \leq 0 \end{aligned}\right\} \quad (4)$$

Where yi^*= 1 for participated in crop diversification and 0 otherwise.
Ui = error term and normally distributed with (0, 1)
$\alpha\mathrm{i}$ = A vector of parameters to be estimated
Xi = vector of independent variables included in the first hurdle

The second hurdle decision: (truncated regression)

$$ti = Zi\beta i + Vi \quad (5)$$

Where ti = extent/intensity of diversification
$\beta\mathrm{i}$= A vector of parameters to be estimated
Zi = the vector of independent variables included in the second hurdle.
Vi = the error term and normally distributed with (0, σ^2)

It is assumed that the two-error terms (Ui and Vi) are independent when the independent double-hurdle model is used for estimation. The first and second decisions can be estimated simultaneously or in stages. The model outputs were identical in both the situations. The "craggit" command is used to perform joint estimation, whereas the "probit" and "truncreg" commands are used to apply step-by-step estimate [41]. As this study followed step-by-step estimation, for a better tabular presentation of the results, the probability of crop diversification decision and intensity of participation were estimated using the "probit" and "truncreg" commands, respectively. In the double-hurdle model estimation, the effect of explanatory variables was interpreted using coefficient values. In both cases, the sign of the coefficient indicates the explanatory variable's direction of influence on the dependent variable.

RESULTS AND DISCUSSION

Characteristics of sample households

As shown in Table 2, nearly 80% of the sample households were male-headed, with the majority (86.4%) classified as married. The mean age of household heads was 41.6 years, placing most within the productive age group. Age often serves as a proxy for farming experience, as older farmers typically have greater exposure to agricultural practices, climate variability and market trends, influencing their decisions on crop selection and diversification strategies. On average, households owned 0.72 hectares of farmland, closely aligned with the national and regional smallholder farmer averages of 0.78 and 0.75 hectares, respectively [7]. Land fragmentation was notably high, with an average of 5.56 plots per household, potentially offering greater opportunities for farm diversification. Additionally, households owned an average of 1.65 oxen, providing essential draft power for timely land preparation and oxen-assisted threshing. In terms of livelihood sources, the vast majority (78.4%) relied solely on farm income, while only 21.6% supplemented their earnings through off-farm or non-farm activities.

As shown in Table 3, 62.7% owned a mobile phone, enhancing their access to market information and supporting informed decisions on marketing and production. More than half (60%) of the households used improved seeds, contributing to higher crop productivity and profitability. On average, it took households around 90 minutes to travel to the main market, providing smallholder farmers with opportunities to sell their produce. Additionally, 65.74% had access to hired labor, helping to compensate for household labor shortages. Regarding institutional support, 80.86% received extension services, promoting crop diversification as part of the government's rural development initiatives. Similarly, 59.7% were cooperative members, facilitating access to agricultural inputs such as chemical fertilizers and improved crop varieties. Close to 60% had irrigation access, enabling double and triple cropping. However, access to credit services remained limited, reaching only 46.6% of households. Credit expected to play a crucial role in enabling smallholder farmers to invest in improved seeds, fertilizers, pesticides and labor, easing financial constraints in the implementation of crop intensification and diversification strategies.

Crop diversification decision by smallholder farmers

Of the total sample households, the majority (78%) practiced crop diversification, while the remaining 22% grew a single crop per season. The mean crop diversification index (SDI) value was 0.48, with a standard deviation of 0.27. The SDI values ranged from a minimum of 0 to a maximum of 0.82. In terms of crop

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diversification categories, approximately half of the sample households (47.61%) were classified as having a medium level of crop diversification, while 24.18% were categorized as low, and 28.21% as high diversification.

As shown in Figure 2, the sample households cultivated a total of 11 crop species, categorized into cereals, legumes and vegetables. The vast majority (98%) of households grew rice, followed by grass pea (52%) and teff (39.79%). In the vegetable category, approximately 30% cultivated onion. On average, each household grew 3 different crops, with the minimum being 1 crop and the maximum 6 crops.

Moreover, most of the diversified households grew at least one crop from each of the three categories: cereals, legumes and vegetables. Such diversification decisions may contribute significantly to multiple benefits via the first two agriculture and nutrition pathways. Specifically, crop diversification can improve food and nutrition security for smallholder farmers by increasing both self-consumption and income from the sale of diversified crops.

Considering the characteristics of the sample households and the untapped natural resource potential in the study area, there is significant potential to scale up crop diversification. Although the current mean crop diversification index (SDI) is 0.48, there remains many opportunities to exploit the numerous advantages of diversifying crops.

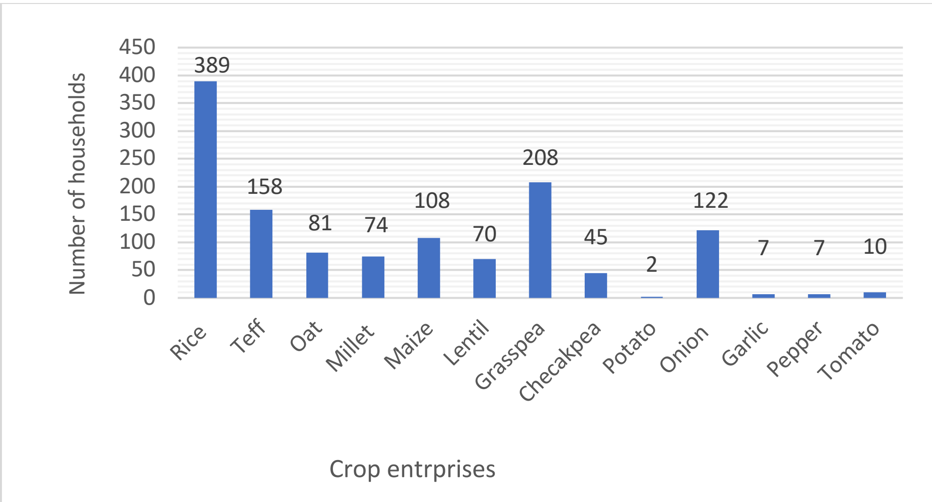

Figure 2: Number of sample households by crop enterprises

Independent continuous variables by farmers' crop diversification decision
The mean differences in the independent variables between diversified and non-diversified households were analyzed using an independent t-test. The results, as shown in Table 4, revealed significant differences at the 1% level of significance in the number of plots, the number of oxen, and the proportion of fertile land between

the two household categories. Additionally, at the 5% level of significance, significant differences were observed in the total land and market distance between diversified and non-diversified households. Specifically, the findings indicated that diversified households had a higher number of oxen, more total land, and more plots compared to non-diversified. However, diversified households had a smaller proportion of fertile land relative to non-diversified. In terms of market access, diversified households were able to reach the main market in fewer walking minutes compared to their non-diversified counterparts. These results suggest that household diversification is associated with greater land resources and better access to markets, but with a relatively lower proportion of fertile land.

Independent categorical variables by farmers' crop diversification decision
Chi-square tests were conducted to examine the relationship between categorical explanatory variables and the diversification decision category. As shown in Table 5, the results revealed statistically significant relationships between the crop diversification decision category and all the categorical explanatory variables included in the study. Specifically, at the 1% level of significance, access to hired labor, irrigation, credit, extension services, occupation, cooperative membership, mobile availability, and the use of improved seeds were all significantly associated with crop diversification decisions. Additionally, the relationship between diversification decisions and marital status was significant at the 5% level, while the relationship with household head sex was significant at the 10% level.

Drivers of smallholder farmers' participation decision in crop diversification
As shown in Table 6, of the eighteen independent variables considered in the probit model (the first component of the double-hurdle model), occupation, number of plots, fertile land proportion, access to irrigation, and use of improved seeds were found to significantly influence the probability of smallholder farmers participating in crop diversification (the farmers' first decision). The significant variables are discussed below.

The relationship between occupation (income diversification) and crop diversification presents two contrasting perspectives. On one hand, households with additional sources of income outside of farming can enhance their crop production capacity by purchasing or renting production factors such as improved seeds, fertilizers, chemicals, and farm implements. This perspective suggests that extra income can be reinvested into farming, leading to greater crop diversification. On the other hand, farmers engaged in non-farm or off-farm activities may have limited time and resources to focus on crop diversification, as the extra income generated may reduce the incentive to diversify crops. The study found that occupation, defined as engagement in non-farm activities, negatively influences crop diversification decisions, with a statistically significant result at the 5% level, indicating a 10.9% reduction in the probability of crop diversification for farmers with alternative sources of income. This finding aligns with the results of Asante *et al.* [37], confirming that non-farm income reduces the likelihood of crop diversification due to time constraints and the satisfaction gained from extra income.

A higher proportion of fertile land may lead to reduced crop diversification, as farmers prioritize high-yield, commercially valuable monocultures over diversified cropping systems. With fertile soil ensuring stable and high crop productivity, there is less incentive to cultivate a variety of crops for risk mitigation. As a result, farmers can achieve greater economic returns by focusing on a single, profitable crop. In contrast, in areas with less fertile soil, diversification helps spread risk and optimize land use. Therefore, highly fertile areas may promote intensive farming of select crops, ultimately reducing overall crop diversity in agricultural systems. In this study, the proportion of fertile land was statistically significant at the 1% level and had a negative influence on farmers' crop diversification decisions. The coefficient indicated that a 1% increase in the proportion of fertile land decrease the probability of crop diversification by 0.0009. This result concurs with the findings of Mussema *et al.* [35].

The use of improved seeds enhances crop diversification by increasing yield stability, expanding viable crop options, and reducing the risks associated with cultivating multiple crops. These seeds are often more resistant to pests, diseases and environmental stress, which allows farmers to grow a wider variety of crops with greater confidence. Additionally, improved seeds enable cultivation in areas where certain crops previously struggled, further promoting diversification. By improving productivity and economic returns, these seeds encourage farmers to invest in multiple crops, thus reducing dependency on a single crop. In this study, the use of improved seeds was found to be statistically significant at the 5% level and positively influenced farmers' decisions regarding crop diversification. Specifically, the use of improved seeds increases the likelihood of practicing in crop diversification by 18.7%.

Improved access to irrigation enhances crop diversification by ensuring a reliable water supply, reducing dependence on seasonal rainfall, and enabling year-round cultivation. With sufficient water availability, farmers can expand their crop choices to include water-intensive and high-value crops that would otherwise be unviable in rain-fed conditions. Irrigation also reduces the risk of crop failure due to drought, encouraging investment in a diverse range of crops without the fear of water scarcity. Additionally, it allows for the simultaneous production of staple foods and cash crops, improving both income stability and dietary diversity. In this study, access to irrigation was found to significantly influence farmers' decisions on crop diversification, with a 5% level of significance. It increases the likelihood of practicing in crop diversification by 10.3%.

The two large rivers tributary to Lake Tana, Gumara and Rib, serve as significant sources of irrigation water, allowing households to cultivate their limited farmland 2-3 times per year. According to farmers' explanations in the FGD, although bylaws exist, there are frequent disputes arising from inappropriate water use schedules among members of the water users' association. Moreover, the construction and use of manual holes at the individual household level has become increasingly common. This technology taps into the area's underground water potential, enabling farmers to practice double and triple cropping. Using manual holes, farmers primarily cultivate vegetables (example, onions) and cereals (oats, teff and wheat). These findings align with the results of Aheibam and Singh [30] and Lighton and Emmanuel [31].

Drivers of smallholder farmers' intensity of participation in crop diversification

As observed in Table 7, the results of the truncated regression model confirm that age of the household head, the number of plots, the number of oxen, and access to credit significantly influence farmers' second decision: the intensity of crop diversification. The significant variables are discussed below.

The relationship between age and crop diversification can be viewed from two different perspectives. Older farmers, with their extensive experience and traditional knowledge, often promote crop diversification as a strategy for risk management, soil fertility, and long-term sustainability. In contrast, younger farmers, who are more open to innovation and modern agricultural techniques, may also drive crop diversification by experimenting with high-value, climate-resilient crops and adopting advanced technologies. Their adaptability to market trends encourages diversified cropping systems to enhance profitability and sustainability. In this study, the age of the household head was statistically significant at the 1% level and positively influenced farmers' crop diversification decisions. As the household head's age increases by one year, the likelihood of farmers diversifying their farms increases by 1%. The FGDs confirmed older (experienced) farmers demonstrate wisdom in choosing crop enterprises that balance multiple benefits, including production risk aversion, profit maximization, self-sufficiency in nutrient-rich crops, and cultural significance while most young farmers prefer market-oriented specialization, such as green maize and onions. This result is consistent with the findings of Derso *et al.* [36].

Households with more oxen can perform farming activities more efficiently, cultivate larger areas, and allocate land to a greater variety of crops. In this study, the number of oxen was found to positively and significantly influence crop diversification intensity at the 5% significance level. For each additional ox, diversification intensity increases by 1.7%. In the study area, oxen serve as the primary source of power for land preparation (tillage) and crop threshing. Farmers with at least a pair of oxen have greater opportunities to cultivate multiple crops. A similar finding was reported by Dembele *et al.* [25].

An increase in the number of plots (land fragmentation) can have varying effects on crop diversification. The first perspective is that more fragmented land encourages higher crop diversification, as farmers can utilize different plots with varying microclimates, soil fertility and water availability to manage risks. The other perspective is that more plots lead to lower levels of diversification due to the reduced efficiency and complexity in managing fragmented land. In this study, the number of plots was found to influence both the participation and intensity of crop diversification positively and significantly at the 1% level. Specifically, as the number of parcels increases by one, the intensity of diversification increases by 1%. Farmers who owned multiple parcels of farmland in the swampy areas around Lake Tana typically cultivated lowland rice varieties during the main rainy season. After harvesting the rice or sometimes through a relay cropping system, they planted legumes such as grass pea and chickpea, utilizing the residual soil moisture. Subsequently, they cultivated crops like tef and oats using supplementary irrigation to ensure adequate growth. This result is consistent with that reported by Azad [28].

Access to credit encourages crop diversification by providing farmers with the financial resources needed to invest in new crops, technologies and farming practices that help reduce risk and increase profitability. With access to credit, farmers can purchase essential inputs like seeds, fertilizers, chemicals and irrigation systems, which are necessary for growing a wider variety of crops. This financial support also enables farmers to mitigate risks by experimenting with new crops or entering niche markets, diversifying their income sources. By spreading investments across different crops, farmers reduce their reliance on a single crop, ensuring more stable and sustainable financial returns, even in the face of market fluctuations or crop failure. In this study, access to credit was found to significantly and positively influence the intensity of crop diversification, at a 5% significance level. The possible reason credit has no influence on the first decision but influences the second is that some farmers start diversifying with low-cost, less risky crops that do not require significant financial resources. As a result, access to credit is not a key factor in deciding whether to diversify. However, once a farmer chooses to diversify, the extent/intensity of diversification, measured by the number of crops grown, the area allocated, and investment in inputs such as fertilizers, irrigation and labor, largely depends on financial capacity. At this stage, access to credit becomes essential, as it enables farmers to expand their crop choices, invest in high-value or input-intensive crops, and adopt modern farming techniques, ultimately increasing the intensity of diversification.

Moreover, despite the Amhara Credit and Saving Association (ACSI) has a capacity to lend a large amount of money to a significant number of farmers at a time, more than half of the sample household responded that they did not have access to credit and there have been complaints raised by its clients primarily concerning the quality of service delivery. In addition to ACSI, the Village Saving and Lending Associations (VSLA), initiated and promoted recently in the area by various NGOs, have provided loans in a more flexible manner, which has helped farmers access smaller amounts of credit. The loans were mainly used for purchasing improved seeds for horticultural crops and agro-chemicals to control pests. A similar finding was reported by Inoni *et al.* [32].

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

This study analyzed the level and drivers of crop diversification among smallholder farmers in Northwest Ethiopia, leading to three key conclusions. First, although the majority (78%) of crop producers diversified their farms, the study area is predominantly characterized by a medium level of crop diversification. Second, most diversifying households grow a relatively high number of crops, at least one from each of the three main categories, cereals, legumes, and vegetables, which likely help enhance their diets. Third, several factors, including the age of the household head, the use of improved seeds, farmland characteristics (like having multiple plots and a higher proportion of fertile land), oxen number, income diversification (through additional occupations), and access to credit and irrigation, all influence decisions related to crop diversification and its intensity. Moreover, the model estimation and observations during FGDs confirm that farmers' wisdom, derived largely from their farming experience, significantly contributes to pursuing crop diversification.

To maximize the benefits of crop diversification, it is crucial to tap into the wealth of knowledge and experience among farmers. This requires the active involvement of stakeholders in the agricultural and rural development sectors. Consequently, strategies like providing improved legume and vegetable crop varieties suitable for different agro-ecological and soil types, improving irrigation infrastructure, enforcing water user associations' bylaws, enhancing cattle health services, promoting alternative tillage technologies, and improving access to quality credit from formal financial institutions are proposed as specific pathways to support and enhance crop diversification efforts in the area.

LIMITATION AND FUTURE RESEARCH DIRECTION

This study had some limitations, particularly regarding the metric used to assess crop diversification. The SDI considered the distribution of planted areas across different crops, without factoring in the economic value of each crop. As a result, crops with small areas but high value were not adequately represented. Consequently, a farm that is economically diversified but not in terms of area might appear less diversified, or even penalized, when evaluated with the SDI. Therefore, using more appropriate metrics in future research would help generate more reliable policy recommendations

Crop diversification is widely promoted as a strategy to improve farm income and food security. However, the relationship between diversification and these outcomes is not linear. Some level of diversification improves resilience and income, but excessive diversification might reduce efficiency and profitability. Therefore, identifying the optimum level is essential for providing farmers and policymakers with guidance on how to balance diversification with specialization, ultimately optimizing productivity, income, and sustainability in agricultural development strategies.

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CONFLICT OF INTEREST

The authors declare that no competing interests exist.

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Table 1: Model specification test-based decision among Tobit, Heckman and double-hurdle

Model	Hypotheses	Calculated value	Tabulated value	Decision
Independent double-hurdle Vs. Tobit	Ho: Tobit model is appropriate H1: double-hurdle is appropriate	Tobit test = 542.95	Df = 18, SL = 5% X2 = 28.86	Reject Tobit model
Independent double-hurdle Vs. Heckman	H0: There no selection bias H1: There is selection bias	[Mills]Lambda = 0.698): $chi^2(1)$ = (0.05,18) Prob > chi^2 = 0.8167		Reject heckman model

Table 2: Demographic and socio-economic characteristics

Variables	Mean/frequency	Standard deviation /Percent
Age	41.63	11.89
Sex (Male)	317	79.85
Education	1.31	2.07
Marital status (Married)	343	86.40
Dependency ratio	.426	.211
Occupation (Yes)	86	21.66
Improved seed used (Yes)	238	59.95
Total land	0.72	0.33
Number of plots	5.56	2.16
Fertile land proportion	.355	.194
Oxen number	1.65	0.76

Table 3: Institutional and infrastructural characteristics

Variable	Mean/Frequency	Standard deviation /Percent
Cooperative (Yes)	237	59.70
Credit (Yes)	185	46.60
Extension service (Yes)	321	80.86
Irrigation (Yes)	238	59.95
Market distance	89.29	59.77
Mobile availability (Yes)	238	59.95
Hired labor (Yes)	261	65.74

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Table 4: Independent t-test for continuous explanatory variables

Variables	Diversified household	Non-diversified household	St Err	t value	p value
	Mean 1	Mean 2			
Age	41.687	41.449	1.445	-.15	.869
Education	1.333	1.242	.252	-.35	.719
Dependency ratio	.428	.416	.026	-.45	.639
Oxen number	1.723	1.403	.091	-3.5	.001***
Market distance	86.016	100.966	7.223	2.05	.039**
Total land	.748	.653	.04	-2.35	.02**
Number of plots	5.99	4.046	.245	-7.95	0.00***
Fertile land proportion	.3275	.4545	.023	5.6	0.00***

***Significance at 1% level (p<0.01). **Significance at 5% level (p<0.05). *Significance at 10% level (p<0.1)

Table 5: A chi-square test for categorical explanatory variables

Variables	Category	Diversified household	Non-diversified household	Total	X² test	Pr (X²)
Sex	Male	253	64	317	2.7358	0.098*
	Female	57	23	80		
Marital status	Married	275	68	343	10.9021	0.012**
	Divorced	16	9	25		
	Widow	18	7	25		
	Never Married	1	3	4		
Occupation	Yes	56	30	86	10.7911	0.001***
	No	254	57	311		
Cooperative	Yes	197	40	237	8.7180	0.003***
	No	113	47	160		
Hired labor	Yes	219	42	261	15.0937	0.000***
	No	91	45	136		
Irrigation	Yes	208	30	238	30.0958	0.000***
	No	102	57	159		
Mobile availability	Yes	195	41	236	7.0141	0.008***
	No	115	46	161		
Credit	Yes	159	26	185	12.5085	0.000***
	No	151	61	212		
Extension service	Yes	263	58	321	14.4931	0.000***
	No	47	29	76		
Improved seed used	Yes	211	27	238	38.7977	0.000***
	No	99	60	159		

***Significance at 1% level (p<0.01) **Significance at 5% level (p<0.05). *Significance at 10% level (p<0.1)

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Table 6: Estimates of double hurdle for farmers' first decision (probit model)

Variables	Coefficient	Robust St. Error	Marginal Effect	p-value
Age	0.00	.007	0.002	.996
Sex	-.404	.254	-0.078	.112
Education	-.025	.038	-0.0055	.508
Marital status	.01	.115	0.002	.929
Dependency ratio	.389	.369	0.086	.292
Occupation	-.434	.189	-0.109	.022**
Total land	-.082	.298	-0.018	.783
Number of plots	.232	.05	0.051	0.00***
Ln Fertile land proportion	-.447	.148	-0.099	.003***
Oxen number	.088	.126	0.019	.484
Market distance	-.002	.001	-0.0004	.111
Hired labor	.171	.227	0.039	.451
Cooperative	.022	.203	0.004	.913
Extension service	.085	.216	0.019	.692
Credit	-.024	.186	-0.005	.898
Irrigation	.445	.207	0.103	.032**
Mobile availability	.269	.18	0.061	.135
Improved seed used	.78	.173	0.187	.000***
Cons	-1.448	.636		.023

Log pseudo likelihood = -147.47106
Number of observations = 397
Wald chi^2 (18) = 109.79
probability > chi^2 = 0.0000
***Significance at 1% level (p<0.01). **Significance at 5% level (p<0.05)
*Significance at 10% level (p<0.1)

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Table 7: Estimates of double hurdle model for second decision (truncated regression)

Variables	Coefficient	Robust St. Error	p-value
Age	.002	.001	.005***
Sex	.01	.02	.613
Education	.004	.003	.203
Marital status	.003	.008	.716
Dependency ratio	-.008	.03	.777
Occupation	0	.014	.988
Total land	-.007	.02	.742
Number of plot	.01	.003	.001***
Ln Fertile land proportion	-.004	.011	.754
Oxen number	.017	.008	.041**
Market distance	0	0	.862
Hired labor	.015	.017	.379
Cooperative	-.005	.013	.724
Extension service	-.017	.018	.331
Credit	.023	.011	.04**
Irrigation	.002	.014	.893
Mobile availability	-.012	.012	.312
Improved seed used	-.016	.012	.192
Cons	.453	.055	0

Log pseudo likelihood = 280.98114
Number of observations = 310
Wald chi^2 (18) = 44.40
Probability > chi^2 = 0.0005
***Significance at 1% level (p<0.01). **Significance at 5% level (p<0.05)
*Significance at 10% level (p<0.1)

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