



# **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, Francesco Accatino, Cecile Godde, Cyrille Rigolot, Jessica Bogard, João Pedro Domingues Santos, Elisabetta Gotor, Mario Herrero, Guillaume Martin, Daniel Mason-D'croz, et al.

## **► To cite this version:**

Katharina Waha, Francesco Accatino, Cecile Godde, Cyrille Rigolot, Jessica Bogard, et al.. The benefits and trade-offs of agricultural diversity for food security in low- and middle-income countries: A review of existing knowledge and evidence. *Global Food Security*, 2022, 33, <10.1016/j.gfs.2022.100645>. <hal-03818575>

**HAL Id: hal-03818575**

**<https://hal.science/hal-03818575v1>**

Submitted on 10 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

# 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<sup>1</sup>, Francesco Accatino<sup>2</sup>, Cecile Godde<sup>1</sup>, Cyrille Rigolot<sup>3</sup>, Jessica Bogard<sup>1</sup>, Joao Pedro Domingues<sup>2</sup>, Elisabetta Gotor<sup>4</sup>, Mario Herrero<sup>1,5</sup>, Guillaume Martin<sup>6</sup>, Daniel Mason-D'Croz<sup>1</sup>, Francesco Tacconi<sup>1,7</sup>, Mark van Wijk<sup>8</sup>

**1** CSIRO, Agriculture & Food, 306 Carmody Rd, St Lucia, QLD, Australia **2** UMR SADAPT, INRAE, AgroParisTech, Université Paris-Saclay, 16 rue Claude Bernard, 75005 Paris, France **3** INRAE, Université Clermont Auvergne, AgroParisTech, Irstea, Vetagrosup, UMR Territoires, 63122 Saint-Genès Champanelle, France **4** Bioversity International, Rome, Italy **5** Department of Global Development, College of Agricultural and Lifesciences and Cornell Atkinson Centre for Sustainability, Cornell University, Warren Hall, Ithaca, NY 14853 USA **6** Université de Toulouse, INPT, INP-PURPAN, INRAE, AGIR, 31320 Auzeville, France **7** Tasmanian Institute of Agriculture, University of Tasmania, Sandy Bay Campus, Hobart, Tasmania 7005, Australia **8** International Livestock Research Institute (ILRI), Nairobi 00100, Kenya

\* Correspondence and requests for materials should be addressed to [katharina.waha@csiro.au](mailto:katharina.waha@csiro.au)

**Keywords:** food security, farming diversity, production diversity, agrobiodiversity, agricultural biodiversity, literature review, low-income countries, middle income countries

## Abstract

Diversity in agricultural systems is often presented as having benefits for multiple purposes like food and nutrition security in low- and middle-income countries. Our review aims to give an overview of the strength and direction of the diversity-food security relationship as presented in research conducted in low- and middle-income countries and published since 2010, based on a

comprehensive search in Web of Science. We present an overview and synthesize results for different spatial scales and units of observation, from individual to global and for the four dimensions of food security: availability, access, stability and utilisation. Eighty-eight of the 924 surveyed publications meet the inclusion criteria and report the direction and magnitude of 314 individual diversity-food security relationships. In almost two thirds of all cases, agricultural diversity had a positive effect on food security. In about one third of the relationships there was no effect of agricultural diversity on food security, or the results were mixed. These numbers hold for the availability, access and utilisation dimensions of food security and at individual, household and farm scales, but the number of studies was too small to draw robust conclusions on the stability dimension and at global scale. Diversity can be an important driver of food security, but the magnitude of the contribution depends on the broader socio-economic and biophysical characteristics of the local farming system. We conclude that diversification can be a potential strategy to improve food and nutrition security. Yet, it is not a necessary characteristic of all agricultural systems at all costs especially in the presence of other strategies that can potentially achieve similar outcomes. We make several recommendations to strengthen future studies that can help identify how strongly related agricultural diversity and food security are.

54 **Table of Contents**

55	Abstract.....	1
56	1. Introduction .....	4
57	2. Search criteria and methods .....	5
58	3. Indicators of agricultural diversity and food security .....	6
59	4. Previous reviews and meta-analysis .....	10
60	5. Diversity and food availability .....	13
61	6. Diversity and stability of food security .....	19
62	7. Diversity and food access.....	21
63	8. Diversity and food utilisation .....	34
64	9. Diversity and food security at the global scale .....	43
65	10. Synthesis and Recommendations .....	44
66	References .....	48

67

68

## 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 any natural or human-made system (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. Firstly, in sustainable intensification (Foley et al., 2011; Tilman et al., 2011), ecological intensification (Bommarco et al., 2013; Cassman, 1999), conservation agriculture (FAO, 2002) and more recently regenerative agriculture (Schreefel et al., 2020). For example, mixed farming and crop rotations can support pest, nutrient and water management (Gaba et al., 2015), reduce external inputs and improve soil biodiversity. Secondly, in 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 and of potential income sources (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 large variety of food types that are nutritionally similar for own consumption 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 (Govere 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

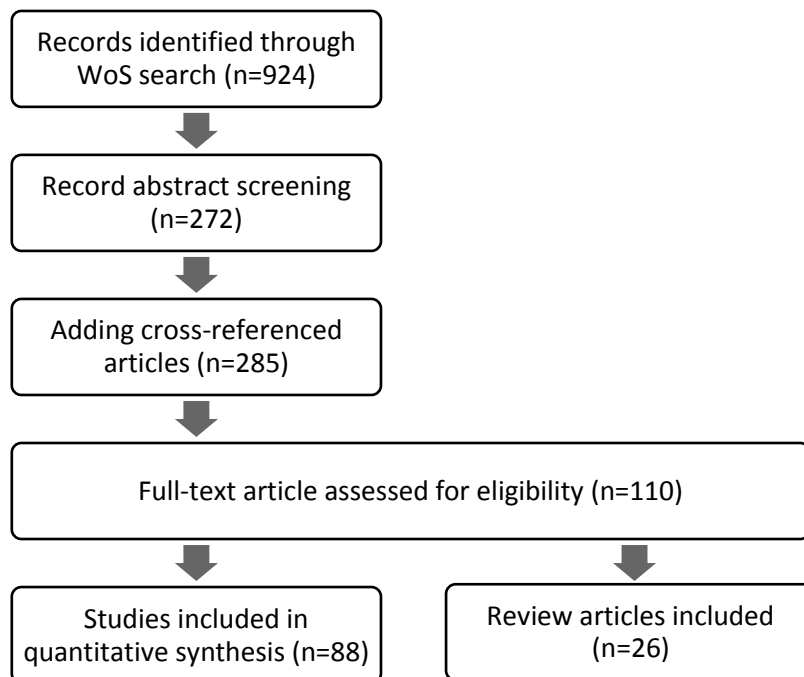
review also explores the interactions at different spatial scales. While many measures of food security relate to individuals, such as meeting dietary energy needs, the challenge to secure healthy and diverse diets is also global in its extent and in that scale often analysed with respect to food availability and stability. A final section provides a synthesis 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 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 25 February 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., 2017, 2016). 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 (Figure 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.



**Figure 1** Publication selection process used in this review.

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.

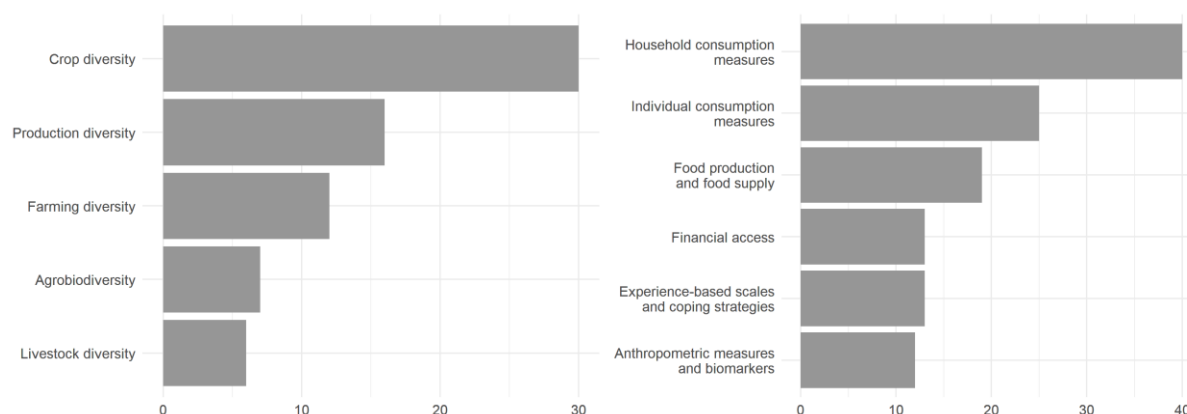
### 3. Indicators of agricultural diversity and food security

#### 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 richness. 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 (Birtal et al., 2015; Boedeker 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.



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

### 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 utilization 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.

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

Availability	Access	Utilization	Stability
<i>Food production and food supply</i>  Crop yield, livestock production, household food supply adequacy, crop production, productivity	<i>Financial access and affordability</i>  Income from agriculture, wealth, poverty status of a household	<i>Individual consumption measures</i>  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)	Crop yield skewness, temporal yield variability, spatial yield variability
	<i>Household consumption measures</i>  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	<i>Anthropometric measures and biomarkers</i>  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)	
<i>Experience-based scales and index scores</i>  Household Food Insecurity Access Scale (HFIAS), Household Hunger Scale (HHS), Coping Strategies Index (CSI), Months of Adequate Household Food Provisioning (MAHFP)			

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 and 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 hours (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 micronutrient intake which weakens any potential association with micronutrient adequacy and diet quality.

Food utilization 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 utilization (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 time aspect of the other three dimensions. Stability has several meanings and is often related to the concepts of resilience, robustness, resistance, vulnerability, and 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*
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 & Chavas 2009 (Ethiopia), Smale et al. 1998 (Pakistan), Widawsky & 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
* 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.		

371

## 372 5. Diversity and food availability

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

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

394 All three conservation agriculture studies included here found a positive effect of crop diversity on  
395 crop yield in India and Bangladesh (Ladha et al., 2016; Pradhan et al., 2018; Samal et al., 2017). In  
396 the context of agroforestry systems, we find four publications for rubber, cocoa and coffee  
397 cultivation (Hondrade et al., 2017; Jessy et al., 2017; Schneider et al., 2017; Souza et al., 2010). The  
398 results are mixed and depend on the year of the experiment, resource competition between crops,  
399 the amount of mutual benefits created by the crop mix and the method for measuring benefits. For  
400 example, the results from a 13- year experiment comparing three agroforestry systems with  
401 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. Dzanku and Sarpong (2013) 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 increasing until diversity levels reach seven species per hectare cropland, and then decreasing beyond this level.

425 **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*
<i>Cropping system, farm or household scale</i>						
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 ( $\beta=0.812$ )
					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.,	Bangladesh	2 seasons, 4	Field experiment	Crop diversity (SC) - four crops	Crop yield	Positive (d =



Reference	Country	Sample size	Method	Indicator of diversity	Indicator of food availability	Description of relationship*
2018		crops in 2 crop patterns		intercropping compared to three crops intercropping maize/rice systems		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 ( $\beta=1.181$ )
					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

Reference	Country	Sample size	Method	Indicator of diversity	Indicator of food availability	Description of relationship*
						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 compared to cocoa monoculture	Crop yield (all marketable crops)	Positive (d = 7,471 kg/ha)
					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 %)
<i><u>Landscape to national scale</u></i>						
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,	28,361 hh	Kruskal-Wallis test for difference in	Farming diversity (C)	Household food supply adequacy (supply / required)	Positive (d = 1.2)

Reference	Country	Sample size	Method	Indicator of diversity	Indicator of food availability	Description of relationship*
	Kenya, Burkina Faso, Ghana, Mali, Malawi, Rwanda, Zambia, Senegal, Mozambique, DR Congo, Congo, Nigeria, Zimbabwe		medians			
<p>* 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.</p> <p>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 &gt; 0.05); <math>\beta</math> = regression coefficient; ATT = adoption effect</p>						

## 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).

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 19<sup>th</sup> 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.

**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*
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

\* 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.

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

## 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 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 than 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.

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
<i>Village to regional scale</i>						
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 ( $\beta=0.0423-0.1187$ )
				Farming diversity (C, BI, RE)	Share of expenditure of food item in the total food budget (RE)	Positive ( $\beta=0.0541-0.2354$ )
KC et al., 2016	Nepal	1,466 hh	Probit model	Crop diversity (C)	More than or less/equal 12 mths food sufficiency	Positive ( $\beta=0.0525$ )
				Livestock diversity (C)	More than or less/equal 12 mths food sufficiency	Positive ( $\beta=0.0910$ )
Brüssow et al., 2017	Tanzania	900 farms	Propensity Score (nearest neighbour) matching	Crop diversity (C)	FCS	Positive (ATT=3.51)
					Household per capita protein intake	Positive (ATT=103.3g)
					MAHFP	Negative (ATT= -1.48)
					CSI	Neutral (ns)
					Household per capita energy intake	Neutral (ns)
					Household net income from crop production	Neutral (ns)
De Jager et al., 2018	Ghana	329 hh	Poisson regression model	Crop diversity (C)	Household self-sufficiency (no. food groups)	Positive ( $\beta=0.1$ )
				Crop diversity (H')		Positive ( $\beta=0.7$ )
			Linear mixed model	Crop diversity (C)	Household self-sufficiency (quantity)	Positive ( $\beta=6.2-6.4$ )
				Crop diversity (H')		Positive ( $\beta=23.4-26.4$ )



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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
					nutrients)	
Jones, 2017b	Malawi	2,526 hh	Generalized estimating equations	Crop diversity (C)	HDDS	Positive ( $\beta = 0.08-0.13$ )
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 ( $\beta = 0.022-0.030$ )
Koppmair et al., 2017	Malawi	408 hh	Simple linear regression	Production diversity (C)	HDDS	Positive ( $\beta = 0.124$ )
			Linear regression with Poisson estimator	Crop diversity (C)	HDDS	Neutral (ns)
Kumar et al., 2015	Zambia	3,340 hh	Ordered logit model	Production diversity (C)	M-HDDS	Positive ( $\beta = 0.387$ )
				Crop diversity (C)	M-HDDS	Positive ( $\beta = 0.250$ )
				Farming diversity (C)	M-HDDS	Positive ( $\beta = 0.451$ )
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)		Neutral (ns)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
				– integrated vegetable system compared to non-integrated system		
M’Kaibi et al., 2017	Kenya	525 hh	Spearman rank correlation, ANOVA	Agricultural biodiversity (C)	HDDS	Positive (F = 14.791)
					HFIAS	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	Positive (β=3.498)
					FSC	Positive (β=0.638)
			Probit regression model		HDDS	Positive (β=3.545)
					HFIAS (Binary)	Neutral (ns)
Murendo et al., 2018	Zimbabwe	2,815 hh	Multiple linear regression	Farming diversity (C)	M-HDDS	Positive (IRR=1.03)
				Crop diversity (C)	M-HDDS	Positive (IRR=1.04)
				Livestock diversity (C)	M-HDDS	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)	HDDS	Neutral (ns)
				Farming diversity (H’)		Neutral (ns)
				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.,	Kenya	30 hh	Pearson correlation	Agrobiodiversity (C)	HHS	Neutral (ns)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
2015				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)
	Tanzania	402 hh			Income from agriculture	Negative (β=-0.838)
					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)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
				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)
					Household per capita	Neutral (ns)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
					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 ( $\beta$ =1.47)
					HDDS	Positive ( $\beta$ =0.29)
Valencia et al., 2019	Brazil	75 farmers	Correlation analysis	Farming diversity (C)	HDDS	Positive (r <sup>2</sup> =0.06)
Vanek et al., 2016	Bolivia	297 hh	Stepwise multiple linear regression	Crop diversity (C)	HFIAS	Positive ( $\beta$ = -0.584)
					HDDS	Neutral (ns)
Whitney et al.,	Uganda	102 hh	Projection to Latent	Agrobiodiversity (H')	HDDS	Neutral (uncorrelated)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship *
2018			Structures (PLS) regression analysis	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)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
<i>National scale</i>						
Asfaw et al., 2018	Niger	3,344 hh	Quantile regression	Crop diversity (C)	Household per capita energy intake	Positive ( $\beta=0.0209-0.0337$ )
				Crop diversity (BP)	Household per capita energy intake	Positive ( $\beta=0.0504-0.0263$ )
				Crop diversity (H')	Household per capita energy intake	Positive ( $\beta=0.0604-0.0249$ )
Ayenew et al., 2018	Nigeria	6,089 hh	Fixed effect model (FE), Random effect model (RE)	Farming diversity (C)	M-HDDS	Positive ( $\beta=0.016$ 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 ( $\beta= -0.0691 - 0.0282$ )
Das and Ganesh-Kumar, 2018	India	26,951 hh	Multivariate regression	Crop diversity (C)	Income from agriculture	Positive ( $\beta=0.290-0.293$ ); Negative for squared counts ( $\beta=-0.07$ )
				Livestock diversity (C)	Income from agriculture	Positive ( $\beta=1.232$ ); Negative for squared counts ( $\beta=-0.27$ )
Dillon et al., 2015	Nigeria	~5,000 hh	Ordinary least squares (OLS) regression and Instrumental variables (IV) regression	Crop diversity (C)	M-HDDS	Positive ( $\beta=0.037$ for OLS and $\beta=0.24$ for IV)
Ecker, 2018	Ghana	11,217 hh	Fixed effect model	Crop diversity (C)	M-HDDS	Mixed: Positive ( $\beta=0.111-0.178$ for all hh, $\beta=0.148$ for non-poor hh); Neutral (ns) for poor hh
				Crop diversity (SID)		Mixed: Positive ( $\beta=0.309-0.551$ for all hh, $\beta=0.396$ for non-poor)

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship *
						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 ( $\beta=0.019$ )
Jones et al., 2014	Malawi	6,623 hh	Multiple linear regression	Crop diversity (C)	M-HDDS	Positive ( $\beta=0.23$ )
					FSC	Positive ( $\beta=0.81$ )
				Crop diversity (SID)	M-HDDS	Positive ( $\beta=0.68$ )
					FSC	Neutral (ns)
				Farming diversity (C)	M-HDDS	Positive ( $\beta=0.20$ )
					FSC	Positive ( $\beta=0.71$ )
Mofya-Mukuka and Hichaambwa, 2018	Zambia	14,212 hh	Poisson regression and Ordinary least squares regression	Crop diversity (SID)	Farm income	Positive ( $\beta=0.9142$ )
					FSC	Positive ( $\beta=0.646-0.702$ )
					MAHFP	Positive ( $\beta=0.727-0.741$ )
			Poisson regression		HDDS	Positive ( $\beta=0.284$ )
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 ( $\beta=9.918$ )
Sibhatu et al., 2015a	Indonesia, Kenya, Ethiopia, Malawi	8,230 hh	Multivariate regression with Poisson estimator	Farming diversity (C)	M-HDDS	Positive ( $\beta=0.009$ )
	Ethiopia	2,045 hh				Neutral (ns)
	Malawi	5,114 hh				Positive ( $\beta=0.015$ ); Negative ( $\beta=-3.2e-04$ ) 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( $\beta=-0.189$ )
				Crop diversity (C) – non-	M-HDDS	Positive (IRR=1.019)



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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
				maize crops	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 – -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)
£ 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						

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of access <sup>§</sup>	Description of relationship <sup>*</sup>
<p>§ 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.</p> <p>* ATT = average treatment effect, ns = not significant (p-value &gt; 0.05); <math>\beta</math> = 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.</p>						

## 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 factors 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 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

604 farm production whereas other strategies such as improved market access to purchase  
605 complementary foods may benefit younger children (Mulmi et al., 2017).

606 Positive associations between agricultural diversity and MDD-W or WDDS were found in seven  
607 studies (Adubra et al., 2019; Bellon et al., 2016; Bellows et al., 2020; Boedecker et al., 2014; Jones et  
608 al., 2018; Murendo et al., 2018; Whitney et al., 2018). For MDD-W the regression coefficients are  
609 0.036-0.23 with odds ratios of 1.08-1.38. For WDDS the regression coefficients are smaller, 0.10 in a  
610 logistic regression and odds ratio of 1.03-1.05 in a multiple linear regression. In Mali, Adubra et al.  
611 (2019) evaluate the impact of a 3 years nutrition-sensitive intervention targeting women and their  
612 children during the first 1000 days of each child's life. In a large sample with more than 5,000  
613 women they found a positive relationship between production diversity and MDD-W and WDDS,  
614 regardless of household's overall food security and wealth status. Specifically, one more food crop or  
615 livestock group on the farm resulted in a 10% increase in WDDS-10 and a better chance of attaining  
616 the minimally needed MDD-W score. In contrast, Gitagia et al. (2019) find no relationship between  
617 agrobiodiversity and the quality of women's diets in central Kenya but an important relationship  
618 between education and diet quality.

619 Four studies used household data from nationally representative surveys for single country or multi-  
620 country studies (Hirvonen and Hoddinott, 2017; Islam et al., 2018; Lovo and Veronesi, 2019; Tobin et  
621 al., 2019) (Table 6). The association between agricultural diversity and food utilization was mostly  
622 positive irrespective of the food utilization and diversity indicator, except for some associations  
623 presented in Tobin et al. 2019. In this study, the authors find a positive association between the  
624 Simpson diversity index and HAZ but a small negative association between crop species richness and  
625 HAZ. This indicates that crop diversity has a benefit only if proportional presence is considered in  
626 addition to total number of species (Tobin et al., 2019). HAZ increased by 0.26-0.30 with each one-  
627 unit increase in the Simpson diversity index but decreased by 0.015 with each one-unit increase in  
628 crop richness.

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

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
<i>Village to regional scale</i>						
Adubra et al., 2019	Mali	4,790 hh, 5,046 mother-child pairs	Logistic regression, simple linear regression	Production diversity (C)	MDD-W	Positive (OR = 1.12)
					WDDS-10	Positive ( $\beta=0.10$ )
Azupogo et al., 2019	Ghana	642 children aged 6-17 years	Multiple linear regression	Farming diversity (C)	Haemoglobin concentration (6-9 yrs)	Positive ( $\beta=0.59$ )
					Haemoglobin concentration (6-17 yrs)	Neutral (ns)
Bellon et al., 2016	Benin	880 hh	Generalized method of moments for parameter estimation	Agrobiodiversity (C)	MDD-W	Positive ( $\beta=0.036$ )
Boedecker et al., 2014	Benin	120 women	ANOVA	Agrobiodiversity (Binary)	WDDS	Positive (d=0.6)
					Individual's nutrient consumption	Neutral (ns)
De Jager et al., 2018	Ghana	329 hh	Linear mixed model, quasi-binomial regression	Crop diversity (C)	IYCDDS	Neutral (ns)
					MPA	Neutral (ns)
				Crop diversity (H')	IYCDDS	Neutral (ns)
					MPA	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)	Positive (DID=0.44)
					Prevalence of stunting (6-24 mths)	Negative (DID=-17%)
					10 other relationships with HAZ, WHZ, WAZ, prevalence of stunting, prevalence of wasting, prevalence of underweight	Neutral (ns)

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
				Production diversity (C)	Food quantity intake	Positive (DID=153 g)
					Energy intake	Positive (DID=294 kcal)
					Protein intake	Positive (DID=8.12 g)
					Iron intake	Positive (DID=1.64 mg)
					Zinc intake	Positive (DID=1.09 mg)
					VitB12 intake	Positive (DID=0.21 µg)
					VitB6 intake	Positive (DID=0.26 mg)
					IDDS (children)	Positive (DID=0.36)
					VitA intake	Neutral (ns)
Gitagia et al., 2019	Kenya	384 women	Logistic regression model	Crop diversity (C)	MDD-W	Neutral (ns)
				Crop diversity (H')		Neutral (ns)
				Production diversity (C)		Neutral (ns)
Jones, 2015	Bolivia	331 hh with children aged 0-23 mths	Multivariate regression	Crop diversity (C)	IFCI	Positive ( $\beta$ =0.25-0.46) for high elevation
				Livestock diversity (C)		Positive ( $\beta$ =0.02-0.03)
Jones et al., 2018	Peru	600 hh	Poisson regression	Crop diversity (C)	WDDS-10	Positive (IRR=1.03)
			Logistic regression		MDD-W	Positive (OR=1.17)
			Poisson regression		DSR	Neutral (ns)
			Ordinary least squares regression		MPA	Mixed; Positive (OR=1.21 for MPA > 60%), Neutral (ns) for all MPA
			Poisson regression	Farming diversity (C)	WDDS-10	Neutral (ns)
			Logistic regression		MDD-W	Positive (OR=1.08)
			Poisson regression		DSR	Neutral (ns)
			Ordinary least squares regression		MPA	Mixed; Positive (OR=1.16= for MPA > 60%, Neutral (ns) for all MPA
Koppmair et al., 2017	Malawi	408 hh, 519 children	Simple linear regression	Production diversity (C)	IDDS (children)	Positive ( $\beta$ =0.168)
					IDDS (mother)	Positive ( $\beta$ =0.144)

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
		aged 6 mths to 5 yrs	Linear regression with Poisson estimator	Crop diversity (C)	IDDS (children)	Positive ( $\beta=0.073$ )
					IDDS (mother)	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 ( $\beta=-0.011$ )
				Production diversity (C)	Prevalence of stunting (24-59 mths)	Negative ( $\beta=-0.015$ )
				Crop diversity (C)	Prevalence of wasting (6-23 mths)	Negative ( $\beta=-0.010$ )
				Farming diversity (C)	Prevalence of stunting (24-59 mths)	Negative ( $\beta=-0.022$ )
			Ordinary least squares regression	Crop diversity (C)	HAZ (6-23 mths)	Negative ( $\beta=-0.083$ )
				Farming diversity (C)	HAZ (6-23 mths)	Negative ( $\beta=-0.097$ )
				Farming diversity (C)	HAZ (24-59 mths)	Positive ( $\beta=0.084$ )
			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 ( $\beta=0.263$ )
					MDD-C	Positive ( $\beta=0.067$ )
				Crop diversity (C)	IDDS (children)	Positive ( $\beta=0.217$ )
					MDD-C	Positive ( $\beta=0.053$ )
				Farming diversity (C)	IDDS (children)	Positive ( $\beta=0.294$ )
					MDD-C	Positive ( $\beta=0.075$ )
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 ( $r^2=0.26$ )
					IDDS (children)	Positive ( $r^2=0.39$ )
				Crop diversity (NFD)	IYCDDS	Neutral (ns)
					IDDS (children)	Positive ( $r^2=0.32$ )

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
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 ( $\beta$ =0.033)
					WHZ	Positive ( $\beta$ =0.034)
					Maternal BMI, HAZ	Neutral (ns)
					IDDS (children)	Positive ( $\beta$ =0.058-0.059)
					IDDS (mother)	Positive ( $\beta$ =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 ( $\beta$ =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 ( $\beta$ =0.43)
					MDD-C, 6-23 mths	Neutral (ns)
					MDD-C, 25-59 mths	Positive ( $\beta$ =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)
				Crop diversity (C)	IDDS (children)	Neutral (ns)
					WDDS	Positive (IRR=1.05)
					IDDS (children)	Neutral (ns)
				Livestock diversity (C)	WDDS	Positive (IRR=1.03)
					IDDS (children)	Positive (IRR=1.04)



Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
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 ( $\beta=-0.041$ ) 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 ( $\beta=0.09-0.10$ , $\rho=0.12$ )
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 $\mu$ g RE)
					VitC intake	Positive (d = 28.7mg)
					VitB6 intake	Positive (d = 0.45mg)
					Calcium intake	Positive (d = 141.3 mg)
					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 ( $\beta=0.102$ )
					ICFI	Neutral (ns)

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
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)
<i><u>National scale</u></i>						
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)

Reference	Country	Sample size	Method	Indicator of diversity <sup>£</sup>	Indicator of utilization <sup>§</sup>	Description of relationship <sup>*</sup>
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 ( $\beta=0.260-0.2921$ )
				Crop diversity (C)	HAZ	Negative ( $\beta=-0.015$ )
			Poisson regression	Crop diversity (SID)	IDDS (children)	Mixed: Positive ( $\beta=9.061-0.139$ ) for SID; Neutral for high-protein crops
				Crop diversity (C)		Neutral (ns)

£ C = count; H' = Shannon diversity index, SID = Simpson diversity index,  $\beta$  = regression coefficient

§ 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, IYCDD = 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, WDD = Women's Dietary Diversity Score, WDD-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 IYCDD in the number of food groups used and/or the age group which is 6-23 months for IYCDD. MDD-C differs from IYCDD in that it measures the prevalence of children consuming at least four of the seven food groups included. IDDS (mother) differs from WDD in the number of food groups considered

\* CC = Canonical correlation coefficient,  $\beta$  = 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.

## 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 19<sup>th</sup>-c. to early 20<sup>th</sup>-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 ( $R^2 = 0.32 - 0.37$ ), 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 utilization are more common than for food availability, 34% and 22% respectively and for both dimensions agricultural diversity had a positive effect in about 55% to 65% of all cases. For food utilization, 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.

**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					

## **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 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, 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 frameworks. 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 a 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.

## Author contribution and acknowledgements

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.



## 175 References

- 176 Adubra, L., Savy, M., Fortin, S., Kameli, Y., Kodjo, N.E., Fainke, K., Mahamadou, T., Le Port, A., Martin-  
177 Prevel, Y., 2019. The Minimum Dietary Diversity for Women of Reproductive Age (MDD-W)  
178 Indicator Is Related to Household Food Insecurity and Farm Production Diversity: Evidence  
179 from Rural Mali. *Curr. Dev. Nutr.* 3, 1–9. <https://doi.org/10.1093/cdn/nzz002>
- 180 Aizen, M.A., Aguiar, S., Biesmeijer, J.C., Garibaldi, L.A., Inouye, D.W., Jung, C., Martins, D.J., Medel,  
181 R., Morales, C.L., Ngo, H., Pauw, A., Paxton, R.J., Sáez, A., Seymour, C.L., 2019. Global  
182 agricultural productivity is threatened by increasing pollinator dependence without a parallel  
183 increase in crop diversification. *Glob. Chang. Biol.* 25, 3516–3527.  
184 <https://doi.org/10.1111/gcb.14736>
- 185 Akerele, D., Shittu, A.M., 2017. Can food production diversity influence farm households' dietary  
186 diversity? An appraisal from two-dimensional food diversity measures. *Int. J. Soc. Econ.* 44,  
187 1597–1608. <https://doi.org/10.1108/IJSE-03-2016-0080>
- 188 Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate  
189 change-resilient farming systems. *Agron. Sustain. Dev.* 35, 869–890.  
190 <https://doi.org/10.1007/s13593-015-0285-2>
- 191 Ampaw, S., Nketiah-Amponsah, E., Senadza, B., 2017. Urban Farm-Nonfarm Diversification,  
192 Household Income and Food Expenditure in Ghana. *Stud. Bus. Econ.* 12, 6–19.  
193 <https://doi.org/10.1515/sbe-2017-0017>
- 194 Antwi-Agyei, P., Stringer, L.C., Dougill, A.J., 2014a. Livelihood adaptations to climate variability:  
195 insights from farming households in Ghana. *Reg. Environ. Chang.* 14, 1615–1626.  
196 <https://doi.org/10.1007/s10113-014-0597-9>
- 197 Antwi-Agyei, P., Stringer, L.C., Dougill, A.J., 2014b. Livelihood adaptations to climate variability:  
198 insights from farming households in Ghana. *Reg. Environ. Chang.* 14, 1615–1626.  
199 <https://doi.org/10.1007/s10113-014-0597-9>
- 200 Asfaw, S., Pallante, G., Palma, A., 2018. Diversification Strategies and Adaptation Deficit: Evidence  
201 from Rural Communities in Niger. *World Dev.* 101, 219–234.  
202 <https://doi.org/10.1016/j.worlddev.2017.09.004>
- 203 Ayenew, H.Y., Biadgilign, S., Schickramm, L., Abate-Kassa, G., Sauer, J., 2018. Production  
204 diversification, dietary diversity and consumption seasonality: Panel data evidence from  
205 Nigeria. *BMC Public Health* 18, 1–9. <https://doi.org/10.1186/s12889-018-5887-6>
- 206 Azupogo, F., Aurino, E., Gelli, A., Bosompem, K.M., Ayi, I., Osendarp, S.J.M., Brouwer, I.D., Folsom, G.,  
207 2019. Agro-ecological zone and farm diversity are factors associated with haemoglobin and  
208 anaemia among rural school-aged children and adolescents in Ghana. *Matern. Child Nutr.* 15,  
209 1–11. <https://doi.org/10.1111/mcn.12643>
- 210 Barrett, C.B., Reardon, T., Webb, P., 2001. Nonfarm income diversification and household livelihood  
211 strategies in rural Africa : concepts , dynamics , and policy implications. *Food Policy* 26, 315–  
212 331.
- 213 Bellon, M.R., Kotu, B.H., Azzarri, C., Caracciolo, F., 2020. To diversify or not to diversify, that is the  
214 question. Pursuing agricultural development for smallholder farmers in marginal areas of  
215 Ghana. *World Dev.* 125, 104682. <https://doi.org/10.1016/j.worlddev.2019.104682>
- 216 Bellon, M.R., Ntandou-Bouzitou, G.D., Caracciolo, F., 2016. On-Farm Diversity and Market  
217 Participation Are Positively Associated with Dietary Diversity of Rural Mothers in Southern

218 Benin, West Africa. PLoS One 11, e0162535. <https://doi.org/10.1371/journal.pone.0162535>

219 Bellows, A.L., Canavan, C.R., Blakstad, M.M., Mosha, D., Noor, R.A., Webb, P., Kinabo, J., Masanja, H.,  
 220 Fawzi, W.W., 2020. The Relationship Between Dietary Diversity Among Women of  
 221 Reproductive Age and Agricultural Diversity in Rural Tanzania. Food Nutr. Bull. 41, 50–60.  
 222 <https://doi.org/10.1177/0379572119892405>

223 Bendahan, A.B., Pocard-Chapuis, R., De Medeiros, R.D., De Lucena Costa, N., Tourrand, J.F., 2018.  
 224 Management and labour in an integrated crop-livestock-forestry system in Roraima, Brazilian  
 225 Amazonia. Cah. Agric. 27. <https://doi.org/10.1051/cagri/2018014>

226 Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L.,  
 227 Msachi, R., Boateng, G.O., Snapp, S.S., Chitaya, A., Maona, E., Gondwe, T., Nkhonjera, P.,  
 228 Luginaah, I., 2019. Participatory agroecological research on climate change adaptation  
 229 improves smallholder farmer household food security and dietary diversity in Malawi. Agric.  
 230 Ecosyst. Environ. 279, 109–121. <https://doi.org/10.1016/j.agee.2019.04.004>

231 Birthal, P.S., Roy, D., Negi, D.S., 2015. Assessing the impact of crop diversification on farm poverty in  
 232 India. World Dev. 72, 70–92. <https://doi.org/10.1016/j.worlddev.2015.02.015>

233 Boedecker, J., Termote, C., Assogbadjo, A.E., Van Damme, P., Lachat, C., 2014. Dietary contribution  
 234 of Wild Edible Plants to women’s diets in the buffer zone around the Lama forest, Benin – an  
 235 underutilized potential. Food Secur. 6, 833–849. <https://doi.org/10.1007/s12571-014-0396-7>

236 Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: Harnessing ecosystem services  
 237 for food security. Trends Ecol. Evol. 28, 230–238. <https://doi.org/10.1016/j.tree.2012.10.012>

238 Brüssow, K., Faße, A., Grote, U., 2017. Implications of climate-smart strategy adoption by farm  
 239 households for food security in Tanzania. Food Secur. 9, 1203–1218.  
 240 <https://doi.org/10.1007/s12571-017-0694-y>

241 Bullock, J.M., Dhanjal-Adams, K.L., Milne, A., Oliver, T.H., Todman, L.C., Whitmore, A.P., Pywell, R.F.,  
 242 2017. Resilience and food security: rethinking an ecological concept. J. Ecol. 105, 880–884.  
 243 <https://doi.org/10.1111/1365-2745.12791>

244 Cassman, K.G., 1999. Ecological intensification of cereal production systems: Yield potential, soil  
 245 quality, and precision agriculture. Proc. Natl. Acad. Sci. U. S. A. 96, 5952–5959.  
 246 <https://doi.org/10.1073/pnas.96.11.5952>

247 Chambers, R., Conway, G.R., 1992. Sustainable rural livelihoods: practical concepts for the 21st  
 248 century. IDS Discuss. Pap. 296.

249 Chengappa, P.G., Devika, C.M., Rudragouda, C.S., 2017. Climate variability and mitigation:  
 250 perceptions and strategies adopted by traditional coffee growers in India. Clim. Dev. 9, 593–  
 251 604. <https://doi.org/10.1080/17565529.2017.1318740>

252 Chimonyo, V.G.P., Snapp, S.S., Chikowo, R., 2019. Grain Legumes Increase Yield Stability in Maize  
 253 Based Cropping Systems. Crop Sci. 59, 1222–1235.  
 254 <https://doi.org/10.2135/cropsci2018.09.0532>

255 Coates, J., 2013. Build it back better: Deconstructing food security for improved measurement and  
 256 action. Glob. Food Sec. 2, 188–194. <https://doi.org/10.1016/j.gfs.2013.05.002>

257 Dardonville, M., Urruty, N., Bockstaller, C., Therond, O., 2020. Influence of diversity and  
 258 intensification level on vulnerability, resilience and robustness of agricultural systems. Agric.  
 259 Syst. 184. <https://doi.org/10.1016/j.agsy.2020.102913>

260 Das, V.K., Ganesh-Kumar, A., 2018. Farm size, livelihood diversification and farmer ’ s income in

261 India. *DECISION* 45, 185–201. <https://doi.org/10.1007/s40622-018-0177-9>

262 De Jager, I., Giller, K.E., Brouwer, I.D., 2018. Food and nutrient gaps in rural Northern Ghana: Does  
263 production of smallholder farming households support adoption of food-based dietary  
264 guidelines? *PLoS One* 13, 1–26. <https://doi.org/10.1371/journal.pone.0204014>

265 Delaquis, E., de Haan, S., Wyckhuys, K.A.G., 2018. On-farm diversity offsets environmental pressures  
266 in tropical agro-ecosystems: A synthetic review for cassava-based systems. *Agric. Ecosyst.*  
267 *Environ.* 251, 226–235. <https://doi.org/10.1016/j.agee.2017.09.037>

268 Di Falco, S., 2012. On the Value of Agricultural Biodiversity. *Annu. Rev. Resour. Econ.* 4, 207–223.  
269 <https://doi.org/10.1146/annurev-resource-110811-114543>

270 Dillon, A., McGee, K., Oseni, G., 2015. Agricultural Production, Dietary Diversity and Climate  
271 Variability. *J. Dev. Stud.* 51, 976–995. <https://doi.org/10.1080/00220388.2015.1018902>

272 Doak, D.F., Bigger, D., Harding, E.K., Marvier, M.A., O'Malley, R.E., Thomson, D., 1998. The Statistical  
273 Inevitability of Stability-Diversity Relationships in Community Ecology. *Am. Nat.* 151, 264–276.  
274 <https://doi.org/10.1086/286117>

275 Douxchamps, S., Van Wijk, M.T., Silvestri, S., Moussa, A.S., Quiros, C., Ndour, N.Y.B., Buah, S., Somé,  
276 L., Herrero, M., Kristjanson, P., Ouedraogo, M., Thornton, P.K., Van Asten, P., Zougmore, R.,  
277 Rufino, M.C., 2016. Linking agricultural adaptation strategies, food security and vulnerability:  
278 evidence from West Africa. *Reg. Environ. Chang.* 16, 1305–1317.  
279 <https://doi.org/10.1007/s10113-015-0838-6>

280 Droppelmann, K.J., Snapp, S.S., Waddington, S.R., 2017. Sustainable intensification options for  
281 smallholder maize-based farming systems in sub-Saharan Africa. *Food Secur.* 9, 133–150.  
282 <https://doi.org/10.1007/s12571-016-0636-0>

283 Dzanku, F.M., Sarpong, D.B., 2011. Agricultural diversification , food self-sufficiency and food  
284 security in Ghana : The role of infrastructure and institutions, in: Djurfeldt, G., Aryeetey, E.,  
285 Isinika, A.C. (Eds.), *African Smallholders: Food Crops, Markets and Policy*. CAB International,  
286 Wallingford, UK, pp. 189–213.

287 Ecker, O., 2018. Agricultural transformation and food and nutrition security in Ghana: Does farm  
288 production diversity (still) matter for household dietary diversity? *Food Policy* 79, 271–282.  
289 <https://doi.org/10.1016/j.foodpol.2018.08.002>

290 Ellis, F., 1998. Household strategies and rural livelihood diversification. *J. Dev. Stud.* 35, 1–38.  
291 <https://doi.org/10.1080/00220389808422553>

292 Eludoyin, A.O., Nevo, A.O., Abuloye, P.A., Eludoyin, O.M., Awotoye, O.O., 2017. Climate events and  
293 impact on cropping activities of small-scale farmers in a part of Southwest Nigeria. *Weather.*  
294 *Clim. Soc.* 9, 235–253. <https://doi.org/10.1175/WCAS-D-16-0032.1>

295 Fadina, A.M.R., Barjolle, D., 2018. Farmers' Adaptation Strategies to Climate Change and Their  
296 Implications in the Zou Department of South Benin. *Environments* 5, 15.  
297 <https://doi.org/10.3390/environments5010015>

298 FAO, 2019. Food security indicators [WWW Document]. URL <http://www.fao.org/economic/ess/ess-fs/ess-fadata>

300 FAO, 2013. Guidelines for measuring household and individual dietary diversity, Fao.  
301 <https://doi.org/613.2KEN>

302 FAO, 2002. Conservation agriculture. Case studies in Latin America and Africa.

303 Foley, J. a, Ramankutty, N., Brauman, K. a, Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D.,  
304 O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda,  
305 C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions  
306 for a cultivated planet. *Nature* 478, 337–42. <https://doi.org/10.1038/nature10452>

307 Fraval, S., Hammond, J., Bogard, J.R., Ng'endo, M., van Etten, J., Herrero, M., Oosting, S.J., de Boer,  
308 I.J.M., Lannerstad, M., Teufel, N., Lamanna, C., Rosenstock, T.S., Pagella, T., Vanlauwe, B.,  
309 Dontsop-NGuezet, P.M., Baines, D., Carpena, P., Njingulula, P., Okafor, C., Wichern, J.,  
310 Ayantunde, A., Bosire, C., Chesterman, S., Kihoro, E., Rao, E.J.O., Skirrow, T., Steinke, J., Stirling,  
311 C.M., Yameogo, V., van Wijk, M.T., 2019. Food Access Deficiencies in Sub-saharan Africa:  
312 Prevalence and Implications for Agricultural Interventions. *Front. Sustain. Food Syst.* 3.  
313 <https://doi.org/10.3389/fsufs.2019.00104>

314 Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douchamps, S., Djurfeldt, A.A., Erenstein, O.,  
315 Henderson, B., Kassie, M., Paul, B.K., Rigolot, C., Ritzema, R.S., Rodriguez, D., van Asten, P.J. a,  
316 van Wijk, M.T., 2016. Drivers of household food availability in sub-Saharan Africa based on big  
317 data from small farms. *Proc. Natl. Acad. Sci. U. S. A.* 113, 458–463.  
318 <https://doi.org/10.1073/pnas.1518384112>

319 Frison, E.A., Cherfas, J., Hodgkin, T., 2011. Agricultural Biodiversity Is Essential for a Sustainable  
320 Improvement in Food and Nutrition Security. *Sustainability* 3, 238–253.  
321 <https://doi.org/10.3390/su3010238>

322 Gaba, S., Lescourret, F., Boudsocq, S., Enjalbert, J., Hinsinger, P., Journet, E.P., Navas, M.L., Wery, J.,  
323 Louarn, G., Malézieux, E., Pelzer, E., Prudent, M., Ozier-Lafontaine, H., 2015. Multiple cropping  
324 systems as drivers for providing multiple ecosystem services: from concepts to design. *Agron.*  
325 *Sustain. Dev.* 35, 607–623. <https://doi.org/10.1007/s13593-014-0272-z>

326 Gelli, A., Margolies, A., Santacroce, M., Roschnik, N., Twalibu, A., Katundu, M., Moestue, H.,  
327 Alderman, H., Ruel, M., 2018. Using a Community-Based Early Childhood Development Center  
328 as a Platform to Promote Production and Consumption Diversity Increases Children's Dietary  
329 Intake and Reduces Stunting in Malawi: A Cluster-Randomized Trial. *J. Nutr.* 148, 1587–1597.  
330 <https://doi.org/10.1093/jn/nxy148>

331 Gillespie, S., Harris, J., Kadiyala, S., 2012. The Agriculture-Nutrition Disconnect in India What Do We  
332 Know? IFPRI Discuss. Pap. 1187 1–56.

333 Gitagia, M.W., Ramkat, R.C., Mituki, D.M., Termote, C., Covic, N., Cheserek, M.J., 2019. Determinants  
334 of dietary diversity among women of reproductive age in two different agro-ecological zones of  
335 rongai sub-county, nakuru, Kenya. *Food Nutr. Res.* 63, 1–12.  
336 <https://doi.org/10.29219/fnr.v63.1553>

337 Glamann, J., Hanspach, J., Abson, D.J., Collier, N., 2017. The intersection of food security and  
338 biodiversity conservation : a review. *Reg. Environ. Chang.* 17, 1303–1313.  
339 <https://doi.org/10.1007/s10113-015-0873-3>

340 Govereh, J., Jayne, T.S., 2003. Cash cropping and food crop productivity: Synergies or trade-offs?  
341 *Agric. Econ.* 28, 39–50. [https://doi.org/10.1016/S0169-5150\(02\)00066-X](https://doi.org/10.1016/S0169-5150(02)00066-X)

342 Hansen, J., Hellin, J., Rosenstock, T., Fisher, E., Cairns, J., Stirling, C., Lamanna, C., van Etten, J., Rose,  
343 A., Campbell, B., 2019. Climate risk management and rural poverty reduction. *Agric. Syst.* 172,  
344 28–46. <https://doi.org/10.1016/j.agsy.2018.01.019>

345 Herforth, A., Harris, J., 2014. Linking Agriculture and Nutrition: Understanding and Applying Primary  
346 Pathways and Principles. *Br. #1. Improv. Nutr. through Agric. Tech. Br. Ser.*

347 Hirvonen, K., Hoddinott, J., 2017. Agricultural production and children's diets: evidence from rural  
 348 Ethiopia. *Agric. Econ.* 48, 469–480. <https://doi.org/10.1111/agec.12348>

349 Hoddinott, J., Yohannes, Y., 2002. *Dietary Diversity as a Household Food Security Indicator*.  
 350 Washington D.C.

351 Hondrade, R.F., Hondrade, E., Zheng, L., Elazegui, F., Duque, J.A.L.J.E., Mundt, C.C., Vera Cruz, C.M.,  
 352 Garrett, K.A., 2017. Cropping system diversification for food production in Mindanao rubber  
 353 plantations: A rice cultivar mixture and rice intercropped with mungbean. *PeerJ* 2017, 1–20.  
 354 <https://doi.org/10.7717/peerj.2975>

355 Huluka, A.T., Wondimagegnhu, B.A., 2019. Determinants of household dietary diversity in the Yayo  
 356 biosphere reserve of Ethiopia: An empirical analysis using sustainable livelihood framework.  
 357 *Cogent Food Agric.* 5, 1–29. <https://doi.org/10.1080/23311932.2019.1690829>

358 Isaacs, K.B., Snapp, S.S., Kelly, J.D., Chung, K.R., 2016. Farmer knowledge identifies a competitive  
 359 bean ideotype for maize-bean intercrop systems in Rwanda. *Agric. Food Secur.* 5, 1–18.  
 360 <https://doi.org/10.1186/s40066-016-0062-8>

361 Islam, A.H.M.S., von Braun, J., Thorne-Lyman, A.L., Ahmed, A.U., 2018. Farm diversification and food  
 362 and nutrition security in Bangladesh: empirical evidence from nationally representative  
 363 household panel data. *Food Secur.* 10, 701–720. <https://doi.org/10.1007/s12571-018-0806-3>

364 Islam, M.A., Islam, M.J., Akkas Ali, M., Mahbubur Rahman Khan, A.S.M., Faruque Hossain, M.,  
 365 Moniruzzaman, M., 2018. Transforming Triple Cropping System to Four Crops Pattern : An  
 366 Approach of Enhancing System Productivity through Intensifying Land Use System in  
 367 Bangladesh. *Hindawi Int. J. Agron.* 2018, 1–7.

368 Jessy, M.D., Joseph, P., George, S., 2017. Possibilities of diverse rubber based agroforestry systems  
 369 for smallholdings in India. *Agrofor. Syst.* 91, 515–526. [https://doi.org/10.1007/s10457-016-](https://doi.org/10.1007/s10457-016-9953-8)  
 370 [9953-8](https://doi.org/10.1007/s10457-016-9953-8)

371 Jones, A.D., 2017a. Critical review of the emerging research evidence on agricultural biodiversity ,  
 372 diet diversity, and nutritional status in low- and middle-income countries. *Nutr. Rev.* 75, 769–  
 373 782. <https://doi.org/10.1093/nutrit/nux040>

374 Jones, A.D., 2017b. On-Farm Crop Species Richness Is Associated with Household Diet Diversity and  
 375 Quality in Subsistence- and Market-Oriented Farming Households in Malawi 1 – 3. *J. Nutr.*  
 376 <https://doi.org/10.3945/jn.116.235879.substituting>

377 Jones, A.D., 2015. The production diversity of subsistence farms in the Bolivian Andes is associated  
 378 with the quality of child feeding practices as measured by a validated summary feeding index.  
 379 *Public Health Nutr.* 18, 329–342. <https://doi.org/10.1017/S1368980014000123>

380 Jones, A.D., Creed-Kanashiro, H., Zimmerer, K.S., De Haan, S., Carrasco, M., Meza, K., Cruz-Garcia,  
 381 G.S., Tello, M., Plasencia Amaya, F., Marin, R.M., Ganoza, L., 2018. Farm-Level Agricultural  
 382 Biodiversity in the Peruvian Andes Is Associated with Greater Odds of Women Achieving a  
 383 Minimally Diverse and Micronutrient Adequate Diet. *J. Nutr.* 148, 1625–1637.  
 384 <https://doi.org/10.1093/jn/nxy166>

385 Jones, A.D., Shrinivas, A., Bezner-kerr, R., 2014. Farm production diversity is associated with greater  
 386 household dietary diversity in Malawi : Findings from nationally representative data. *J. FOOD*  
 387 *POLICY* 46, 1–12. <https://doi.org/10.1016/j.foodpol.2014.02.001>

388 Kahane, R., Hodgkin, T., Jaenicke, H., Hoogendoorn, C., Hermann, M., Keatinge, J., Hughes, J.D.,  
 389 Looney, N., Kahane, R., Hodgkin, T., Jaenicke, H., Hoogendoorn, C., Hermann, M., Kahane, R.,  
 390 Hodgkin, T., Jaenicke, H., 2015. Agrobiodiversity for food security , health and income To cite

391 this version : HAL Id : hal-01201396. *Agron. Sustain. Dev.* 33, 671–693.  
 392 <https://doi.org/10.1007/s13593-013-0147-8>

393 Kasem, S., Thapa, G.B., 2011. Crop diversification in Thailand: Status, determinants, and effects on  
 394 income and use of inputs. *Land use policy* 28, 618–628.  
 395 <https://doi.org/10.1016/j.landusepol.2010.12.001>

396 Kassie, M., Teklewold, H., Marennya, P., Jaleta, M., Erenstein, O., 2015. Production Risks and Food  
 397 Security under Alternative Technology Choices in Malawi: Application of a Multinomial  
 398 Endogenous Switching Regression. *J. Agric. Econ.* 66, 640–659. <https://doi.org/10.1111/1477-9552.12099>  
 399

400 KC, K.B., Pant, L.P., Fraser, E.D.G., Shrestha, P.K., Shrestha, D., Lama, A., 2016. Assessing links  
 401 between crop diversity and food self-sufficiency in three agroecological regions of Nepal. *Reg.*  
 402 *Environ. Chang.* 16, 1239–1251. <https://doi.org/10.1007/s10113-015-0851-9>

403 Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-villegas, J., Guarino, L., 2014. Increasing  
 404 homogeneity in global food supplies and the implications for food security. *PNAS* 111, 4001–  
 405 4006. <https://doi.org/10.1073/pnas.1313490111>

406 Kissoly, L., Faße, A., Grote, U., 2018. Implications of smallholder farm production diversity for  
 407 household food consumption diversity: Insights from diverse agro-ecological and market access  
 408 contexts in rural tanzania. *Horticulturae* 4, 7–11.  
 409 <https://doi.org/10.3390/horticulturae4030014>

410 Koppmair, S., Kassie, M., Qaim, M., 2017. Farm production, market access and dietary diversity in  
 411 Malawi. *Public Health Nutr.* 20, 325–335. <https://doi.org/10.1017/S1368980016002135>

412 Kremen, C., Miles, A., 2012. Ecosystem Services in Biologically Diversified versus Conventional  
 413 Farming Systems : Benefits , Externalities , and Trade-Offs. *Ecol. Soc.* 17, 40.

414 Kumar, N., Harris, J., Rawat, R., 2015. If They Grow It, Will They Eat and Grow? Evidence from Zambia  
 415 on Agricultural Diversity and Child Undernutrition. *J. Dev. Stud.* 51, 1060–1077.  
 416 <https://doi.org/10.1080/00220388.2015.1018901>

417 Kurosaki, T., 2003. Specialization and Diversification in Agricultural Transformation: The Case of West  
 418 Punjab, 1903–92. *Am. J. Agric. Econ.* 85, 372–386. <https://doi.org/10.1111/1467-8276.00126>

419 Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh,  
 420 P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R.,  
 421 Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R., 2003. How extensive are yield  
 422 declines in long-term rice-wheat experiments in Asia? *F. Crop. Res.* 81, 159–180.  
 423 [https://doi.org/10.1016/S0378-4290\(02\)00219-8](https://doi.org/10.1016/S0378-4290(02)00219-8)

424 Ladha, J.K., Rao, A.N., Raman, A.K., Padre, A.T., Dobermann, A., Gathala, M., Kumar, V., Saharawat,  
 425 Y., Sharma, S., Piepho, H.P., Alam, M.M., Liak, R., Rajendran, R., Reddy, C.K., Parsad, R., Sharma,  
 426 P.C., Singh, S.S., Saha, A., Noor, S., 2016. Agronomic improvements can make future cereal  
 427 systems in South Asia far more productive and result in a lower environmental footprint. *Glob.*  
 428 *Chang. Biol.* 22, 1054–1074. <https://doi.org/10.1111/gcb.13143>

429 Lele, U., Masters, W.A., Kinabo, J., Meenakshi, J. V, Ramaswami, B., Tagwireyi, J., Goswami, S., 2016.  
 430 Measuring Food and Nutrition Security: An Independent Technical Assessment and User’s  
 431 Guide for Existing Indicators, Measuring Food and Nutrition Security: An Independent Technical  
 432 Assessment and User’s Guide for Existing Indicators. Rome, Italy.

433 Leroy, J.L., Ruel, M., Frongillo, E.A., Harris, J., Ballard, T.J., 2015. Measuring the Food Access  
 434 Dimension of Food Security : A Critical Review and Mapping of Indicators. *Food Nutr. Bull.* 36,

435 167–195. <https://doi.org/10.1177/0379572115587274>

436 Limbu, S.M., Shoko, A.P., Lamtane, H.A., Kishe-Machumu, M.A., Joram, M.C., Mbonde, A.S., Mgana,  
 437 H.F., Mgaya, Y.D., 2017. Fish polyculture system integrated with vegetable farming improves  
 438 yield and economic benefits of small-scale farmers. *Aquac. Res.* 48, 3631–3644.  
 439 <https://doi.org/10.1111/are.13188>

440 Lin, B.B., 2011. Resilience in Agriculture through Crop Diversification: Adaptive Management for  
 441 Environmental Change. *Bioscience* 61, 183–193. <https://doi.org/10.1525/bio.2011.61.3.4>

442 Lovo, S., Veronesi, M., 2019. Crop Diversification and Child Health: Empirical Evidence From  
 443 Tanzania. *Ecol. Econ.* 158, 168–179. <https://doi.org/10.1016/j.ecolecon.2019.01.005>

444 Löw, F., Biradar, C., Fliemann, E., Lamers, J.P.A., Conrad, C., 2017. Assessing gaps in irrigated  
 445 agricultural productivity through satellite earth observations—A case study of the Fergana  
 446 Valley, Central Asia. *Int. J. Appl. Earth Obs. Geoinf.* 59, 118–134.  
 447 <https://doi.org/10.1016/j.jag.2017.02.014>

448 Luna-González, D. V., Sorensen, M., 2018. Higher agrobiodiversity is associated with improved  
 449 dietary diversity, but not child anthropometric status, of mayan achí people of Guatemala.  
 450 *Public Health Nutr.* 21, 2128–2141. <https://doi.org/10.1017/S1368980018000617>

451 M’Kaibi, F.K., Steyn, N.P., Ochola, S., Du Plessis, L., 2015. Effects of agricultural biodiversity and  
 452 seasonal rain on dietary adequacy and household food security in rural areas of Kenya. *BMC*  
 453 *Public Health* 15, 1–11. <https://doi.org/10.1186/s12889-015-1755-9>

454 M’Kaibi, F.K., Steyn, N.P., Ochola, S.A., Du Plessis, L., 2017. The relationship between agricultural  
 455 biodiversity, dietary diversity, household food security, and stunting of children in rural Kenya.  
 456 *Food Sci. Nutr.* 5, 243–254. <https://doi.org/10.1002/fsn3.387>

457 Mabhaudhi, T., Chimonyo, V.G.P., Modi, A.T., 2017. Status of underutilised crops in South Africa:  
 458 Opportunities for developing research capacity. *Sustain.* 9. <https://doi.org/10.3390/su9091569>

459 Mabhaudhi, T., O’Reilly, P., Walker, S., Mwale, S., 2016. Opportunities for underutilised crops in  
 460 Southern Africa’s post-2015 development agenda. *Sustain.* 8, 1–16.  
 461 <https://doi.org/10.3390/su8040302>

462 Makate, C., Wang, R., Makate, M., Mango, N., 2016. Crop diversification and livelihoods of  
 463 smallholder farmers in Zimbabwe : adaptive management for environmental change.  
 464 *Springerplus* 5, 18. <https://doi.org/10.1186/s40064-016-2802-4>

465 Malapit, H.J.L., Kadiyala, S., Quisumbing, A.R., Cunningham, K., Tyagi, P., 2015. Women’s  
 466 Empowerment Mitigates the Negative Effects of Low Production Diversity on Maternal and  
 467 Child Nutrition in Nepal. *J. Dev. Stud.* 51, 1097–1123.  
 468 <https://doi.org/10.1080/00220388.2015.1018904>

469 Markowitz, H., 1952. Portfolio selection. *J. Finance* 7, 77–91. <https://doi.org/10.1111/j.1540-6261.1952.tb01525.x>

471 Martin-Prevel, Y., Allemand, P., Wiesmann, D., Arimond, M., Ballard, T., Deitchler, M., Dop, M.-C.,  
 472 Kennedy, G., Lee, W.T.K., Moursi, M., 2015. Moving forward. On choosing a standard  
 473 operational indicator of women’s dietary diversity. Rome, Italy.

474 Mavengahama, S., McLachlan, M., de Clercq, W., 2013. The role of wild vegetable species in  
 475 household food security in maize based subsistence cropping systems. *Food Secur.* 5, 227–233.  
 476 <https://doi.org/10.1007/s12571-013-0243-2>

477 Mavhura, E., Manatsa, D., Mushore, T., 2015. Adaptation to drought in arid and semi-arid

478 environments: Case of the Zambezi Valley, Zimbabwe. *Jàmá J. Disaster Risk Stud.* 7.  
479 <https://doi.org/10.4102/jamba.v7i1.144>

480 Maxwell, D., Caldwell, R., 2008. The Coping Strategies Index. A tool for rapid measurement of  
481 household food security and the impact of food aid programs in humanitarian emergency.,  
482 Educational and Psychological Measurement. <https://doi.org/10.1177/0013164412465875>

483 Mitchodigni, I.M., Amoussa Hounkpatin, W., Ntandou-Bouzitou, G., Avohou, H., Termote, C.,  
484 Kennedy, G., Hounhouigan, D.J., 2017. Complementary feeding practices: determinants of  
485 dietary diversity and meal frequency among children aged 6–23 months in Southern Benin.  
486 *Food Secur.* 9, 1117–1130. <https://doi.org/10.1007/s12571-017-0722-y>

487 Mofya-Mukuka, R., Hichaambwa, M., 2018. Livelihood effects of crop diversification: a panel data  
488 analysis of rural farm households in Zambia. *Food Secur.* 10, 1449–1462.  
489 <https://doi.org/10.1007/s12571-018-0872-6>

490 Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L.A.,  
491 Group, P., 2015. Preferred reporting items for systematic review and meta-analysis protocols (   
492 PRISMA-P ) 2015 statement. *Syst. Rev.* 4, 1–9.

493 Mulmi, P., Masters, W.A., Ghosh, S., Namirembe, G., Rajbhandary, R., Manohar, S., Shrestha, B.,  
494 West, K.P., Webb, P., 2017. Household food production is positively associated with dietary  
495 diversity and intake of nutrient-dense foods for older preschool children in poorer families:  
496 Results from a nationally-representative survey in Nepal. *PLoS One* 12, 1–23.  
497 <https://doi.org/10.1371/journal.pone.0186765>

498 Murendo, C., Nhau, B., Mazvimavi, K., Khanye, T., Gwara, S., 2018. Nutrition education, farm  
499 production diversity, and commercialization on household and individual dietary diversity in  
500 Zimbabwe. *Food Nutr. Res.* 62. <https://doi.org/10.29219/fnr.v62.1276>

501 N’Danikou, S., Vodouhe, R.S., Bellon, M.R., Sidibé, A., Coulibaly, H., 2017. Foraging is determinant to  
502 improve smallholders’ food security in rural areas in Mali, West Africa. *Sustain.* 9.  
503 <https://doi.org/10.3390/su9112074>

504 Nabhan, G.P., Wilson, K., Aknazarov, O., Kassam, K., Monti, L., Cavagnaro, D., Kelly, S., Johnson, T.,  
505 Sekacucu, F., 2012. Agrobiodiversity Shifts on Three Continents Since Vavilov and Harlan :  
506 Assessing Causes , Processes , and Implications for Food Security, in: Gepts, P., Famula, T.R.,  
507 Bettinger, R.L., Brush, S.B., Damania, A.B., McGuire, P.E., Qualset, C.O. (Eds.), *Biodiversity in*  
508 *Agriculture: Domestication, Evolution, and Sustainability*. Cambridge University Press, pp. 407–  
509 435.

510 Naeem, S., Li, S., 1997. Biodiversity enhances ecosystem reliability. *Nature* 390, 507–509.

511 Nagothu, U.S., Tesfai, M., 2018. Pulses–millets crop diversification by smallholders and their  
512 potential for sustainable food and nutrition security. *Agric. Dev. Sustain. Intensif.* 136–161.  
513 <https://doi.org/10.4324/9780203733301-6>

514 Ng’endo, M., Bhagwat, S., Keding, G.B., 2016. Influence of Seasonal On-Farm Diversity on Dietary  
515 Diversity: A Case Study of Smallholder Farming Households in Western Kenya. *Ecol. Food Nutr.*  
516 55, 403–427. <https://doi.org/10.1080/03670244.2016.1200037>

517 Ng’Endo, M., Keding, G.B., Bhagwat, S., Kehlenbeck, K., 2015. Variability of on-farm food plant  
518 diversity and its contribution to food security: A case study of smallholder farming households  
519 in western Kenya. *Agroecol. Sustain. Food Syst.* 39, 1071–1103.  
520 <https://doi.org/10.1080/21683565.2015.1073206>

521 Nkomoki, W., Bavorová, M., Banout, J., 2018. Adoption of sustainable agricultural practices and food



522 security threats: Effects of land tenure in Zambia. *Land use policy* 78, 532–538.  
523 <https://doi.org/10.1016/j.landusepol.2018.07.021>

524 Parvathi, P., 2018. Does mixed crop-livestock farming lead to less diversified diets among  
525 smallholders? Evidence from Laos. *Agric. Econ. (United Kingdom)* 49, 497–509.  
526 <https://doi.org/10.1111/agec.12431>

527 Passarelli, S., Mekonnen, D., Bryan, E., Ringler, C., 2018. Evaluating the pathways from small-scale  
528 irrigation to dietary diversity: evidence from Ethiopia and Tanzania. *Food Secur.* 10, 981–997.  
529 <https://doi.org/10.1007/s12571-018-0812-5>

530 Paul, B.K., Frelat, R., Birnholz, C., Ebong, C., Gahigi, A., Groot, J.C.J., Herrero, M., Kagabo, D.M.,  
531 Notenbaert, A., Vanlauwe, B., Wijk, M.T. Van, 2017. Agricultural intensification scenarios ,  
532 household food availability and greenhouse gas emissions in Rwanda: Ex-ante impacts and  
533 trade-offs. *Agric. Syst.* in press. <https://doi.org/10.1016/j.agry.2017.02.007>

534 Penafiel, D., Lachat, C., Espinel, R., Van Damme, P., Kolsteren, P., 2011. A Systematic Review on the  
535 Contributions of Edible Plant and Animal Biodiversity to Human Diets. *Ecohealth* 8, 381–399.  
536 <https://doi.org/10.1007/s10393-011-0700-3>

537 Perdoná, M.J., Soratto, R.P., 2015. Irrigation and intercropping with macadamia increase initial  
538 arabica coffee yield and profitability. *Agron. J.* 107, 615–626.  
539 <https://doi.org/10.2134/agronj14.0246>

540 Pimm, S.L., 1984. The complexity and stability of ecosystems.

541 Ponisio, L.C., M’Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2015.  
542 Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. B Biol. Sci.* 282,  
543 20141396. <https://doi.org/10.1098/rspb.2014.1396>

544 Ponisio, L.C., M’Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2014.  
545 Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. B Biol. Sci.* 282,  
546 20141396. <https://doi.org/10.1098/rspb.2014.1396>

547 Powell, B., Thilsted, S.H., Ickowitz, A., Termote, C., Sunderland, T., Herforth, A., 2015. Improving  
548 diets with wild and cultivated biodiversity from across the landscape. *Food Secur.* 7, 535–554.  
549 <https://doi.org/10.1007/s12571-015-0466-5>

550 Pradhan, A., Chan, C., Roul, P.K., Halbrendt, J., Sipes, B., 2018. Potential of conservation agriculture  
551 (CA) for climate change adaptation and food security under rainfed uplands of India: A  
552 transdisciplinary approach. *Agric. Syst.* 163, 27–35. <https://doi.org/10.1016/j.agry.2017.01.002>

553 Rammohan, A., Pritchard, B., Dibley, M., Vicol, M., 2018. The links between agricultural production  
554 and the nutritional status of children in rural Myanmar. *Food Secur.* 10, 1603–1614.  
555 <https://doi.org/10.1007/s12571-018-0864-6>

556 Raseduzzaman, M., Jensen, E.S., 2017. Does intercropping enhance yield stability in arable crop  
557 production? A meta-analysis. *Eur. J. Agron.* 91, 25–33.  
558 <https://doi.org/10.1016/j.eja.2017.09.009>

559 Remans, R., Flynn, D.F.B., DeClerck, F., Diru, W., Fanzo, J., Gaynor, K., Lambrecht, I., Mudiope, J.,  
560 Mutuo, P.K., Nkhoma, P., Siriri, D., Sullivan, C., Palm, C. a, 2011. Assessing nutritional diversity  
561 of cropping systems in African villages. *PLoS One* 6, e21235.  
562 <https://doi.org/10.1371/journal.pone.0021235>

563 Remans, R., Wood, S.A., Saha, N., Anderman, T.L., DeFries, R.S., 2014. Measuring nutritional diversity  
564 of national food supplies. *Glob. Food Sec.* 3, 174–182.

565 <https://doi.org/10.1016/j.gfs.2014.07.001>

566 Renard, D., Bennett, E.M., Rhemtulla, J.M., 2016. Agro-biodiversity has increased over a 95 year  
567 period at sub-regional and regional scales in southern Quebec , Canada. *Environ. Res. Lett.* 11.

568 Renard, D., Tilman, D., 2019. National food production stabilized by crop diversity. *Nature* 571, 257–  
569 260. <https://doi.org/10.1038/s41586-019-1316-y>

570 Ritzema, R.S., Douxchamps, S., Fraval, S., Bolliger, A., Hok, L., Phengsavanh, P., Long, C.T.M.,  
571 Hammond, J., van Wijk, M.T., 2019. Household-level drivers of dietary diversity in transitioning  
572 agricultural systems: Evidence from the Greater Mekong Subregion. *Agric. Syst.* 176, 102657.  
573 <https://doi.org/10.1016/j.agsy.2019.102657>

574 Romeo, A., Meerman, J., Demeke, M., Scognamillo, A., Asfaw, S., 2016. Linking farm diversification to  
575 household diet diversification: evidence from a sample of Kenyan ultra-poor farmers. *Food*  
576 *Secur.* 8, 1069–1085. <https://doi.org/10.1007/s12571-016-0617-3>

577 Ruel, M.T., Alderman, H., 2013. Nutrition-sensitive interventions and programmes: How can they  
578 help to accelerate progress in improving maternal and child nutrition? *Lancet* 382, 536–551.  
579 [https://doi.org/10.1016/S0140-6736\(13\)60843-0](https://doi.org/10.1016/S0140-6736(13)60843-0)

580 Rufino, M.C., Thornton, P.K., Ng'ang'a, S.K., Mutie, I., Jones, P.G., van Wijk, M.T., Herrero, M., 2013.  
581 Transitions in agro-pastoralist systems of East Africa: Impacts on food security and poverty.  
582 *Agric. Ecosyst. Environ.* 179, 215–230. <https://doi.org/10.1016/j.agee.2013.08.019>

583 Saaka, M., Osman, S.M., Hoeschle-Zeledon, I., 2017. Relationship between agricultural biodiversity  
584 and dietary diversity of children aged 6-36 months in rural areas of northern Ghana. *Food Nutr.*  
585 *Res.* 61. <https://doi.org/10.1080/16546628.2017.1391668>

586 Samal, S.K., Rao, K.K., Poonia, S.P., Kumar, R., Mishra, J.S., Prakash, V., Mondal, S., Dwivedi, S.K.,  
587 Bhatt, B.P., Naik, S.K., Choubey, A.K., Kumar, V., Malik, R.K., Mc Donald, A., 2017. Evaluation of  
588 long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-  
589 Gangetic Plains of South Asia: Carbon dynamics and productivity. *Eur. J. Agron.* 90, 198–208.  
590 <https://doi.org/10.1016/j.eja.2017.08.006>

591 Sanogo, K., Binam, J., Bayala, J., Villamor, G.B., Kalinganire, A., Dodiomon, S., 2017. Farmers'  
592 perceptions of climate change impacts on ecosystem services delivery of parklands in southern  
593 Mali. *Agrofor. Syst.* 91, 345–361. <https://doi.org/10.1007/s10457-016-9933-z>

594 Sardos, J., Muller, S., Duval, M.F., Noyer, J.L., Lebot, V., 2016. Root crops diversity and agricultural  
595 resilience: a case study of traditional agrosystems in Vanuatu (Oceania). *Agric. Human Values*  
596 33, 721–736. <https://doi.org/10.1007/s10460-015-9657-0>

597 Sauer, C.M., Mason, N.M., Maredia, M.K., Mofya-Mukuka, R., 2018. Does adopting legume-based  
598 cropping practices improve the food security of small-scale farm households? Panel survey  
599 evidence from Zambia. *Food Secur.* 10, 1463–1478. [https://doi.org/10.1007/s12571-018-0859-](https://doi.org/10.1007/s12571-018-0859-3)  
600 3

601 Schneider, M., Andres, C., Trujillo, G., Alcon, F., Amurrio, P., Perez, E., Weibel, F., Milz, J., 2017.  
602 Cocoa and total system yields of organic and conventional agroforestry vs. monoculture  
603 systems in a long-term field trial in Bolivia. *Exp. Agric.* 53, 351–374.  
604 <https://doi.org/10.1017/S0014479716000417>

605 Schreefel, L., Schulte, R.P.O., de Boer, I.J.M., Schrijver, A.P., van Zanten, H.H.E., 2020. Regenerative  
606 agriculture – the soil is the base. *Glob. Food Sec.* 26, 100404.  
607 <https://doi.org/10.1016/j.gfs.2020.100404>

608 Schroth, G., Ruf, F., 2014. Farmer strategies for tree crop diversification in the humid tropics. A  
609 review. *Agron. Sustain. Dev.* 34, 139–154. <https://doi.org/10.1007/s13593-013-0175-4>

610 Sibhatu, K.T., Krishna, V. V, Qaim, M., 2015. Production diversity and dietary diversity in smallholder  
611 farm households. *Proc. Natl. Acad. Sci. U. S. A.* 112, 10657–10662.  
612 <https://doi.org/10.1073/pnas.1510982112>

613 Sibhatu, K.T., Qaim, M., 2018a. Farm production diversity and dietary quality: linkages and  
614 measurement issues. *Food Secur.* 10, 47–59. <https://doi.org/10.1007/s12571-017-0762-3>

615 Sibhatu, K.T., Qaim, M., 2018b. Review: The association between production diversity, diets, and  
616 nutrition in smallholder farm households. *Food Policy* 77, 1–18.  
617 <https://doi.org/10.1016/j.foodpol.2018.04.013>

618 Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can  
619 support a greener revolution in Africa. *Proc. Natl. Acad. Sci. U. S. A.* 107, 20840–20845.  
620 <https://doi.org/10.1073/pnas.1007199107>

621 Snapp, S.S., Fisher, M., 2015. “Filling the maize basket” supports crop diversity and quality of  
622 household diet in Malawi. *Food Secur.* 7, 83–96. <https://doi.org/10.1007/s12571-014-0410-0>

623 Somé, J.W., Jones, A.D., 2018. The influence of crop production and socioeconomic factors on  
624 seasonal household dietary diversity in Burkina Faso. *PLoS One* 13, 1–16.  
625 <https://doi.org/10.1371/journal.pone.0195685>

626 Souza, H.N., Cardoso, I.M., Fernandes, J.M., Garcia, F.C.P., Bonfim, V.R., Santos, A.C., Carvalho, A.F.,  
627 Mendonça, E.S., 2010. Selection of native trees for intercropping with coffee in the Atlantic  
628 Rainforest biome. *Agrofor. Syst.* 80, 1–16. <https://doi.org/10.1007/s10457-010-9340-9>

629 Termote, C., Bwama Meyi, M., Dhed’a Djailo, B., Huybregts, L., Lachat, C., Kolsteren, P., van Damme,  
630 P., 2012. A biodiverse rich environment does not contribute to a better diet: A case study from  
631 DR Congo. *PLoS One* 7. <https://doi.org/10.1371/journal.pone.0030533>

632 Tesfaye, W., Tirivayi, N., 2020. Crop diversity, household welfare and consumption smoothing under  
633 risk: Evidence from rural Uganda. *World Dev.* 125, 104686.  
634 <https://doi.org/10.1016/j.worlddev.2019.104686>

635 Thapa, G., Kumar, A., Roy, D., Joshi, P.K., 2018. Impact of Crop Diversification on Rural Poverty in  
636 Nepal. *Can. J. Agric. Econ. Can. d’agroéconomie* 66, 379–413.  
637 <https://doi.org/10.1111/cjag.12160>

638 Thrupp, L.A.L.A., 2000. Linking Agricultural Biodiversity and Food Security : The Valuable Role of  
639 Sustainable Agriculture Lori Ann Thrupp International Affairs. *Int. Aff.* 76, 265–281.

640 Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable  
641 intensification of agriculture. *Proc. Natl. Acad. Sci. U. S. A.* 108, 20260–20264.  
642 <https://doi.org/10.1073/pnas.1116437108>

643 Tobin, D., Jones, K., Thiede, B.C., 2019. Does crop diversity at the village level influence child  
644 nutrition security? Evidence from 11 sub-Saharan African countries. *Popul. Environ.* 41, 74–97.  
645 <https://doi.org/10.1007/s11111-019-00327-4>

646 Traoré, S.A., Reiber, C., Megersa, B., Zárate, A.V., 2018. Contribution of cattle of different breeds to  
647 household food security in southern Mali. *Food Secur.* 10, 549–560.  
648 <https://doi.org/10.1007/s12571-018-0795-2>

649 Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., Arrow, K.J., Barrett, S.,  
650 Crépin, A.-S., Ehrlich, P.R., Gren, Å., Kautsky, N., Levin, S.A., Nyborg, K., Österblom, H., Polasky,

651 S., Scheffer, M., Walker, B.H., Xepapadeas, T., de Zeeuw, A., 2014. Does aquaculture add  
652 resilience to the global food system? *Proc. Natl. Acad. Sci.* 111, 13257–13263.  
653 <https://doi.org/10.1073/pnas.1404067111>

654 Urruty, N., Tailliez-lefebvre, D., Huyghe, C., Tailliez-lefebvre, D., 2016. Stability, robustness ,  
655 vulnerability and resilience of agricultural systems . A review. *Agron. Sustain. Dev.*  
656 <https://doi.org/10.1007/s13593-015-0347-5>

657 Valencia, V., Wittman, H., Blesh, J., 2019. Structuring Markets for Resilient Farming Systems. *Agron.*  
658 *Sustain. Dev.* 39, 1–14. <https://doi.org/10.1007/s13593-019-0572-4>

659 Vanek, S.J., Jones, A.D., Drinkwater, L.E., 2016. Coupling of soil regeneration, food security, and  
660 nutrition outcomes in Andean subsistence agroecosystems. *Food Secur.* 8, 727–742.  
661 <https://doi.org/10.1007/s12571-016-0598-2>

662 Waha, K., van Wijk, M.T.M.T., Fritz, S., See, L., Thornton, P.K.P.K., Wichern, J., Herrero, M., 2018.  
663 Agricultural diversification as an important strategy for achieving food security in Africa. *Glob.*  
664 *Chang. Biol.* 24, 3390–3400. <https://doi.org/10.1111/gcb.14158>

665 Whitney, C.W., Luedeling, E., Hensel, O., Tabuti, J.R.S., Krawinkel, M., Gebauer, J., Kehlenbeck, K.,  
666 2018. The Role of Homegardens for Food and Nutrition Security in Uganda. *Hum. Ecol.* 46, 497–  
667 514. <https://doi.org/10.1007/s10745-018-0008-9>

668 Whittaker, R.H., 1972. Evolution and Measurement of Species Diversity. *Taxon* 21, 213–251.  
669 <https://doi.org/10.2307/1218190>

670 WHO, 1995. Physical status: the use and interpretation of anthropometry.

671 Williams, N.E., Carrico, A.R., Edirisinghe, I., Jayamini Champika, P.A., 2018. Assessing the Impacts of  
672 Agrobiodiversity Maintenance on Food Security Among Farming Households in Sri Lanka’s Dry  
673 Zone. *Econ. Bot.* 72, 196–206. <https://doi.org/10.1007/s12231-018-9418-2>

674 Working Group on Infant and Young Child Feeding Indicators, 2007. Developing and Validating  
675 Simple Indicators of Dietary Quality of Infants and Young Children in Developing Countries :  
676 Additional Analysis of 10 Data Sets. Washington D.C.

677 World Health Organization, 2008. Indicators for assessing infant and young child feeding practices.  
678 Part 1 Definitions. Geneva, Switzerland.

679 Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment:  
680 The insurance hypothesis. *Proc. Natl. Acad. Sci.* 96, 1463–1468.  
681 <https://doi.org/10.1073/pnas.96.4.1463>

682 Yigrem, S., Markemann, A., Abebe, G., Ogutu, J.O., Piepho, H.-P., Zárate, A.V., 2015. Assessing the  
683 relative importance of dairy products to family nutrition in mixed crop-livestock production  
684 systems of Ethiopia. *Food Secur.* 7, 1003–1015. <https://doi.org/10.1007/s12571-015-0487-0>

685 Zanello, G., Shankar, B., Poole, N., 2019. Buy or make? Agricultural production diversity, markets and  
686 dietary diversity in Afghanistan. *Food Policy* 87, 101731.  
687 <https://doi.org/10.1016/j.foodpol.2019.101731>

688