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The benefits and trade-offs of agricultural diversity for food security in low- and middle-income countries: A review of existing knowledge and evidence

Katharina Waha[a,*], Francesco Accatino[b], Cecile Godde[a], Cyrille Rigolot[c], Jessica Bogard[a], Joao Pedro Domingues[b], Elisabetta Gotor[d], Mario Herrero[a,e], Guillaume Martin[f], Daniel Mason-D'Croz[a,e,i], Francesco Tacconi[a,g], Mark van Wijk[h]

[a] *CSIRO, Agriculture & Food, 306 Carmody Rd, St Lucia, QLD, Australia*
[b] *UMR SADAPT, INRAE, AgroParisTech, Université Paris-Saclay, 16 rue Claude Bernard, 75005, Paris, France*
[c] *INRAE, Université Clermont Auvergne, AgroParisTech, Vetagrosup, UMR Territoires, 63122, Saint-Genès Champanelle, France*
[d] *Bioversity International, Rome, Italy*
[e] *Department of Global Development, College of Agricultural and Lifesciences and Cornell Atkinson Centre for Sustainability, Cornell University, Warren Hall, Ithaca, NY, 14853, USA*
[f] *AGIR, Université de Toulouse, INRAE, Castanet-Tolosan, France*
[g] *Tasmanian Institute of Agriculture, University of Tasmania, Sandy Bay Campus, Hobart, Tasmania, 7005, Australia*
[h] *International Livestock Research Institute (ILRI), Nairobi, 00100, Kenya*
[i] *Agricultural Economics and Rural Policy Group, Wageningen University & Research, The Netherlands*

1. Introduction

Diversification, the process of becoming more diverse, is studied in many scientific disciplines. At its core it is opposed to specialization, uniformity, and homogeneity and as such it is often seen as beneficial for the stability and productivity of natural or human-made systems (Gaba et al., 2015; Lin, 2011; Markowitz, 1952; Naeem and Li, 1997; Yachi and Loreau, 1999).

In food systems, diversification, defined often as an increase in crop, livestock, production or farming diversity (i.e. agrobiodiversity), has been considered as a key strategy for improving the productivity and stability of many socio-economic and ecological aspects of agricultural systems. It is a central element for example in three areas of research. Firstly, in sustainable intensification (Foley et al., 2011; Tilman et al.,

* Corresponding author.
E-mail address: katharina.waha@csiro.au (K. Waha).

2011), ecological intensification (Bommarco et al., 2013; Cassman, 1999), conservation agriculture (FAO, 2002) and more recently regenerative agriculture (Schreefel et al., 2020). Mixed farming and crop rotations, for example, can support pest, nutrient and water management (Gaba et al., 2015), reduce external inputs and improve soil biodiversity. Secondly, in research on rural development and sustainable livelihoods (Chambers and Conway, 1992; Ellis, 1998) as livelihood diversification has often been highlighted as contributing to reduced poverty. And thirdly, in nutrition-sensitive agriculture describing pathways from agriculture to nutrition security where diversification can increase the diversity of foods produced, consumed or sold (De Jager et al., 2018; Herforth and Harris, 2014; Ruel and Alderman, 2013).

While diversification is often presented by the scientific and policy community as socially and environmentally beneficial, evidence from the literature warns about too broad generalizations. The outcomes of agricultural diversity can vary across spatial scales, from the genetic and species level to the ecosystem, landscape, national and global levels. While, for example, food security in subsistence farming can be achieved at the farm scale by producing a wide variety of foods, the same can be achieved at the landscape scale by having a number of specialised farms producing a single food type and trading the surplus with others (Renard et al., 2016). However, a subsistence farming system that produces a large variety of food types that are nutritionally similar will not ensure a balanced and healthy diet for the household, so a consideration of the functions added to the system along with the species is important (Remans et al., 2011).

Another potential limitation of agricultural diversification as a key leverage for food security is that diversity can be difficult to manage and can increase the workload for members of the household (Bendahan et al., 2018). Specialization, on the other hand, can reduce costs, increase efficiency through economies of scale and give farmers a comparative advantage for selling their produce at markets (Govereh and Jayne, 2003; Kurosaki, 2003). Moreover, diversification is not the only strategy to increase resilience, as farmers might favour other risk management strategies. While diversification can be an agricultural intervention for improved nutrition and health outcomes, other pathways can be as effective. For example, bio-fortification to increase nutritional quality of existing crops or increasing incomes through improvements to cash crop production if the income is spent on purchasing healthy foods. The latter, however, depends on appropriate market access and requires that the household prioritises the purchase of healthy foods over other competing food or non-food purchases (Fiorella et al., 2016) .

In this review, we aim at synthesising the evidence on the relationship between agricultural diversity and all four dimensions of food security as defined in the FAO's conceptual framework – availability, stability, access, and utilisation. Food security is a major concern in low- and middle-income countries and has been enacted as one of the United Nations Sustainable Development Goals. Our review also explores the interactions at different spatial scales. While many measures of food security relate to individuals, such as meeting dietary energy needs, the challenge to secure healthy and diverse diets is also global in its extent and at that scale often analysed with respect to food availability and stability. A final section provides a synthesis, recommendations and conclusions.

2. Search criteria and methods

The review is based on an exhaustive, comprehensive search in Web of Science (v.5.32). We searched with the objective of presenting evidence from original scientific studies, define eligibility criteria and attempt to identify all studies meeting them. We assess the validity of findings in the reviewed studies and present the results in a systematic way (Moher et al., 2015). We include articles and reviews that use at least one measure of both agricultural diversity and food security, were written in English and were published between January 2010 and February 2020. Key words used in the search included a combination of terms associated with agricultural diversity (e.g. crop, farming or production diversity, agricultural biodiversity) and food security (e.g. child nutrition, dietary diversity, food availability, food access, stability, food production, income). The search on February 25, 2020 resulted in 924 articles. The Web of Science search syntax is:

(TS=((on-farm OR "on farm" OR crop OR farming OR production) near/1 divers*) AND TS=("food security" OR "food and nutrition security" OR "child nutrition" OR "diet* diversity" OR "food availab*" OR "food access*" or "food product*" OR "income")) OR (TS=("agricultural biodivers*" OR "agro-biological divers*") AND TS=("food security" OR "food and nutrition security" OR "child nutrition" OR "diet* diversity" OR "food availab*" OR "food access*" or "food product*" OR "income"))

In the next step the abstracts of these articles were screened on whether they: (1) used a study area in a low-to middle income country as per the World Bank 2021 country classification; (2) evaluated at least one metric of diversity at farm-, regional-, or global-level as specified within the search terms; (3) evaluated at least one measure of a food security dimension, and (4) presented original work quantifying the diversity-food security relationship which goes beyond qualitatively describing drivers and trends in agricultural diversity. Articles describing theoretical frameworks were also included to inform the broader context and to link to existing literature. We excluded studies on nonfarm diversification although we are aware that they can be critical strategies to increasing food security (e.g. Ampaw et al., 2017; Barrett et al., 2001) but we consider studies on agricultural activities that increase farmer's income as a component of food access. We also exclude studies that discuss benefits of specific crops without also clearly stating that agricultural diversity increases overall, for example high-value or wild crops (Mavengahama et al., 2013) or crops perceived as being underutilized or neglected (Kahane et al., 2015; Mabhaudhi et al., 2016, 2017). Applying these criteria in the abstract screening leads to a shorter list of 272 publications to which we added 13 publications that were cross-referenced or otherwise known to the authors (Fig. 1). After reading the full manuscripts, 110 publications were identified as relevant to the purpose of our study, 88 articles and 26 reviews. In terms of geographical spread, about two thirds of all publications have a study area in sub-Saharan Africa, and the remaining in Asia or South America. Some African countries are studied more than others, for example Malawi (14 publications) and Kenya (10 publications) while other countries with high levels of food insecurity were not found in the literature search, for example Chad and Madagascar. The most common measures of diversity and food security used were crop diversity and household consumption measures (see Fig. 2).

Articles were grouped by unit of observation and level of analysis into individual, household, farm, landscape, national or global scale. The landscape scale publications focused on discussing interaction of multiple farming households with each other or a local market that in turn influences individuals and landscape environmental or economic indicators. An example of a national scale analysis is one that uses a nationally representative agricultural and nutrition census or survey, even with households as the unit of observation. A large sample size alone is not necessarily indicative of representativeness at the national scale. Finally, the global scale publications include multi-countries studies and studies analysing global data sets such as those collated by the Food and Agriculture Organization, the World Bank or the World Health Organization.

The relationship between agricultural diversity and food security was categorized in a synthesis table according to two dimensions: the direction, i.e. positive, negative or neutral and the level of agreement, i.e. high, medium or low agreement. The synthesis table allows to put together relevant quantitative figures which helps to identify knowledge gaps and controversies.

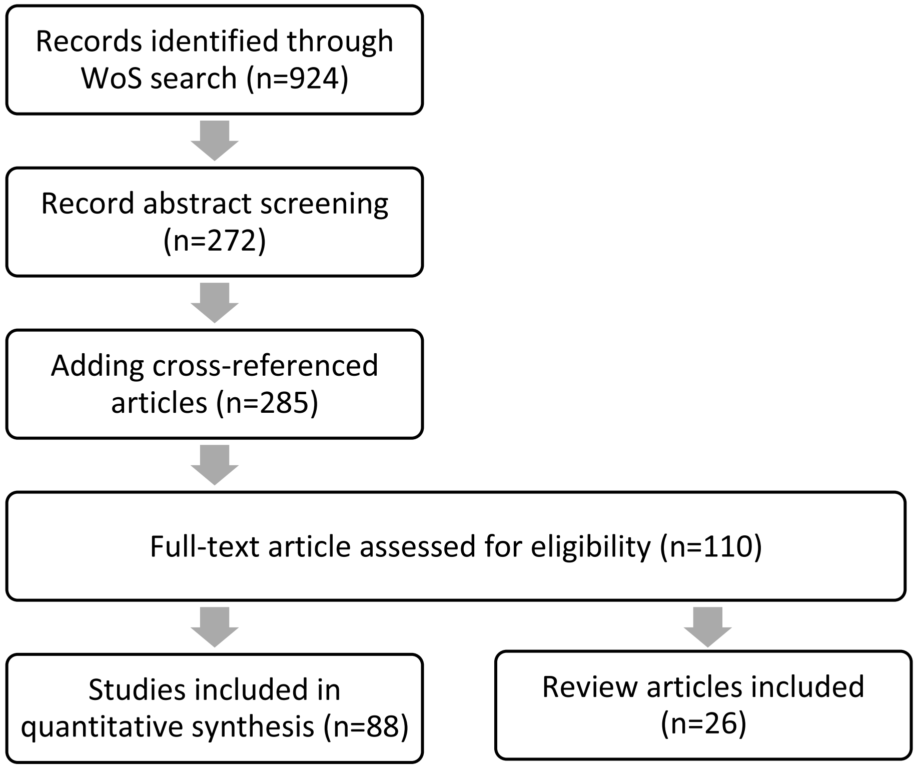

Fig. 1. Publication selection process used in this review.

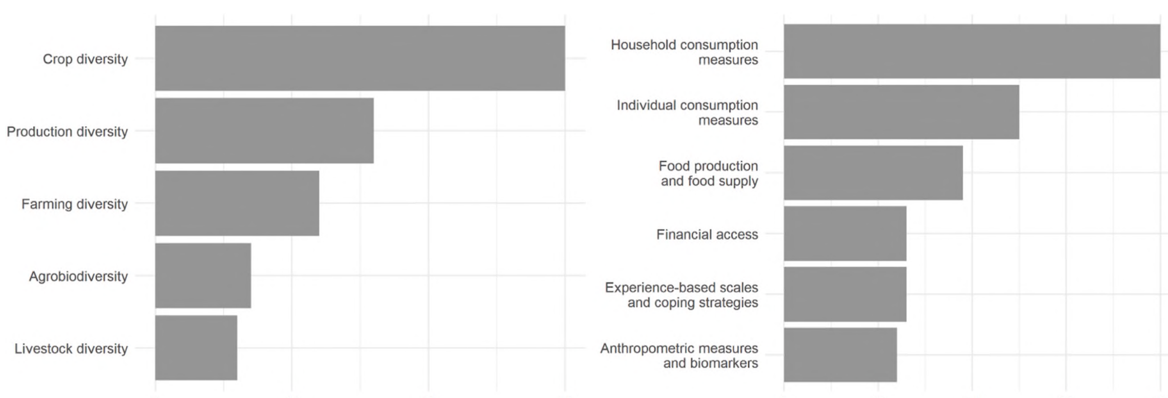

Fig. 2. Number of studies using different measures of diversity (left) and different food security indicators (right) (N = 88). Studies that use multiple metrics are counted multiple times accordingly.

3. Indicators of agricultural diversity and food security

3.1. Agricultural diversity

Diversity can be defined for different types of agricultural commodities, plant species for food or fodder, or domesticated animals raised for food or for labour. The categories used here follow a hierarchy from including 1) cultivated plant species (crop diversity), 2) raised livestock species (livestock diversity), 3) cultivated plant and raised livestock species (farming diversity), 4) food products derived from plant and animal species (production diversity), to 5) the full diversity of organisms living in landscapes that are under agricultural management, beyond cultivated species and foods produced (agrobiodiversity or agricultural biodiversity).

Production diversity refers to the different food products, while farming diversity refers to the plant and animal species. For example, a farm raising chickens for meat and eggs and cultivating maize for corn would have a production diversity of three (chicken meat, chicken eggs, corn) and a farming diversity of two (chickens, maize) if measured as a count variable. Crop diversity can sometimes be measured as “crop group diversity” where crops are grouped together by similar characteristics, for example ecological functions in the agricultural system, nutrient content or importance for creating income from crop sales. Agricultural biodiversity is a broader characterisation that encompasses for example genetic resources, edible plants and crops including traditional varieties, and other genetic material, livestock and freshwater fish, soil organism vital to soil fertility, naturally occurring insects, bacteria and fungi that control insect pests and diseases, and wild resources or natural habitats which can provide ecosystem functions and services (Thrupp, 2000). Throughout the paper agricultural biodiversity and agrobiodiversity are used interchangeably.

Several indicators can be used to measure agricultural diversity, integrating different aspects of diversity, richness and evenness. Richness is the number of species or agricultural products in a sample. Some studies express this by comparing characteristics of cropping systems with different numbers of crops cultivated or creating a binary variable to distinguish between adopters and non-adopters of diversification (Birthal et al., 2015; Boedecker et al., 2014). Measures of evenness consider relative dominance or concentration of species or products in the sample by measuring also the abundance of each species (Whittaker, 1972). Examples of measures of evenness are the Simpson diversity index (SDI) and the Shannon diversity index (H'). They differ slightly by expressing dominance of the first few species in the sample (Simpson index) or relative evenness across the whole sample (Shannon diversity index) (Whittaker, 1972). Abundance can be measured as area used for each species, weight of produce, nutrient or energy content of each product or monetary value of products. Using area can be challenging when including livestock (Sibhatu and Qaim, 2018a), as livestock can source feed from outside the farm, graze on public land or be fed purchased feed.

3.2. Food security

The FAO's conceptual framework for food security distinguishes between four dimensions, physical availability to food, economic and physical access to food, food utilisation and stability. This framework, and national level indicators to measure progress on each dimension, are used in the annual reports on the 'The State of Food Security and Nutrition in the World' published since 1999 by FAO, IFAD, UNICEF, WFP and WHO (until 2015 as 'The State of Food Insecurity in the World') (FAO, 2019). In addition to these national level indicators, this literature review identified indicators to measure food security status of an individual or a household. The full list of indicators considered in this review is shown in Table 1.

For food availability, yield is a frequently used indicator. A special case is nutritional yield when yield expressed in weight is multiplied with the content of a certain nutrient or converted to calories. The unit change is not to be confused with a change in the food security dimension. It is still a measure of availability as it is unclear how the product is used, for self-consumption, markets, or livestock feed and if consumed within the household who is eating what. An example of a household food supply adequacy indicator is the food availability indicator used in some studies and calculated as a ratio of energy produced and bought to the physiological requirements for energy (Douxchamps et al., 2016; Frelat et al., 2016; Paul et al., 2017; Rufino et al., 2013; Waha et al., 2018).

Food access indicators are very diverse, but some standard indicators have been developed by the Food and Agriculture Organization of the United Nations (FAO), the Food and Nutrition Technical Assistance Project (FANTA) and the World Food Programme (WFP). Within the food access domain, we identify two groups of indicators. The first group are indicators reflecting the financial dimension and affordability of food access and the second group are indicators pertaining to consumption patterns measured at the household level. The household dietary diversity score (HDDS) is the most frequently used indicator to measure food access. HDDS is constructed based on consumption of 12 food groups and ranges from 0 (no food group consumed) to 12 (all 12 food groups consumed) with a recall period of 24 h (FAO, 2013) but many studies reviewed here modified the recall period to be seven days. The food consumption score (FSC) is a similar, but composite score ranging between 0 (food insecure) and 16 (food secure) and measures the frequency of consumption of different food groups by a household during the seven days before the survey. HDDS has been validated as a good indicator of diet quantity i.e. energy consumption (Hoddinott and Yohannes, 2002) but not of diet quality i.e nutrient adequacy (Leroy et al., 2015). One reason for that is that HDDS measures also the consumption of three food groups (sweets; oils and fats; spices, condiments and beverages) that do not necessarily contribute positively to micronutrient intake which weakens any potential association with micronutrient adequacy and diet quality.

Table 1
Indicators of food security used in the reviewed literature.

Availability	Access	Utilisation	Stability
Food production and food supply Crop yield, livestock production, household food supply adequacy, crop production, productivity	*Financial access and affordability* Income from agriculture, wealth, poverty status of a household *Household consumption measures* Household dietary diversity score (HDDS), food consumption score (FSC), food variety score (FVS), food expenditure, household per capita energy intake, household per capita protein intake, household food self-sufficiency, household food quantity intake, household nutrient intake, household nutrient adequacy	*Individual consumption measures* Infant and Young Child Dietary Diversity (IYCDDS), Minimum Dietary Diversity for Women (MDD-W), Women's Dietary Diversity Score (WDDS), Infant and Child Feeding Index (IFCI), Individual Dietary Diversity Score (IDDS), Mean Probability of Adequacy of Micronutrient Intake (MPA), Nutrient Adequacy Ratio (NAR), Dietary Species Richness (DSR) *Anthropometric measures and biomarkers* Vitamin A deficiency, haemoglobin status, prevalence of anaemia among women, weight-for-age z-score (WAZ), height-for-age z-score (HAZ), weight-for-height z score (WHZ), prevalence of stunting, prevalence of wasting, body mass index (BMI), middle upper arm circumference for age z score (MUAC)	Crop yield skewness, temporal yield variability, spatial yield variability
Experience-based scales and index scores. Household Food Insecurity Access Scale (HFIAS), Household Hunger Scale (HHS), Coping Strategies Index (CSI), Months of Adequate Household Food Provisioning (MAHFP).			

Food utilisation is commonly measured as individual dietary consumption or nutritional status based on anthropometry or biomarkers. It therefore describes a dimension of food security as well as the outcome linked to nutritional status (Coates, 2013). Around 8% of all studies reviewed use a measure of anthropometric status such as height-for-age, weight-for-height and weight-for-age. Height-for-age below two standard deviations of the mean for healthy children indicates stunting which implies insufficient nutrient intake and/or poor health over a longer time period. Weight-for-height indicates wasting which implies acute significant food shortage and/or disease. Weight-for-age indicates underweight which implies both acute and chronic malnutrition (WHO, 1995). All three are sometimes used as validation measures for indicators of food utilisation. This can however result in mixed conclusions as anthropometric status is not only evidence for nutrient or energy deficits but also for the occurrence of diseases that lead to impaired nutrient absorption or increased rate of nutrient utilisation (WHO, 1995). We group food consumption indicators within the utilisation domain when measured at the individual level, and within the food access domain when measured at the household level. This is consistent with the evidence that various individual consumption indicators such as Infant and Young Child Dietary Diversity (IYCDDS), Minimum Dietary Diversity for Women (MDD-W) and Women's Dietary Diversity Score (WDDS) are validated measures of nutrient adequacy (Jones, 2017a; Leroy et al., 2015; Martin-Prevel et al., 2015; Working Group on Infant and Young Child Feeding Indicators, 2007). IYCDDS and WDDS include seven and nine food groups, respectively that are directly related to micronutrient intake. WDDS has been further developed to the MDD-W indicator, sometimes also referred to as the 10-food group women's dietary diversity indicator, which is used to define women as having an adequate diet diversity if consuming at least five of the ten food groups included.

Stability includes the temporal aspect of the other three dimensions. Stability has several meanings and is often related to the concepts of resilience, robustness, resistance, vulnerability, or variability. While a natural ecosystem might be considered stable if the system variables return to the initial equilibrium after a perturbation (Pimm, 1984), a more useful definition for agricultural systems might be related to low fluctuation or constancy in a system faced with perturbations as the definition of equilibrium state as such is more difficult. Perturbations are then shocks external to the system and ranging from short-term to long-term or chronic (Bullock et al., 2017). In the reviewed literature, stability is often measured as the spatial or temporal variability of production or income.

Experience-based indicators such as the Household Food Insecurity Access Scale (HFIAS), the Household Hunger Scale (HHS), Coping Strategies Index (CSI) and Months of Adequate Household Food Provisioning (MAHFP) are grouped separately in Table 1 because they are composite scores based on information that span the four dimensions of food security. For example, the CSI reflects all possible answers to one single question, namely "what do you do when you do not have enough food and don't have the money to buy?" (Maxwell and Caldwell, 2008). This is in contrast to some studies which consider HFIAS to be an indicator of food access (Leroy et al., 2015), food stability (Coates, 2013) or food availability (Lele et al., 2016). HFIAS can be seen as a good measure of both quantity and quality, in that there is no need to adopt coping strategies that lead to cheaper, less appealing and less micronutrient dense foods (Leroy et al., 2015) but not in the sense of micronutrient adequacy. We group experience-based indicators together with food access indicators in the respective results section.

4. Previous reviews and meta-analysis

Previous reviews and meta-analyses are listed here for completeness and as reference. They can provide a systematic overview of a specific group of literature that is outside the scope of this review, such as intercropping systems or agroforestry. Some reviews were considering both indicators of food access and utilisation, so they are described here together in one section.

4.1. Food availability

In the context of food availability, eight review articles and meta-analyses discuss the benefits of crop and agrobiodiversity for productivity (Delaquis et al., 2018; Droppelmann et al., 2017; Frison et al., 2011; Gaba et al., 2015; Kremen and Miles, 2012; Nagothu and Tesfai, 2018; Ponisio et al., 2015; Schroth and Ruf, 2014). For cassava intercropping, Delaquis et al. (2018) found a positive relationship between intercropping and system productivity in most studies reviewed which was evidenced by land equivalent ratios above 1. Other reviews for specific crops are provided in Nagothu and Tesfai (2018) for pulses-millet crop diversification and Schroth and Ruf (2014) for tree crop diversification in the humid tropics. In another review based on 17 studies on sustainable intensification practices in maize small-scale farms in sub-Saharan Africa, Droppelmann et al. (2017) show that the addition of a grain legume increased maize response to fertilizer but reduced annualized maize grain yields. Other benefits of intercropping and multiple cropping include improved soil and water regulation, reduced consumption of fertilizers and pesticide, reduced soil erosion and nitrate leaching, increased biodiversity and pest and disease suppression (Frison et al., 2011; Gaba et al., 2015). In a meta-analysis using 115 studies, Ponisio et al. (2014) find that multi-cropping and crop rotations can improve yields in organic systems. According to Gaba et al. (2015) the co-existence of multiple species can be beneficial if the species are carefully selected to provide resources for one another or to use a resource in different forms or at different times or in different places. Otherwise resource competition can result in lower system yields compared to monocultures (Gaba et al., 2015). Kremen and Miles (2012) compared ecosystem services such as food production and environmental performance in biologically diversified, including organic, versus chemically based simplified farming systems, relying on monoculture, inorganic fertilizers, and synthetic pesticide input. They found that conclusions on yield gaps varied widely in previously published articles.

4.2. Food access and utilisation

We find four previous literature reviews published between 2011 and 2015 that give a systematic overview of agricultural diversity, dietary intake and consumption associations (Jones, 2017a; Penafiel et al., 2011; Powell et al., 2015; Sibhatu and Qaim, 2018b). On the basis of a meta-analysis reviewing 45 studies from 26 countries, Sibhatu and Qaim (2018b) found that farming diversity is positively associated with dietary diversity and nutritional status in some but not in all cases and that this association depended on the indicator used to measure dietary quality and nutrition outcomes and the level of production diversity. Twenty-nine studies had mixed results with positive association in some cases and insignificant or negative associations in others, eleven studies found no association and five studies found only positive associations between production and dietary diversity or nutrition. The mean marginal effect of increasing farming diversity by one crop or livestock species increases the number of food groups consumed by 0.062 (N observations = 160, standard error 0.027) and the number of foods consumed by 0.716 (N observations = 25, standard error = 0.327) (Sibhatu and Qaim, 2018b). Reasons for small effects include production diversity being already high with further diversification efforts hindering development opportunities through other pathways. In a previous literature review with 23 studies, of which 21 were also later included in Sibhatu and Qaim (2018b), Jones (2017b) found a consistent, but small, positive relationship between production diversity and dietary diversity and in addition, a very small positive relationship between production diversity and nutritional status in least developed countries. Interestingly, the conclusions are different in both reviews. While Sibhatu and Qaim (2018b) conclude that there is little evidence to support policies for increasing production diversity as a strategy for improved smallholder diets and nutrition, Jones (2017b) concludes that agricultural diversification may contribute to diversified diets and may be an important strategy for improving nutrition outcomes. Similarly to Jones (2017b), Powell et al. (2015) concluded that the relationship between crop diversity or agrobiodiversity and dietary diversity or nutrition outcomes is overall positive in most of the 12 reviewed studies. Altogether, Powell et al. (2015), Jones (2017b) and Sibhatu and Qaim (2018b) reviewed 50 studies, of which 19 are included in our review as well as the remaining did not match our selection criteria. Publications were excluded because of publication year, or because they are not peer-reviewed research articles or review articles or because of a lack of a measure of agricultural diversity as defined in this study.

4.3. Stability

A meta-analysis of 37 studies showed that cereal-grain legume intercropping significantly increased temporal and spatial yield stability (CV = 22.1) compared with the respective grain legume sole crops (CV = 31.7). Temporal yield variability in cereal-grain legume intercropping was 58% lower than for grain legume sole crop but not significantly lower than for the cereal sole crop. Spatial yield variability in cereal-grain legume intercropping was 14–19% lower than grain legume and cereal sole crops (Raseduzzaman and Jensen, 2017). Hansen et al. (2019) reviewed 12 articles that describe benefits of diversified farming systems including agroforestry. They concluded that interventions that encouraged diversification showed moderately positive effects on stabilizing production and consumption, as well as improving livelihoods and welfare. Crop diversification can also contribute to stabilizing income, because some crops like rubber and oil palm can provide revenue throughout the year and the mix of perennial with annual crops can secure a more regular income from harvests in different months (Schroth and Ruf, 2014).

Five qualitative reviews give examples of studies that present empirical evidence on differences in stability and resilience between diversified and non-diversified agricultural systems (Altieri et al., 2015; Di Falco, 2012; Frison et al., 2011; Lin, 2011; Urruty et al., 2016). Between them they cite 31 studies but none of them provide a systematic overview of the empirical evidence which we attempt to show in Table 2. We select the 11 studies for low- and middle-income countries that were cited before and published as research articles or peer-reviewed book sections, written in English and reporting original data on a relevant measure of stability and summarise their main findings in Table 2. The most common measure of stability in the cited studies was variability of crop yield and income and resistance. For resistance there are two types of studies, one that attempts to assess the resistance of a diversified vs non-diversified system after a major perturbation, a hurricane or a drought, and one that assesses resistance to pest infestation, or heat and water stress without studying the system variables before or after an external shock.

Table 2
Summary of studies on agricultural diversity and stability cited in previous reviews.

Measure of stability	Finding	Reference[a]
Variability of crop yield and income	Crop variety richness reduces the within-household variance of yields above a certain diversity level	Di Falco et al., 2007 (Ethiopia), Di Falco and Chavas, 2009 (Ethiopia), Smale et al., 1998 (Pakistan), Widawsky and Rozelle, 1998 (China) cited in Di Falco (2012)
Resistance to water stress after a short-term external shock (water shortage)	Landraces yield higher than modern cultivars in water stress conditions and have less yield variability between stress and no stress conditions; Grain yield decrease in stress condition was smaller in replacement intercropping system than in sole crops	Ceccarelli, 1996 (Syria) cited in Frison et al., (2011); Natarajan and Willey, 1996 (India) cited in Altieri et al., (2015)
Resistance to erosion after a short-term external shock (hurricane)	Fewer arable land loss due to landslides in agroecological plots compared to conventionally managed plots	Holt-Giménez, 2002 (Nicaragua), Philpott et al., 2009 (Mexico) cited in Altieri et al., (2015)
Resistance to pest infestation through biological control	Within-field crop genetic diversity reduces pest infestation and disease severity	Zhu et al., 2000 (China), Kahn et al., 1998 (Kenya) cited in Altieri et al., (2015)
Resistance to heat and water stress through shade control	Shade trees in agroforestry reduce water stress for coffee plants compared to systems with fewer shade trees.	Lin, 2007 (Mexico) cited in Altieri et al., (2015)

[a] These are selected references fulfilling the criteria of this literature review except for year of publication and cited in section 6 in Altieri et al., (2015) on agrobiodiversity and vulnerability, section 2 in Frison et al., (2011) on productivity and stability, Table 1 in Di Falco (2012) and Table 1 in Lin (2011).

5. Diversity and food availability

Of the 88 studies evaluated, 19 studies reported 26 separate diversity-food security relationships using a measure of food availability. Most relationships were positive (17 cases, 65%) and only a few were negative (2 cases, 8%), neutral or ambiguous (7 cases, 27%) (Table 3). Most of the studies on food availability conducted field experiments to measure the effect of crop diversity on crop yield or crop production. The field experiments include growing crops in intercropping or rotation systems without making any other changes or embedding crop diversity as one strategy of alternative land use management systems such as agroforestry or conservation agriculture. The second experimental design makes it more difficult to assess the effect of diversification separately from other changes but also highlights the linkages between crop and soil management. In any case, the effect of crop diversity tends to be positive when an additional crop adds an additional function to the system, for example because it is a nitrogen-fixing crop, provides shade for the companion crop, can be commercialized as an additional product or adds specific nutrients to a household's diet. The direction of the relationship between diversity and food availability often depends on the crop studied, the row arrangement in intercropping and the type of crop mix.

For example, Isaacs et al. (2016) report that when grown as sole crop, beans exhibited yields that were often more than twice that of beans intercropped with maize in Rwanda which can be related to reduced resource competition for light and nutrients in the monoculture. In another experiment in Bangladesh Islam et al. (2018) found that a four crop pattern performed better than a three crop pattern which is mostly related to the introduction of maize as a relay crop for onion. In a country-wide trial in Malawi with 991 observations, Snapp et al. (2010) found a positive effect on crop yield when diversifying maize with legumes when compared with an unfertilized maize monoculture.

All three conservation agriculture studies included here found a positive effect of crop diversity on crop yield in India and Bangladesh (Ladha et al., 2016; Pradhan et al., 2018; Samal et al., 2017). In the context of agroforestry systems, we find four publications for rubber, cocoa and coffee cultivation (Hondrade et al., 2017; Jessy et al., 2017; Schneider et al., 2017; Souza et al., 2010). The results are mixed and depend on the year of the experiment, resource competition between crops, the amount of mutual benefits created by the crop mix and the method for measuring benefits. For example, the results from a 13- year experiment comparing three agroforestry systems with traditional rubber cultivation in India indicate that a range of crops can be integrated with rubber without any adverse effect on growth and yield of rubber. Crop diversification increased rubber yield but only in the first year, after which the effect was not significant (Jessy et al., 2017). In Brazil, a diversified agroforestry system for coffee cultivation allowed more products from a larger range of food crops to be harvested and commercialized leading to a lower cost/benefit ratio than in the coffee monoculture (Souza et al., 2010).

Other data sources used are surveys and farmer interviews which also allows studying effects on farm or household scale (Douxchamps et al., 2016; Dzanku and Sarpong, 2011; Makate et al., 2016). We cannot compare the studies to each other but each of them highlights the context in which diversity can be beneficial. For example, Douxchamps et al. (2016) found that crop diversity positively influenced land productivity in Burkina Faso, Senegal and Ghana, but only for a specific type of household practicing intensified farming with strong market orientation and a high proportion of income from growing pulses.

Table 3
Summary of studies examining the association between diversity and food availability.

Reference	Country	Sample size	Method	Indicator of diversity	Indicator of food availability	Description of relationship[a]
Cropping system, farm or household scale						
Chimonyo et al. (2019)	Malawi	6 field experiments, 5 seasons, 6 cropping systems	Field experiments	Crop diversity (SC) – maize intercropped compared to maize sole crop	Crop yield (maize grown in sequence with soybeans, peanut or peanut-pigeon pea)	Positive
					Crop yield (maize intercropped with pigeonpea)	Negative
Douxchamps et al. (2016)	Burkina Faso, Ghana, Senegal	600 hh	Stepwise multiple linear regression	Crop diversity (SC)	Land productivity (type IV intensified farming)	Positive (β = 0.812)
					Land productivity (type I subsistence farming)	Neutral (ns)
					Land productivity (type II diversified farming)	Neutral (ns)
					Land productivity (type III extensive farming)	Neutral (ns)
Dzanku and Sarpong (2011)	Ghana	416 hh	Random effects model	Crop diversity (SID)	Household food supply adequacy	Neutral (ns)
Hondrade et al. (2017)	Philippines	6 farmers' fields in 3 seasons and 8 cropping treatments	Field experiments	Crop diversity (SC) - rice-mungbean intercropping compared to rice monoculture	Crop yield	Mixed depending on year and proportion of intercropped rows
Isaacs et al. (2016)	Rwanda	2 cropping systems planted by 13 farmers association	Field experiments	Crop diversity (SC) - maize-bean intercropping compared to sole bean crop	Crop yield	Negative (d = 0.9–1.7 t/ha)
Islam et al. (2018)	Bangladesh	2 seasons, 4 crops in 2 crop patterns	Field experiment	Crop diversity (SC) - four crops intercropping compared to three crops intercropping maize/rice systems	Crop yield	Positive (d = 7.45–8.94 t/ha)
Jessy et al. (2017)	India	4 years	Field experiment	Crop diversity (SC) – agroforestry system with rubber	Crop yield	Positive in first year (d = 6.8 g/tree/tap), not significant in subsequent years
Kassie et al. (2015)	Malawi	1,925 hh	Multinomial endogenous switching treatment regression using survey data	Crop diversity (SC) – maize-legume rotation or intercropping compared to no diversification	Crop yield	Positive (ATT = 505 kg/ha)
Ladha et al. (2016)	India, Bangladesh	4 locations, 6 seasons, 2 years	Field experiment	Crop diversity (CI)	Crop yield	Positive (d = 73 GJ/ha)
Limbu et al. (2017)	Tanzania	6 vegetable plots, 4 fish ponds	Field experiment	Production diversity (SC) – integrated fish-vegetable system compared to non-integrated system	Net yield of fish	Positive (d = 9.13 t/ha)
				Production diversity (SC) – integrated fish-vegetable system compared to non-integrated system	Net yield of vegetables	Positive (d = 3.95 t/ha)
Makate et al. (2016)	Zimbabwe	~600 hh	Multiple linear regression	Crop diversity (SDI-b)	Crop yield (cereals)	Positive (β = 1.181)
					Crop yield (legumes)	Neutral (ns)
Perdoná and Soratto (2015)	Brazil	4 cropping systems, 5 years	Field experiment	Crop diversity (coffee monoculture vs coffee-macadamia intercropping)	Crop production (hulled green-bean, rainfed)	Positive (difference = 15–196 g per plant)
					Crop production (irrigated)	Neutral (ns)
Pradhan et al. (2018)	India	3 years experiment	Field experiment	Crop diversity (SC) - additive crop rotation design	Crop yield	Positive (d = 6,550–7,098 kg/ha)
Samal et al. (2017)	India	7 years experiment	Field experiment	Crop diversity (SC) – introduction of a third crop in wheat-rice rotation	Crop yield	Positive (d = 5.4–6.1 t/ha)
Schneider et al. (2017)	Bolivia	6 cropping systems, 3 years	Field experiment	Crop diversity (SC) - agroforestry system	Crop yield (all marketable crops)	Positive (d = 7,471 kg/ha)

(*continued on next page*)

Table 3 (*continued*)

Reference	Country	Sample size	Method	Indicator of diversity	Indicator of food availability	Description of relationship[a]
				compared to cocoa monoculture	Crop yield (cocoa)	Negative (d = - 414 kg/ha)
Souza et al. (2010)	Brazil	Trials on 17 family farms	Field experiment	Crop diversity (SC) – agroforestry system compared to coffee monoculture	Cost/benefit ratio	Positive (d = 0.32%)
Landscape to national scale						
Löw et al. (2017)	Uzbekistan, Kyrgyzstan, Tajikistan	~54,000 fields covering an area of ~400,000 ha	Remote sensing, Conditional Random Forests	Crop diversity (SDI)	Crop yield (spatial variability, rotation diversity)	Positive (variable importance rank = 1–6 for cotton and wheat, 1–9 for rice out of 23)
Snapp et al. (2010)	Malawi	>1,000 farm sites	Field experiment	Crop diversity (SC) - maize-legume rotation compared to unfertilized maize monoculture	Crop yield	Positive (d = 1.014–1.21 t/ha)
Waha et al. (2018)	Ethiopia, Tanzania, Niger, Uganda, Kenya, Burkina Faso, Ghana, Mali, Malawi, Rwanda, Zambia, Senegal, Mozambique, DR Congo, Congo, Nigeria, Zimbabwe	28,361 hh	Kruskal-Wallis test for difference in medians	Farming diversity (C)	Household food supply adequacy (supply/required)	Positive (d = 1.2)

C = count, SC = cropping system or farming typology, CI = multiple cropping index in %, SDI = Simpson diversity index, SDI-b = Simpson diversity index converted to binary variable, d = difference in means or medians, ns = not significant (p-value > 0.05); β = regression coefficient; ATT = adoption effect.

[a] The magnitude of the relationships cannot be compared directly across studies as the methods and indicators used differ. Some indicators such as the Shannon diversity index cannot be compared across different locations as they depend on the total number of species. The type of regression model, number and types of crops and livestock species for example will all influence the result. The table shows selected results from each study as assumed relevant to the topic of this review.

Dzanku and Sarpong (2011) find a positive relationship between more diverse non-staple crop production and household food supply in one region only and the authors suggest that this is due to regional differences associated with better market conditions rather than crop diversity. They concluded that a more diverse crop portfolio did not necessarily lead to a higher probability of household level food security, with other important predictors being household composition, education, wealth, age, and other non-farm sources of income. In a multi-country study with 28,000 farming households in sub-Saharan Africa, Waha et al. (2018) found that median food availability increased with farming diversity. The farming households with highest farming diversity also had significantly more cropland than others, which partly explains this result. This study also find that increasing farming diversity can result in diminished returns, with food availability

Table 4
Summary of studies examining the association between diversity and stability.

Reference	Country	Sample size	Method	Indicator of diversity	Indicator of stability	Description of relationship[a]
Chimonyo et al. (2019)	Malawi	6 field experiments, 5 seasons, 6 cropping systems with 6 maize cropping systems	Field experiments	Crop diversity (SC) –fertilized sole maize compared to (1) rotation with soybean and peanut-pigeon pea, (2) rotation with peanut, (3) intercropped with pigeon pea	Inter-site CV of crop yield: (1)	Positive (d = -0.98–4.87% compared to fertilized sole maize)
					Inter-site CV of crop yield: (2)	Negative (d = +3.4% compared to fertilized sole maize)
					Inter-site CV of crop yield: (3)	Negative (d = +6% compared to fertilized sole maize)
Kassie et al. (2015)	Malawi	1,925 hh with 2,937 maize plots	Multinomial endogenous switching treatment regression using	Crop diversity (SC) – maize-legume rotation or intercropping	Crop yield skewness as a proxy for risk exposure	Positive (adoption effect = 0.67
Snapp et al. (2010)	Malawi	>1,000 farm sites	Field experiment	Crop diversity (SC) – unfertilized sole maize compared to (1) rotation with peanut, (2) rotation with annual and semi-perennial legumes, (3) intercropped with pigeon pea	Inter-site variability of system grain yield (CV): (1)	Positive (d = -1-2%)
					Inter-site variability of system grain yield (CV): (2)	Positive (d = -8-14% compared to unfertilized sole maize)
					Inter-site variability of system grain yield (CV): (3)	Mixed

d = difference, SC = cropping system, CV = Coefficient of variation.

[a] The magnitude of the relationships cannot be compared directly across studies as the methods and indicators used differ. The type of regression model, number and types of crops and livestock species for example will all influence the result. The table shows selected results from each study as assumed relevant to the topic of this review.

increasing until diversity levels reach seven species per hectare cropland, and then decreasing beyond this level.

6. Diversity and stability of food security

We found only 3 studies focusing on this dimension of food security, reporting 7 separate diversity-stability relationships. Of these, 4 relationships were positive, 2 were negative and 1 mixed (Table 4). All three studies are for Malawi, two on the farm scale and one on the landscape scale (Chimonyo et al., 2019; Kassie et al., 2015; Snapp et al., 2010). They measure the magnitude of fluctuation in a cropping systems as spatial crop yield variability or inter-site crop yield variability, rather than temporal variability. Crop yield stability is a function of environment and crop. For example, crop yield variability in a maize-legume system compared to a fertilized sole crop was lower when maize was grown in rotation with soybean and peanut/pigeon pea intercropped, but not when grown in rotation with peanut or intercropped with pigeon pea only (Chimonyo et al., 2019). This is only partly confirmed by an extensive field experiment with more than 1,000 farm sites where crop yield variability of maize was lower compared to an unfertilized sole maize when grown in rotation with peanut but not when intercropped with pigeon pea (Snapp et al., 2010) (see Table 5).

We also found an alternative method for understanding how agricultural diversity and stability of agricultural production are related in the literature we reviewed. Farm-scale adaptation strategies often include diversification and we identified six publications researching if farmers use diversification to mitigate risks from perceived changes in weather or climate (Antwi-Agyei et al., 2014a; Chengappa et al., 2017; Eludoyin et al., 2017; Fadina and Barjolle, 2018; Mavhura et al., 2015; Sanogo et al., 2017). These ‘perception studies’ rarely discuss the relationship to food security directly thus are not included in the summary table below but can help to understand farmer’s coping or adaptation strategies when faced with short- or long-term environmental changes. The sample size is often small. The number of farmers interviewed in the six studies reviewed ranged from 120 to 400 farmers and it is mostly unclear to what extent the chosen adaptation strategy was effective. For example, if it increased production or stability over time. Also, it is not always clear if diversification was a hypothetically preferred or a practised adaptation strategy, to what extent farmers already practiced diversification in general and in response to perturbations. Although households might claim that they have diversified their cropping patterns in response to climate variability, such patterns might have been partly influenced by non-climatic factors such as economic shocks and opportunities (Antwi-Agyei et al., 2014b). However, this method can reveal farmer’s motivation to adapt and preferring a specific strategy over others. The conclusions from the six studies suggest that diversification is practiced as a risk management strategy (Chengappa et al., 2017; Eludoyin et al., 2017; Fadina and Barjolle, 2018), to cope with climate shocks (Sanogo et al., 2017) and to take advantage of multiple growing seasons (Eludoyin et al., 2017). One perception study found that on-farm diversification was not an option for farmers in Zimbabwe faced with lower than average rainfall, and that they instead relied on food aid, income diversification and collecting wild food (Mavhura et al., 2015). This is perhaps an indication that major shocks cannot be compensated by diversifying as every agricultural activity is impacted severely.

To our knowledge no study has measured the relationship between diversification and stability of any food security indicator on the national scale. However, an interesting contribution is Sardos et al. (2016) who discuss changes to the agricultural systems and its resilience in Vanuatu since the introduction of root and tree crops such as white and Indian yam, cocoyam, cassava and sweet potato during European settlement in the 19th century. This seems to have neither compromised agricultural diversity nor changed the systems drastically which before consisted of local or naturalized root and tree crops such as wild yam and taro. Farmers instead used the new crops to increase the resilience of the system through increasing the farmer’s ability to switch to alternative crops when facing an unforeseen change.

7. Diversity and food access

Fifty-two studies reported 148 separate diversity-food security relationships used a measure of food access. Of these, the authors reported positive relationships in 96 cases (65%), no or ambiguous relationships in 47 cases (32%) and negative relationships in only 5 cases (3%) (Table 5). Most of the studies reviewed used at least one indicator of food access, either to describe household dietary diversity, average household energy and nutrient intake, household food consumption or financial constraints to food security. We here include studies using measures for coping strategies at times of food shortage or self-reported food insecurity using experience-based scales.

By far the most common indicators of food access were household consumption measures, for example HDDS. Thirty-three studies used household dietary diversity as a measure for food access, sometimes modified by changing the recall period or number and types of food groups (M-HDDS). Where the relationship between a measure of agricultural diversity and HDDS or M-HDDS is positive the regression coefficients differ between different statistical methods (e.g. Ayenew et al., 2018; Huluka and Wondimagegnhu, 2019; Jones, 2017b; Kissoly et al., 2018; Koppmair et al., 2017; Kumar et al., 2015; Makate et al., 2016; Murendo et al., 2018; Romeo et al., 2016; Sibhatu et al., 2015a; Sibhatu and Qaim, 2018a; Somé and Jones, 2018; Tesfaye and Tirivayi, 2020; Traoré et al., 2018). Sibhatu and Qaim (2018a) find that increasing agricultural diversity by one crop or livestock species slightly increases the number of food groups consumed by 0.05–0.07 in Kenya, 0.16 in Indonesia and 0.2–0.33 in Uganda. Other explaining factors such as cultivated land area and educational level of the household head also have a positive effect on M-HDDS but to a smaller extent than agricultural diversity. Murendo et al. (2018) also find a relatively small effect of increasing agricultural diversity. Producing one additional crop or livestock species leads to a 3% increase in M-HDDS whereas market participation results in a 6% increase in M-HDDS which indicates a reliance on purchased food. Other studies found much larger effects of increased agricultural diversity on HDDS and M-HDDS (Makate et al., 2016; Tesfaye and Tirivayi, 2020) where crop diversity was strongly associated with HDDS and M-HDDS. A few studies also measure mean household nutrient and/or energy intake or adequacy and found positive associations with agricultural diversity for some indicators (Brüssow et al., 2017; De Jager et al., 2018; Sibhatu and Qaim, 2018a).

Some studies examine the diversity-food access relationship differentiated by type of household. For example, while the crop diversity and HDDS relationship was positive overall, it was not significant or very weak for poorer households which depend more on income growth for increasing dietary diversity (Ecker, 2018). Somé and Jones (2018) found that in Burkina Faso seasonal differences between post-harvest, lean and harvest period in household dietary diversity was greater among households with greater crop production and value of crop sales but not with greater crop diversity.

Nine of the twelve studies on the association between agricultural diversity and economic access found a positive association (Bellon et al., 2020; Das and Ganesh-Kumar, 2018; Kasem and Thapa, 2011; Ladha et al., 2003; Limbu et al., 2017; Makate et al., 2016; Mofya-Mukuka and Hichaambwa, 2018; Pradhan et al., 2018; Thapa et al., 2018). For example, in Thailand, diversifying rice mono-cropping systems by including asparagus and okra for international markets lead to an increase in net income (Kasem and Thapa, 2011). Crop diversification by adding high-value crops in Nepal reduced the probability of being poor (Thapa et al., 2018). However, marginal households must diversify more than one third of total agricultural production value into high-value crops to move above the poverty line. Also agricultural income was significantly higher if households shifted their crop portfolio by substituting certain crops or cultivars for others instead of diversifying it

Table 5
Summary of studies examining the association between diversity and food access.

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of access [b]	Description of relationship [c]
Village to regional scale						
Akerele and Shittu (2017)	Nigeria	1,148 hh	Fixed effects model	Farming diversity (C, BI, RE)	Share of expenditure of food item in the total food budget (BI)	Positive (β = 0.0423–0.1187)
				Farming diversity (C, BI, RE)	Share of expenditure of food item in the total food budget (RE)	Positive (β = 0.0541–0.2354)
KC et al. (2016)	Nepal	1,466 hh	Probit model	Crop diversity (C)	More than or less/ equal 12 mths food sufficiency	Positive (β = 0.0525)
				Livestock diversity (C)	More than or less/ equal 12 mths food sufficiency	Positive (β = 0.0910
Brüssow et al. (2017)	Tanzania	900 farms	Prospensity Score (nearest neighbour) matching	Crop diversity (C)	FCS Household per capita protein intake MAHFP CSI Household per capita energy intake Household net income from crop production	Positive (ATT = 3.51) Positive (ATT = 103.3g) Negative (ATT = −1.48) Neutral (ns) Neutral (ns) Neutral (ns)
De Jager et al. (2018)	Ghana	329 hh	Poisson regression model	Crop diversity (C) Crop diversity (H′)	Household self-sufficiency (no. food groups)	Positive (β = 0.1) Positive (β = 0.7)
			Linear mixed model	Crop diversity (C) Crop diversity (H′)	Household self-sufficiency (quantity nutrients)	Positive (β = 6.2–6.4) Positive (β = 23.4–26.4)
Jones (2017b)	Malawi	2,526 hh	Generalized estimating equations	Crop diversity (C)	HDDS	Positive (β = 0.08–0.13)
Kasem and Thapa (2011)	Thailand	245 hh	Interviews, calculated income from farm gate prices and input prices	Crop diversity (SC) - diversified rice cropping system compared to rice monoculture	Net income from agriculture per hh	Positive (d = 55,447 Baht/year)
Kissoly et al. (2018)	Tanzania	899 hh	Poisson regression model	Production diversity (C)	M-HDDS	Positive (β = 0.022–0.030)
Koppmair et al. (2017)	Malawi	408 hh	Simple linear regression Linear regression with Poisson estimator	Production diversity (C) Crop diversity (C)	HDDS HDDS	Positive (β = 0.124) Neutral (ns)
Kumar et al. (2015)	Zambia	3,340 hh	Ordered logit model	Production diversity (C) Crop diversity (C) Farming diversity (C)	M-HDDS M-HDDS M-HDDS	Positive (β = 0.387) Positive (β = 0.250) Positive (β = 0.451)
Ladha et al. (2016)	India, Bangladesh	4 locations, six seasons, 2 years	Field experiment	Crop diversity (multiple cropping index in %)	Income from crop sales	Positive (d = 1,029 US $/ha)
Limbu et al. (2017)	Tanzania	6 vegetable plots, 4 fish ponds	Field experiment	Production diversity (SC) – integrated fish-vegetable system compared to non-integrated system	Annual net cash flow	Positive (d = 57.43 USD)
				Production diversity (SC) – integrated vegetable system compared to non-integrated system		Neutral (ns)
M'Kaibi et al. (2017)	Kenya	525 hh	Spearman rank correlation, ANOVA	Agricultural biodiversity (C)	HDDS HFIAS	Positive (F = 14.791) Positive (rho = −0.136)
M'Kaibi et al. (2015)	Kenya	525 hh	Spearman rank order correlations	Agricultural biodiversity (C)	HFIAS	Positive (rho = −0.10)
Makate et al. (2016)	Zimbabwe	~600 hh	Multiple linear regression	Crop diversity (SID-binary)	Income from agriculture FSC HDDS	Positive (β = 3.498) Positive (β = 0.638) Positive (β = 3.545)
			Probit regression model		HFIAS (Binary)	Neutral (ns)
Murendo et al. (2018)	Zimbabwe	2,815 hh	Multiple linear regression	Farming diversity (C) Crop diversity (C) Livestock diversity (C)	M-HDDS M-HDDS M-HDDS	Positive (IRR = 1.03) Positive (IRR = 1.04) Positive (IRR = 1.03)
N'Danikou et al. (2017)	Mali	180 hh	Correlation analysis	Agricultural biodiversity (C)	Food insecurity index based on CSI	Negative (r = - 0.22)
Ng'endo et al. (2016)	Kenya	30 hh	Spearman rank order correlation	Farming diversity (C) Farming diversity (H′)	HDDS	Neutral (ns) Neutral (ns)

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Table 5 (*continued*)

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of access [b]	Description of relationship [c]
				Farming diversity (SID)		Neutral (ns)
				Farming diversity (NFD)		Neutral (ns)
				Farming diversity (C)	FSC	Neutral (ns)
				Farming diversity (H′)		Neutral (ns)
				Farming diversity (SID)		Neutral (ns)
				Farming diversity (NFD)		Neutral (ns)
Ng'Endo et al. (2015)	Kenya	30 hh	Pearson correlation	Agrobiodiversity (C)	HHS	Neutral (ns)
				Agrobiodiversity (H′)		Neutral (ns)
				Agrobiodiversity (SID)		Neutral (ns)
Nkomoki et al. (2018)	Zambia	400 hh	Correlation analysis	Crop diversity (Binary)	FCS	Positive
					HHS	Positive
Parvathi (2018)	Laos	556 hh	Fixed effects regression model	Farming diversity (C)	FSC	Mixed: Positive (β = 6.59); Negative (β = 0.145) for squared farm diversity
Passarelli et al. (2018)	Ethiopia	373 hh	Simultaneous equation models	Production diversity (C)	HDDS	Neutral (ns)
					Income from agriculture	Negative (β = −0.838)
	Tanzania	402 hh			HDDS	Neutral (ns)
					Income from agriculture	Neutral (ns)
Pradhan et al. (2018)	India	3 years experiment	Field experiment	Crop diversity (SC) - Additive crop rotation design with maize	Profit	Positive (d = 359–527 USD/ha)
Romeo et al. (2016)	Kenya	1,353 hh	Ordinary Least Squares multivariate regression	Farming diversity, incl. purchased and gifted food (C)	M-HDDS	Positive (β = 0.195–0.317)
					Share of food expenditure (SID)	Positive (β = 0.006–0.01)
					Share of food expenditure (H′)	Positive (β = 0.025–0.039)
Sibhatu et al., 2015a	Indonesia	674 hh	Multivariate regression with Poisson estimator	Farming diversity (C)	M-HDDS	Positive (β = 0.054)
	Kenya	397 hh				Neutral (ns)
Sibhatu and Qaim (2018a)	Indonesia	672 hh	Regression model with Probit estimator for M-HDDS, regression model with ordinary least squares for others	Production diversity (C)	M-HDDS	Neutral (ns)
					Household per capita energy consumption	Neutral (ns)
					Household micronutrient adequacy-mean, zinc, iron, VitA	Neutral (ns)
				Farming diversity (C)	M-HDDS	Positive (ME = 0.155)
					Household per capita energy consumption,	Positive (ME = 300.4)
					Household calorie adequacy	Positive (ME = 0.078)
					Household micronutrient adequacy-mean	Positive (ME = 0.067)
					Household nutrient adequacy - zinc	Positive (ME = 0.065)
					Household nutrient adequacy - iron	Positive (ME = 0.065)
					Household nutrient adequacy - VitA	Positive (ME = 0.071)
	Kenya	393 hh		Production diversity (C)	M-HDDS	Positive (ME = 0.067–0.070)
					Household per capita energy consumption,	Neutral (ns)
					Household micronutrient adequacy-mean, zinc, iron, VitA	Neutral (ns)
				Farming diversity (C)	M-HDDS	Positive (ME = 0.045)
					Household per capita energy consumption	Neutral (ns)
					Household micronutrient adequacy	Neutral (ns)
	Uganda	417 hh		Production diversity (C)	HDDS	Positive (ME = 0.316–0.334)
						Neutral (ns)

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Table 5 (*continued*)

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of access [b]	Description of relationship [c]
					Household per capita energy consumption	
					Household micronutrient adequacy-mean, zinc, iron, VitA	Neutral (ns)
				Farming diversity (C)	HDDS	Positive (ME = 0.194–0.198)
					Household per capita energy consumption	Positive (ME = 83.035)
					Household calorie adequacy	Positive (ME = 0.030)
					Household mean nutrient adequacy	Positive (ME = 0.025)
					Household zinc adequacy	Positive (ME = 0.024)
					Household - VitA adequacy	Positive (ME = 0.030)
					Household - iron adequacy	Neutral (ns)
Traoré et al. (2018)	Mali	258 hh	Linear mixed model	Crop diversity (C)	FSC	Positive (β = 1.47)
					HDDS	Positive (β = 0.29)
Valencia et al. (2019)	Brazil	75 farmers	Correlation analysis	Farming diversity (C)	HDDS	Positive (r2 = 0.06)
Vanek et al. (2016)	Bolivia	297 hh	Stepwise multiple linear regression	Crop diversity (C)	HFIAS	Positive (β = −0.584)
					HDDS	Neutral (ns)
Whitney et al. (2018)	Uganda	102 hh	Projection to Latent Structures (PLS) regression analysis	Agrobiodiversity (H′)	HDDS	Neutral (uncorrelated)
				Agrobiodiversity (C)		Positively correlated
Williams et al. (2018)	Sri Lanka	50 hh	Bivariate tests	Agrobiodiversity (H′)	FCS	Neutral (ns)
Ritzema et al. (2019)	Cambodia	631 hh	Multivariate stepwise regression	Crop diversity (C)	M-HDDS	Neutral (ns)
				Livestock diversity (C)		Neutral (ns)
	Lao	365 hh		Crop diversity (C)		Neutral (ns)
				Livestock diversity (C)		Positive (β = 0.049)
	Vietnam	310 hh		Crop diversity (C)		Neutral (ns)
				Livestock diversity (C)		Positive (β = 0.068)
Bellon et al. (2020)	Ghana	637 hh	Linear regression	Crop diversity (SID)	Income from agriculture	Positive (β = 0.425)
					Value of products for own consumption	Positive (β = 0.175)
Tesfaye and Tirivayi (2020)	Uganda	4,523 hh	Fixed-effects instrumental variable regressions, Fixed-effects Poisson model, Ordinary least squares regression	Crop diversity (C)	M-HDDS	Positive (β = 0.153–0.158, IRR = 1.008)
				Crop diversity (H′)		Positive (β = 0.619–1.317, IRR = 1.051)
				Crop diversity (CE)		Positive (β = 1.195–4.682, IRR = 1.135)
				Crop diversity (BP)		Positive (β = 0.162–0.648, IRR = 1.012)
Bezner Kerr et al. (2019)	Malawi	425 hh	Multivariate regression	Crop diversity (C)	HFIAS (binary)	Neutral (ns)
					M-HDDS	Neutral (ns)
Huluka and Wondimagegnhu (2019)	Ethiopia	306 hh	Probit and simple linear regression	Crop diversity (C)	HDDS	Positive (β = 0.2921–0.3132)
National scale						
Asfaw et al. (2018)	Niger	3,344 hh	Quantile regression	Crop diversity (C)	Household per capita energy intake	Positive (β = 0.0209–0.0337)
				Crop diversity (BP)	Household per capita energy intake	Positive (β = 0.0504–0.0263)
				Crop diversity (H′)	Household per capita energy intake	Positive (β = 0.0604–0.0249)
Ayenew et al. (2018)	Nigeria	6,089 hh	Fixed effect model (FE), Random effect model (RE)	Farming diversity (C)	M-HDDS	Positive (β = 0.016 for FE and 0.025 for RE)
Birthal et al. (2015)	India	51,770 h	Multiple linear regression, Instrumental variable (IV) regression	Crop diversity (SC) – system with or without high-value crops	Likelihood of being under the poverty line	Negative (β = −0.0691 - 0.0282)
	India	26,951 hh	Multivariate regression	Crop diversity (C)		

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Table 5 (*continued*)

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of access [b]	Description of relationship [c]
Das and Ganesh-Kumar (2018)					Income from agriculture	Positive (β = 0.290–0.293); Negative for squared counts (β = −0.07)
				Livestock diversity (C)	Income from agriculture	Positive (β = 1.232); Negative for squared counts (β = −0.27)
Dillon et al. (2015)	Nigeria	~5,000 hh	Ordinary least squares (OLS) regression and Instrumental variables (IV) regression	Crop diversity (C)	M-HDDS	Positive (β = 0.037 for OLS and β = 0.24 for IV)
Ecker (2018)	Ghana	11,217 hh	Fixed effect model	Crop diversity (C)	M-HDDS	Mixed: Positive (β = 0.111–0.178 for all hh, β = 0.148 for non-poor hh); Neutral (ns) for poor hh
				Crop diversity (SID)		Mixed: Positive (β = 0.309–0.551 for all hh, β = 0.396 for non-poor hh); Neutral (ns) for poor hh
Islam et al. (2018)	Bangladesh	6,040 hh	Pooled and random effects model, Poisson regression	Crop diversity (C)	HDDS	Positive (β = 0.019)
Jones et al. (2014)	Malawi	6,623 hh	Multiple linear regression	Crop diversity (C)	M-HDDS	Positive (β = 0.23)
					FSC	Positive (β = 0.81)
				Crop diversity (SID)	M-HDDS	Positive (β = 0.68)
					FSC	Neutral (ns)
				Farming diversity (C)	M-HDDS	Positive (β = 0.20)
					FSC	Positive (β = 0.71)
Mofya-Mukuka and Hichaambwa (2018)	Zambia	14,212 hh	Poisson regression and Ordinary least squares regression	Crop diversity (SID)	Farm income	Positive (β = 0.9142)
					FSC	Positive (β = 0.646–0.702)
					MAHFP	Positive (β = 0.727–0.741)
			Poisson regression		HDDS	Positive (β = 0.284)
Sauer et al. (2018)	Zambia	5,381 hh	Two-stage least squares regression	Crop diversity (SC) – cereal-legume intercropping yes/no	MAHFP	Neutral (ns)
					HDDS	Positive (β = 9.918)
Sibhatu et al., 2015a	Indonesia, Kenya, Ethiopia, Malawi	8,230 hh	Multivariate regression with Poisson estimator	Farming diversity (C)	M-HDDS	Positive (β = 0.009)
	Ethiopia	2,045 hh				Neutral (ns)
	Malawi	5,114 hh				Positive (β = 0.015); Negative (β = −3.2e-04) for squared C
Snapp and Fisher (2015)	Malawi	9,291 hh	Poisson regression, Ordinary least squares regression	Crop diversity (C) – crops intercropped with maize	M-HDDS	Positive (IRR = 1.019)
					FSC	Negative (β = −0.189)
				Crop diversity (C) – non-maize crops	M-HDDS	Positive (IRR = 1.019)
					FSC	Positive (β = 0.333)
Somé and Jones (2018)	Burkina Faso	10,860 hh	Mixed linear regression model	Crop diversity (C)	HDDS	Positive (β = 0.085)
Thapa et al. (2018)	Nepal	8,066 hh	Ordinary least squares regression, two-stage least squares regression	Crop diversity (value share of high-value crops cultivated)	Probability of being poor	Positive (β = −0.002 to −0.004)
				Crop diversity (binary) - growers and non-growers of high-value crops	Poverty head-count ratio	Positive (d = 9.18%)
Fraval et al. (2019)	Burkina Faso; Democratic Republic of Congo Ethiopia; Kenya; Malawi; Mali; Tanzania; Uganda; Zambia	7,708 hh	Logistic regression model	Crop production diversity (C)	M-HFIAP	Positive (β = 0.10)
				Livestock production diversity (C)		Positive (β = 0.32)
			Negative binomial regression	Crop production diversity (C)	M-HDDS	Mixed: Positive (β = 0.03); Neutral for M-HDDS and crop diversity in best period (ns)
				Livestock production diversity (C)		Positive (β = 0.05)
Zanello et al. (2019)	Afghanistan	14,079 hh	Ordinary least squares (OLS) regression, Instrumental variable (IV) regression	Crop diversity (C)	FSC	Positive (β = 0.862–1.852)
				Livestock diversity (C)		Positive (β = 2.322–3.144)

[a] C = count, BP = Berger Parker index, H' = Shannon Diversity index, SID = Simpson Diversity index, BI = Berry index, RE = Relative Entropy, NFD = Nutritional Functional Diversity, SC = cropping system or farming typology, CE = Composite Entropy Index.

[b] CSI = Coping Strategy Index, DSR = Dietary Species Richness, FCS = Food consumption score, FVS = Food Variety Score, HDDS = Household Dietary Diversity Score, HFIAS = Household Food Insecurity Access Scale, HHS = Household Hunger Scale, MAHFP = Months of Adequate Household Food Provisioning, M-HDDS = Modified Household Dietary Diversity Score (recall period and/or number and type of food groups modified), M-HFIAP = Modified Household Food Insecurity of Access Prevalence.

[c] ATT = average treatment effect, ns = not significant (p-value > 0.05); β = regression coefficient; IRR = incidence rate ratios; VIP = variable importance in projection statistic; DID = difference-in-difference estimator, OR = Odds ratio, d = difference in means or median, r/r2 = Pearson correlation coefficient, rho = Spearman rank order correlation coefficient, F = ANOVA F statistic, ME = marginal effects, ns = not significant at the 95% level. The magnitude of the relationships cannot be compared directly across studies as the methods and indicators used differ. Some indicators such as the Shannon diversity index cannot be compared across different locations as they depend on the total number of species. The type of regression model, number and types of crops and livestock species for example will all influence the result. The table shows selected results from each study as assumed relevant to the topic of this review.

by adding crops (Brüssow et al., 2017).

Six of the ten studies using experience-based food insecurity scales or measuring the extent of coping strategies find a positive association with diversity at least for one indicator studied (Brüssow et al., 2017; KC et al., 2016; M'Kaibi et al., 2017, 2015; Nkomoki et al., 2018; Vanek et al., 2016). For example, HFIAS, the Household Food Insecurity Access Scale was lower at higher levels of agricultural diversity (M'Kaibi et al., 2017, 2015; Vanek et al., 2016). However, when HFIAS was converted into a binary variable ("food secure" and "not food secure" households), the relationship between HFIAS and agricultural diversity was not statistically significant (Bezner Kerr et al., 2019; Makate et al., 2016). The results also differ between studies using the same indicator, for example HHS, the Household Hunger Scale. Whereas Ng'Endo et al. (2015) find no association between HHS and agrobiodiversity, Nkomoki et al. (2018) report that 82% of the households reporting to experience little to no hunger practiced crop diversification.

Some studies used national agricultural, livelihoods or household surveys that present results across a representative national sample including both diversified and non-diversified farming households. For example, both Snapp and Fisher (2015) and Jones et al. (2014) use data from the 2010/11 Malawi Integrated Household Survey. For the same measures of diversity and food access, both studies find a positive effect. Jones et al. (2014) highlight that the relationship may be further influenced by gender and wealth as the effect of farming diversity on household dietary diversity was stronger in women-headed households and in wealthier households. Snapp and Fisher (2015) find a small positive effect on food security as growing one additional crop increased HDDS by only 2%. Similarly, in Nigeria the positive effect of agricultural diversity on HDDS is significant but small. A 10 per cent increase in agricultural diversity results in a 0.16–2.4 per cent increase in HDDS (Ayenew et al., 2018; Dillon et al., 2015) which is still a larger effect then that from increasing agricultural revenue by 10 per cent (Dillon et al., 2015). In some multi-country studies it was possible to compare the results across countries and geographies (Fraval et al., 2019; Passarelli et al., 2018; Ritzema et al., 2019; Sibhatu et al., 2015; Sibhatu and Qaim, 2018a; Tesfaye and Tirivayi, 2020) and some results suggest that the association depends on geographic locations. In sub-Saharan Africa for example, the effect of production diversity is positive in semi-arid zones but negative in the humid/sub-humid zones (Fraval et al., 2019). In Malawi, HDDS increased with production diversity but in Ethiopia, with almost double the average production diversity of Malawi, there is no association with household dietary diversity (Sibhatu et al., 2015).

Five studies on food access have attempted to test whether the diversity-food access relationship is linear or rather follows an inverted U-shape and to estimate an optimal level of agricultural diversity. Sibhatu et al. (2015b) for example find that HDDS increases with production diversity initially, but then declines with further increases in production diversity. This was evident from a negative regression coefficient for squared production diversity which indicates that the effect on dietary diversity declines. Similarly Parvathi (2018) and Das and Ganesh-Kumar (2018), find that the positive effect of production diversity on FCS and agricultural income declines as household diversify more. Das and Ganesh-Kumar (2018) find that most household already engage in the optimal number of crops, two, but not in the optimal number of animal husbandry and non-farm activities. This is confirmed by other studies (Islam et al., 2018; Mofya-Mukuka and Hichaambwa, 2018) that find that HDDS, HDDS and FSC tended to decline with increasing diversification after a peak point which was not further quantified in the studies.

8. Diversity and food utilisation

Finally, 29 studies reported 125 separate diversity-food security relationships focused on food utilisation. Of these, the authors reported, positive relationships in 65 cases (52%), no or ambiguous relationships in 49 cases (40%) and negative relationships in 11 cases (8%) (Table 6).

There are mixed results for different measures of food utilisation and for different age groups. The indicators either measure individual food consumption or anthropometric status. We found eleven studies that assess the association between agricultural diversity and anthropometric status of children and/or their mothers. The results differ for different age groups, for example between children aged 2 years or younger and 3 years or older (Gelli et al., 2018). Even if the same age group is studied, there are mixed results for different countries. For example, crop diversity measured as species richness and HAZ of children aged 6–24 months has a positive relationship in Malawi (Gelli et al., 2018) but a negative relationship in Zambia (Kumar et al., 2015). The negative relationship with HAZ of children in Zambia is strongest for children with HAZ scores 0 or higher. The relationship between crop diversity and HAZ and crop diversity and WAZ of children aged 6–60 months is neutral in Guatemala (Luna-González and Sorensen, 2018) but positive in Ethiopia (Yigrem et al., 2015). Where there is no significant association between diversity and nutritional status of children, other explanatory variables associated with nutritional status are socio-economic status such as housing conditions, assets ownership, household wealth and income, water, sanitation and hygiene, access to clean drinking water, maternal education, maternal age and child morbidity which indicates that improved nutrition can be achieved through multiple pathways in addition to diets (Luna-González and Sorensen, 2018; M'Kaibi et al., 2017).

The results depend also on the anthropometric measure used. Malapit et al. (2015), analysing data from three agro-ecological zones in Nepal, found a positive relationship between production diversity and some anthropometric scores but not all. While production diversity is positively correlated with WHZ, it is not with maternal body mass index and HAZ. While stunting and wasting indicated by low HAZ and WHZ scores share common risk factors, and both indicate impaired growth and development from poor nutrition it is possible that only one of them (stunting) is associated with production diversity. This is because stunting indicates chronic malnutrition and wasting indicates acute malnutrition and is moderated by the age of the child (Saaka et al., 2017).

Another twenty-three studies measured nutrient intake or a validated proxy for nutrient intake or adequacy, MDD-W or WDDS for women and IYCDDS, IDDS or MDD-C for children. Fifteen studies used adequacy of diet diversity of children as a measure of nutrient intake, and nine of them find a positive association with agricultural diversity (e.g. Gelli et al., 2018; Koppmair et al., 2017; Malapit et al., 2015; Saaka et al., 2017). The results differ by age group (Mulmi et al., 2017), the measure of agricultural diversity used, and are mediated by other fators such as access to nutrition education on child feeding and care practices market participation (Murendo et al., 2018) and other characteristics such as household size and wealth (Saaka et al., 2017). Another consideration is that instead of having to increase the number of food groups a child consumes it is important to reach a certain cut off point when their diet can be considered adequately diverse, i.e. consuming four or more different food groups according to the World Health

Table 6
Summary of studies examining the association between diversity and utilisation.

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of utilisation [b]	Description of relationship [c]
Village to regional scale						
Adubra et al. (2019)	Mali	4,790 hh, 5,046 mother-child pairs	Logistic regression, simple linear regression	Production diversity (C)	MDD-W WDDS-10	Positive (OR = 1.12) Positive (β = 0.10)
Azupogo et al. (2019)	Ghana	642 children aged 6–17 years	Multiple linear regression	Farming diversity (C)	Haemoglobin concentration (6–9 yrs) Haemoglobin concentration (6–17 yrs)	Positive (β = 0.59) Neutral (ns)
Bellon et al. (2016)	Benin	880 hh	Generalized method of moments for parameter estimation	Agrobiodiversity (C)	MDD-W	Positive (β = 0.036)
Boedecker et al. (2014)	Benin	120 women	ANOVA	Agrobiodiversity (Binary)	WDDS Individual's nutrient consumption	Positive (d = 0.6) Neutral (ns)
De Jager et al. (2018)	Ghana	329 hh	Linear mixed model, quasi-binomial regression	Crop diversity (C)	IYCDDS MPA	Neutral (ns) Neutral (ns)
				Crop diversity (H′)	IYCDDS MPA	Neutral (ns) Neutral (ns)
Gelli et al. (2018)	Malawi	1,199 hh, 304 children aged 6–24 mths, 1,248 children 36–72 mths)	Multilevel regression models using difference-in-difference estimator	Crop diversity (C)	HAZ (6–24 mths) Prevalence of stunting (6–24 mths) 10 other relationships with HAZ, WHZ, WAZ, prevalence of stunting, prevalence of wasting, prevalence of underweight	Positive (DID = 0.44) Negative (DID = −17%) Neutral (ns)
				Production diversity (C)	Food quantity intake Energy intake Protein intake Iron intake Zinc intake VitB12 intake VitB6 intake IDDS (children) VitA intake	Positive (DID = 153 g) Positive (DID = 294 kcal) Positive (DID = 8.12 g) Positive (DID = 1.64 mg) Positive (DID = 1.09 mg) Positive (DID = 0.21 μg) Positive (DID = 0.26 mg) Positive (DID = 0.36) Neutral (ns)
Gitagia et al. (2019)	Kenya	384 women	Logistic regression model	Crop diversity (C) Crop diversity (H′) Production diversity (C)	MDD-W	Neutral (ns) Neutral (ns) Neutral (ns)
Jones (2015)	Bolivia	331 hh with children aged 0–23 mths	Multivariate regression	Crop diversity (C) Livestock diversity (C)	IFCI	Positive (β = 0.25–0.46) for high elevation Positive (β = 0.02–0.03)
Jones et al. (2018)	Peru	600 hh	Poisson regression Logistic regression Poisson regression Ordinary least squares regression	Crop diversity (C)	WDDS-10 MDD-W DSR MPA	Positive (IRR = 1.03) Positive (OR = 1.17) Neutral (ns) Mixed; Positive (OR = 1.21 for MPA >60%), Neutral (ns) for all MPA
			Poisson regression Logistic regression Poisson regression Ordinary least squares regression	Farming diversity (C)	WDDS-10 MDD-W DSR MPA	Neutral (ns) Positive (OR = 1.08) Neutral (ns) Mixed; Positive (OR = 1.16 = for MPA >60%, Neutral (ns) for all MPA
Koppmair et al. (2017)	Malawi	408 hh, 519 children aged 6 mths to 5 yrs	Simple linear regression	Production diversity (C)	IDDS (children) IDDS (mother)	Positive (β = 0.168) Positive (β = 0.144)
			Linear regression with Poisson estimator	Crop diversity (C)	IDDS (children) IDDS (mother)	Positive (β = 0.073) Neutral (ns)
Kumar et al. (2015)	Zambia	3,340 hh, 1,153 children aged 6–23 mths, 2,385 children aged 24–59 mths	Marginal probit model	Production diversity (C)	Prevalence of wasting (6–23 mths)	Negative (β = −0.011)
				Production diversity (C)	Prevalence of stunting (24–59 mths)	Negative (β = −0.015)
				Crop diversity (C)	Prevalence of wasting (6–23 mths)	Negative (β = −0.010)
				Farming diversity (C)	Prevalence of stunting (24–59 mths)	Negative (β = −0.022)
				Crop diversity (C)	HAZ (6–23 mths)	Negative (β = −0.083)

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Table 6 (*continued*)

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of utilisation [b]	Description of relationship [c]
			Ordinary least squares regression	Farming diversity (C)	HAZ (6–23 mths)	Negative (β = −0.097)
				Farming diversity (C)	HAZ (24–59 mths)	Positive (β = 0.084)
			Marginal probit model for stunting and wasting, Ordinary least squares regression	Production diversity, farming diversity, crop diversity (C)	17 other relationships with HAZ, WHZ, prevalence of stunting, prevalence of wasting	Neutral (ns)
			Ordered logit model	Production diversity (C)	IDDS (children)	Positive (β = 0.263)
					MDD-C	Positive (β = 0.067)
				Crop diversity (C)	IDDS (children)	Positive (β = 0.217)
					MDD-C	Positive (β = 0.053)
				Farming diversity (C)	IDDS (children)	Positive (β = 0.294)
					MDD-C	Positive (β = 0.075)
Luna-González and Sorensen (2018)	Guatemala	154 children aged 6–60 mths	Pearson correlation	Crop diversity (C)	HAZ	Neutral (ns)
					WAZ	Neutral (ns)
					IYCDDS	Positive (r2 = 0.26)
					IDDS (children)	Positive (r2 = 0.39)
				Crop diversity (NFD)	IYCDDS	Neutral (ns)
					IDDS (children)	Positive (r2 = 0.32)
M'Kaibi et al. (2017)	Kenya	525 children aged 24–59 mths	Correlation analysis	Agricultural biodiversity (C)	WHZ	Neutral (ns)
					HAZ	Neutral (ns)
					WAZ	Neutral (ns)
M'Kaibi et al. (2015)	Kenya	525 hh	Spearman rank order correlations	Agricultural biodiversity (C)	NAR-mean	Positive (rho = 0.194)
					NAR-protein, iron, zinc, vit B12, vit B6, vit C, folate, riboflavin	Positive (rho = 0.091–0.193)
					NAR-energy	Neutral (ns)
Malapit et al. (2015)	Nepal	3,332 hh with children aged 6–59 mths	Ordinary least squares regression	Production diversity (C)	WAZ	Positive (β = 0.033)
					WHZ	Positive (β = 0.034)
					Maternal BMI, HAZ	Neutral (ns)
					IDDS (children)	Positive (β = 0.058–0.059)
					IDDS (mother)	Positive (β = 0.089–0.096)
Mitchodigni et al. (2017)	Benin	1,225 hh, 1,182 children aged 6–23 mths	Multilevel logistic regression	Production diversity (C)	MDD-C	Positive (β = 0.16, OR = 1.17)
Mulmi et al. (2017)	Nepal	5,978 hh, 2,989 children aged 6–59 mths)	Logit regression models	Production diversity (C)	MDD-C, 6–11 mths	Neutral (ns)
					MDD-C, 12–17 mth	Neutral (ns)
					MDD-C, 18–23 mths	Positive (β = 0.43)
					MDD-C, 6–23 mths	Neutral (ns)
					MDD-C, 25–59 mths	Positive (β = 0.253)
Murendo et al. (2018)	Zimbabwe	2,815 hh, 499 children aged 6–23 mths	Multiple linear regression	Farming diversity (C)	WDDS	Positive (IRR = 1.04)
					IDDS (children)	Neutral (ns)
				Crop diversity (C)	WDDS	Positive (IRR = 1.05)
					IDDS (children)	Neutral (ns)
				Livestock diversity (C)	WDDS	Positive (IRR = 1.03)
					IDDS (children)	Positive (IRR = 1.04)
Rammohan et al. (2018)	Myanmar	1,037 children aged 7–60 mths	Ordered probit model	Farming diversity (Categorical)	Prevalence of stunting, prevalence of underweight	Neutral (ns)
					Prevalence of wasting	Mixed; negative (β = −0.041) only for hh with highest farming diversity score and children 7–18 mths
Saaka et al. (2017)	Ghana	1,200 children aged 6–36 mths	Correlation analysis, Three-step moderated hierarchical multiple regression	Farming diversity (C)	IDDS (children)	Positive (β = 0.09–0.10, rho = 0.12)
Termote et al. (2012)	DR Congo	184 hh and 129 women	ANOVA for difference in means	Agricultural biodiversity (Binary) – consumers and non-consumers of wild edible plants	Total carbohydrate intake	Neutral (ns)
					Thiamine intake	Neutral (ns)
					Niacin intake	Neutral (ns)
					Folate intake	Neutral (ns)
					VitB12 intake	Neutral (ns)
					Iron intake	Neutral (ns)
					Zinc intake	Neutral (ns)
					Dietary intake	Positive (d = 125 g)
					Energy intake	Positive (d = 214 kcal)
					Fibre intake	Positive (d = 6.1 g)
					VitA intake	Positive (d = 64 μg RE)
					VitC intake	Positive (d = 28.7 mg)
					VitB6 intake	Positive (d = 0.45 mg)
					Calcium intake	Positive (d = 141.3 mg)

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Table 6 (*continued*)

Reference	Country	Sample size	Method	Indicator of diversity [a]	Indicator of utilisation [b]	Description of relationship [c]
					Riboflavin intake	Negative (d = −0.36 mg)
Vanek et al. (2016)	Bolivia	297 hh with children <2 yrs	Stepwise multiple linear regression	Crop diversity (C)	HAZ	Positive (β = 0.102)
					ICFI	Neutral (ns)
Whitney et al. (2018)	Uganda	102 hh, 325 individuals, children aged 2–5.9 yrs	Projection to Latent Structures (PLS) regression analysis	Production diversity (H′)	WHZ	Positive (VIP>1) for WHZ
					BMI, HAZ, % underweight	Neutral (VIP<1)
				Production diversity (C)	HAZ	Positive (VIP>1)
					BMI, HAZ, % underweight	Neutral (VIP <1)
				Agrobiodiversity (H′)	MDD-W	Neutral (uncorrelated)
					IDDS (children)	Neutral (uncorrelated)
					IDDS (toddler)	Neutral (uncorrelated)
				Agrobiodiversity (C)	MDD-W	Positively correlated
					IDDS (children)	Neutral (uncorrelated)
					IDDS (toddler)	Negatively correlated
Yigrem et al. (2015)	Ethiopia	270 hh, 225 children aged 6–60 mths	Canonical correlation analysis	Crop diversity (C)	WAZ	Positive (CC = 0.2601, β = 0.320)
					HAZ	Positive (CC = 0.0940)
					MUAC	Positive (CC = 0.0308)
					WHZ	Negative for WHZ (CC = 0.0111)
Bellows et al. (2020)	Tanzania	1,006 hh	Generalized linear mixed effects models	Production diversity (C)	MDD-W	Positive (β = 0.16–0.23, OR = 1.24–1.38)
				Crop diversity		Neutral (ns)
National scale						
Hirvonen and Hoddinott (2017)	Ethiopia	7,011 hh, 3,448 children aged 6–59 mths	Regression models (OLS, Poisson, Linear)	Crop diversity (C)	IDDS (children)	Positive (β = 0.092–0.62)
Islam et al. (2018)	Bangladesh	6,040 hh	Pooled and random effects model, Poisson regression	Crop diversity (C)	WDDS	Positive (β = 0.009)
Lovo and Veronesi (2019)	Tanzania	6,361 hh, 2,771 children	Endogenous regressor models	Crop diversity (C)	HAZ	Positive (β = 0.023–0.025)
Tobin et al. (2019)	Benin, Burkina Faso, Cameroon, Ethiopia, Ghana, Guinea, Malawi, Nigeria, Tanzania, Uganda, Zimbabwe	36,542 children aged ≤36 mths	Ordinary least squares regression	Crop diversity (SID)	HAZ	Positive (β = 0.260–0.2921)
				Crop diversity (C)	HAZ	Negative (β = −0.015)
			Poisson regression	Crop diversity (SID)	IDDS (children)	Mixed: Positive (β = 9.061–0.139) for SID; Neutral for high-protein crops
				Crop diversity (C)		Neutral (ns)

[a] C = count; H' = Shannon diversity index, SID = Simpson diversity index, β = regression coefficient.
[b] WAZ = weight-for-age z-score, HAZ = height-for-age z-score, WHZ = weight-for-height z score, MUAC = middle upper arm circumference for age z score, BMI = Body mass index, IDDS = Individual Dietary Diversity Score, IFCI = Infant and Child Feeding Index, IYCDDS = Infant and Young Child Dietary Diversity, MDD = Minimum dietary diversity, MDD-C = Minimum Dietary Diversity of Children, MDD-W = Minimum Dietary Diversity for Women, MPA = Mean Probability of Adequacy of Micronutrient Intake, NAR = Nutrient Adequacy Ratio, NAR-mean = mean nutrient adequacy ratio, WDDS = Women's Dietary Diversity Score, WDDS-10 = 10-Food Group Women's Dietary Diversity Score. Prevalence of stunting and wasting is defined as the percentage of children with HAZ and WHZ, respectively, of more than 2 standard deviations below median. IDDS (children) differs from IYCDDS in the number of food groups used and/or the age group which is 6–23 months for IYCDDS. MDD-C differs from IYCDDS in that it measures the prevalence of children consuming at least four of the seven food groups included. IDDS (mother) differs from WDDS in the number of food groups considered.
[c] CC = Canonical correlation coefficient, β = regression coefficient, DID = difference-in-difference estimator, VIP = variable importance in the projection. The magnitude of the relationships cannot be compared directly across studies as the methods and indicators used differ. Some indicators such as the Shannon diversity index cannot be compared across different locations as they depend on the total number of species. The type of regression model, number and types of crops and livestock species for example will all influence the result. The table shows selected results from each study as assumed relevant to the topic of this review.

Organization (2008). The prevalence of children aged 6–23 months with MDD-C, minimum dietary diversity was found to be positively (Kumar et al., 2015; Mitchodigni et al., 2017) or not (Mulmi et al., 2017) associated with agricultural diversity. However, diet quality of children older than 18 months improved with diversification of farm production whereas other strategies such as improved market access to purchase complementary foods may benefit younger children (Mulmi et al., 2017).

Positive associations between agricultural diversity and MDD-W or WDDS were found in seven studies (Adubra et al., 2019; Bellon et al., 2016; Bellows et al., 2020; Boedecker et al., 2014; Jones et al., 2018; Murendo et al., 2018; Whitney et al., 2018). For MDD-W the regression coefficients are 0.036–0.23 with odds ratios of 1.08–1.38. For WDDS the regression coefficients are smaller, 0.10 in a logistic regression and odds ratio of 1.03–1.05 in a multiple linear regression. In Adubra et al. (2019) evaluate the impact of a 3 years nutrition-sensitive intervention targeting women and their children during the first 1000 days of each child's life. In a large sample with more than 5,000 women they found a positive relationship between production diversity and MDD-W and WDDS, regardless of household's overall food security and wealth status. Specifically, one more food crop or livestock group on the farm resulted in a 10% increase in WDDS-10 and a better chance of attaining the minimally needed MDD-W score. In contrast, Gitagia et al. (2019) find no relationship between agrobiodiversity and the quality of women's diets in central Kenya but an important relationship between education and diet quality.

Four studies used household data from nationally representative surveys for single country or multi-country studies (Hirvonen and

Hoddinott, 2017; Islam et al., 2018; Lovo and Veronesi, 2019; Tobin et al., 2019) (Table 6). The association between agricultural diversity and food utilisation was mostly positive irrespective of the food utilisation and diversity indicator, except for some associations presented in Tobin et al., (2019). In this study, the authors find a positive association between the Simpson diversity index and HAZ but a small negative association between crop species richness and HAZ. This indicates that crop diversity has a benefit only if proportional presence is considered in addition to total number of species (Tobin et al., 2019). HAZ increased by 0.26–0.30 with each one-unit increase in the Simpson diversity index but decreased by 0.015 with each one-unit increase in crop richness.

9. Diversity and food security at the global scale

We found five studies study the relation of agricultural diversity to food security on the global scale. Because of the low sample size, results are summarized in this separate section for all four food security dimensions together. Since 1961, global crop diversity increased which may have influenced national food supply overall. Crop diversity (H') increased by about 20% between 1961 and 2016 and crop species richness increased more strongly than evenness in two studies using different national agricultural data (Aizen et al., 2019; Khoury et al., 2014). In contrast to species richness, the results for evenness were mixed between different world regions with Europe being the only region with a decline in evenness but increase in richness. Dominance of the most abundant crop commodities declined and agricultural production is increasingly homogeneous (Aizen et al., 2019; Khoury et al., 2014). Going back even further in time, Nabhan et al. (2012) analysed how agrobiodiversity has changed over time by comparing late 19th-c. to early 20th-c. records with their own fieldwork in 2005 in three regions of Tajikistan, Egypt, and the United States. They find that farmers adopt and abandon crop varieties for different reasons in the three locations and that local and global factors influence the conservation of agrobiodiversity. While for example diversity in the Tajikistan study area remained roughly the same over time and only certain species changed their distribution in space or time, diversity declined in the study area in the United States (northern Arizona). The reason is that water scarcity led to a loss of varieties, and livelihoods shifted away from farming.

To our knowledge, only one study relates national food supply diversity with food utilisation and finds a negative relationship between national food supply diversity (H') and the national prevalence of child stunting ($\beta = -3.1$), wasting ($\beta = -1.15$) and being underweight ($\beta = -2.39$) across 113 countries (Remans et al., 2014). Functional diversity (MFAD) has a significant relation only to the prevalence of wasting ($\beta = -1.90$) and being underweight ($\beta = -3.10$). Income per capita has a strong influence on nutritional outcomes too (Remans et al., 2014, Table 2). For low-income countries, agrobiodiversity was a good predictor of national food diversity, because their national food supply tends to be that which they produce. Middle-to high income countries are less dependent on own production and have greater access to international markets to increase and diversify their food supply.

The diversity-stability hypothesis was tested for national crop yield between 1961 and 2010 across the 100 most populous countries (Renard and Tilman, 2019). Crop diversity at the national level (exp(H')) is statistically associated with increased temporal stability of crop yield, irrespective of aggregation to crop groups ($R2 = 0.32–0.37$), and this stabilizing effect is similar in magnitude than the destabilizing effect of rainfall variability. The study did not find any crop group contributing more to yield stability than others. Troell et al. (2014) shows price indices for individual food sectors and for food in the aggregate during the period 1990–2013. Cereal and oilseed prices have shown much stronger variation than have price indices for meat, aquaculture, and capture fisheries. The coefficient of variation for food in the aggregate is 0.33 over the entire period— substantially higher than that of aquaculture (0.16), fisheries, and meat (0.21) but below that of grains and oils (0.4). Lower volatility in the meat and fish sectors suggests a significant share of substitution possibilities between various animal protein products and various feed ingredients.

10. Synthesis and recommendations

We performed a survey of 924 studies that yielded 88 studies meeting the inclusion requirements and giving 314 individual diversity-food security relationships across low- and middle-income countries. In almost two thirds of all cases, agricultural diversity had a positive effect on food security (Table 7). In about one third of the relationships there was no effect of agricultural diversity on food security, or the results were mixed. In very few cases food security declined when agricultural diversity increased (6%). Food access was the dimension of food security most assessed with 59% of all studies and 47% of all relationships. Thirty-three studies used household dietary diversity as a measure of food access and twenty-two studies used at least one food utilisation indicator validated as a proxy for nutrient adequacy. Studies for food utilisation are more common than for food availability, 34% and 22% respectively and for both dimensions agricultural diversity had a positive effect in about 55%–65% of all cases. For food utilisation, of the 47 neutral or mixed relationships, 13 times a measure of anthropometric and nutritional status is used and 34 times a measure of individual consumption is used. The most common spatial scale of the analysis was the household and farm scale. Crop species richness was the most common indicator of agricultural diversity.

Common reasons for positive and negative relationships

There is no food security dimension that would primarily have a negative or neutral relationship with agricultural diversity. However, for each food security dimension studied there is a considerable number of relationships that are found to be neutral or ambiguous. An often-stated reason for a neutral relationship between agricultural diversity and food security is that households sourced significant proportions of their food from markets. Hence, a positive relationship between agricultural diversity at the farm scale and food security is plausible, particularly when farming households produce most of what they consume. The direction of the relationship between crop diversity and food availability often depends on the crop studied, the row arrangement in intercropping and the type of crop mix. The effect of crop diversity tends to be positive when a crop has an additional function for the system, for example because it is a nitrogen-fixing crop, provides shade for the companion crop or contain specific nutrients. Functional diversity can also exist in a different context, for example where a new crop or animal type increases farm income or nutrition. On the other hand, a simple coexistence of species might benefit income or nutrition but not ecosystem functioning. Other factors cited to have had a stronger influence on food security are socio-economic status such as housing conditions, assets ownership, income and education, farm characteristics such as access to improved management strategies and farmland size, and other characteristics such as household composition and size, sanitation and hygiene, access to clean drinking water, and child morbidity (Dzanku and Sarpong, 2011; Luna-González and Sorensen, 2018; M'Kaibi et al., 2017; Passarelli et al., 2018; Saaka et al., 2017; Yigrem et al., 2015). Also, the benefits of diversification are context specific and there exist potentially other solutions to improve food security. Sometimes diversity is only beneficial in conjunction with other changes in the system, for example increasing market participation or soil conservation systems. In other situations, it might be the primary coping strategy, for example, when due to limited market access households are more reliant on own food production.

The different branches of literature

The articles reviewed can be broadly grouped into three clusters,

Table 7
Synthesis table summarizing the diversity-food security relationships found in literature on three levels of data collection.

		Food security dimension			
Spatial scale of data collection		Availability	Access	Stability	Utilisation
	Household/ Farm/Village/ Region	++ 16 studies with 23 relationships: 14 positive, 7 neutral or mixed, 2 negatives	++ 35 studies with 109 relationships: 65 positive, 41 neutral or mixed, 3 negatives	< 2 studies with 4 relationships: 2 positive, 2 negatives	++ 25 studies with 118 relationships: 61 positive, 47 neutral or mixed, 10 negatives
	National	< 3 studies with 3 positive relationships	++ 17 studies with 40 relationships: 31 positive, 6 neutral or mixed, 3 negatives	< 1 study with 3 relationships: 2 positive, 1 mixed	< 4 studies with 7 relationships: 4 positive, 1 negative, 2 neutral or mixed
	Global	/ No studies found	/ No studies found	< 1 study with 1 positive relationship	< 1 study with 6 relationships: 5 positive, 1 neutral

Code for symbols: ++ more than half of relationships are positive; < small sample size.

similar to Glamann's clusters of literature analysing the food security-biodiversity association (Glamann et al., 2017). Each cluster tends to be more closely related to one of the food security dimensions. One cluster is dominated by the natural sciences focusing on the production and ecological aspects of food security (e.g. Samal et al., 2017; Snapp et al., 2010). A second cluster is dominated by the social sciences and emphasize for example economic dimensions of food security (Das and Ganesh-Kumar, 2018; Parvathi, 2018). Less studies consider broader aspects of sustainability, social-ecological development and empowerment (Jones et al., 2014; Malapit et al., 2015). A third cluster is dominated by nutrient science emphasizing human nutrition and health aspects of food security (Gelli et al., 2018; Tobin et al., 2019). As Glamann et al. (2017) explained, each group has specific approaches and conceptual basis for investigating the relationship, using specific measures of food security and including or excluding particular themes.

Recommendations for future research on diversity and food security

Based on our observations from the literature review, some methodological recommendations for future research can be made.

- The food dimension and indicators representing that dimension should be clearly stated and explained. Where possible researchers should use established indicators. They have often been tested or validated in several case studies and were developed and discussed by a commission of experts. If new indicators are introduced, they should be validated and compared with existing ones.
- Some studies speak of "diversifying into" and it is important to clarify the nature of diversification studied in this case. A new crop can be an addition to the existing crop portfolio or a replacement for another crop. Specific crops such as cash crops can have benefits to farmers also in the absence of overall diversification of the system.
- When measuring the diversity-stability relationship, future studies should consider that the relationship might be always positive for some measures of stability, but not for others. From a statistical point of view the mean of variables is more stable as more variables and their fluctuations are averaged (Doak et al., 1998).
- When choosing a measure of diversity, consider that evenness in the distribution of different food items or food groups is not necessarily desired from a nutritional perspective. A high score only indicates health benefits if calculated from a list of healthy foods. Even then it is not necessary to consume equal quantities of everything, but the amount required for a specific age and sex group.
- An element of scale-dependency should be introduced into diversity analysis. Conclusions on the benefits of agricultural diversity on the national or global scale might not be scalable to the field scale and vice versa. The effect might be explained by a certain combination of production/agroecological zones on a larger scale that cannot be reproduced on the field scale and vice versa.
- Several alternative strategies for increasing food security should be studied along with diversification to compare the relative importance of each strategy for similar outcomes.

Several research questions are understudied in the reviewed literature and constitute interesting challenges for future research.

- An interesting question is related to thresholds in achieving benefits from diversification. There are three considerations here. Firstly, such a threshold is probably a relative, rather than absolute threshold, depending on the ecological and economic context of the farm and potential benefits from diversification. High diversity in one context might be average in another. Secondly, there might be a minimum requirement to achieve gains from diversification. Achieving minimum dietary diversity of children through increasing agricultural diversity is a good example. Thirdly, from a certain point, the benefits of diversity might diminish, which suggests a challenge of "optimal" level of diversity.
- The relationship between diversity, a characteristic of a farming system, and diversification, the process of increasing diversity in a farming system, should be explored further. Existing diversity can limit or enable further diversification. Already diversified systems might have characteristics such as high level of flexibility in allocating resources, that enable even more diversification. On the other hand, at already high levels of diversity there might be no further benefit from diversification, or only at high costs, that may be diminishing returns. In some reviewed articles 80% of the farmers already practiced diversification so further diversification might not be their priority.
- The question of complementarity and redundancy between several species of crops for example is understudied. This means that the benefits of diversification are not necessarily proportional to the increase in diversity and relevant functions can on the other hand be maintained at lower levels of diversity. Drought resilience for example can be achieved through the right species composition irrespective of diversity (Dardonville et al., 2020).
- Apart from modelling and quantifying the diversity-food security relationships, more focus on the pathways from diversification to food security should be researched. The most researched pathway is perhaps through consumption of own production but there might also be market-based agricultural diversification (Bellon et al., 2020). Consumption versus income-generating pathways are for example discussed for India in Gillespie et al. (2012).
- There are noticeable gaps in understanding the relationship between diversity and food security; on the national/global scale. On a national scale for example it would be interesting to know if the prevalence of mal- or undernutrition change when the country decreased the number of commodities produced nationally?

In conclusion agricultural diversity can be beneficial for food security, but it is not the only available strategy to promote food security. Where diversification is also the cheapest strategy in terms of monetary and labour costs it can be an appealing and effective option to improve agricultural practices and profits. Therefore, holistic study designs considering the natural, social and economic aspects of agricultural and food systems are best suited to represent interactions between them and understand the complex effects of diversification.

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KW, FA, CG and CR had the idea for this review article and were supported by the CSIRO-INRA Linkage scheme. KW designed the search syntax and pre-selected publications based on the initial abstract screening. All authors either reviewed the pre-selected publications, extracted data from the included publications and/or wrote parts of the manuscript with KW. KW and JPD reviewed and cleaned data for the synthesis tables describing the magnitude of the observed effects and details of methods. All authors read and reviewed the full articles included in the review after initial screening to assess their relevance and contributed to revising the manuscript multiple times before submission.

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.

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