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Drivers and constraints of on-farm diversity. A review

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Abstract

Enhancing and maintaining on-farm diversity is a potential strategy to improve farming systems' sustainability and resilience. However, diversification is driven or constrained by different factors and dynamics that vary across environmental, socio-economic and political contexts. Identifying drivers and constraints of diversification can help to support the adoption of on-farm diversification strategies, where doing so is beneficial. For the first time, we systematically review and summarise recent peer-reviewed studies assessing drivers and constraints of on-farm diversity from 42 different countries. From 2312 studies, we selected a total of 97, reporting 239 drivers and constraints, which we categorised using the Sustainable Rural Livelihood Framework. We extracted the number of times they were assessed as having a positive, negative or neutral relationship with on-farm diversity. Some factors mainly have a positive relationship, such as the need to adapt to risks or belonging to indigenous ethnicities, but for most of the others the results are mixed. Our major conclusions are as follows: (1) The adoption of diversification strategies is affected by both production and demand dynamics, with differences depending on farms and contexts; (2) small subsistence-oriented farms tend to adopt on-farm diversification strategies to cope with environmental characteristics and risks and satisfy their subsistence needs; (3) farmers may shift towards specialisation strategies if the comparative advantage of diversification and its natural insurance effect gets displaced by market opportunities, financial capital, technologies and the availability of alternative and more profitable sources of income; (4) the availability of technologies enabling farm diversification and the access to alternative market options are crucial to stimulate the implementation and maintenance of on-farm diversity; (5) future policies and research promoting the adoption of on-farm diversification strategies need to design mechanisms and incentives that consider the opportunity-cost of alternative livelihood opportunities, and that are suitable for the local context and for farmers' objectives.

Keywords Agricultural diversity · Agrobiodiversity · Farmers decision-making · Diversified farming systems

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1 Introduction

Promoting and supporting agricultural diversity at different scales represents an important approach to averting diverse challenges for the implementation of more sustainable agricultural systems (Bioversity International 2019; FAO 2019; HLPE 2019). In the past decades, agricultural production and productivity have increased remarkably, mainly driven by processes of expansion, intensification and specialisation (Pingali 2012). These processes also increased pressure on the natural environment and a progressive homogenisation of rural landscapes and food consumption (Khoury et al. 2014; Herrero et al. 2017; Ramankutty et al. 2018; Benton and Bailey 2019).

At farm level, diversification strategies have shown some promise to increase biodiversity and ecosystem services, reduce the dependence for external input and, also, improve yields and yield stability (Di Falco and Perrings 2003; Renard and Tilman 2019; Rosa-Schleich et al. 2019; Sirami et al. 2019). Moreover, agricultural diversification can potentially benefit households' food and nutritional security status by providing access to a broader variety of food products and a more balanced and diversified diet (Remans et al. 2014; Jones 2017). However, it is still far from clear where, why, how and to what conditions and degree farm-level diversification is a viable strategy.

Growing international attention to farm diversification (FAO 2019; HLPE 2019) creates an imperative to ensure that future research and interventions that aim to respectively understand and promote it are well-reasoned, allow for comparability and are well-targeted. Other recent reviews have assessed different approaches to define crop diversification (Hufnagel et al. 2020) and provided evidence about the impacts and the ecological and economic trade-offs generated by diversified farming systems (Kremen and Miles 2012; Beillouin and Ben-ari 2019; Rosa-Schleich et al. 2019; Tamburini et al. 2020). However, to our knowledge, this study is the first review following a systematic approach that summarises the recent scientific literature about the drivers and constraints of on-farm diversity at farm scale, cross-referencing studies conducted across different farming systems and world regions. The only recent review assessing drivers and processes of agricultural diversification by Schroth and Ruf (2014) focused specifically on agroforestry systems in tropical regions.

In this study, we review recent literature to identify what drivers and constraints influence farm-level diversification. We focus on farm-scale diversity of agricultural products, which we refer to as on-farm diversity—the number of crops, plants, trees and livestock species grown, and that are consumed, traded and used in different ways in the farming system (Fig. 1). The extent of on-farm diversity varies considerably across the world regions and spatial scales (Herrero et al. 2017; Ramankutty et al. 2018). Farms are dynamic systems that farmers adapt, not least by changing, increasing, or maintaining their on-farm diversity, to satisfy their needs and objectives. Such decisions are influenced by the interaction of numerous factors (McIntire et al. 1992; Scoones 1998; Ellis 2000; Herrero et al. 2013) that we examine as drivers and constraints. We define drivers as the factors that create impetus towards greater diversification at farm scale, and constraints as factors acting in the opposite direction. Understanding these interacting features is crucial to identify where investments and interventions to support diversification are likely to be appropriate and effective, and how they should be targeted.

The overall objectives of this study are (1) to review recent studies that examine drivers and constraints of on-farm diversification around the world; (2) to categorise the most applied indices and measures to quantify on-farm diversification; (3) to identify which drivers and constraints are the most relevant and most studied, the methodologies used to assess their relationship with diversification and to discuss their impact on farmers' choices; and (4) to identify agroecological and socio-economic patterns associated with these drivers and constraints. First, we present the methods used to select the studies and the approach adopted to identify and categorise the drivers and constraints of diversification (Section. 2). Second, we present and discuss the results of the review and the different categories of drivers and constraints (Sections. 3–4). Finally, we discuss overall results and limitations, and draw the conclusions (Sections. 5–6).

2 Methodology

2.1 Definitions of agricultural diversity

There are multiple approaches to defining and addressing diversity in agricultural systems. According to Hufnagel et al. (2020), definitions of agricultural diversity vary across geographical contexts, the spatial or temporal scale considered, and the discipline and objective of the study. At farm level—the scale of analysis of this review—we can identify four broad definitions of diversity in the agricultural context that have been used. First, *on-farm diversity*, such as the crop or livestock species and varieties produced or part of the farming system; crop-livestock integrated production systems; agroforestry systems, when woody or herbaceous perennials are grown in mixture with crops and/or animals. This is extended as *agrobiodiversity*, which includes wild

Fig. 1 Diversified on-farm production in a small farm close to Hanoi, Vietnam. Photograph courtesy of Jeda Palmer.

plant species maintained and used in the farm. Second, a broader definition of agricultural diversity can refer to the "whole" *biological diversity* of the farming system, taking into account the presence of insects, wild animal species and the richness of the soil microbial community (Kremen and Miles 2012). This definition expands the role of diversity to species that might provide ecosystem services, such as pollination, pests and diseases control, cycling of nutrients and water and other physico-chemical processes (Garibaldi et al. 2014; McDaniel et al. 2014; Gaba et al. 2015). Third, *livelihood diversity* is another type of diversity. Farmers often engage in off-farm activities, in other farms or in different businesses to increase, or diversify, their sources of income (Nguyen et al. 2019). Fourth, *Multifunctional farming* includes additional components respect to the intrinsic agricultural production. It defines a "vertical" diversification of the farming business, which involves an additional set of farm-based and -related activities, such as agritourism, agricultural education, promotion of ecological services and bio-energy production (van der Ploeg et al. 2009).

We are aware that all these forms of diversification can be important and, in some contexts, more impactful in improving farmers' livelihoods than on-farm diversity (Barrett et al. 2001; Sibhatu et al. 2015). Nevertheless, in this review, we are interested in understanding the factors that lead farmers to maintain, increase or simplify their production diversity. Therefore, we focus on the analysis of drivers and constraints of on-farm diversity.

2.2 Literature search and screening criteria

We first ran a literature search on two online databases for multidisciplinary research, Scopus (www.scopus.com) and Web of Science (www.webofknowledge.com). We focused on peer-reviewed publications only. The key terms employed focused on "agricultural diversity", "drivers and constraints" and respective synonyms or similar terms (Table 1). We filtered the results to journal articles or literature reviews published in English. The search was run on 6th December 2019. We obtained 1680 studies from Scopus and 1662 from Web of Science, for a total of 3342 from interdisciplinary journals. We then excluded the duplicates using the reference management software EndNote X9.2 (https://endnote.com/), obtaining 3054 studies. The number of studies published per year increased considerably after 2010, with the studies published after 2010 accounting for 76% of the total (from 1975 to 2020). To focus the review on current literature we only selected studies published after 2010, obtaining a new total of 2312 studies.

Second, we proceeded by screening titles and abstracts. Our selection criteria required that the studies (1) presented the analysis of drivers and constraints of on-farm diversification among their main objectives; (2) focused on on-farm diversity (crops, livestock, mixed systems, agrobiodiversity and agroforestry systems), rather than other definitions of agricultural diversification, such as livelihood diversification or off-farm diversification; (3) focused on-farm and household level rather than on a global or landscape scale. At this stage, we removed 2172 studies and selected 140.

The final step was the full-text reading that led to the removal of 43 studies, as they did not meet the previous

Table 1 Literature review query strings key used on Scopus and Web of Science.

Search tool	Key of search
Scopus	TITLE-ABS-KEY ("agricultur* diversity" OR "agrobiodiversity" OR "agricultur* diversification" OR "crop diversi*" OR "production diversi*" OR "livelihood diversi*" OR "farming diversi*") AND ("driver*" OR "constraint*" OR "factor*" OR "enabler*" OR "enabling factor*" OR "motivation*" OR "motivating" OR "reason*" OR "incentiv*" OR "influenc*" OR "obstacl*") AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re"))
Web of Science	(TS = ("agricultur* diversity" OR""agrobiodiversity" OR "agricultur* diversification" OR "crop diversi*" OR "production diversi*" OR "livelihood diversi*" OR "farming diversi*") AND ("driver*" OR "constraint*" OR "factor*" OR "enabler*" OR "enabling factor*" OR "motivation*" OR "motivating" OR "reason*" OR "incentiv*" OR "influenc*" OR "obstacl*")) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article OR Review)

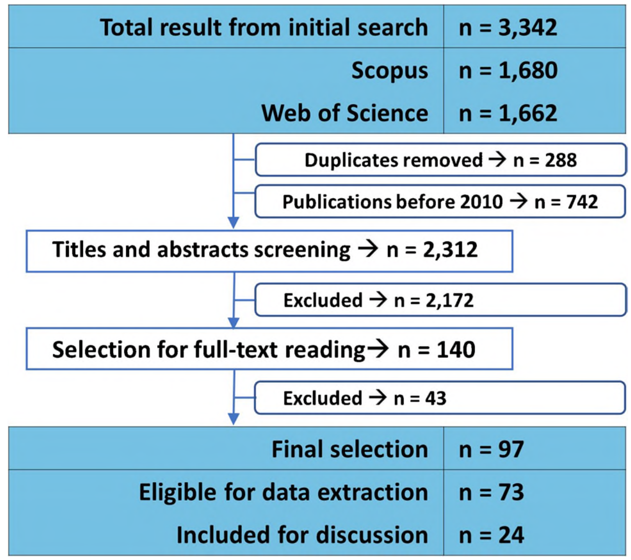


Fig. 2 Workflow diagram of literature review and selection.

selection criteria or the expected quality requirements (i.e. missing relevant information on the dataset and methodology). The 97 remaining studies were the final selection. Within this final group, we identified 73 studies eligible for data extraction, as they provided a quantitative assessment of the relationship between on-farm diversity and drivers and constraints. The remaining studies ($n = 24$) were kept in support of the discussion. A workflow diagram of the literature search and screening is shown in Fig. 2.

2.3 Data extraction

The data extraction aimed to identify variables studied as potential drivers or constraints of on-farm diversification and to report if their effect was positive, negative and consistent across different studies and contexts. For this, we collected the following information:

(i) The *definition of on-farm diversity* used in the study, namely *crop diversity* (accounting for crop species), *livestock diversity* (livestock species), *mixed production* (both crop and livestock species), *agroforestry* and *agrobiodiversity*. Grasslands were either allocated to crop diversity or agrobiodiversity depending by classification provided in the specific studies.

(ii) The *indices* and *measures* used to quantify on-farm diversity (Table 2).

(iii) The *geographical location*(s) covered by the study (country and continent).

(iv) The explanatory variables studied as *potential drivers or constraints* of on-farm diversity. For each of these variables, we reported and counted the times (number of assessments) in which the effect on on-farm diversity was assessed as *significantly positive* (P), *significantly negative* (N) or *statistically not significant* (NS). We based our evaluation on the significance level used in each study. For some categorical variables (e.g. ethnicity, agroecological region, topography), we could not report an overall positive or negative effect on on-farm diversity. Therefore, we only reported whether these variables had a *significant* (S) or not significant effect.

In the event that, in a single study, the robustness of the effect of one or more variables on the same on-farm diversity indicator was assessed by employing more than one statistical method of analysis (e.g. Bezabih and Sarr, (2012)), we only reported the predominant effect to avoid double counting. For example, we registered the effect as positive if an explanatory variable had significantly positive effect in two of the statistical methods applied and none in a third one. In the event of an even number of conflicting results, we prioritised the statistically significant effect (e.g. if the effect resulted 1 P and 1 NS, it was reported as

Table 2 On-farm diversity indices and measures identified in the selected studies.

Index	Measure	Formula/Description		Results
Species richness	Richness	Count of the number of species cultivated (or sold) in the farm		36
Diversity adoption	Motivations	Boolean operator: -the farm is diversified/intend to diversify = 1 -the farm is not diversified/does not intend to diversify = 0		18
Simpson index (SID)	Relative abundance	$SID = 1 - \sum_i^S p_i^2$ with $0 < SID < 1$	a_i = area cultivated with crop i A = Total area cultivated $p_i = a_i/A$; S = total number of species (species richness) $SID = \begin{cases} \sim 1 \rightarrow \text{perfect diversification} \\ 0 \rightarrow \text{perfect specialisation} \end{cases}$	16
Shannon index (H)	Evenness, proportional abundance	$H = -\sum_{i=1}^S p_i \ln p_i$ with $H \geq 1$	As species evenness increases, H assumes higher values.	15
Pielou index (J)	Evenness, proportional abundance	$J = H/H_{max} = H/\ln S$ with $0 < J < 1$	H = Shannon Index H_{max} = max possible value of H (species distribution is perfectly even) $J = \begin{cases} \sim 1 \rightarrow \text{max evenness} \\ \sim 0 \rightarrow \text{min evenness} \end{cases}$	6
Margalef index (MI)	Richness	$MI = (S-1)/\ln S$ with $MI \geq 0$	N = total number of individuals MI increases with the increasing of Species richness.	2
Berger–Parker index (BPI)	Relative abundance	$BPI = 1/\max(p_i)$ with $BPI \geq 1$	As BPI increases, it is assumed a higher diversity.	2
Composite entropy index (CEI)	Evenness, proportional abundance	$CEI = -\sum_{i=1}^N p_i \ln(p_i)(1 - \frac{1}{N})$ with $0 \leq CEI \leq 1$	$CEI = \begin{cases} 1 \rightarrow \text{max diversification} \\ \sim 0 \rightarrow \text{max specialisation} \end{cases}$	2
Herfindahl–Hirschman index (HHI)	Specialisation (inverse of *Simpson index*)	$HHI = \sum_i^P p_i^2$ with $0 \leq HHI \leq 1$	$HHI = \begin{cases} 1 \rightarrow \text{max specialisation} \\ \sim 0 \rightarrow \text{max diversification} \end{cases}$	1

1 P). We did not encounter any case of conflicting results between significantly positive and significantly negative effects within the same study. However, we reported the same explanatory variables more than once if, in the same study, it was assessed for different on-farm diversity definitions and measures or on different data. Finally, anytime we identified the same variables named differently across different studies, we re-named them under a common label to be able to match and compare them (e.g. "age of the household head (HH)" and "household head age" were both coded as "HH age").

The dataset with all the extracted data and information about the original variables from each study are available in the following online digital repository: https://doi.org/10.6084/m9.figshare.14151659.v2 (Tacconi et al. 2021).

2.4 Data assessment

We extracted a total of 239 different explanatory variables and grouped them following the approach of the Sustainable Rural Livelihood Framework (Scoones 1998; Ellis 2000). The framework (Fig. 3) defines that farmers' opportunity to adopt different livelihood strategies, including on-farm diversification, is driven or constrained by *external* (agro-ecological context, the political and institutional context at local, regional and wider scales, and exposure to environmental and market risks and shocks) and *internal* factors (human, economic/financial, socio-cultural and physical capitals). The previous or current implementation of *other livelihood strategies* has also an important potential influence on farmers' choices and possibilities to adopt farm diversification strategies. We dedicated a specific section to other livelihood strategies (Section. 4.3), in which the results mostly emphasised the role of the engagement in off-farm activities. In this regard, it is necessary to remark that on-farm diversification is not a farmers' goal per se, but only one of the potential strategies in their livelihood portfolio. The trade-offs associated with choices among livelihood strategies are likely to have an important role in farmers' decision-making (Scoones 1998).

Finally, the extracted variables were evaluated based on the total number of statistically positive, statistically negative, statistically significant and not significant assessments encountered across the selected studies.

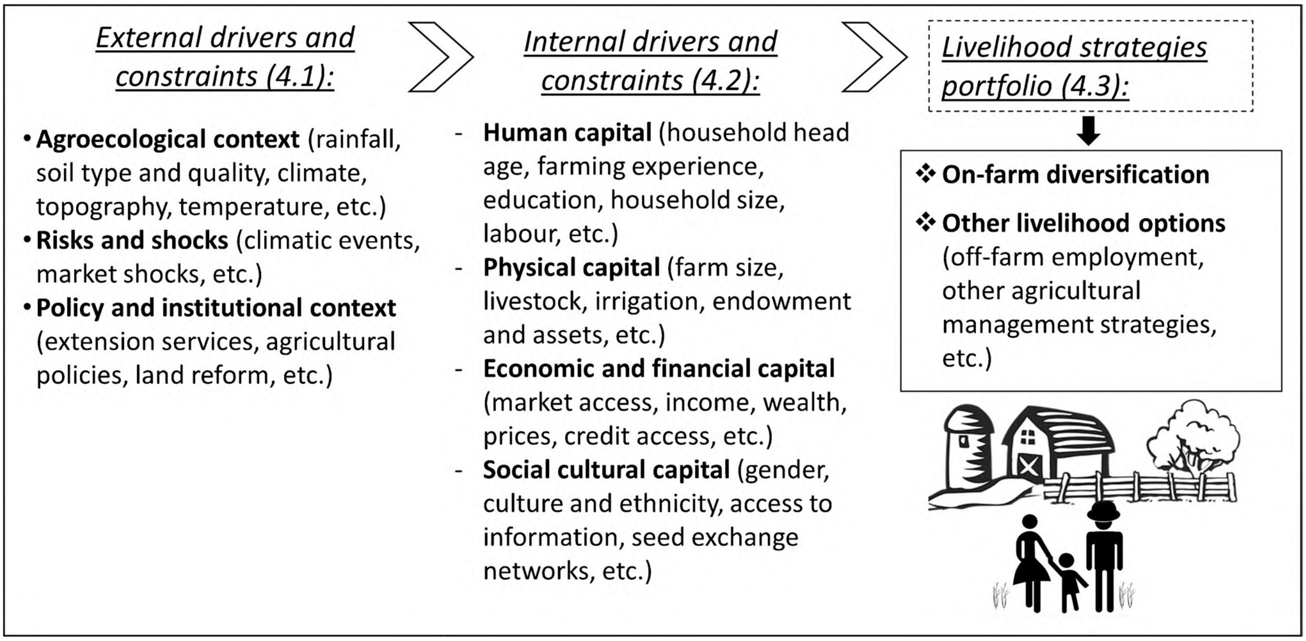


Fig. 3 Sustainable Rural Livelihood Framework applied to on-farm diversity drivers and constraints. External and internal drivers and constraints affect livelihood strategies portfolio and the decision to diversify (adapted from Scoones, 1998 and Ellis, 2000).

3 Geographical focus and different definitions of on-farm diversity

The 97 studies included in the final selection were published in a total of 53 different journals of various disciplines, from agricultural economics, food security, agricultural policies, social sciences to ecology, biology and forestry (Tacconi et al. 2021).

The studies covered 42 different countries in total (Fig. 4a). If grouped by income (World Bank 2021), lower-middle-income (48% of the total) and upper-middle-income economies (26%) were the most represented in the sample of studies, while low-income and high-income economies accounted for 13% each (Fig. 4b). Most of the studies focused on Africa ($n = 32$) and Asia ($n = 25$) (Fig. 4b). This might be explained by the topic of the review itself, as on-farm diversification is often associated with small and subsistence farms, which are prevalent in these regions (McCord et al. 2015; HLPE 2019; Bellon et al. 2020). In other regions, like Europe, the attention might be more focused on broader definitions of farm diversification such as multifunctionality (van der Ploeg et al. 2009; Manning et al. 2018), which were not in the scope of this review. In Section. 4, we reported when the results came from specific countries if relevant to understanding the relationship between diversification and a driver or constraint.

We encountered five different definitions of on-farm diversity across the selected studies, with some studies that used more than one (Fig. 5). Crop diversity was the most investigated ($n = 59$), followed by agrobiodiversity ($n = 19$), agroforestry systems ($n = 12$), crop-livestock mixed systems ($n = 11$) and livestock diversity ($n = 1$) (Fig. 5). This shows that crop diversity is the most popular indicator of on-farm diversification in use. Also in this case, the imbalance did not allow us to compare the different diversity definitions. The data analysed span from small samples of local rural households collected for the purposes of single studies (Kawa et al. 2015; Sander and Vandebroek 2016) to large and regionally or nationally representative household datasets (Herrera et al. 2018; Weigel et al. 2018), covering farms of different land size, objectives and level of diversity. For instance, among the 20 studies measuring crop species richness, we identified a range in average species richness from 1 to 27 (Tacconi et al. 2021). Fifty-three studies reported the average land size in their sample and two thirds of them reported land size being inferior or equal to 5 ha (Tacconi et al. 2021).

4 Drivers and constraints of on-farm diversity

An overview of the total results for each category of drivers and constraints accordingly to the Sustainable Rural Livelihood Framework is provided in Fig. 6. The category of internal drivers and constraints presented the highest number of

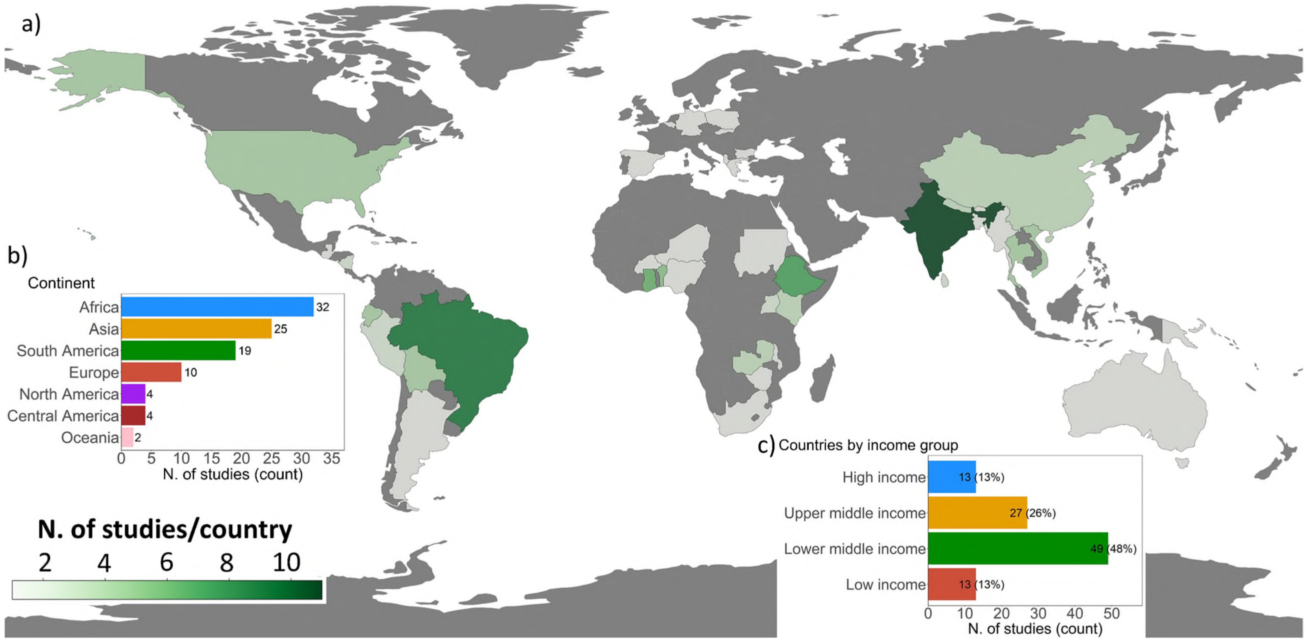
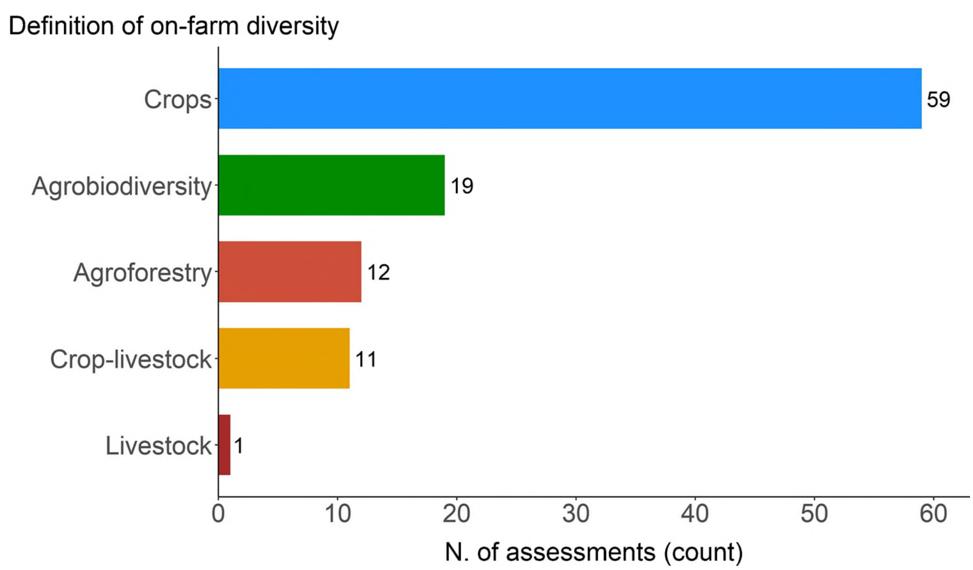


Fig. 4 Number of studies by (**a**) country (green scale), (**b**) continent, and (**c**) income groups according to the World Bank classification (2021). Dark grey areas in the map indicate regions for which no data were available.

Fig. 5 Number of assessments by on-farm diversity type.



assessments and variables (Fig. 6). Interestingly, the assessment of the human capital variables had overall a higher number of not significant cases. This might indicate that the effect of this category of variables may be highly dependent on other factors. Each category among the external drivers and constraints and other livelihoods strategies produced less results; however, this does not mean that they are less relevant in farmers' decision-making. The in-depth interpretation of the role of each category requires the analysis of the single variables that we provided in the continuation of this section.

4.1 External drivers and constraints

4.1.1 Agroecological context

Agroecological characteristics set the natural boundaries for the possible farm configurations (species richness) and

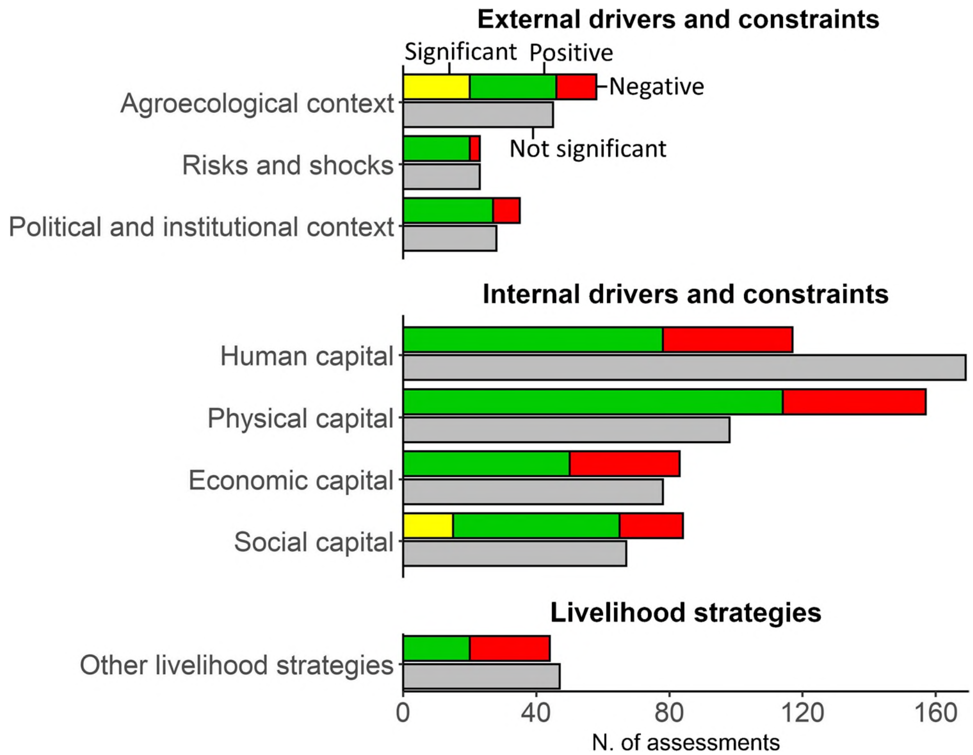


Fig. 6 Categories of drivers and constraints of on-farm diversity. For each category of variables (*y*-axis), the upper stack bar represents the total count of statistically significant effects reported on on-farm diversity, divided between positive (green), negative (red) and significant non-directional effects (yellow); the lower bar (grey) represents the total count of not significant assessments.

composition (species choice), and become even more relevant in regions where the access to technical skills, technology and capital is scarce (Katwal et al. 2015; Kankwamba et al. 2018). In the studies analysed, the correlation between the overall agroecological characteristics and the level of on-farm diversification was studied by adopting proxy variables that compared farm locations by local district ("District") (10 S, 5 NS) or based on the climatic and ecological characteristics of the region in which farms are located ("Agroecological region") (6 S, 5 NS). As expected, the results showed evidence that farms' geographic location has a significant influence on on-farm diversity as different environments and ecosystems require species with different characteristics (Fig. 7a). The most analysed variables representing specific environmental characteristics were topography, rainfall level and soil. We did not find enough evidence about the role of average temperatures, with only four assessments, all not significant and from the same study (Tesfaye and Tirivayi 2020) (Fig. 7a).

Topographic features, such as altitude and slope, affect other environmental characteristics like temperatures, soil erosion, wind and solar radiation exposure, but also the accessibility to farms and roads. When studied as a categorical variable topography had significant association with the extent of on-farm diversity (3 P) (Fan et al. 2019; Rayol et al. 2019), farmland slope may drive diversification (3 P, 4 NS) (Fig. 7a), as uneven conditions of agricultural land require the farmers to adapt by growing the appropriate crop combination for each area (Abebe 2013; Abebe et al. 2013; Schroth and Ruf 2014). This is one of the cases in which diversification becomes more a necessity than a choice. The results about the impact of farm altitude were mixed (7 P, 5 N, 7 NS) (Fig. 7a). A higher altitude generally means a more complex and vulnerable environment for agriculture to which farmers adapt in different ways, depending on other socio-economic indicators (Samberg et al. 2010). For instance, in regions characterised by monocultures or few species that do not perform well at high altitudes, farmers located at higher elevations may need to diversify by adopting a mix of species that better adapt to the different environment (Min et al. 2017; Nguyen et al. 2017; Tesfaye and Tirivayi 2020). In contrast, where farms tend to diversify more, altitude represents a constraint. At lower elevations, the environmental conditions often allow the production of a broader set of crop or livestock species (Abebe et al. 2013; Skarbø 2014) and provide better access to roads and markets. This makes it easier to manage more complex and diverse farming systems and commercialise the products (Samberg et al. 2013).

On-farm diversification decisions are also influenced by rainfall level and farmers' rainfall expectation (Di Falco et al. 2010a; Bezabih and Sarr 2012; Bhatta et al. 2016). We identified a total of 22 assessments of different rainfall indicators with mixed results on the diversification strategies (Fig. 7a). The assessments were mainly conducted in arid and semi-arid regions. Some studies reported that higher rainfall levels can allow farmers to produce a broader array of crops and reduce their reliance on investment in irrigation

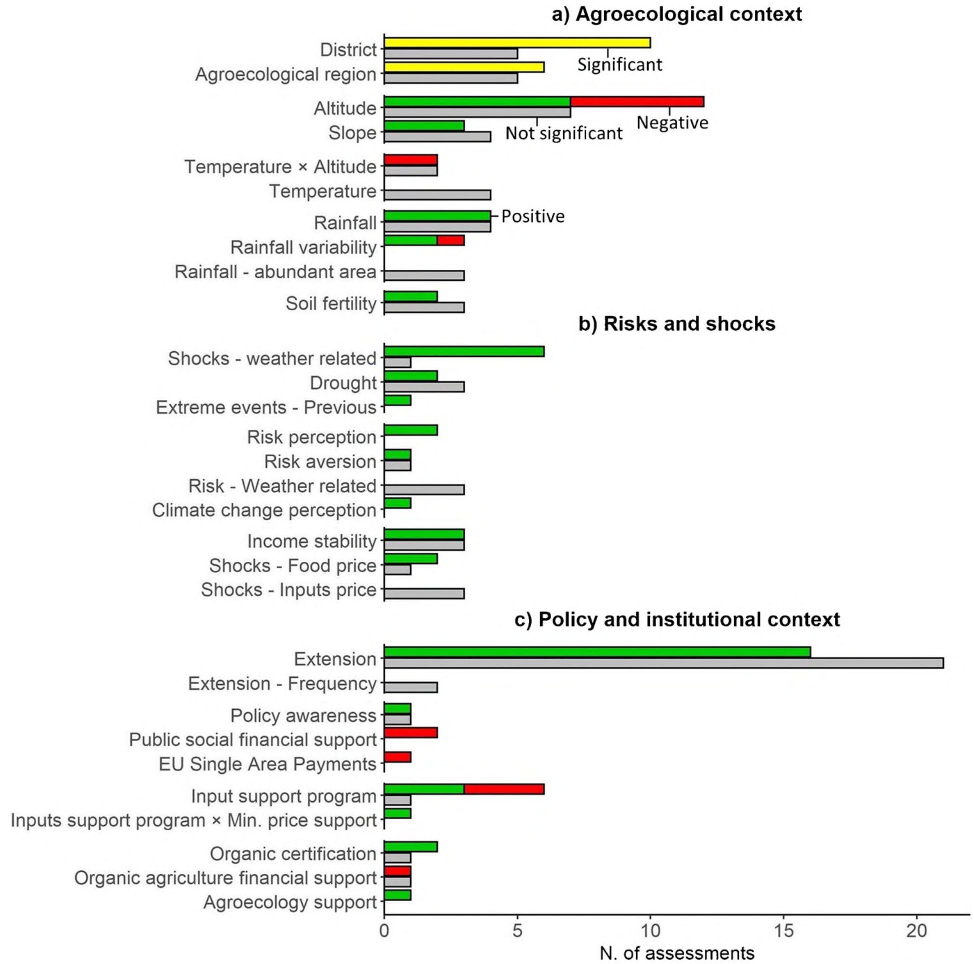


Fig. 7 Number of assessements for selected external drivers and constraints of on-farm diversification. The barplots show the ten variables with the highest number of assessments identified for each sub-category: (**a**) agroecological context, (**b**) risks and shocks, (**c**) policy and institutions. For each variable (*y*-axis), the upper stack bar represents the total count of statistically significant effects reported on on-farm diversity [Positive (green), Negative (red) and Significant non-directional (yellow)]; the lower bar (grey) represents the total count of Not Significant assessments. The symbol "×" indicates the interaction between two variables.

systems (Di Falco et al. 2010a; McCord et al. 2015). However, in areas characterised by rapid and excessive rainfall, the potential of farm diversification can be negatively affected. Bhatta et al. (2016) compared three different regions of India, Nepal and Bangladesh and identified an inverted-*U* relationship between annual rainfall and on-farm diversification with an optimal annual rainfall regime in correspondence of 1500–2100 mm. Rainfall inter-seasonal or -annual variability emerged as another relevant determinant of diversification (Di Falco et al. 2010a; Bezabih and Sarr 2012). Increasing both crop richness and evenness resulted a common strategy to cope against rainfall variation and farmers' rainfall expectations play an important role in this (Bezabih and Sarr 2012; Saenz and Thompson 2017). In Ethiopia, Di Falco et al. (2010b) and Bezabih and Sarr (2012) found that current (in the same year) and lagged (previous year or season) rainfall level impact in a different way the richness of crop species grown. With a previous year characterised by scarce or highly variable rainfall, farmers were more likely to adopt crop diversification strategies to spread the risk or simply to introduce some draught-resistant crops. On the contrary with positive rainfall expectation, farmers would focus more on few high-value and marketable crops. In the same year, the effect was the opposite as farmers would increase their on-farm diversity if the current rainfall level would allow them to grow different crop varieties (Di Falco et al. 2010a; Bezabih and Sarr 2012). The diversification strategies related to rainfall variability are not only limited to the level of species richness but has also an influence on the type of crop adopted. With increasing rainfall uncertainty, farmers may prefer to allocate more land and give priority to food crops over cash crops, with the aim of ensuring the household's food security threshold (Min et al. 2017; Saenz and Thompson 2017).

We only identified 12 quantitative assessments about soil characteristics (e.g. fertility, texture, quality and erodibility) and 5 of them were not significant (Tacconi et al. 2021). Some studies found that low-fertile soils may limit farm diversification potential, by reducing the conditions to grow certain crops and feed livestock (Kasem and Thapa 2011; Lazíková et al. 2019). On the other hand, fertile and high-quality soils reduce production risks and may lead to profit-maximisation strategies including the specialisation few high-value crops. Crop diversification may be instead the preferred adaptation strategy for farmers cultivating on poor soils to cope with production risks (Bezabih and Sarr 2012; Makate et al. 2016; Roesch-McNally et al. 2018). This matches with the results of Weigel et al. (2018) that found that in Bavaria soils with a better quality [according to the definition of Mueller et al. (2012)] were mainly dedicated to intensified and simplified farming system, whereas farms located in areas with less fertile soil adopted a more diversified production, as a strategy of natural insurance (Weigel et al. 2018).

4.1.2 Risks and shocks

Farming activity is highly vulnerable to climatic and market risks and shocks, to which farmers react based on their "buffer, adaptive and transformative capability" (Darnhofer 2014). Previous studies have shown that farm diversification has the potential to stabilise yield variability (Di Falco and Perrings 2003; Renard et al. 2016). Therefore, farmers may diversify if they expect bad, variable or uncertain outcomes (risks) (Bezabih and Sarr 2012; Komarek et al. 2020), or in response to events that are experienced and lead to sudden and significant change (shocks) (Schroth and Ruf 2014; Nguyen et al. 2017; Tesfaye and Tirivayi 2020). The adoption of a diversified portfolio of activities can be also a strategy of natural insurance against market risks, such as commodity prices volatility, or adverse natural events, such as droughts, heat waves, or pests and diseases outbreaks (Markowitz 1959; Chavas and Di Falco 2012; Bioversity International 2019). On-farm diversification was often studied as an adaptation strategy in the studies reviewed and we identified a total of 48 assessments analysing directly the effect of variables representing factors of risk or previous shock events (Fig. 4). The statistically significant results were consistent across the different studies, confirming the assumptions above: farmers are likely to adopt on-farm diversification as a risk management strategy (21 P, 4 N and 23 NS).

In particular, the results showed that the farmers use of diversification strategies was more frequent in flood prone areas (Mandal and Bezbaruah 2013), subjected to a strong incidence of droughts (Asfaw et al. 2018), previous extreme weather events or shocks (Huang et al. 2014; Nguyen et al. 2017; Tesfaye and Tirivayi 2020) (Fig. 7b). In this regard, farmers' risk aversion and expectations based on the occurrence of previous extreme events emerged as drivers of on-farm diversification (Bezabih and Sarr 2012; Huang et al. 2014; Min et al. 2017; Tun Oo et al. 2017; Asravor 2019).

Markets represent another major source of risk and shocks for farming activities and market dynamics are essential components of farmers' decision-making process (Zawedde et al. 2014; Asante et al. 2018; Lancaster and Torres 2019). We identified 14 quantitative assessments of market risks and shocks variables. The statistically significant results confirm that the use of on-farm diversification as a risk management strategy is also a response to market-generated risks (6 P, 8 NS). A case study on rubber farms in Thailand found that the adoption of diversified farming system was a common response to rubber price fluctuations (Longpichai 2013). Similar results emerged from a study in Niger, which found that in presence of short-term food price fluctuations, farmers tended to rely more on the diversification of self-produced food (Asfaw et al. 2018). However, this capacity to respond to market shocks is highly dependent on farm characteristics. For instance, farms focussing on annual production will have different opportunities and flexibility to adapt through agricultural diversification strategies compared to farms with perennial productions (Schroth and Ruf 2014).

4.1.3 Policy and institutional context

Policies and institutions can influence farmers' decisions through different measures, such as subsidies, taxes, agricultural support schemes, investments in research and rural training programmes. We identified a total of 63 assessments of variables within this category (27 P, 8 N and 28 NS) (Fig. 4). The most common were rural extension, agricultural support programmes, organic certifications, and research and technology investments in agriculture (Fig. 7c).

The effect of agricultural extension services on the adoption of diversified farming systems was the most studied variable within the policy and institutional context. The results showed a total of 17 positive assessments and 21 not significant (Fig. 7c), providing some evidence that extension services can stimulate on-farm diversification. Agricultural trainings are not only a source technical knowledge and skills, but can promote and create awareness about the potential benefits of diversification and the adoption of new varieties (Makate et al. 2016; Kankwamba et al. 2018; Mofya-Mukuka and Hichaambwa 2018). Moreover, rural extension can be a channel to access new planting material (Samberg et al. 2013; Williams et al. 2018) and a source of updated information about market opportunities, new technologies, climate change and risk management strategies (McCord et al. 2015; Adjimoti et al. 2017; Tun Oo et al. 2017). The efficacy of extension services can be affected by farm accessibility (McCord et al. 2015), as less connected communities may have more difficulties in receiving visits and communicating with extension workers and NGOs operating in rural development projects (Williams 2016; Asante et al. 2018; Kankwamba et al. 2018).

The analysis of the impact of rural subsidies and agricultural development programmes showed that these measures can drive or constraint on-farm diversification, depending on their target and the local context (7P, 7 N, 2NS) (Fig. 7c).

Policies based on strict agricultural planning and crop restrictions deter diversification strategies, as they push farmers towards specific crop or livestock species (Di Falco et al. 2010b; Markussen et al. 2011; Ciaian et al. 2018). Moreover, when these measures last for extended periods, they can generate structural changes or lock-ins. Therefore, they have the potential to continue hindering diversification after they are lifted because farmers may need time to re-adjust their farms (Di Falco et al. 2010b; Kasem and Thapa 2011). Similar findings emerged from the analysis of other crop-specific measures such as subsidies or minimum support price. For instance, policies supporting rice in Asia (Chhatre et al. 2016; Aditya et al. 2017; Burchfield and Poterie 2018) or maize in Africa (Saenz and Thompson 2017; Mofya-Mukuka and Hichaambwa 2018) acted as market distortions and drivers of specialisation by increasing the financial risk and opportunity-cost of alternative, or unsupported crops.

We found mixed evidence about the impact of policies supporting the access to agricultural inputs like seeds and fertiliser (3 P, 3 N, 1 NS) (Fig. 7c). Farmers can use the inputs to grow more species (Asante et al. 2018; Kankwamba et al. 2018) or to expand the production of the dominant crops (Saenz and Thompson 2017; Mofya-Mukuka and Hichaambwa 2018). Other forms of farmers' support, like direct payments and income integration, may reduce the importance of farm diversification as a risk management strategy and consequently its adoption (Lazíková et al. 2019; Ochoa. M. et al. 2019). On the contrary, policies promoting and supporting agroecological management resulted potentially effective in increasing on-farm diversity. For instance, in Brazil, the Brazilian School Feeding Programme (PNAE) and the Food Acquisition Plan (PAA) obtained encouraging results in stimulating on-farm diversification, even on farms previously involved in monocropping or different farming activities (Blesh and Wittman 2015; Valencia et al. 2019). However, as argued by Valencia et al. (2019), these policies may also create the risk of shifting farmers "from commodity markets to institutional markets". When these changes are not structural adaptations but policy dependent, their benefits might end once the same policy gets changed or removed.

Organic certification is another form of incentive for farmers to diversify. Five analyses investigated how organic certification affect farm diversification (2 P, 1 N, 1 NS). Farms with organic certification showed a higher extent of farm diversity in studies conducted in Bolivia (Jacobi et al. 2014) and in the USA (Lancaster and Torres 2019). Alternatively, Nastis et al. (2013), analysing a small sample of farms in Greece about the implication of the European Union's Common Agricultural Policy support on selected organic crops, found that this measure was likely to compete with crop diversity as a strategy of income stabilisation and to lead farmers to focus on the few supported crops (Nastis et al. 2013). Similar conclusions were drawn by other studies conducted in Europe by Lazíková et al. (2019) and Weigel et al (2018), which however, did not find statistical evidence in support of that.

We did not find any quantitative analysis involving the role of research and investments in agriculture on farmers' adoption of diversification strategies. However, studies covering different geographical areas, namely India, France, Belgium, and the USA, identified and discussed the necessity to expand research and innovations towards diversification practices (Chhatre et al. 2016; Casagrande et al. 2017; Borremans et al. 2018; Meynard et al. 2018; Roesch-McNally et al. 2018). Over time, a prevalent focus of policies and research towards few dominant crops (i.e. maize, rice and wheat) contributed in creating trajectories of socio-technological lock-ins and hindering the adoption of minor species and more diversified systems (Meynard et al. 2018; Roesch-McNally et al. 2018). In conclusion, the development of crop-specific research, breeding programmes, technologies and dedicated markets inevitably reduce the competitiveness and viability of alternative crops and farm management strategies, despite other potential benefits.

4.2 Internal drivers and constraints

4.2.1 Human capital

The human capital consists of characteristics of the farmers and their households. The main variables that we identified were the household head's age (HH age), farming experience, level of education, household size, hired and family labour, and share of non-working members in the household (dependency ratio) (Fig. 8a).

Household head's age was the most assessed variable within the human capital ($n=68$). However, the findings are scattered and do not provide strong evidence about how farmers' age influence on-farm diversity (14 P, 16 N, 40 NS) (Fig. 8a). Similarly, we did not find enough evidence from the analysis of the effect of farming experience (6 P, 2 N, 10 NS). Some of the studies that identified a negative correlation between farmers' age and farm diversification explained that older farmers have more experience and consolidated farming strategies; thus, they might be more reluctant and less in need to test and adopt new crop species, animals or management strategies (Huang et al. 2014; Ali 2015; Fan et al. 2019). Older farmers may have less skills in using information technologies and, as a consequence, less access to updated knowledge and information (Fan et al. 2019). Young farmers are generally more flexible and open in adopting new species and technologies to take advantage of market opportunities (Nkomoki et al. 2018). The studies that found a positive relationship between household head's age

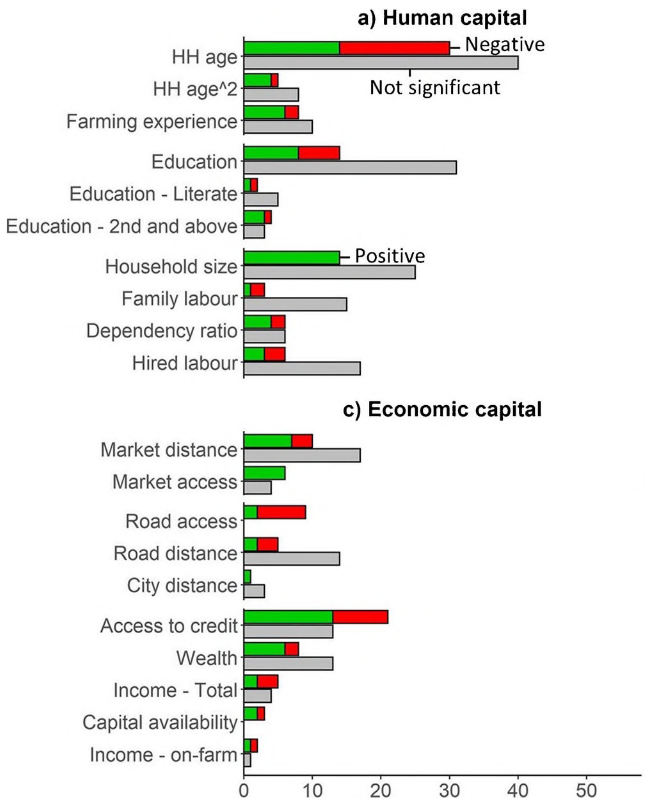


Fig. 8 Number of assessements for selected internal drivers and constraints of on-farm diversification. The barplots show the ten variables with the highest number of assessments identified for each subcategory: (**a**) human capital, (**b**) physical capital, (**c**) economic and financial capital, (**d**) social capital. For each variable (*y*-axis), the upper stack bar represents the total count of statistically significant effects reported on on-farm diversity [positive (green), negative (red) and significant non-directional (yellow)]; the lower bar (grey) represents the total count of not significant assessments.

and on-farm diversity provided different explanations. Older and more experienced farmers usually have more knowledge to manage farm diversity and awareness of its potential benefits (Kawa et al. 2015; Tesfaye and Tirivayi 2020). Experienced farmers may be more interested in preserving varieties with a traditional value (Eyssartier et al. 2011) and are more likely to have selected more species over the years than less experienced farmers (Kawa et al. 2015; Ng'Endo et al. 2015). Farmers tend to become more risk-averse when they age, so diversification can become the preferred option to reduce farming risks, as also explained in paragraph 4.1.2 (Abebe 2013; Tesfaye and Tirivayi 2020), while younger households might prefer to focus on fewer cash crops (Kawa et al. 2015) or more lucrative livelihood sources (Williams and Kramer 2019). Due to these contrasting results in the literature, some studies used scatter plots (Skarbø 2014) or added the squared term of household head age (HH age^2) in the regression models (Herrera et al. 2018; Kankwamba et al. 2018) to assess the existence of a non-linear relationship between the age of the household head and on-farm diversity (Fig. 8a). Skarbø (2014) identified an inverted-*U* relationship, with a turning point in correspondence to the age of 60. This trend, also found in Herrera et al. (2018), may indicate that farmers tend to increase on-farm diversity with the experience and age up to a certain point when eventually; they need to simplify and reduce the number of activities because of their decreasing labour efficiency. Kankwamba et al. (2018) found an opposite relationship (*U*-shaped), but in their regression model, the effect size of the squared term of household head age (HH age^2) on crop diversification was negligible ($<0.0\%$ with $p<0.1$).

Education was another component of the human capital for which we identified ambiguous findings (8 P, 6 N, 31 NS) (Fig. 8a). Literate and more educated farmers generally have a better capacity to access information and awareness about different production options and their potential benefits, both in terms of income and nutrition (Pandey 2015; Fadina and Barjolle 2018; Fan et al. 2019). Still, the gradient of the effect of education on on-farm diversity seems to be also influenced by the local context (Nguyen et al. 2017). As emerged in Longpichai (2013), which studied a region in Thailand characterised by rubber monocultures, when farmers are used to grow monocultures or a few products, the lack of education may reduce their ability to manage additional activities. On the other hand, in areas where farms are highly diversified, more educated and skilled farmers may have a higher incentive in specialising on few commercial and lucrative crops, if economically convenient (Huang et al. 2014; Hitayezu et al. 2016; Kurdyś-Kujawska et al. 2018). Education was also assessed based on the different levels of schooling. For instance, literacy (1 P, 1 N, 5 NS), primary school (4 P), secondary and above (3 P, 1 N, 3 NS). According to some of these assessments, the positive effect of schooling on diversity decreases with a higher level of education (Herrera et al. 2018; Kankwamba et al. 2018; Mofya-Mukuka and Hichaambwa 2018). If, as mentioned above, more skilled farmers are more capable to manage diversified farms, when they reach a certain level of education, they may also decide to invest less time on farm diversification and prioritise alternative and more remunerative off-farm livelihood strategies.

Another group of variables analysed within the human capital is the number of household members (household size) and the labour availability (Family labour and Hired labour) (Fig. 8a). Household size was a driver of on-farm diversity 14 times, while 25 assessments could not identify a statistical evidence of this correlation (14 P, 25 NS). Large families have more people depending on the farm. Hence, they require more food production and diversity to ensure that the nutrition requirements are met, especially in the case of subsistence farming (Adjimoti et al. 2017; Aheibam and Singh 2017; Ochoa. M. et al. 2019). Furthermore, larger households usually have more agricultural labour force that provides the potential to manage a broader number of farm activities and therefore increasing diversity (Zampaligré et al. 2014; Nguyen et al. 2019; Daudu et al. 2019). Diversified farming systems can be more labour-intensive then specialised systems (e.g. different sowing and harvesting seasons) (Schroth and Ruf 2014; Casagrande et al. 2017). For instance, farmers in Thailand (Kasem and Thapa 2011) and Sri Lanka (Burchfield and Poterie 2018) indicated labour shortage as a major driver of rice monocultures (Kasem and Thapa 2011; Burchfield and Poterie 2018). However, the assessments of the effects of hired labour (3 P, 3 N, 17 NS) and family labour (5 P, 2 N, 16 NS) did not provide enough evidence about their influence on farm diversification strategies (Fig. 8a).

4.2.2 Physical capital

Physical capital includes all the physical assets that farmers employ in their agricultural activity. The most analysed variables involved farm characteristics (i.e. farm area, land fragmentation and distance), livestock ownership, irrigation facilities, fertilisers, seeds and other endowments (Fig. 8b).

Farm size was the variable with the highest number of assessments among all the publications analysed ($n = 84$). A vast majority of the results showed a positive correlation between agricultural diversity and the farm area (46, 8 N and 30 NS). Nevertheless, to explain the characteristics of this relationship, also the studies that reported negative results, explored the existence of non-linear correlation (Skarbø 2014; Makate et al. 2016; Kankwamba et al. 2018) or the interaction effect with other variables (Pandey 2015; Weigel et al. 2018) are relevant. Generally, the potential for on-farm diversification is low if farms have limited space, especially in regions where the average farm size is particularly small (Huang et al. 2014; Bhatta et al. 2016; Makate et al. 2016). Bigger farms can expand their production diversity and spread the risk by growing a broader array of crops or livestock species, while smallholder farmers have limited possibilities to add or test new crops (Baul et al. 2013; Samberg et al. 2013). On the contrary, some studies showing a negative correlation between farm size and diversification argued that smallholders have a greater need to diversify to reduce risks and stabilise their income (Aheibam and Singh 2017). As a large land endowment, in some contexts, can be an indicator of wealth, bigger and wealthier farms may have more technologies and resources to specialise in commercial products and intensive farming (Adjimoti et al. 2017). These contrasting outcomes also emerged in studies that assessed the existence of a non-linear relationship between farm size and diversity (Skarbø 2014; Makate et al. 2016; Kankwamba et al. 2018). Their findings showed that on-farm diversity tended to increase together with farm size but only up to a certain point, specifically 0.7 ha in Skarbø (2014) in Ecuador and 1.5 ha in Kankwamba et al. (2018) in Malawi. This may suggest that farmers benefit from diversification until other factors like labour cost (Kasem and Thapa 2011) and economies of scale, make specialisation a more convenient strategy (Bowman and Zilberman 2013). Other studies, like Pandey (2015) in Nepal and Hitayezu et al. (2016) in South Africa, found that the magnitude and elasticity of the positive effect of farm size on diversity may also decrease with the increase of farmers wealth. Finally, Weigel et al. (2018) suggested that the positive correlation between farm size and diversity may be also policy driven, as in the case of the European Common Agricultural Policy, which introduced the requirement of a minimum of crop diversity threshold that increases with cropland area(farms between 10 and 30 ha, min two crops; farms > 30 ha, min 3 crops).

Another farmland characteristic assessed was the difference of diversity between consolidated and fragmented farms. Fragmentation, defined as the number of non-contiguous plots belonging to the same farm/household, resulted to drive diversification strategies (4 P, 2 NS). Spatially dispersed plots are likely to have different environmental characteristics (i.e. altitude and soil) and then not be suitable for the same type of cultivation or livestock (Di Falco et al. 2010b; Adjimoti et al. 2017; Ciaian et al.

2018). Moreover, the distance between plots can create logistic issues for transferring tools or machineries necessary for specific productions that might be too expensive or simply not suitable to be moved across different locations. Lastly, farmers might just prefer to use different plots for different products, as in the example of the home gardens. Home gardens usually presented a richer diversity then other farm plots, as they are also used to preserve plants with low- or even null-market price due to their religious and cultural value or to test new crops to transfer in larger plots if successful (Steward 2013; Pandey 2015).

Beyond size and fragmentation, land access and tenure security influence farmers' decision-making. The analysis of the correlation between land tenure and diversity found a prevalence of positive results (Fig. 8b). A major point is that without a legal title guaranteeing the security of land tenure, farmers are more likely to focus on annual crops and simplified cultivations with short-term returns. Farmers with a secure tenure have a higher incentive in adopting practices that preserve their land and can invest more in the inclusion of new species, and plan for medium- and long-term production, as in the case of tree species (Schroth and Ruf 2014; Segnon et al. 2015; Min et al. 2017). Two of the studies that reported a negative correlation between land titling and diversity, did not provide an explanation about the result, while the negative result in Asante et al. (2018) came from the analysis of livestock species diversity, in Ghana. The authors explained that farmers with land tenure certificates were more likely to focus on crops and instead of raising livestock (Asante et al. 2018).

The analysis of the relationship between livestock ownership and overall farm diversity showed some evidence of positive correlation (13P, 3 N, 15 NS). Livestock and crop production can be complementary activities. The animals can contribute through the production of manure and draught power, and benefits by eating crop residues (Di Falco et al. 2010a; Ciaian et al. 2018; Roesch-McNally et al. 2018). However, when livestock production becomes the main households' livelihood source, it may then lead to specialisation and lower levels of diversity (Skarbø 2014; Torres et al. 2018).

The access to irrigation facilities provides the farmers with the opportunity to plan more efficiently their production, extend the cropping season and the conditions to grow a broader array of crop and animal species (Aheibam and Singh 2017; Alemayehu et al. 2018; Lazíková et al. 2019). Irrigation was studied using indicators measuring the availability of water for irrigation or surface of irrigated land, which were coded as irrigation access (9 P, 3 NS) and share of irrigated land (3 N, 2 NS); the proximity with sources of water, coded as water access (3 P, 1 N, 2 NS); the ownership of irrigation tools, such as water pumps (3 N) and agricultural wells (1 P); or the reliance on rain (2 P, 1 NS) (Fig. 8b). The majority of positive assessments confirms that the lack of access to water for irrigation can represent a relevant constraint for implementing and maintaining diversified farming systems, especially in contexts with irregular or scarce rainfall regimes (Longpichai 2013; Mandal and Bezbaruah 2013; Burchfield and Poterie 2018). Still, also in this case, the gradient of this relationship can be influenced by other factors, as informed by the negative results (Nguyen et al. 2017). The availability of irrigation facilities also reduces farming risks. Therefore, distinct from rainfed systems, reliable access to water may reduce the need of diversification and allow specialisation on high-value crops (Skarbø 2014; Nguyen et al. 2017, 2019).

Finally, we identified few studies analysing the implication of using/accessing agricultural inputs such as fertilisers (4 P, 2 N, 2NS) and high yielding/improved seed varieties (1P, 4 N, 4NS). Also in this case, the results were context specific. In areas characterised by low productivity, inputs like fertilisers increase the potential of cultivating a broader array of crops (Aheibam and Singh 2017; Asante et al. 2018). On the other hand, where diversification is used as a risks-response strategy, the access to fertilisers (Adjimoti et al. 2017) or high yielding (Asfaw et al. 2018) varieties may drive farmers to specialise on particular crops.

4.2.3 Economic and financial capital

The economic and financial capital includes households' economic and financial opportunities and assets, such as sources of income, wealth, and access to market and credit (Fig. 8c). These variables are key components of farmers' decision-making because they allow (or limit) the adoption of different livelihood strategies, investments in farm improvements, and contribute to shape and satisfy farmers' objectives (Bowman and Zilberman 2013; Schroth and Ruf 2014; Bhatta et al. 2016).

Markets have a complex and conflicting influence on farmers' decisions and possibility to diversify. The indicators of farmers' access to markets, namely market distance (7 P, 3 N, 17 NS), market access (6 P, 4 NS), road distance (2 P, 3 N, 14 NS), road access (2 P, 7 N) and city distance (1 P, 3 NS), were the most studied variables within the economic capital category (Fig. 8c). The mixed results show that farmers react differently to markets depending on their characteristics, orientation (subsistence or market-oriented) and the local context. The presence and access to fresh food markets, for instance, arose as important drivers of crop diversification for vegetables and fruit farmers in studies conducted in different regions, such as the USA (Roesch-McNally et al. 2018; Lancaster and Torres 2019), France (Casagrande et al. 2017), India (Ali 2015) and Brazil (Valencia et al. 2019), as they diminish farmers' dependency from mainstream market channels and the requirements of products standardisation. Proximity to markets and roads, they reduce marketing and transaction costs. Also, road access simplify the connection with extension services, and hence trainings, inputs, seeds and new varieties (Gbedomon et al. 2017; Williams and Kramer 2019). This allows farmers, especially those with none or limited means of transport and storage facilities, to grow and sell a broader variety of products, including the more perishable ones (Makate et al. 2016; Torres et al. 2018).

Despite these arguments suggesting a positive relationship between market access and on-farm diversification strategies, other studies provided an opposite perspective. Farmers with means of transport, road access and a broader range of market options can access and choose better prices and conditions (Nguyen et al. 2017). Therefore, they are in a better position to maximise their income by specialising on high-value activities, and then purchasing food with the earnings (Abebe 2013). Subsistence farmers with poor connections to roads and markets, instead, may need to diversify more their production to reduce farming risks and satisfy their families' nutritional needs (Asante et al. 2018; Tesfaye and Tirivayi 2020). Finally, it is essential to highlight the role of prices. Switching between different cultivations and farm activities requires skills, time, investments and effort. Therefore, the mere presence of markets is not sufficient to influence farmers' decisions if prices are not considered sufficiently convenient (Kasem and Thapa 2011; Williams and Kramer 2019).

The analysis of the role of the access to economic and financial resources through indicators like credit access (13 P, 8 N, 13 NS), wealth (6 P, 2 N, 13 NS) and income (2 P, 3 N, 4 NS) returned again conflicting results (Fig. 8c). The lack of the sufficient economic and financial resources to implement and maintain a diversified agricultural production is often studied as another potential limitation by agricultural producers (Iles and Marsh 2012; Bowman and Zilberman 2013; Schroth and Ruf 2014). Farmers require capital to undertake farm improvements and add new activities (i.e. equipment, new crops, trees and livestock breeds). Reliable access to credit provides more flexibility in land allocation decisions and in increasing farm production mix. This allows farmers to have enough resources and time for the investment to pay off (Mandal and Bezbaruah 2013; Nguyen et al. 2017; Asante et al. 2018). For instance, agroforestry systems often require substantial initial costs to plant and preserve the new trees and crop species, and time before they become profitable. Therefore, the lack of financial capital is likely to discourage their adoption (Aneani et al. 2011; Schroth and Ruf 2014). The evidence about a positive association between wealth, income and on-farm diversification seems to support that wealthier farmers have a higher ability to absorb these investments and the eventual consequences of losses from a potential failure of the new activities (Longpichai 2013; McCord et al. 2015). On the other hand, farmers with less economic resources and credit access may diversify more to cope with potential risks and provide their family subsistence. Ultimately, the sign of this correlation may differ between different income groups, as shown in Weigel et al. (2018), where farmers with an average whole-farm revenue per hectare were the most diversified if compared with farms with low and high whole-farm revenue per hectare.

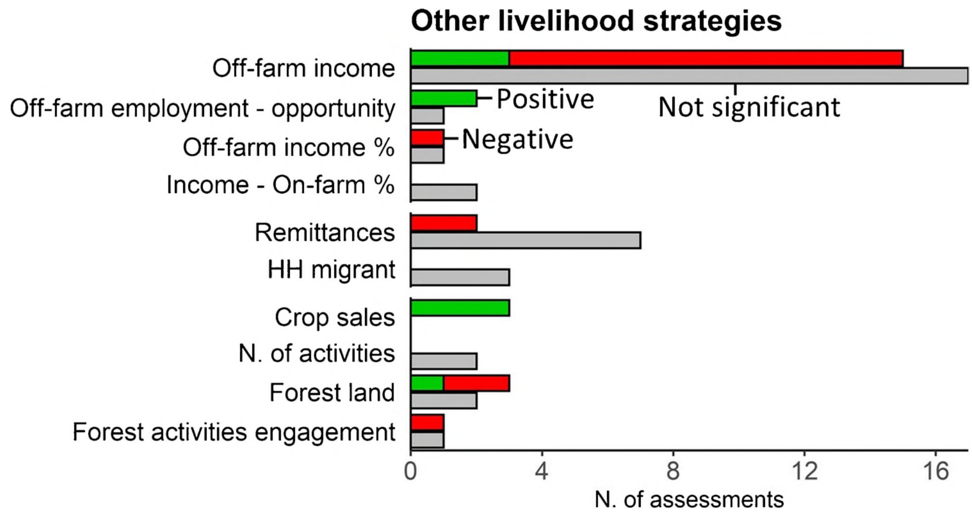
4.2.4 Social capital

Social capital includes farmers' gender, cultural values, involvement in the communities, access to information and social networks (Fig. 8d).

The influence of household head's gender on on-farm diversity level was the variable most often analysed ($n = 47$) within the social capital. The results were mixed (Fig. 8d). All the studies that identified a significant effect were conducted in low- and lower-middle-income counties. Ten assessments reported that female-headed farms were more diversified than male-headed ones. This was mostly associated with women's role in the household and in the community. Often in charge of preparing food, women can be more risk-averse than men (Nguyen et al. 2017; Asfaw et al. 2018; Kankwamba et al. 2018), more concerned with providing the family with diversified nutrition (Zawedde et al. 2014; Adjimoti et al. 2017) and growing nutritious crops, such as pulses or vegetables, sometimes considered "women's crops" (Mofya-Mukuka and Hichaambwa 2018). Moreover, one study conducted in the Brazilian Amazon emphasised the central role of women in the seed exchange networks of their communities (Díaz-Reviriego et al. 2016). In contrast, nine assessments reported a higher on-farm diversity level in male-headed households. This was attributed to the better access to information, technologies and production resources, which males may have because of social customs and traditions (Tun Oo et al. 2017; Asante et al. 2018).

Farmers' groups, such as cooperatives and associations, can be vehicles of knowledge and information (Kasem and Thapa 2011; Jacobi 2016), planting material and technologies, and also improve market access with more competitive prices (Alemayehu et al. 2018; Nkomoki et al. 2018). The membership in farmers' organisations was assessed 21 times (8 P, 2 N, 11 NS) (Fig. 8d). Farmers that are member of this organisations and with an active network of social relationship have in general a better access to market and resources to manage of diversified faming systems (Samberg et al. 2013; Schroth and Ruf 2014; Herrera et al. 2018; Valencia et al. 2019). However, the studies that reported a negative effect showed that cooperatives may also discourage farm diversification and drive specialisation when they only target

Fig. 9 Number of assessments for selected livelihood strategies that drive or constrain on-farm diversification. The barplot show the ten variables with the highest number of assessments. For each variable (*y*-axis), the upper stack bar represents the total count of statistically significant effects reported on on-farm diversity [Positive (green), Negative (red)]; the lower bar (grey) represents the total count of Not Significant assessments.



and promote one or a specific group of crops or farm products (Nguyen et al. 2017; Saenz and Thompson 2017).

Another meaningful component of social capital consists in the farmers' social networks and access to information. Information about market prices and opportunities, new technologies, crop varieties and climate conditions may reduce farming risks, and therefore can affect farmers' decision-making substantially. There are different channels to access information that span from the information exchange between farmers (Casagrande et al. 2017) to the institutional channels like local government, extension workers and information and communications technologies (Nguyen et al. 2017; Senger et al. 2017; Asfaw et al. 2018). The results showed that, in general, better access to information corresponded to higher diversification (12 P, 4 N, 8 NS). For instance, access to market information allow farmers to plan and diversify their production to meet consumers' demand and respond to prices changes (Makate et al. 2016; Alemayehu et al. 2018; Asante et al. 2018). Prompt and reliable information about weather and climate can support the selection of an appropriate cultivation mix (Tun Oo et al. 2017; Saenz and Thompson 2017). Nevertheless, it is also true that reliable information about market and climate change reduces risks, hence informed farmers may also choose to only focus on few crops or activities that are highly demanded and suitable for the expected conditions (Gunathilaka et al. 2018).

Traditional knowledge and cultural values preserved in communities or ethnic groups represent a fundamental component of social capital, especially in rural areas. Cultural identity has often been assessed using categorical variables, comparing differences in the extent of farm diversity between farmers belonging to different ethnicity (9 S, 5 NS), communities (2 S), socio-political context (2 S), neighbouring groups (1 S) and clans (1 S) (Fig. 8d). Most of the assessments involving this group of variables captured a statistically significant association with diversification. Farmers' ethnicity and cultural values are strongly reflected through the species richness and composition of their farms (Labeyrie et al. 2014; Díaz-Reviriego et al. 2016). This relationship has proven to be particularly relevant for indigenous communities or areas where cultural identity is still strongly rooted as they generally showed a higher extent of diversification (Williams 2016; Torres et al. 2018). In such contexts, agriculture is considered a cultural component itself, through the maintenance of traditional management practices and plants for food, medicine, rituals and aesthetic value (Samberg et al. 2013; Skarbø 2014; Torres et al. 2018). These practices are important for the conservation of landraces and underutilised species that due to the market pressure have lost their economic and commercial value (Skarbø 2014; Pandey 2015; Díaz-Reviriego et al. 2016).

Finally, the involvement of the family in the farming activity may guide farmers' decision to diversify. Valliant et al. (2017) interviewed farmers in the east of the U.S. Corn Belt to investigate the role played by their future expectation on the motivations to diversify their farms. Their findings showed that families willing to create future opportunities of employment in the farm for their descendants presented a higher level of diversity. Similar conclusions were found by Senger et al. (2017) in a study conducted in Brazil.

4.3 Other livelihood strategies

On-farm diversification is only one of the possible livelihood strategies that farmers can adopt to maximise their utility (Di Falco 2012; Bowman and Zilberman 2013). The possibility to adopt on-farm diversification strategies results from external and internal capitals (Scoones 1998; Ellis 2000), but it is also influenced by other livelihood strategies currently or previously adopted that can be complementary or alternative to diversification (Ellis and Freeman 2005).

The studies assessing the effect of off-farm income on the level of on-farm diversity showed some evidence that they often work as alternative livelihood strategies (3 P, 12 N, 17 NS) (Fig. 9). Off-farm employment is an important source of income, and reduces rural poverty (De Janvry and Sadoulet 2001; Barrett et al. 2001). On-farm diversification is time- and labour-intensive, as it involves the management different crop or livestock species (i.e. different sowing and harvesting seasons), while monocultures or simplified farming systems instead are more suitable to standardised and mechanised processes (Burchfield and Poterie 2018; Roesch-McNally et al. 2018). Households earning part of their income from external activities have less time to dedicate to the farm than full-time farmers, and hence may tend to simplify their farms and reduce number of farming activities (Hitayezu et al. 2016; Adjimoti et al. 2017; Kundu and Chattopadhyay 2018; Lancaster and Torres 2019). Therefore, the availability of off-farm work alternatives increases the opportunity-cost of managing diverse agricultural systems (Hitayezu et al. 2016; Adjimoti et al. 2017; Alemayehu et al. 2018). The prevalence of negative correlation was consistent across different regions (Hitayezu et al. 2016; Min et al. 2017; Alemayehu et al. 2018; Lancaster and Torres 2019; Ochoa. M. et al. 2019). The studies reporting off-farm income as a driver did not provide detailed explanation for this result, besides the financial opportunity to re-invest the external income in new on-farm activities (Abebe et al. 2013; Asante et al. 2018; Herrera et al. 2018). The analysis of the effect of migration and remittances also showed a negative correlation with farm diversification; nevertheless, only two studies found a statistically significant relationship (Nguyen et al. 2017, 2019).

The remaining livelihood strategies showed in Fig. 9 are crop sales (3P) (Kankwamba et al. 2018) and the share of forest land in the farms and the engagement in forest activities (1 P, 3 N, 3 NS), while we did not identify any further livelihood strategies with more than three assessments (Tacconi et al. 2021). The studies assessing the role of the engagement in forest activities showed that its effect on diversification may depend on the use that farmers make of their forested areas. For instance, Abebe et al. (2013) found that increasing the area of managed woodlots would increase species richness but decreased the species evenness when farmers focused on increasing density of specific tree species for commercial values. Torres et al. (2018) showed that despite the level of crop species evenness of farms based on forest activities was lower than in those mostly focused on crops, it was still higher than in farms relying on livestock or off-farm activities.

5 Discussion and limitations

The purpose of this review was to provide an overview of how on-farm diversity is defined and measured in the recent peer-reviewed literature and of its drivers and constraints in different farming systems and regions.

Overall, our results show that the decision to maintain or increase on-farm diversity is commonly embedded in strategies to cope with environmental features and risks and influenced by market characteristics and access (Di Falco et al. 2010a; Longpichai 2013; Nguyen et al. 2017; Asfaw et al. 2018). Additionally, access to information, social connections, cultural values and ethnicity emerged as significant factors for the maintenance and use of diversity. In particular, communities where cultural ties and traditional knowledge are still strongly rooted showed to be important in preserving diversity, especially of landraces and underutilised species (Velásquez-Milla et al. 2011; Segnon et al. 2015). Still, drivers and constraints of diversification appeared highly context- and farm-dependent, with several variables working as drivers or constraints across different studies. For instance, altitude was a driver of diversification in seven assessments (Nguyen et al. 2017; Tesfaye and Tirivayi 2020), a constraints in five (Abebe 2013; Samberg et al. 2013) and neutral in seven (Gunathilaka et al. 2018). The age of the household head was found to have a positive effect on diversification in 14 analyses, a negative effect in 16 (Eyssartier et al. 2011; Kawa et al. 2015) and neutral in forty (Asante et al. 2018; Mofya-Mukuka and Hichaambwa 2018).

We can identify some patterns across the studies analysed. Small subsistence-oriented farms tend to adopt on-farm diversification strategies mostly to cope with environmental characteristics and risks and satisfy their subsistence needs (Nguyen et al. 2017; Asfaw et al. 2018). However, the adoption of diversification strategies is influenced by farmers' possibilities and objectives, depending on production and demand dynamics. When small farms practice subsistence or semi-subsistence agriculture and face production limitations, they may aim to increase on-farm diversification, given their internal capital endowment (Adjimoti et al. 2017; Tesfaye and Tirivayi 2020). Therefore, at this stage, the variables reducing production constraints are likely to drive on-farm diversification.

Furthermore, farmers may shift their orientation towards specialisation strategies once the comparative advantage generated by market demand and opportunities, financial capital, technologies and the availability of alternative sources of income displace diversification benefits and its natural insurance effect. This shift seems to be identified and explained by the inverted-*U* relationships that emerged between on-farm diversification and some of the variables analysed, for instance land size (Skarbø 2014; Makate et al. 2016) or education (Herrera et al. 2018; Kankwamba et al. 2018; Mofya-Mukuka and Hichaambwa 2018). In this regard, studies comparing differences between and within groups of farms with different characteristics and exploring the potential existence of non-linear correlation between on-farm diversity and the variables analysed provided a more accurate understanding of these dynamics (Skarbø 2014; Bhatta et al. 2016; Nguyen et al. 2017).

Studies conducted in Europe and the USA suggested that on-farm diversification has the potential to represent an additional option to specialisation, also in these regions. The transition towards diversified systems seems to be highly affected by markets structure, previous production choices and trajectories of the agricultural systems (Bowman and Zilberman 2013; Roesch-McNally et al. 2018). In particular, the availability of knowledge and technologies for farm diversification (Casagrande et al. 2017; Meynard et al. 2018) and the access to different market alternatives such as fresh food markets (Iles and Marsh 2012; Borremans et al. 2018; Lancaster and Torres 2019), emerged as crucial features to stimulate the implementation and maintenance of on-farm diversity.

These results summarise the findings of a range of systematically selected peer-reviewed studies published in the last decade, and intend to add to previous reviews about farm diversification that focused on the use of different definitions found in the literature (Hufnagel et al. 2020), specific type of diversity and regions, such as agroforestry systems in the tropics (Schroth and Ruf 2014) or on the socio-ecological benefits and trade-off of the adoption of this farming strategy (Kremen et al. 2012; Beillouin et al. 2019; Rosa-Schleich et al. 2019; Tamburini et al. 2020).

There is a range of limitations to consider when interpreting the results of this review. Firstly, they are drawn based on our systematic literature search that provided an imbalance between country regions with a higher concentration of studies in Africa, Asia and South America and in lower middle-income countries that did not allow us to make generalised statements and comparisons between regions. Second, due to our choice of limiting the literature search to peer-reviewed journal, it is important to consider that more knowledge is available in grey literature, in the form of national dataset and technical reports, and that could be used for further research. Finally, another limitation is represented by the high "diversity" of definitions of agricultural diversification utilised in agricultural research, as also explained in Hufnagel et al. (2020) for crop diversification. This might have led to the exclusion of some potentially relevant studies from the total results of our literature search. Taking all these limitations into account, our results are indicative of the wide range of drivers and constraints across settings, rather than representative of all drivers and constraints. They nevertheless provide the most comprehensive account to date of the factors that influence on-farm diversification globally.

6 Conclusions

This study was the first systematic review focussing on identifying, summarising and discussing the results from recent scientific literature about farm-scale drivers and constraints of on-farm diversification. Our analysis of the drivers and constraints showed mixed results, with several variables acting as drivers or constraints of on-farm diversification depending on the context or the characteristics of the farm. Given their internal capital endowment, subsistence and semi-subsistence farmers tend to diversify their production to cope with environmental and market characteristics and risks and satisfy their subsistence needs. In this context, communities with a strong cultural identity are particularly important in preserving diversity, especially of landraces and underutilised species. The results suggest a shift towards specialisation strategies if market demand and opportunities, access to capital, technologies or alternative income sources generate a comparative advantage that displaces the benefits from diversification. In higher income countries, the access to knowledge and technologies for diversification and to alternative market options emerged as key drivers of on-farm diversification.

These conclusions are far from the final word on drivers and constraints of diversification, being drawn from a limited selection of peer-reviewed studies conducted from different regions and analysing samples with different characteristics, size and objectives. Further research exploring the existence of non-linear patterns between on-farm diversification strategies and potential drivers/constraint and how these patterns change depending on the farm typologies analysed is needed to identify and quantify when, where and under what conditions the shift from diversification to specialisation takes place. Finally, to promote and enhance on-farm diversification where it is a useful strategy, we suggest policymakers and researchers should further explore mechanisms and incentives that produce farm-level benefits, are suitable for the local contexts and, carefully consider farmers' objectives and the opportunity-cost of alternative livelihood strategies.

Authors' contributions All authors contributed to the study conception and design. Paper search and selection, data collection and analysis were performed by FT. The first draft of the manuscript and the following versions were written by FT and commented and critically revised by all the authors. All authors read and approved the final manuscript.

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Data availability The datasets generated and/or analysed during the current study are available in the Figshare repository, https://doi.org/10.6084/m9.figshare.14151659.v2

Declarations

Conflict of interest The authors declare no competing interests.

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