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Farm diversification strategies, dietary diversity and farm size: Results from a cross-country sample in South and Southeast Asia

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ABSTRACT

South and Southeast Asia host almost half of the world's undernourished people. Food and agricultural systems in these regions are highly dependent on the production and consumption of staple cereals such as rice, maize and wheat. More diverse farming systems can potentially improve rural people's nutrition, while reducing the environmental impact of agriculture. Yet, it remains uncertain whether farm diversification is always the most suitable and viable strategy for all types of smallholder farms. We use generalised linear regression models to analyse the farm diversification strategies of 4772 rural households in Cambodia, India, Lao PDR and Vietnam. Our analysis is twofold and focuses first on drivers of farm diversification, and second, on the impacts of farm diversification and other livelihood strategies on dietary diversity. We find that (1) farm diversification is significantly influenced by environmental and climate variables, including rainfall patterns, as well as household and farm characteristics such as farm size and education level; and (2) farm diversification, market orientation and off-farm income generation are all strategies that can improve household and individual dietary diversity. However, their relative effects resulted influenced by farm size. Specifically, the positive effect of farm diversification on dietary diversity was larger for smaller farms, while it decreased for farms of larger size that may improve their diet more by increasing their engagement in off-farm activities and markets. These findings highlight that characteristics such as farm size can represent substantial determinants in production and consumption decisions, suggesting the importance of understanding and considering the type of farm and the situational context of analysis when targeting interventions for improving smallholder farm livelihoods.

1. Introduction

There has been significant progress in reducing rural poverty and food insecurity in South and Southeast Asia over the past twenty years, but they still comprise 46% of the total undernourished people in the world (FAO et al., 2021). While these regions have undergone a process of rapid economic growth, agricultural policies have mostly focused on Green Revolution approaches to increasing cereal production and productivity (Ramankutty et al., 2018; Khoury et al., 2022). This led to higher calorie availability, but also gradually increased the dependency of farming systems and diet on high-value staple cereals, such as rice, maize and wheat (Pingali, 2012; Dawe et al., 2014; Verbowski et al., 2018; Chandrasekhar et al., 2022).

South and Southeast Asia have been considered regional hotspots of crop diversity and are still among the regions with the highest level of crop diversity in the world (Ramankutty et al., 2018; FAO, 2019). However, policies supporting cereal production, through subsidies and rural planning, have discouraged the adoption of diversified farming

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production (Markussen et al., 2011; Chandrasekhar et al., 2022) and neglected alternative sources of other critical micronutrients, especially in rural areas (Pingali, 2012; Dawe et al., 2014; Verbowski et al., 2018). Yet, farm production diversification, defined here as the adoption of a wide range of crop and/or livestock species, is often considered a beneficial strategy to increase the availability of a wide range of nutrients and food security (Remans et al., 2014; Jones, 2017; Bezner Kerr et al., 2021). There is also evidence of the multiple benefits provided by agricultural diversification strategies at farm scale on production and productivity stability (Beillouin et al., 2019; Renard and Tilman, 2019; Rosa-Schleich et al., 2019), climatic and market risks adaptation (Bezabih and Sarr, 2012; McCord et al., 2015; Bozzola and Smale, 2020), the provision of ecosystem services (Kremen and Miles, 2012; Tamburini et al., 2020; Wood et al., 2015) and finally the conservation of genetic resources (Brush and Perales, 2007).

Previous studies have explored the relationship between food security and farm diversity and analysed the factors that determine farmers decisions to adopt diversification strategies. A number of empirical studies show that farm diversification strategies in South and Southeast Asia can improve farmers' livelihoods by providing higher income from agriculture (Kasem and Thapa, 2011; Ladha et al., 2016) and higher dietary diversity (Malapit et al., 2015; Islam et al., 2018; Gupta et al., 2020a). Recent systematic reviews examined the effect on food security of adopting agroecological practices (Bezner Kerr et al., 2021) and, more specifically, agricultural diversification strategies (Waha et al., 2022). Positive outcomes were found in 78% and 66% of the articles selected by Bezner Kerr et al. (2021) and Waha et al. (2022) respectively. Nevertheless, the increase of farm production diversity is not the only option for improving farmers' livelihoods and food security (Scoones, 1998; Ellis, 2000) and controversies remain in defining effective interventions for improving rural household livelihoods. Some studies suggest that market access can be more effective in increasing farmers' income and, consequently, their opportunity to purchase a more diverse range of food, while increasing diversity in some cases may promote subsistence production, reduce farmers' income potential and hence their diet diversity (Koppmair et al., 2017; Parvathi, 2018; Sibhatu and Qaim, 2018b). Barrett et al. (2001) and De Janvry and Sadoulet (2001) show that farmer livelihood diversification in off-farm activities can be more beneficial than on-farm diversification, especially in reducing vulnerability by providing an additional and more stable income source. Other studies highlight the importance of understanding the context and the type of farm, to define up to what point farm diversity is beneficial, suggesting that the benefits of diversification on food security may not be linear and decrease after a certain threshold (Das and Ganesh-Kumar, 2018; Kumar et al., 2018; Parvathi, 2018; Islam et al., 2018).

The factors influencing the adoption of farm diversification strategies should also be considered. Farmers face several constraints in their activities and despite the potential benefits discussed above, they may not have the capacity and/or opportunity to adopt, maintain or increase farm diversity for multiple reasons. As posited by the Sustainable Rural Livelihood Framework (SRLF), the choice among different farming strategies depends on a combination of external factors (local and national policies, agroecological context, climatic and market risks) and internal factors, relating to human, economic and financial, physical and social capital (Scoones, 1998; Ellis, 2000). Previous studies have analysed the drivers and constraints of farm diversity, with mixed results depending on the differences in farm objectives, characteristics or environmental and socio-economic context (Tacconi et al., 2022).

The primary aim of this study is to contribute addressing debates concerning the role of agricultural diversity in improving food security. Our analysis focuses on rural households in four countries across South and Southeast Asia: Cambodia, India, Lao PDR and Vietnam. These countries are of significant interest from the perspectives of food and nutrition security, and the transitioning of farming production strategies (Ritzema et al., 2019; Giller et al., 2021). First, we test what the main drivers and constraints of farm diversification are to understand under what conditions farmers are more likely to decide or have the opportunity of adopting diversification strategies, instead of (or along with) other strategies. Second, we analyse the effect of farm diversity on dietary diversity and compare it with other livelihood strategies such as the level of market orientation and off-farm employment. Finally, we repeat this analysis targeting different farm groups, defined by the area of land cultivated, with the aim to investigate whether the role of farm diversity and its impact on food security vary when farm size is considered.

2. Materials and methods

2.1. Data sources

The data used consisted of a pooled dataset compiled from secondary cross-sectional data publicly available from the Rural Household MultiIndicator Survey (RHoMIS) data repository (Van Wijk et al., 2020; RHoMIS, 2021). The pooled dataset includes 12 different rural household surveys conducted between 2015 and 2020 in different regions of Cambodia ($n = 1301$), India ($n = 2455$), Lao PDR ($n = 415$) and Vietnam ($n = 1553$) for a total of 5724 households (Table A1). RHoMIS data are collected through a standardised survey tool that has been in use since 2015 and is composed of different modules to collect information and rapidly calculate a set of indicators about rural households' socio-economic status, farm production, livelihood strategies, risk and food security (Hammond et al., 2017; Van Wijk et al., 2020; RHoMIS, 2021). Therefore, the use of RHoMIS data allows analyses of household performance in terms of food security based on the characteristics of their farms. The RHoMIS surveys are conducted selecting samples of the rural population based on the sampling strategies of each specific project and, hence, are not nationally representative (Ritzema et al., 2019; Pagnani et al., 2020; Burra et al., 2021). In our pooled dataset, rural households are mostly located in tropical ($n = 1340$) and temperate ($n = 2902$) climate regions, and only a few in dry climates ($n = 328$), tundra ($n = 17$) and continental regions ($n = 14$) (Fig. 1). The geographical heterogeneity of the different samples in the dataset used for this study provides the opportunity to compare farms from diverse agroecological, socio-economic and political context.

Using the farms' geolocations, we complemented RHoMIS data with topographic (altitude) and climatic (rainfall and temperature) variables. Altitude data were retrieved from GTOPO30, a global digital elevation dataset with a 30-arc second spatial resolution (Earth Resources Observation Science Center/U.S. Geological Survey/U.S. Department of the Interior, 1997), while 30-year rainfall and temperature data were extracted from the CRU TS 4.05 climate dataset (Harris et al., 2020).

2.2. Data cleaning

We undertook a process of data cleaning, outlier detection and harmonisation of the variables prior to the data analysis. All steps were conducted using the statistical software R (https://cran.r-project.org/). We identified and removed observations with missing or incomplete data, or inconsistent values for the variables of interest that could not be adjusted, such as evident data collection errors. We defined as outliers the observations above the 97.5th percentile and removed them. The final sample selected for the data analysis consist of 4772 observations (Table A1).

2.3. Description of the key variables

2.3.1. Farm diversity

There is a wide range of definitions and indicators of farm diversity in the literature, which vary substantially across scale and objective of the analysis (Hufnagel et al., 2020; Tacconi et al., 2022). We use species richness as a proxy indicator of farm diversity, by counting the number of different crop groups and livestock species produced on each farm

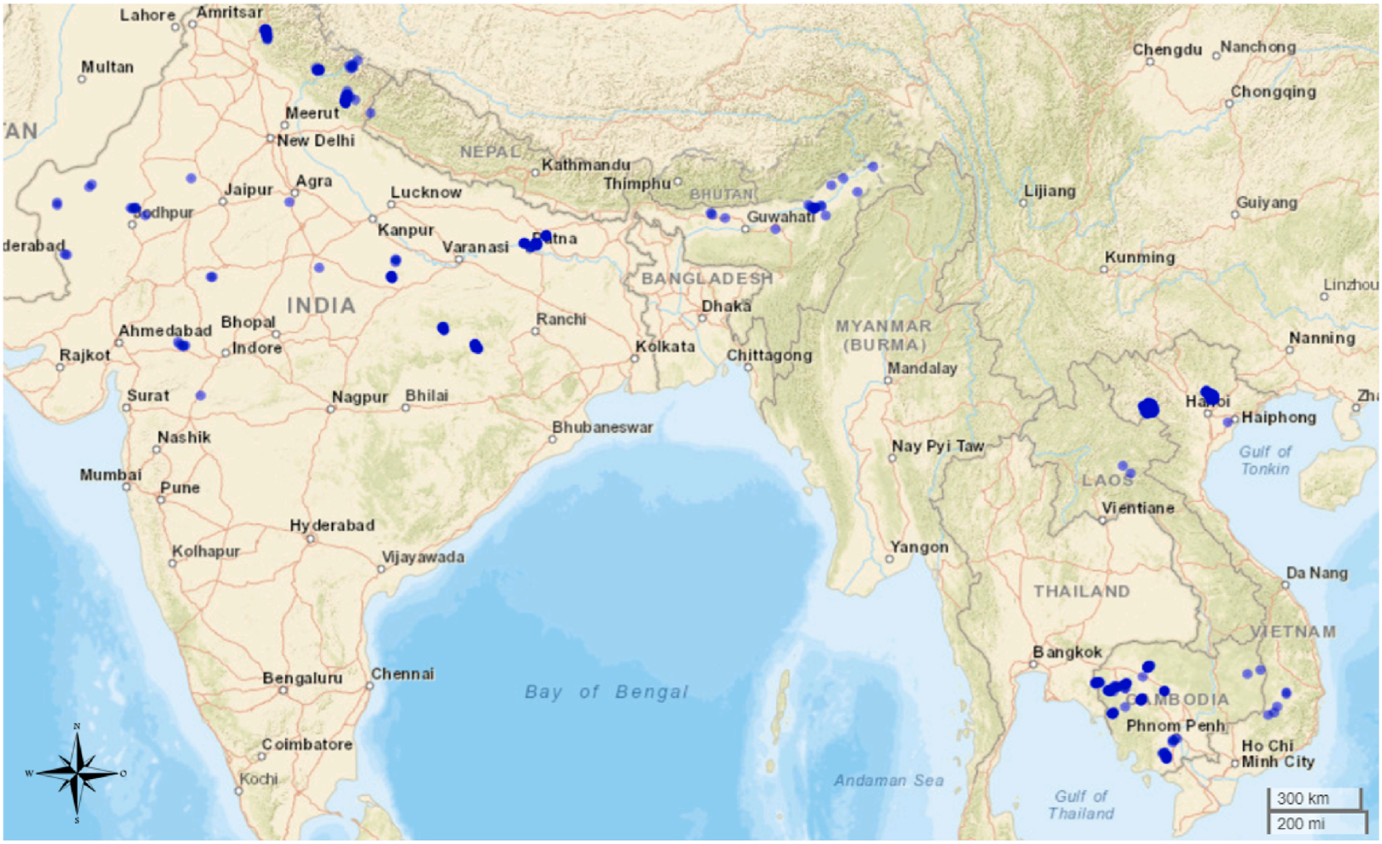

Fig. 1. Locations of RHoMIS surveys in India, Vietnam, Lao PDR and Cambodia (blue dots).

during the previous 12 months. This indicator is among the most widely used quantifications of diversity at the farm scale (Tacconi et al., 2022). The advantage of using an indicator of species richness is that it provides the quantity of different crop and livestock species grown and raised on a farm. The main limitation is that, unlike other indicators (e.g. Simpson Index (Simpson, 1949) or Shannon Index (Shannon, 1948)), species richness does not capture the relative abundance of each species. We could not calculate this due to data limitations. For crop diversity, we used an indicator of crop group diversity, where we do not count the single crop species, but the "type" of crops produced, based on their commodity group. This is because crop names were reported with different levels of detail across the individual RHoMIS surveys. For example, in some surveys, it is possible to identify individual vegetables such as cauliflower and cucumbers, while others report them already aggregated as vegetables. This limitation created a need to standardise across all the surveys. We created 12 different crop groups, consistent across the surveys: cereals and pseudo-cereals, flowers, fodder crops, fruit/fruit trees, legumes, non-food trees/shrubs, nuts, oilseeds, roots and tubers, spices/herbs, sugar-rich and vegetables (Table A2). Therefore, a household growing rice, maize (both cereals) and papaya (fruit) would have a crop group diversity of 2. Measuring crop diversity in terms of commodity groups instead of individual crop species also accounts for the different functions provided in terms of nutritional diversity availability (Jones et al., 2014; Bergau et al., 2022) and agroecological services (McCord et al., 2015). For livestock diversity, we count the number of different livestock species on the farm. The sum of crop group diversity and livestock diversity is production diversity, our indicator for overall farm diversity (Table 1).

2.3.2. *Dietary diversity*

We use two indicators of dietary diversity: a modified Household Dietary Diversity Score (HDDS) and the Minimum Dietary Diversity for Women (MDD-W) (Kennedy et al., 2011; Fraval et al., 2019). We analyse two different sub-samples, as the MDD-W is available for 1108 households from one Indian survey (IN_GEF_2019) and the modified HDDS is available for 3433 households from all surveys, except for "IN_GEF_2019" (Table A1). Using these two different indicators permitted to test two different dimensions of dietary diversity, access, and consumption at the household (HDDS) and individual level (MDD-W) (Table 1).

The HDDS is among the most utilised indicators of dietary diversity (Waha et al., 2022), and it is considered a robust qualitative proxy of food consumption and access to a variety of foods at the household level (Kennedy et al., 2011). It is a count indicator based on the food groups consumed by a household over a certain period (Swindale and Bilinsky, 2006; Kennedy et al., 2011). Different applications of the HDDS can be found in the literature, depending on the food groups considered and the consumption recall period (Jones et al., 2014; Sibhatu et al., 2015; Burra et al., 2021; Mehraban and Ickowitz, 2021; Bergau et al., 2022). Unlike the original HDDS applications, which typically consist of 12 or 16 food groups (Swindale and Bilinsky, 2006; Kennedy et al., 2011), RHoMIS surveys provide a different classification based on the same 10 food groups used for the MDD-W (Fraval et al., 2019; Van Wijk et al., 2020): (1) grains, flour, or starchy white vegetables; (2) beans, peas and lentils; (3) nuts or seeds; (4) leafy green vegetables; (5) orange-coloured vegetables or fruits; (6) other vegetables; (7) other fruits; (8) meat, poultry or fish; (9) eggs; and (10) milk or dairy foods. This different classification excludes food groups such as fats/oils, sweets, and all beverages to avoid inflating the indicator with food that poorly contributes to micronutrient adequacy (Sibhatu et al., 2015; FAO and FHI 360, 2016; Gupta et al., 2020b). Each of these food groups, if consumed at least once weekly within a 4-week recall period, counts as 1 point, giving a total HDDS of 10 for the most diversified diet at the household level (Hammond et al., 2017; Fraval et al., 2019). Hereafter, we will refer to it as

Table 1
Description of the variables used.

Variable	Variables type	Description
Farm diversity indicators (dv)		
Crop group diversity	count	Count of different crop groups grown in the farm during the previous 12 months. The classification in groups includes: 1. Cereals and pseudo-cereals, 2. Flowers, 3. Fodder crops, 4. Fruit/Fruit trees, Legumes, 5. Non-food trees/Shrubs, 6. Nuts, 7. Oilseeds, 8. Roots and tubers, 10. Spices/Herbs, 11. Sugar-rich, 12. Vegetable (From 0 to 12).
Livestock diversity	count	Count of the different livestock species in the farm (including poultry), during the previous 12 months.
Production diversity	count	Crop group diversity + Livestock diversity
Dietary diversity indicator (dv)		
HDDS10	count	Indicator of household dietary diversity. Count of the different food groups (min = 1, max = 10) a household consumed at least once weekly within a 4-week recall period. Food groups: 1. Grains, flour, or starchy white vegetables; 2. beans, peas, lentils; 3. nuts or seeds; 4. leafy green vegetables; 5. orange-coloured vegetables or fruits. 6. other vegetables; 7. other fruits; 8. meat, poultry or fish; 9. eggs; 10. milk or dairy foods).
MDD-W10	count	Indicator of individual dietary diversity. Count of the different food groups (min = 1, max = 10) that women 15-49 years of age consumed within the previous 24-h. Food groups: see HDDS10 above.
Climate and environmental vars. (Sources: GTOPO30 and CRU TS 4.05)		
Altitude (m)	numeric	Altitude of the location of the farm. (Source: GTOPO 30)
Annual rainfall (mm/year)	numeric	Total annual rainfall. Calculated as the average of the annual rainfall in the 30 years prior the survey.
Inter. rainfall var	ratio	Inter-annual rainfall variability. Coefficient of variation of the total annual rainfall in the 30 years prior the survey.
Intr. rainfall var	ratio	Intra-annual rainfall variability. Average of the coefficient of variation of the monthly total rainfall calculated on each year in the 30 prior the survey.
Avg temperature (°C)	numeric	Average annual temperature based on the 30 years prior the survey.
Inter. temp var	ratio	Inter-annual temperature variability. Coefficient of variation of the average annual temperatures in the 30 years prior the survey.
Intr. temp var	ratio	Intra-annual temperature variability. Average of the coefficient of variation of the monthly average temperatures calculated on each year in the 30 prior the survey.
Households' characteristics		
Economic and financial capital		
Debts (Y/N)	count	The farm has debts (yes = 1, no = 0)
Farm income (USD PPP2016)	numeric	Total income coming from the sales of farm products. All the monetary values have been converted to USD purchasing power parity (PPP) with 2016 as base year.
Value farm produce (USD PPP, 2016)	numeric	Sum of the total value of farm produce. All the monetary values have been converted to USD purchasing power parity (PPP) with 2016 as base year.
Human capital		
Education	factor	Highest level of education of the household head: none, primary, secondary, post-secondary.
HH size	count	Number of households members
Physical capital		
Irrigation (Y/N)	binary	The farm uses irrigation (yes = 1, no = 0).
Fertiliser (Y/N)	binary	The farm uses mineral fertilisers (yes = 1, no = 0).
Improved seeds (Y/N)	binary	The farm uses improved seeds (yes = 1, no = 0).
Pesticides (Y/N)	binary	The farm uses pesticides (yes = 1, no = 0).
Agricultural inputs	count	Total number of agricultural inputs used. Calculated as the sum of Irrigation, Fertiliser, Improved seeds, Pesticides. From 0 to 4.
Land cultivated (ha)	numeric	Total hectares used for cultivations in the farm.
Land cultivatedˆ2 (ha)	numeric	Squared term of land cultivated.
Social capital		
Gender (male)	ratio	Gender equity indicator that quantifies the share of Total Value of Activities (TVA) controlled by a male in the household (0 = 100% female control, 1 = 100% male control). TVA consists of the sum of the value of each activity on the farm (crop and livestock products that are consumed or sold, and income from off-farm activities). For each of these activities, it is asked whether the household member controlling it (does most of the work and decides how to use it) is male or female. Hence, male control is determined as follows: Gender (male) = value controlled by male/TVA.
Other livelihood strategies		
Livestock orientation	ratio	Proportion of farm produce value coming from livestock activities (N.B. farm produce is measured in cash value, not mass). Calculated as follows: value of livestock production/Value Farm Produce.
Market orientation	ratio	Proportion of farm produce which is sold. Calculated as follows: Farm Income/Value Farm Production. (RhOMIS calculates this the main crops and livestock species)
Off-farm income %	%	Share of farm income coming from off-farm activities.
Survey_ID	factor	Project in which the interview was conducted

Note: dv = dependent variable.

HDDS10.

The MDD-W is an indicator of individual diet quality validated as a proxy indicator for micronutrient adequacy (Martin-Prevel et al., 2015; FAO and FHI 360, 2016). It is a dichotomous indicator that measures if, in the previous 24 h, the women interviewed consumed (MDD-W = 1) or not (MDD-W = 0) at least five of the same ten food groups used for the calculations of the HDDS10 (FAO and FHI 360, 2016). The MDD-W can also be used as a count variable of the total number of food groups consumed (from 0 to 10). In this study, we used it as a count variable (MDD-W10) to simplify the comparability with the HDDS10 results (Gupta et al., 2020b).

2.3.3. Households' characteristics and climate variables

The variables analysed as potential drivers and constraints of farm diversity were selected based on a previous literature review (Tacconi et al., 2022) and grouped following the approach used in the Sustainable Rural Livelihood Framework (SRLF). The SRLF is a widely applied framework for examining how farmers' access to different livelihood strategies is influenced by their "*external context*", "*internal assets/capitals*" and previous decisional pathways (Scoones, 1998; Ellis, 2000).

In the SRLF, the external context includes the agroecological context, climate risks, and the socio-political context. Farmer decisions and adaptation strategies are highly influenced by local climate and environmental conditions (Bezabih and Sarr, 2012; Bhatta et al., 2016; Bozzola and Smale, 2020). Altitude was used to reflect different agroecological conditions among farms. We used both rainfall and temperature information (Harris et al., 2020) as indicators of climate and its variability. We calculated the total annual rainfall and average annual temperature to represent the local climate conditions, intra-annual (or monthly) variability to indicate the seasonal variability, while inter-annual variability provided the year-to-year variability which was used as a proxy for climate risk (Table 1). Country, region and surveys were used as proxies for socio-political context and to control for potential bias depending on the year and specific data collection project (Sibhatu et al., 2015).

RHoMIS surveys provide key measures that, albeit imperfectly, can act as proxies for internal assets in the SRLF (Table 1): human, social, physical, economic, and financial capitals. Within the *human capital*, we selected the number of household members and the level of education of the household head. The number of household members is an indicator of household labour availability and of the number of people dependent on the farm. It is often positively correlated with diversification (Kasem and Thapa, 2011; Nguyen et al., 2019). The level of education of the household head is used as a proxy for knowledge, higher capacity for adaptation and access to information. However, there is mixed evidence about the effect of education on farm diversification (Tacconi et al., 2022). While highly educated farmers may have a broader skillset for managing diversified farms, they may also have greater opportunities to engage in more remunerative off-farm livelihood strategies, potentially leading to a reduced involvement in farming (Longpichai, 2013; Herrera et al., 2018). The share of farm activities controlled by the male household members was the variable selected within *social capital* (Hammond et al., 2017; Tavenner et al., 2019), as gender often emerged as a relevant cultural factor in influencing household decision-making, and in particular the decision to diversify (Díaz-Reviriego et al., 2016; Asfaw et al., 2018). The *physical capital* consists of the physical endowment of a farm, of which we analyse the area of land cultivated and the use of agricultural inputs. Area of land cultivated is often an important factor which determines whether growing additional crops is possible (Tacconi et al., 2022). The effect of farm size on farm diversity may be non-linear, with a positive effect of increasing farm size for small farms and a negative one for larger farms (Skarbø, 2014; Makate et al., 2016; Kankwamba et al., 2018). To explore this potentially non-linear relationship, we also tested the quadratic term of land cultivated. We selected four different agricultural inputs, namely fertilisers, improved seeds, irrigation and pesticides, to analyse their effect on farm diversity. In the literature results are mixed (Tacconi et al., 2022). Farm diversification can be used as a strategy to reduce dependency on agricultural inputs (Kremen et al., 2012; Rosa-Schleich et al., 2019), but under certain environmental conditions, the use of inputs can increase the possibility to grow a different array of species. For *economic and financial capital,* we selected three variables: current debts, total income generated from the sale of farm products (farm income) and total value of farm produce (including products that have been produced but not sold). Current debts can represent access to credit but also a stress factor when farms find repayment difficult (Pagnani et al., 2020). The monetary variables were used as proxies for the economic dimensions of the farms in terms of production and sales.

The decision and possibility to diversify can be also influenced, positively or negatively, by the other strategies that farmers adopt to achieve their objectives (Tacconi et al., 2022). We selected the level of market orientation, involvement in off-farm income and livestock orientation (Table 1) as these other livelihood strategies are frequently studied for their potential to increase rural household income and the opportunity to access a more diverse and balanced diet (Sibhatu et al., 2015; Koppmair et al., 2017; Rahman and Mishra, 2020).

2.4. Data analysis

2.4.1. Drivers and constraints of farm diversity

To analyse the effect of the variables selected as potential drivers and constraints of farm diversity, we used a generalised linear model (GLM) for each of the three indicators of farm diversity (D): Production diversity, Crop group diversity and Livestock diversity.

As the response variables are all count variables, we fitted a model assuming a Poisson distribution for the excess of the response over 1, (that is, D = Diversity-1). As a robustness check, we also tested the model by fitting a Negative Binomial distribution and a Quasi-Poisson (Venables and Ripley, 2002), but the results were consistent across the three different models, reinforcing the choice of a Poisson distribution. With the working model assumption, namely:

$$D \sim \text{Poisson}(\mu)$$

where μ is the mean, our econometric model is represented generically by Eq. (1):

$$\log \mu = \boldsymbol{\beta_0} + \mathbf{E^A}\boldsymbol{\beta_1} + \mathbf{E^G}\boldsymbol{\beta_2} + \mathbf{E^R}\boldsymbol{\beta_3} + \mathbf{I^H}\boldsymbol{\beta_4} + \mathbf{I^P}\boldsymbol{\beta_5} + \mathbf{I^E}\boldsymbol{\beta_6} + \mathbf{I^S}\boldsymbol{\beta_7} + \mathbf{L}\boldsymbol{\beta_8} \quad (1)$$

where the term E corresponds to the external variables: agroecological context (E^A), policies and institutional context (E^G) and climate risks (E^R). The letter I represents the household internal capital, namely human (I^H), physical (I^P), economic and financial (I^E), social (I^S); and the other livelihood strategies are expressed with L. The β are the regression coefficients. We standardised the numeric variables to transform them into comparable scales. The models also include Survey ID as an added random effect, thus making it technically a generalised linear mixed model, (GLMM). Country was not included as having Survey_ID in the model rendering it effectively redundant. The models were fitted using all the explanatory variables, to present the results for all of them. To consider the risk of overfitting the model, we also selected the most parsimonious models for each of the dependent variables (Table A4). Variable selection was performed using the Bayesian information criterion (BIC) approach from the R function *stepAIC* of the MASS package (Venables and Ripley, 2002).

2.4.2. Association between farm diversity and dietary diversity

This study also aims at testing the effect of farm diversity on dietary diversity and compare it with other livelihood strategies. As dependent variables, we use two different indicators of dietary diversity (*DDI*), the HDDS10 and MDD-W10, both count variables. In contrast to the farm diversity indicators, the HDDS10 and the MDD-W10 (being from 0 to 10) have, by definition, an upper boundary (Table 1). Therefore, in this case the use of a binomial GLM regression is more appropriate than Poisson. We used a quasi-binomial model when the data suggested overdispersion with respect to a binomial model. Since 10 is the maximum dietary diversity, the distribution may be represented as

$$DDI \sim \text{Binomial}(10, p)$$

where p is the probability an additional food group is selected. The model then relates this probability to the predictors using the logistic regression model, namely setting as:

$$\eta = \log(p / (1 - p))$$

the log odds (which has an unrestricted range), then η has the same form as $\log \mu$ in expression (1) above. Both models include the same explanatory variables and are represented by the following equation:

$$\eta = f(D, L, C;\ \beta) \quad (2)$$

where D represents crop group diversity and livestock diversity and L other livelihood strategies, namely market orientation, livestock orientation and off-farm income. C consists of education, agricultural inputs and land cultivated that were included as control variables. Finally, β and ε represent the regression coefficients and the random error term, respectively.

As we also want to identify if the association between farm diversity and dietary diversity relationship changes between different types of farms, we divided our sample in four groups depending on the size of land cultivated, to compare farms of different size. The groups were created as follows: very-small farms (land cultivated <1 ha), small farms (land cultivated≥1 ha and <2 ha), medium farms (land cultivated≥2 ha and <4 ha) and large farms (≥4 ha). We repeated the models for each farm group. We used Survey_ID as a fixed factor for the models that tested HDDS10 (Table A.12); while we used region for the models that tested MDD-W10, as the observations are all from the same Survey_ID (IN_GEF_2019) (Table A.13).

To check robustness, we also re-estimated the models without the control variables (Table A.5 and Table A.7) and used production diversity as dependent variable (Table A.6 and A.8).

3. Results

3.1. Descriptive statistics

The descriptive statistics in Table 2 provide the main household characteristics and context for the pooled sample and each farm group by area of land cultivated.

On average, households cultivate four different groups of crops and have two different types of livestock species. Only 17 farms do not grow crops, while 535 farms do not have any livestock. Over 62% of the households grow between four and six groups of crops on their farms, 31% grow three or less and 7% grow seven or more. Cereals and pseudo-cereals are grown by 85% of the farms, predominantly rice (~70%), maize (~35%) or wheat (~25%) (Fig. 2). Vegetables, fruit, and roots/tubers are very common, produced by 78%, 74% and 65% of the households, respectively. Cattle (55%) and chicken (51%) are the most common livestock species, followed by pigs (25%). Crop groups grown are similar between the farm groups, but smaller farms seem to rely more on cereals and pseudo-cereals, while larger farms' production is more spread across vegetables, fruit, roots/tubers and legumes (Fig. A1).

The average HDDS10 in the sample is five, however 40% of households consume under five different food groups and 8% under three. The HDDS10 is slightly higher for larger farms, but the difference between farms of different sizes is relatively small, although there is a rather large variation within each farm group (Fig. A2). Twenty-four percent of the households do not reach the minimum dietary diversity threshold for women. In contrast to HDDS10, the MDD-W10 decreases with the area cultivated (Fig. A3).

There is a large geographic spread in climate and altitude in the sample. Altitude ranging from 3 to 4113 m. a.s.l; annual rainfall from 176 to 3390 mm/year, and; mean annual temperature from 1 to 28 °C

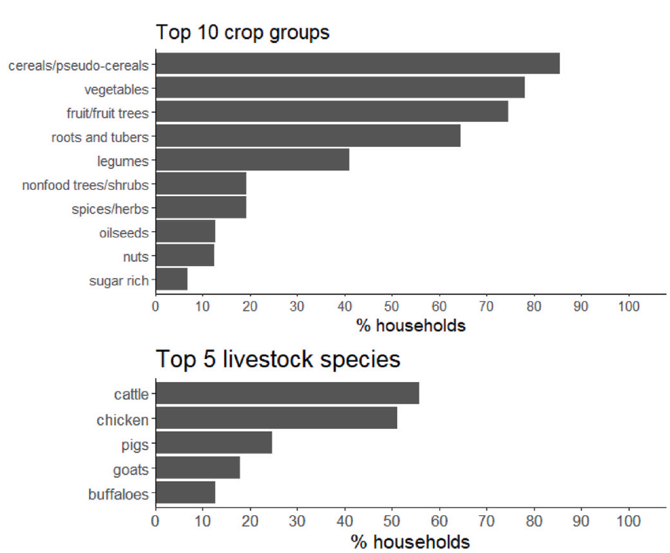

Fig. 2. Main crop groups (top 10) and livestock species (top 5) produced.

(Table A3). On average, farms cultivate less than 2 ha of land which is in the range of the average rural holdings in India, Cambodia, Vietnam and Laos (Giller et al., 2021). The four countries are represented in each of the farm groups that were created, although with some imbalance due to the sample size, country- and region-specific characteristics (Tables A.11, A.12 and A.13). Very-small farms, the largest group in the sample (43%), are mostly represented by Indian (54%) and Vietnamese farms (36%). Small (21%) and medium (21%) farms are more spread across the four countries, while large farms are mainly Cambodian (57%) or Indian (30%) (Table A.11). Households mostly comprised 5 to 6 people, and the average level of education is low, with 31% of the household heads without any formal school education and 32% of household heads with primary school education only. The level of education decreases from very small to large farms. The use of agricultural inputs is low overall, with only 50% of the households having irrigation, 59% using fertiliser and 44% pesticides. Improved seed varieties are used by less than 40% of the sample.

45% of farms have a debt, while average farm income and value of farm produce are particularly low for very-small farms. Very-small farms have an average farm income of USD PPP 1988 per year which increases with land size to USD PPP 4901 per year on average for large farms.

Cropping accounts for the majority of farm production value, as on average, livestock accounts for about one third of the total (Table 2). Market orientation is high with, on average, 65% of the value of farm produce sold. Larger farms are more market-oriented than smaller farms. The opposite is true for off-farm income, which is significantly higher for smaller farms (Figs. A4 and A5). However, only around 25% of household income comes from off-farm activities.

3.2. Drivers and constraints of farm diversity

In Table 3, we present the results of the models analysing drivers and constraints of the three indicators of farm diversity: production, crop group and livestock species diversity.

Annual rainfall and inter-annual rainfall variation have a positive and statistically significant effect on both production and crop group diversity, while they are not significant for livestock species diversity. The effect of intra-annual rainfall variation is negative for all the diversity indicators, and it is also the variable with the highest coefficient among the climate and environmental variables. Average temperature is statistically significant and negatively associated only with crop group diversity. None of the measures of temperature variability show a significant effect. Finally, altitude is only significant in the model analysing livestock species diversity to which is negatively associated (Table 3).

Debt and the value of farm production are positively associated with farm diversity, while farm income has a negative effect. The level of education of the household head has a positive effect on crop group diversity and its magnitude increases from primary to post-secondary education. Livestock diversity is negatively associated with secondary and post-secondary education. Household size, the other human capital variable included in the model, has a positive effect on all the diversity indicators, meaning that households composed of a larger number of people generally show higher levels of diversity. The area of land cultivated shows the highest positive effect on production diversity. On the other hand, the quadratic of land cultivated is negative. This suggests that production diversity tends to increase from very small to medium farms and then decreases from medium to large farms (Figs. 3 and A6).

The use of agricultural inputs produced different results. Use of fertiliser is negatively associated with all the three diversity indicators, perhaps suggesting that it is more common for specialised farms. Meanwhile irrigation has a positive effect on farm diversity. The use of improved seeds and pesticides has a positive effect on both production and crop diversity, but not on livestock diversity.

We did not find any significant effect from the indicator of gender control on farm activities.

Table 2
Descriptive statistics of the numeric variables of interest for the total sample and the farm groups by size of land cultivated. The value corresponds to the mean, with standard deviation in parenthesis.

Variables	Pooled (n = 4772)	Very small (n = 2067)	Small (n = 1015)	Medium (n = 1001	Large (n = 689)
Farm diversity					
Production diversity	6.2 (2.3)	5.6 (2.2)	6.4 (2.3)	6.8 (2.4)	6.7 (2.2)
Crop group diversity	4.2 (1.6)	3.9 (1.5)	4.21 (1.6)	4.5 (1.6)	4.6 (1.6)
Livestock diversity	2 (1.3)	1.7 (1.2)	2.2 (1.3)	2.3 (1.4)	2.1 (1.2)
Dietary diversity					
HDDS10 (n = 3433)	5.1 (2.2)	5.1 (2.3)	5.1 (2.1)	5.1 (2.1)	5.3 (2)
MDD-W (n = 1108)	0.76 (0.43)	0.81 (0.39)	0.83 (0.37)	0.76 (0.43)	0.55 (0.50)
MDD-W10 (n = 1108)	6.54 (2.4)	7.7 (2.6)	6.7 (2.1)	6 (2)	5 (2)
Climate and environmental variables.					
Altitude	448 (557)	476 (683)	547 (506)	416 (391)	262 (305)
Annual rainfall	1482 (507)	1334 (358)	1559 (471)	1624 (537)	1606 (730)
Inter. rainfall var	0.14 (0.06)	0.14 (0.04)	0.13 (0.06)	0.13 (0.07)	0.15 (0.08)
Intr. rainfall var	1.04 (0.26)	1.09 (0.22)	1.01 (0.27)	0.99 (0.28)	1 (0.3)
Avg temperature	24.2 (3.2)	23.5 (4.1)	24.2 (2.9)	24.9 (2.1)	25.8 (1.7)
Inter. temp var	0.02 (0.03)	0.02 (0.05)	0.02 (0.02)	0.02 (0.02)	0.01 (0.01)
Intra. temp var	0.18 (0.33)	0.24 (0.46)	0.16 (0.19)	0.14 (0.18)	0.12 (0.08)
Households' characteristics					
Debts	0.45 (0.5)	0.39 (0.49)	0.43 (0.49)	0.49 (0.5)	0.63 (0.48)
Farm income	3478 (6372)	1988 (4977)	4102 (6414)	4941 (6851)	4901 (8119)
Produce value	4781 (7924)	3274 (6656)	5893 (8565)	6207 (8197)	5592 (9184)
Education[a]	1.14 (0.95)	1.27 (0.97)	1.23 (0.95)	1.02 (0.9)	0.81 (0.95)
HH size	5.8 (2.8)	5.5 (2.8)	5.7 (2.7)	6 (2.6)	6.7 (3.1)
Irrigation	0.5 (0.5)	0.63 (0.48)	0.4 (0.49)	0.38 (0.49)	0.41 (0.49)
Fertiliser	0.59 (0.49)	0.78 (0.41)	0.59 (0.49)	0.43 (0.49)	0.29 (0.45)
Seeds improved	0.39 (0.49)	0.45 (0.5)	0.4 (0.49)	0.4 (0.49)	0.23 (0.42)
Pesticides	0.44 (0.5)	0.6 (0.49)	0.4 (0.49)	0.31 (0.46)	0.19 (0.39)
Agricultural inputs	1.93 (1.42)	2.46 (1.37)	1.79 (1.38)	1.51 (1.33)	1.12 (1.18)
Land cultivated	1.91 (2.28)	0.38 (0.26)	1.33 (0.28)	2.62 (0.53)	6.3 (2.81)
Gender (male)	0.59 (0.27)	0.57 (0.3)	0.61 (0.26)	0.61 (0.25)	0.61 (0.25)
Other livelihood strategies					
Livestock Orientation	0.32 (0.35)	0.33 (0.36)	0.33 (0.36)	0.32 (0.35)	0.29 (0.34)
Market Orientation	0.65 (0.39)	0.49 (0.39)	0.69 (0.39)	0.81 (0.32)	0.85 (0.31)
Off-farm Income	0.3 (0.29)	0.39 (0.31)	0.26 (0.27)	0.21 (0.25)	0.19 (0.23)

[a] Education is expressed here as a numeric variable (0 = none, 1 = primary, 2 = secondary, 3 = post-secondary).

Also, we did not find any significant association between farm diversity indicators with market orientation and the involvement in off-farm activities, which suggests that these are not necessarily complementary or alternative to farm diversification strategies. The orientation towards livestock activities was statistically significant and positively associated with all the three indicators of farm diversity.

Table 3
Drivers and constraints of farm diversity (production, crop groups and livestock species). Results of the Poisson generalised linear model with SURVEY_ID as random effect.

Variable	Production diversity		Crop group diversity		Livestock diversity	
Altitude	−0.015 (0.024)		−0.017 (0.03)		−0.102 (0.057)	*
Annual rainfall	0.047 (0.016)	***	0.059 (0.021)	***	0.062 (0.041)	
Inter. rainfall var	0.086 (0.019)	***	0.122 (0.023)	***	−0.015 (0.048)	
Intr. rainfall var	−0.162 (0.023)	***	−0.153 (0.028)	***	−0.165 (0.057)	***
Avg temperature	−0.037 (0.025)		−0.052 (0.031)	*	0.025 (0.06)	
Inter. temp var	−0.059 (0.178)		0.127 (0.217)		−0.024 (0.459)	
Intr. temp var	0.026 (0.179)		−0.169 (0.218)		0.049 (0.461)	
Debts	0.023 (0.008)	***	0.024 (0.01)	**	0.033 (0.017)	*
Farm income	−0.03 (0.012)	**	−0.029 (0.016)	*	−0.038 (0.022)	*
Value farm production	0.07 (0.011)	***	0.063 (0.015)	***	0.102 (0.019)	***
Education (primary)	0.046 (0.017)	***	0.058 (0.022)	***	0.008 (0.037)	
Education (secondary)	0.039 (0.018)	**	0.064 (0.023)	***	−0.067 (0.039)	*
Education (postsecondary)	0.003 (0.03)		0.082 (0.037)	**	−0.211 (0.075)	***
HH size	0.028 (0.007)	***	0.019 (0.009)	**	0.046 (0.016)	***
Irrigation	0.06 (0.008)	***	0.055 (0.01)	***	0.093 (0.017)	***
Fertiliser	−0.046 (0.012)	***	−0.052 (0.015)	***	−0.099 (0.028)	***
Improved seeds	0.033 (0.009)	***	0.038 (0.011)	***	0.018 (0.018)	
Pesticides	0.045 (0.01)	***	0.063 (0.013)	***	−0.014 (0.023)	
Land cultivated	0.169 (0.019)	***	0.191 (0.024)	***	0.149 (0.04)	***
Land cultivated^2	−0.096 (0.016)	***	−0.114 (0.021)	***	−0.079 (0.034)	**
Gender (male)	0.004 (0.007)		−0.001 (0.009)		0.025 (0.016)	
Livestock orientation	0.078 (0.008)	***	0.027 (0.01)	***	0.148 (0.016)	***
Market orientation	0.006 (0.01)		0.003 (0.012)		0.028 (0.022)	
Off farm income %	−0.002 (0.007)		0.004 (0.009)		−0.005 (0.016)	
(Intercept)	1.436 (0.085)	***	0.867 (0.111)	***	−0.064 (0.187)	
N. of observations	**4772**		**4755**		**4237**	

"*" Significant at 10%, "**" significant at 5%, "***" significant at 1%. Standard error in parentheses.

3.3. Association between farm diversity and dietary diversity

The regression models show that crop group diversity is statistically significant and positively associated both with HDDS10 (Table 4) and MDD-W10 (Table 5). For instance, all else equal, for an additional type of crop group produced we would expect an 8% increase in the odds of increasing household dietary diversity by one food group. Livestock diversity is not statistically significant for the HDDS10, while it shows a significant and positive association with MDD-W10. Market orientation and off-farm income are positively associated with HDDS10 but statistically insignificant for MDD-W10. Among the other livelihood strategies, livestock orientation shows a positive and significant effect for both the indicators. Finally, all control variables, such as education, the use of agricultural inputs and the size of land cultivated are all positively

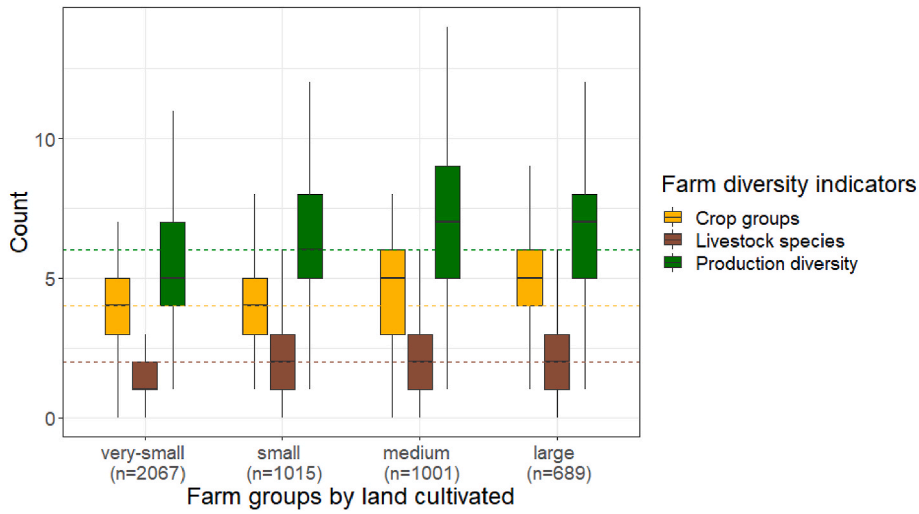

Fig. 3. Farm diversity (crop groups, livestock and overall production) comparison between very-small (<1 ha), small (1-2 ha), medium (2-4 ha) and large (>4 ha) farms. The dashed horizontal lines represent the median of each farm diversity indicator for the pooled dataset.

Table 4
Household Dietary Diversity Score (HDDS10) and farm diversity (crop group and livestock diversity). Results of the quasi-binomial generalised linear models for the pooled sample and each farm groups by the size of land cultivated. The models are estimated with SURVEY_ID as fixed effects.

Variables	Pooled[qb]	Very-small[qb]	Small[qb]	Medium	Large
Crop group diversity	0.079 (0.013)***	0.099 (0.021)***	0.104 (0.031)***	0.061 (0.029)**	0.037 (0.033)
Livestock diversity	0.019 (0.015)	0.054 (0.025)**	−0.012 (0.033)	0.057 (0.032)*	−0.022 (0.038)
Market orientation	0.173 (0.055)***	0.035 (0.087)	0.158 (0.135)	0.453 (0.14)***	0.128 (0.159)
Off-farm income %	0.424 (0.058)***	0.273 (0.085)***	0.292 (0.126)**	0.857 (0.144) ***	0.725 (0.177) ***
Livestock orientation	0.112 (0.053)**	0.224 (0.085)***	0.193 (0.12)	0.018 (0.128)	−0.229 (0.15)
Education - primary	0.231 (0.042)***	0.145 (0.063)**	0.201 (0.1)**	0.329 (0.093) ***	0.269 (0.099) ***
Education - secondary	0.289 (0.043)***	0.168 (0.065)***	0.268 (0.097)***	0.333 (0.098) ***	0.547 (0.125) ***
Education – postsecondary	0.262 (0.061)***	0.127 (0.084)	0.243 (0.134)*	0.549 (0.164) ***	0.362 (0.262)
Agricultural inputs	0.145 (0.019)***	0.185 (0.028)***	0.107 (0.043)**	0.106 (0.044)**	0.11 (0.052)**
Land cultivated	0.042 (0.008)***	−0.081 (0.115)	−0.017 (0.132)	0.016 (0.068)	0.035 (0.014)**
(Intercept)	−1.845 (0.094) ***	−1.92 (0.135)***	−1.504 (0.28)***	−1.809 (0.391) ***	−1.005 (0.483)**
N. of observations	**3433**	**1590**	**679**	**678**	**486**

"*" Significant at 10%, "**" significant at 5%, "***" significant at 1%. Standard error in parentheses.[qb] These models showed overdispersion, hence were estimated using a quasibinomial distribution.

associated with the HDDS10, which means that household dietary diversity benefits from access to these assets. In contrast, the use of agricultural inputs was insignificant for MDD-W10, while land cultivated had a negative association.

The analysis for different farm groups identified some differences. Crop group diversity has a positive, but decreasing, association with HDDS10 from very small to medium farms. This association is insignificant for large farms, suggesting a decreasing effect from small to large farms of the benefits from crop group diversity (Table 4). A similar effect can be observed when analysing MDD-W10, with the only difference that crop group diversity has a negative effect on large farms (Table 5). Livestock species diversity has only a positive effect on HDDS10 for very-small and medium farms (Table 4) and on MDD-W10 for small farms (Table 5). Market orientation has a significant and

Table 5
Minimum Dietary Diversity for Women (MDD-W10) and farm diversity. Results of the Poisson generalised linear models for the pooled sample and each farm groups by the size of land cultivated. The models are estimated with Region as fixed effects.

Variable	Pooled[qb]	Very-small[qb]	Small	Medium	Large
Crop group diversity	0.174 (0.026) ***	0.601 (0.079)***	0.153 (0.05)***	0.086 (0.047)*	−0.079 (0.04)**
Livestock diversity	0.242 (0.045) ***	0.115 (0.106)	0.135 (0.081)*	0.065 (0.085)	0.078 (0.099)
Market orientation	0.047 (0.122)	−0.517 (0.294)*	−0.25 (0.207)	0.015 (0.234)	0.732 (0.463)
Off-farm income %	0.151 (0.125)	−0.477 (0.347)	−0.152 (0.214)	0.172 (0.196)	0.907 (0.26)***
Livestock orientation	0.211 (0.095) **	1.275 (0.338)***	−0.067 (0.145)	0.054 (0.145)	0.071 (0.196)
Education - primary	0.121 (0.071)*	0.162 (0.221)	−0.106 (0.115)	0.07 (0.105)	0.033 (0.134)
Education - secondary	0.238 (0.082) ***	0.317 (0.226)	0.113 (0.129)	0.084 (0.124)	−0.037 (0.175)
Education – postsecondary	0.124 (0.192)	0.19 (0.506)	0.253 (0.331)	−0.071 (0.322)	−0.115 (0.355)
Agricultural inputs	−0.038 (0.039)	−0.258 (0.103)**	0.056 (0.076)	0.048 (0.07)	0.201 (0.074)***
Land cultivated	−0.049 (0.018) ***	−0.398 (0.425)	0.106 (0.191)	0.052 (0.088)	−0.025 (0.034)
(Intercept)	−1.938 (0.218) ***	−3.402 (0.585)***	−1.237 (0.509)**	−1.023 (0.478)**	−0.533 (0.642)
N. of observations	**1108**	**349**	**283**	**293**	**183**

"*" Significant at 10%, "**" significant at 5%, "***" significant at 1%. Standard error in parentheses.[qb] These models showed overdispersion, hence were estimated using a quasibinomial distribution.

positive effect on household dietary diversity only for medium farms. It is insignificant for large farms, but this may be caused by the low variability within the sample of large farms, as they show high levels of market orientation across the four countries (Fig. A4). Off-farm income is significant and positively associated with HDDS10 for all farm groups. Comparing its coefficients with other variables in the same scale (market orientation and livestock orientation), off-farm income has the largest effect. Table 5 shows that only large farms have a significant positive effect on MDD-W10 from off-farm income, but in the model without control variables it is also positive and significant for the pooled sample (Table A6). Livestock orientation is only significant and positive for very-small farms for both the indicators.

4. Discussion and conclusions

4.1. Association between diet diversity and farm diversity

There is substantial evidence supporting the beneficial role of diversified farm production on rural household dietary diversity (Waha et al., 2022). Yet, it is still unclear whether and to what extent rural households' livelihoods benefit from specific strategies, namely: prioritising farm production diversification (Kasem and Thapa, 2011; Bellon et al., 2020; Bergau et al., 2022), specialising in cash crops to increase market engagement (Sibhatu et al., 2015; Koppmair et al., 2017), or increasing the involvement in off-farm activities (De Janvry and Sadoulet, 2001; Rahman and Mishra, 2020). The households in our sample showed low dietary diversity overall, with an average 40% of the households and 24% of the women interviewed consuming less than five food groups out of the ten included in the HDDS10 and MDD-W10 indicators. The interpretation of results and their comparison was approached with caution as the two dietary diversity indicators were measured for households from different countries and agro-ecologies, across different farming systems in South and Southeast Asia. However, consistent patterns and interesting contrasts have also emerged.

Overall, our findings show that farm diversity is beneficial for improving dietary diversity, at both household and individual levels. However, the analysis of the different farm groups by the size of the land cultivated provides novel evidence that the role of farm diversity can vary depending on the type of farm considered, showing patterns that have previously not been clear from the literature. A higher diversity of crop and livestock production enhances rural households' access to a broader variety of food items, but the magnitude and effect of production diversity on dietary diversity changed between farms of different land sizes. The countries included in this study are characterised by farm smallholdings, primarily as a result of high population density in rural areas and land tenure policies (Markussen et al., 2011; Giller et al., 2021). As such, farm size represents a key variable within these contexts. Farm diversity was particularly important for increasing household and individual dietary diversity of very small and small farms, but its effect and significance decreased for larger farms. This is pertinent because the evidence about the relationship between production diversity and dietary diversity found in the literature is often equivocal (Sibhatu et al., 2015; Parvathi, 2018; Islam et al., 2018), but here we show that with the right segmentation we can identify a clear pattern across a wide range of contrasting systems. In agreement with Bellon et al. (2020), we provide evidence that farm diversification strategies can be more beneficial for farms that are too small to generate economies of scale if they specialise in cash crops. This may also be supported by the negative correlation between MDD-W10 and market orientation for very-small farms. Another point to consider is that, in our sample, larger farms are also the most diversified and may already benefit from diversity. This interpretation agrees with studies showing that the beneficial effect of increasing farm diversity on diet diversity is not linear, but tends to decrease after certain thresholds are reached (Das and Ganesh-Kumar, 2018; Sibhatu and Qaim, 2018b; Islam et al., 2018).

Regarding the other livelihood strategies considered, the analyses produced some contrasting results between the two dietary diversity indicators. The involvement in off-farm activities and market orientation were confirmed as important strategies with a highly positive effect on improving household dietary diversity overall. Off-farm activities provide households with additional and more stable sources of income, that reduce the reliance on farm production and the vulnerability to farming risks (Barrett et al., 2001). A higher share of off-farm income was positively associated with household dietary diversity for all farm groups. Higher market orientation can increase farmers' income and their access to food items that are not produced on-farm (Koppmair et al., 2017). The level of market orientation did not show clear trends in the farm groups analysis, as market orientation had a significant and positive association with household dietary diversity only for medium sized farms. It is important to consider variables mean and dispersion when interpreting these results. For instance, large farms, that have the highest HDDS10 compared to other groups, have an average market orientation of above 85% with low variable dispersion, explaining the low statistical significance for this group. In line with the results for production diversity, these findings may suggest that market orientation has a greater link with dietary diversity for medium and large farms. Unexpectedly, neither the share of income from off-farm activities nor market orientation were significant in the main regression model analysing the sub-sample for MDD-W10 and we did not observe significant trends in the analysis of the farm groups, where off-farm income was only significant and positive for large farms. These results suggest that key regional characteristics that were not captured in the model may need to be considered in the interpretation of the results. For instance, MDD-W10 decreases from very-small to larger farms, as the largest farms are mostly from Rajasthan (58.5%) and Assam (23.5%), regions, that also have the lowest MDD-W10 in the subsample (Table A.9 and Table A.10).

4.2. Drivers and constraints of farm diversity

Our findings confirm that climate and environmental variables are significant determinants of farm diversity. Farm diversity is recognised as a farming strategy to adapt to environmental conditions and cope with climate risks and variability (Bezabih and Sarr, 2012; Asfaw et al., 2018; Bozzola and Smale, 2020; Antonelli et al., 2022). The geographical spread in the survey data allowed us to compare households from different climatic and agroecological regions. As only 50% of the farms analysed use irrigation, the positive effect of total annual rainfall may indicate that more precipitation allows for greater diversity via increased water availability and the opportunity to grow different types of crops, as explained in previous studies (McCord et al., 2015; Bhatta et al., 2016). The analysis of the effect of rainfall variability on farm diversity, between and within years, also produced interesting results and considerations. The positive effect of inter-annual rainfall variability may reflect an adaptation to diversify to cope with the risk of climate related production loss. Conversely, the negative relationship of intra-annual rainfall variability, similar to the results of Bellon et al. (2020), suggests that high variability between seasons in a year may limit the variety of crops that can be grown due to the presence of seasonally dry or very wet conditions.

As anticipated, the level of farm diversity was influenced by some farm assets and characteristics. Household size seems to enable the management of a higher number of crops or livestock species through higher labour availability (Nguyen et al., 2019). Education has a positive effect on the overall diversity; however, the results differ between crop group and livestock diversity. According to previous literature, the relationship between farm diversity and education can be ambiguous and take different directions (Longpichai, 2013; Nguyen et al., 2017). Higher education increases farmer skills and ability to access information, which are beneficial when managing diversified farming systems. However, it also increases the opportunity to engage in off-farm activities, therby reducing the labour available on the farm. Among the main benefits of farm diversity is the provision of ecosystem services that can potentially reduce the need for inputs, such as fertilisers and pesticides (Gaba et al., 2015; Tamburini et al., 2020). While this is indicated by the negative correlation of mineral fertiliser use with all three diversity indicators, the positive correlation between the use of pesticides and crop group diversity was not expected and should be further explored. However, in these regions farming is heavily dependent on pesticides, especially for growing vegetables (Schreinemachers et al., 2017) and this is a potential interpretation of this result. The positive effect of irrigation on diversity agrees with previous literature (Tacconi et al., 2022), suggesting that access to irrigation allows for a higher variety of crops and livestock species. Despite the overall value of farm production is positively associated with farm diversity, earnings from sales of farm products have a negative effect on diversity. This may indicate that farms focusing on marketable products are also less diversified. The role of land cultivated size in the decision to diversify has been much discussed in the literature and our results confirmed its importance when drawing conclusions on farmer decision making and land use strategies. The area of cultivated land was a significant driver of farm diversity, but, the negative effect of its quadratic term indicates that the correlation with farm diversity may be not linear, along with previous studies (Skarbø, 2016; Kankwamba et al., 2018).

Finally, we did not identify any trade-offs between diversification and the other livelihood strategies analysed. This suggests that the strategies of increasing market orientation or the involvement in off-farm activities are not necessarily alternative to diversification, as emerged in recent literature (Bellon et al., 2020; Bergau et al., 2022). Still, these relationships may depend on other factors that we could not explore in this study, such as the availability and type of off-farm opportunities or market characteristics, that may be worth investigating in future studies.

4.3. Final conclusions

Our study presents new evidence about the contribution of farm diversity to household and individual dietary diversity, compared to the adoption of other livelihood strategies. We also explored the different factors driving or constraining the adoption of farm diversification strategies in South and Southeast Asia.

Our findings highlight the importance of considering different farm characteristics and contexts in which they operate when looking for the most effective strategies and developing policies to improve rural household livelihoods. Farm diversity, level of market orientation and involvement in off-farm activities are all strategies that can potentially improve dietary diversity. Importantly, we show that the magnitude and significance of the effect of these livelihood strategies differ depending on other household characteristics, such as farm size, which played a central role in the analysis. In particular, the effect of farm diversity on dietary diversity was greater in smaller farms. It decreased for farms with larger dimensions, which may benefit from increasing their engagement in off-farm activities and markets. In conclusion, our results suggest that the identification of farming strategies that benefit more rural household dietary diversity depends necessarily on the understanding of the type of farm and the situational context of analysis.

This study builds on prior research on the relationship between farm diversity and dietary diversity (Jones, 2017; Sibhatu and Qaim, 2018a; Tacconi et al., 2022; Waha et al., 2022), presenting a novel and promising pathway that requires, although, further exploration. We encourage future studies to adopt methodologies that complement quantitative analyses with a qualitative approach, to provide more detailed and nuanced information about the adopted indicators. For example, we used a comprehensive indicator of group diversity, distinguishing between different crop types and livestock species, but due to data limitations we could not test the type of management adopted by farmers (e.g., intercropping, seasonal rotations, organic certified or not certified), which may change the outcome on diet and food security. The indicator of market orientation consisted of the share of farm produce sold to the market, while other studies used the distance from the closest market, road, or city (Sibhatu and Qaim, 2018a; Bergau et al., 2022) as a proxy for market access. However, these indicators do not provide information about the type of market (i.e., local, middleman, exports, etc.), the extent and affordability of additional foods from market purchases, or the number of commercialisation alternatives available. Finally, involvement in off-farm activities did not include the type of work (seasonal, casual, part-time, sector, etc.). To our knowledge, this level of detail for these variables has been rarely investigated in the literature in this field, mostly due to lack of data and the complexity of capturing farm- or region-specific nuances when analysing large samples. In our view, this would provide significant insights to evaluate what specific types of these strategies are more beneficial and in which context they can be adopted, to further understand the potential of farm diversity in improving dietary diversity, its compatibility with other livelihood strategies and ultimately targeting interventions.

Authors' contribution

FT, KW, PL and JO conceived and designed the study. JH coordinated data acquisition and compilation. FT performed the data cleaning and analysis. WV provided advice and guidance on statistical modelling and inference. FT wrote the draft and the following versions of the manuscript. MvW contributed to the discussion with in-depth knowledge of the data and supported FT with the results interpretation. KW, CM, JO and PL edited the final version of the manuscript. The final version was commented and critically revised by all the authors. Regarding the IN_GEF_2019 dataset: JCR and SPA – identification and finalisation of dataset and review of final draft, RB – finalisation of parameters for dietary diversity and help in data collection. RY – coordination, supervision and help in data collection in the field, inputs for draft paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2023.100706.

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