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

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

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

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19
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21 biodiversity, literature review, low-income countries, middle income countries
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32 **Abstract**

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

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

53

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69 1. Introduction

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

74 In food systems, diversification, defined often as an increase in crop, livestock, production or farming
75 diversity (i.e. agrobiodiversity), has been considered as a key strategy for improving the productivity
76 and stability of many socio-economic and ecological aspects of agricultural systems. It is a central
77 element for example in three areas. Firstly, in sustainable intensification (Foley et al., 2011; Tilman
78 et al., 2011), ecological intensification (Bommarco et al., 2013; Cassman, 1999), conservation
79 agriculture (FAO, 2002) and more recently regenerative agriculture (Schreefel et al., 2020). For
80 example, mixed farming and crop rotations can support pest, nutrient and water management (Gaba
81 et al., 2015), reduce external inputs and improve soil biodiversity. Secondly, in rural development
82 and sustainable livelihoods (Chambers and Conway, 1992; Ellis, 1998) as livelihood diversification
83 has often been highlighted as contributing to reduced poverty. And thirdly, in nutrition-sensitive
84 agriculture describing pathways from agriculture to nutrition security where diversification can
85 increase the diversity of foods produced and of potential income sources (De Jager et al., 2018;
86 Herforth and Harris, 2014; Ruel and Alderman, 2013).

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

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

109 In this review, we aim at synthesising the evidence on the relationship between agricultural diversity
110 and all four dimensions of food security as defined in the FAO's conceptual framework – availability,
111 stability, access, and utilisation. Food security is a major concern in low- and middle-income
112 countries and has been enacted as one of the United Nations Sustainable Development Goals. Our

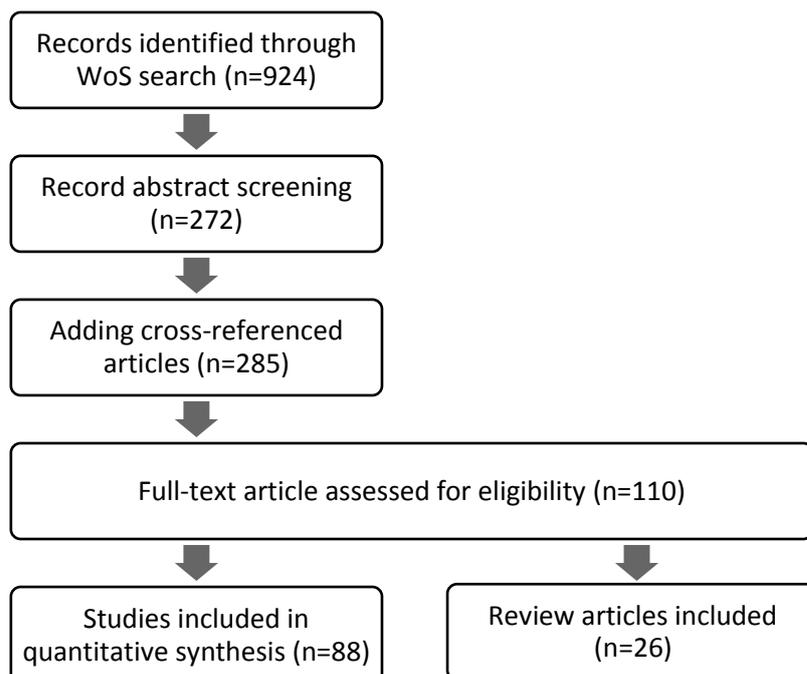
113 review also explores the interactions at different spatial scales. While many measures of food
114 security relate to individuals, such as meeting dietary energy needs, the challenge to secure healthy
115 and diverse diets is also global in its extent and in that scale often analysed with respect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

117 2. Search criteria and methods

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

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

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



155

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

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

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

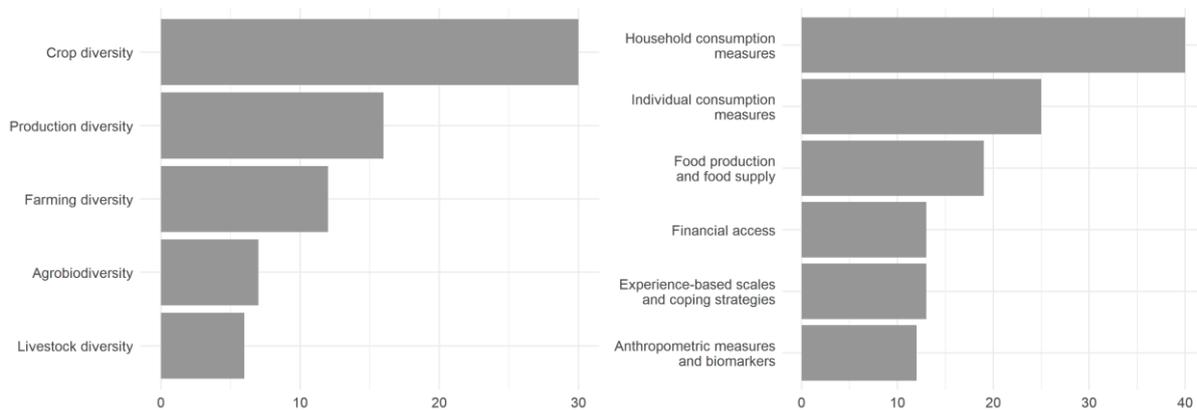
170 3. Indicators of agricultural diversity and food security

171 3.1 Agricultural diversity

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

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

191 Several indicators can be used to measure agricultural diversity, integrating different aspects of
 192 diversity, richness and evenness. Richness is the number of species or agricultural products in a
 193 sample. Some studies express this by comparing characteristics of cropping systems with different
 194 numbers of crops cultivated or creating a binary variable to distinguish between adopters and non-
 195 adopters of diversification (Birthal et al., 2015; Boedecker et al., 2014). Measures of evenness
 196 consider relative dominance or concentration of species or products in the sample by measuring also
 197 the abundance of each species (Whittaker, 1972). Examples of measures of evenness are the
 198 Simpson diversity index (SDI) and the Shannon diversity index (H’). They differ slightly by expressing
 199 dominance of the first few species in the sample (Simpson index) or relative evenness across the
 200 whole sample (Shannon diversity index) (Whittaker, 1972). Abundance can be measured as area
 201 used for each species, weight of produce, nutrient or energy content of each product or monetary
 202 value of products. Using area can be challenging when including livestock (Sibhatu and Qaim,
 203 2018a), as livestock can source feed from outside the farm, graze on public land or be fed purchased
 204 feed.



205
 206 **Figure 2** Number of studies using different measures of diversity (left) and different food security
 207 indicators (right) used in reviewed publications (N=88). Studies that use multiple metrics are counted
 208 multiple times accordingly.

209 3.2 Food security

210 The FAO’s conceptual framework for food security distinguishes between four dimensions, physical
 211 availability to food, economic and physical access to food, food utilization and stability. This
 212 framework, and national level indicators to measure progress on each dimension, are used in the

213 annual reports on the ‘The State of Food Security and Nutrition in the World’ published since 1999
 214 by FAO, IFAD, UNICEF, WFP and WHO (until 2015 as ‘The State of Food Insecurity in the World’)
 215 (FAO, 2019). In addition to these national level indicators, this literature review identified indicators
 216 to measure food security status of an individual or a household. The full list of indicators considered
 217 in this review is shown in Table 1.

218 **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)			

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

227 Food access indicators are very diverse, but some standard indicators have been developed by the
228 Food and Agriculture Organization of the United Nations (FAO), the Food and Nutrition Technical
229 Assistance Project (FANTA) and the World Food Programme (WFP). Within the food access domain,
230 we identify two groups of indicators. The first group are indicators reflecting the financial dimension
231 and affordability of food access and the second group are indicators pertaining to consumption
232 patterns measured at the household level. The household dietary diversity score (HDDS) is the most
233 frequently used indicator to measure food access. HDDS is constructed based on consumption of 12
234 food groups and ranges from 0 (no food group consumed) to 12 (all 12 food groups consumed) with
235 a recall period of 24 hours (FAO, 2013) but many studies reviewed here modified the recall period to
236 be seven days. The food consumption score (FSC) is a similar, but composite score ranging between
237 0 (food insecure) and 16 (food secure) and measures the frequency of consumption of different food
238 groups by a household during the seven days before the survey. HDDS has been validated as a good
239 indicator of diet quantity i.e. energy consumption (Hoddinott and Yohannes, 2002) but not of diet
240 quality i.e. nutrient adequacy (Leroy et al., 2015). One reason for that is that HDDS measures also the
241 consumption of three food groups (sweets; oils and fats; spices, condiments and beverages) that do
242 not necessarily contribute positively to micronutrient intake which weakens any potential association
243 with micronutrient adequacy and diet quality.

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

264 indicator, which is used to define women as having an adequate diet diversity if consuming at least
265 five of the ten food groups included.

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

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

286 4. Previous reviews and meta-analysis

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

291 4.1 Food availability

292 In the context of food availability, eight review articles and meta-analyses discuss the benefits of
293 crop and agrobiodiversity for productivity (Delaquis et al., 2018; Droppelmann et al., 2017; Frison et
294 al., 2011; Gaba et al., 2015; Kremen and Miles, 2012; Nagothu and Tesfai, 2018; Ponisio et al., 2015;
295 Schroth and Ruf, 2014). For cassava intercropping, Delaquis et al. (2018) found a positive
296 relationship between intercropping and system productivity in most studies reviewed which was
297 evidenced by land equivalent ratios above 1. Other reviews for specific crops are provided in
298 Nagothu and Tesfai (2018) for pulses-millet crop diversification and Schroth and Ruf (2014) for tree
299 crop diversification in the humid tropics. In another review based on 17 studies on sustainable
300 intensification practices in maize small-scale farms in sub-Saharan Africa, Droppelmann et al. (2017)
301 show that the addition of a grain legume increased maize response to fertilizer but reduced
302 annualized maize grain yields. Other benefits of intercropping and multiple cropping include
303 improved soil and water regulation, reduced consumption of fertilizers and pesticide, reduced soil
304 erosion and nitrate leaching, increased biodiversity and pest and disease suppression (Frison et al.,
305 2011; Gaba et al., 2015). In a meta-analysis using 115 studies, Ponisio et al. (2014) find that multi-

306 cropping and crop rotations can improve yields in organic systems. According to Gaba et al. (2015)
307 the co-existence of multiple species can be beneficial if the species are carefully selected to provide
308 resources for one another or to use a resource in different forms or at different times or in different
309 places. Otherwise resource competition can result in lower system yields compared to monocultures
310 (Gaba et al., 2015). Kremen and Miles (2012) compared ecosystem services such as food production
311 and environmental performance in biologically diversified, including organic, versus chemically
312 based simplified farming systems, relying on monoculture, inorganic fertilizers, and synthetic
313 pesticide input. They found that conclusions on yield gaps varied widely in previously published
314 articles.

315 4.2 Food access and utilisation

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

345 4.3 Stability

346 A meta-analysis of 37 studies showed that cereal-grain legume intercropping significantly increased
347 temporal and spatial yield stability (CV =22.1) compared with the respective grain legume sole crops
348 (CV= 31.7). Temporal yield variability in cereal-grain legume intercropping was 58% lower than for

349 grain legume sole crop but not significantly lower than for the cereal sole crop. Spatial yield
 350 variability in cereal-grain legume intercropping was 14-19% lower than grain legume and cereal sole
 351 crops (Raseduzzaman and Jensen, 2017). Hansen et al. (2019) reviewed 12 articles that describe
 352 benefits of diversified farming systems including agroforestry. They concluded that interventions
 353 that encouraged diversification showed moderately positive effects on stabilizing production and
 354 consumption, as well as improving livelihoods and welfare. Crop diversification can also contribute
 355 to stabilizing income, because some crops like rubber and oil palm can provide revenue throughout
 356 the year and the mix of perennial with annual crops can secure a more regular income from harvests
 357 in different months (Schroth and Ruf, 2014)

358 Five qualitative reviews give examples of studies that present empirical evidence on differences in
 359 stability and resilience between diversified and non-diversified agricultural systems (Altieri et al.,
 360 2015; Di Falco, 2012; Frison et al., 2011; Lin, 2011; Urruty et al., 2016). Between them they cite 31
 361 studies but none of them provide a systematic overview of the empirical evidence which we attempt
 362 to show in Table 2. We select the 11 studies for low- and middle-income countries that were cited
 363 before and published as research articles or peer-reviewed book sections, written in English and
 364 reporting original data on a relevant measure of stability and summarise their main findings in Table
 365 2. The most common measure of stability in the cited studies was variability of crop yield and
 366 income and resistance. For resistance there are two types of studies, one that attempts to assess the
 367 resistance of a diversified vs non-diversified system after a major perturbation, a hurricane or a
 368 drought, and one that assesses resistance to pest infestation, or heat and water stress without
 369 studying the system variables before or after an external shock.

370 **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

402 without any adverse effect on growth and yield of rubber. Crop diversification increased rubber yield
403 but only in the first year, after which the effect was not significant (Jessy et al., 2017). In Brazil, a
404 diversified agroforestry system for coffee cultivation allowed more products from a larger range of
405 food crops to be harvested and commercialized leading to a lower cost/benefit ratio than in the
406 coffee monoculture (Souza et al., 2010).

407 Other data sources used are surveys and farmer interviews which also allows studying effects on
408 farm or household scale (Douxchamps et al., 2016; Dzanku and Sarpong, 2011; Makate et al., 2016).
409 We cannot compare the studies to each other but each of them highlights the context in which
410 diversity can be beneficial. For example, Douxchamps et al. (2016) found that crop diversity
411 positively influenced land productivity in Burkina Faso, Senegal and Ghana, but only for a specific
412 type of household practicing intensified farming with strong market orientation and a high
413 proportion of income from growing pulses. Dzanku and Sarpong (2013) find a positive relationship
414 between more diverse non-staple crop production and household food supply in one region only
415 and the authors suggest that this is due to regional differences associated with better market
416 conditions rather than crop diversity. They concluded that a more diverse crop portfolio did not
417 necessarily lead to a higher probability of household level food security, with other important
418 predictors being household composition, education, wealth, age, and other non-farm sources of
419 income. In a multi-country study with 28,000 farming households in sub-Saharan Africa, Waha et al.
420 (2018) found that median food availability increased with farming diversity. The farming households
421 with highest farming diversity also had significantly more cropland than others, which partly explains
422 this result. This study also find that increasing farming diversity can result in diminished returns, with
423 food availability increasing until diversity levels reach seven species per hectare cropland, and then
424 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 > 0.05); β = regression coefficient; ATT = adoption effect</p>						

426 6. Diversity and stability of food security

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

439 We also found an alternative method for understanding how agricultural diversity and stability of
440 agricultural production are related in the literature we reviewed. Farm-scale adaptation strategies
441 often include diversification and we identified six publications researching if farmers use
442 diversification to mitigate risks from perceived changes in weather or climate (Antwi-Agyei et al.,
443 2014a; Chengappa et al., 2017; Eludoyin et al., 2017; Fadina and Barjolle, 2018; Mavhura et al., 2015;
444 Sanogo et al., 2017). These 'perception studies' rarely discuss the relationship to food security
445 directly thus are not included in the summary table below but can help to understand farmer's
446 coping or adaptation strategies when faced with short- or long-term environmental changes. The
447 sample size is often small. The number of farmers interviewed in the six studies reviewed ranged
448 from 120 to 400 farmers and it is mostly unclear to what extent the chosen adaptation strategy was
449 effective. For example, if it increased production or stability over time. Also, it is not always clear if
450 diversification was a hypothetically preferred or a practised adaptation strategy, to what extent
451 farmers already practiced diversification in general and in response to perturbations. Although
452 households might claim that they have diversified their cropping patterns in response to climate
453 variability, such patterns might have been partly influenced by non-climatic factors such as economic
454 shocks and opportunities (Antwi-Agyei et al., 2014b). However, this method can reveal farmer's
455 motivation to adapt and preferring a specific strategy over others. The conclusions from the six
456 studies suggest that diversification is practiced as a risk management strategy (Chengappa et al.,
457 2017; Eludoyin et al., 2017; Fadina and Barjolle, 2018), to cope with climate shocks (Sanogo et al.,
458 2017) and to take advantage of multiple growing seasons (Eludoyin et al., 2017). One perception
459 study found that on-farm diversification was not an option for farmers in Zimbabwe faced with
460 lower than average rainfall, and that they instead relied on food aid, income diversification and
461 collecting wild food (Mavhura et al., 2015). This is perhaps an indication that major shocks cannot be
462 compensated by diversifying as every agricultural activity is impacted severely.

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

470 increase the resilience of the system through increasing the farmer's ability to switch to alternative
 471 crops when facing an unforeseen change.

472 **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

473 7. Diversity and food access

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

481 By far the most common indicators of food access were household consumption measures, for
482 example HDDS. Thirty-three studies used household dietary diversity as a measure for food access,
483 sometimes modified by changing the recall period or number and types of food groups (M-HDDS).
484 Where the relationship between a measure of agricultural diversity and HDDS or M-HDDS is positive
485 the regression coefficients differ between different statistical methods (e.g. Ayenew et al., 2018;
486 Huluka and Wondimagegnhu, 2019; Jones, 2017b; Kissoly et al., 2018; Koppmair et al., 2017; Kumar
487 et al., 2015; Makate et al., 2016; Murendo et al., 2018; Romeo et al., 2016; Sibhatu et al., 2015a;
488 Sibhatu and Qaim, 2018a; Somé and Jones, 2018; Tesfaye and Tirivayi, 2020; Traoré et al., 2018).
489 Sibhatu and Qaim (2018a) find that increasing agricultural diversity by one crop or livestock species
490 slightly increases the number of food groups consumed by 0.05-0.07 in Kenya, 0.16 in Indonesia and
491 0.2-0.33 in Uganda. Other explaining factors such as cultivated land area and educational level of the
492 household head also have a positive effect on M-HDDS but to a smaller extent than agricultural
493 diversity. Murendo et al. (2018) also find a relatively small effect of increasing agricultural diversity.
494 Producing one additional crop or livestock species leads to a 3% increase in M-HDDS whereas market
495 participation results in a 6% increase in M-HDDS which indicates a reliance on purchased food. Other
496 studies found much larger effects of increased agricultural diversity on HDDS and M-HDDS (Makate
497 et al., 2016; Tesfaye and Tirivayi, 2020) where crop diversity was strongly associated with HDDS and
498 M-HDDS. A few studies also measure mean household nutrient and/or energy intake or adequacy
499 and found positive associations with agricultural diversity for some indicators (Brüssow et al., 2017;
500 De Jager et al., 2018; Sibhatu and Qaim, 2018a).

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

507 Nine of the twelve studies on the association between agricultural diversity and economic access
508 found a positive association (Bellon et al., 2020; Das and Ganesh-Kumar, 2018; Kasem and Thapa,
509 2011; Ladha et al., 2003; Limbu et al., 2017; Makate et al., 2016; Mofya-Mukuka and Hichaambwa,
510 2018; Pradhan et al., 2018; Thapa et al., 2018). For example, in Thailand, diversifying rice mono-
511 cropping systems by including asparagus and okra for international markets lead to an increase in
512 net income (Kasem and Thapa, 2011). Crop diversification by adding high-value crops in Nepal
513 reduced the probability of being poor (Thapa et al., 2018). However, marginal households must
514 diversify more than one third of total agricultural production value into high-value crops to move
515 above the poverty line. Also agricultural income was significantly higher if households shifted their

516 crop portfolio by substituting certain crops or cultivars for others instead of diversifying it by adding
517 crops (Brüssow et al., 2017).

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

529 Some studies used national agricultural, livelihoods or household surveys that present results across
530 a representative national sample including both diversified and non-diversified farming households.
531 For example, both Snapp and Fisher (2015) and Jones et al. (2014) use data from the 2010/11
532 Malawi Integrated Household Survey. For the same measures of diversity and food access, both
533 studies find a positive effect. Jones et al. (2014) highlight that the relationship may be further
534 influenced by gender and wealth as the effect of farming diversity on household dietary diversity
535 was stronger in women-headed households and in wealthier households. Snapp and Fisher (2015)
536 find a small positive effect on food security as growing one additional crop increased HDDS by only
537 2%. Similarly, in Nigeria the positive effect of agricultural diversity on HDDS is significant but small. A
538 10 per cent increase in agricultural diversity results in a 0.16-2.4 per cent increase in HDDS (Ayenew
539 et al., 2018; Dillon et al., 2015) which is still a larger effect than that from increasing agricultural
540 revenue by 10 per cent (Dillon et al., 2015). In some multi-country studies it was possible to compare
541 the results across countries and geographies (Fraval et al., 2019; Passarelli et al., 2018; Ritzema et
542 al., 2019; Sibhatu et al., 2015; Sibhatu and Qaim, 2018a; Tesfaye and Tirivayi, 2020) and some results
543 suggest that the association depends on geographic locations. In sub-Saharan Africa for example, the
544 effect of production diversity is positive in semi-arid zones but negative in the humid/sub-humid
545 zones (Fraval et al., 2019). In Malawi, HDDS increased with production diversity but in Ethiopia, with
546 almost double the average production diversity of Malawi, there is no association with household
547 dietary diversity (Sibhatu et al., 2015).

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

560

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

Reference	Country	Sample size	Method	Indicator of diversity [£]	Indicator of access [§]	Description of relationship [*]
<i>Village to regional scale</i>						
Akerlele 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 [£]	Indicator of access [§]	Description of relationship *
					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 [£]	Indicator of access [§]	Description of relationship *
				– 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 ($\beta=3.498$)
					FSC	Positive ($\beta=0.638$)
			Probit regression model		HDDS	Positive ($\beta=3.545$)
			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 [£]	Indicator of access [§]	Description of relationship *
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 ($\beta=6.59$); Negative ($\beta=0.145$) 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 ($\beta=-0.838$)
					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 ($\beta=0.195-0.317$)
					Share of food expenditure (SID)	Positive ($\beta=0.006-0.01$)
					Share of food expenditure (H')	Positive ($\beta=0.025-0.039$)
Sibhatu et al., 2015a	Indonesia	674 hh	Multivariate regression with Poisson estimator	Farming diversity (C)	M-HDDS	Positive ($\beta=0.054$)
	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 [£]	Indicator of access [§]	Description of relationship [*]	
				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 [£]	Indicator of access [§]	Description of relationship [*]
					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 ² =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 [£]	Indicator of access [§]	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 ($\beta=0.049$)				
	Vietnam	310 hh		Crop diversity (C)		Neutral (ns)
				Livestock diversity (C)		Positive ($\beta=0.068$)
Bellon et al., 2020	Ghana	637 hh	Linear regression	Crop diversity (SID)	Income from agriculture	Positive ($\beta=0.425$)
					Value of products for own consumption	Positive ($\beta=0.175$)
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 ($\beta=0.153-0.158$, IRR=1.008)
				Crop diversity (H')		Positive ($\beta=0.619-1.317$, IRR=1.051)
				Crop diversity (CE)		Positive ($\beta=1.195-4.682$, IRR=1.135)
				Crop diversity (BP)		Positive ($\beta=0.162-0.648$, 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 ($\beta=0.2921-0.3132$)

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

Reference	Country	Sample size	Method	Indicator of diversity [£]	Indicator of access [§]	Description of relationship *
<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 ($\beta=0.0604-0.0249$)
Ayew 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 [£]	Indicator of access [§]	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 ($\beta=0.646-0.702$)
			Poisson regression		MAHFP	Positive ($\beta=0.727-0.741$)
					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 [£]	Indicator of access [§]	Description of relationship [*]
				maize crops	FSC	Positive ($\beta=0.333$)
Somé and Jones, 2018	Burkina Faso	10,860 hh	Mixed linear regression model	Crop diversity (C)	HDDS	Positive ($\beta=0.085$)
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 ($\beta=-0.002 - -0.004$)
				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 ($\beta=0.10$)
				Livestock production diversity (C)		Positive ($\beta=0.32$)
			Negative binomial regression	Crop production diversity (C)	M-HDDS	Mixed: Positive ($\beta=0.03$); Neutral for M-HDDS and crop diversity in best period (ns)
				Livestock production diversity (C)		Positive ($\beta=0.05$)
Zanello et al., 2019	Afghanistan	14,079 hh	Ordinary least squares (OLS) regression, Instrumental variable (IV) regression	Crop diversity (C)	FSC	Positive ($\beta=0.862-1.852$)
				Livestock diversity (C)		Positive ($\beta=2.322-3.144$)
[£] 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 [£]	Indicator of access [§]	Description of relationship [*]
<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 > 0.05); β = regression coefficient; IRR = incidence rate ratios; VIP = variable importance in projection statistic; DID = difference-in-difference estimator, OR = Odds ratio, d = difference in means or median, r/r2 = Pearson correlation coefficient, rho = Spearman rank order correlation coefficient, F = ANOVA F statistic, ME = marginal effects, ns = not significant at the 95% level. The magnitude of the relationships cannot be compared directly across studies as the methods and indicators used differ. Some indicators such as the Shannon diversity index cannot be compared across different locations as they depend on the total number of species. The type of regression model, number and types of crops and livestock species for example will all influence the result. The table shows selected results from each study as assumed relevant to the topic of this review.</p>						

561 8. Diversity and food utilisation

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

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

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

590 Another twenty-three studies measured nutrient intake or a validated proxy for nutrient intake or
591 adequacy, MDD-W or WDDS for women and IYCDDS, IDDS or MDD-C for children. Fifteen studies
592 used adequacy of diet diversity of children as a measure of nutrient intake, and nine of them find a
593 positive association with agricultural diversity (e.g. Gelli et al., 2018; Koppmair et al., 2017; Malapit
594 et al., 2015; Saaka et al., 2017). The results differ by age group (Mulmi et al., 2017), the measure of
595 agricultural diversity used, and are mediated by other factors such as access to nutrition education on
596 child feeding and care practices market participation (Murendo et al., 2018) and other
597 characteristics such as household size and wealth (Saaka et al., 2017). Another consideration is that
598 instead of having to increase the number of food groups a child consumes it is important to reach a
599 certain cut off point when their diet can be considered adequately diverse, i.e. consuming four or
600 more different food groups according to the World Health Organization (2008). The prevalence of
601 children aged 6-23 months with MDD-C, minimum dietary diversity was found to be positively
602 (Kumar et al., 2015; Mitchodigni et al., 2017) or not (Mulmi et al., 2017) associated with agricultural
603 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 [£]	Indicator of utilization [§]	Description of relationship [*]
<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 [£]	Indicator of utilization [§]	Description of relationship [*]
				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 [£]	Indicator of utilization [§]	Description of relationship [*]
		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 [£]	Indicator of utilization [§]	Description of relationship *
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)
					IDDS (children)	Neutral (ns)
				Crop diversity (C)	WDDS	Positive (IRR=1.05)
					IDDS (children)	Neutral (ns)
				Livestock diversity (C)	WDDS	Positive (IRR=1.03)
IDDS (children)	Positive (IRR=1.04)					

Reference	Country	Sample size	Method	Indicator of diversity [£]	Indicator of utilization [§]	Description of relationship [*]
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 μ 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 [£]	Indicator of utilization [§]	Description of relationship [*]
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
				Agrobiodiversity (C)	IDDS (children)	Neutral (uncorrelated)
					IDDS (toddler)	Neutral (uncorrelated)
					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
				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 [£]	Indicator of utilization [§]	Description of relationship [*]
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, β = 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, IYCDSD = Infant and Young Child Dietary Diversity, MDD = Minimum dietary diversity, MDD-C=Minimum Dietary Diversity of Children, MDD-W = Minimum Dietary Diversity for Women, MPA = Mean Probability of Adequacy of Micronutrient Intake, NAR = Nutrient Adequacy Ratio, NAR-mean = mean nutrient adequacy ratio, WDDS = Women's Dietary Diversity Score, WDDS-10 = 10-Food Group Women's Dietary Diversity Score. Prevalence of stunting and wasting is defined as the percentage of children with HAZ and WHZ, respectively, of more than 2 standard deviations below median. IDDS (children) differs from IYCDSD in the number of food groups used and/or the age group which is 6-23 months for IYCDSD. MDD-C differs from IYCDSD in that it measures the prevalence of children consuming at least four of the seven food groups included. IDDS (mother) differs from WDDS in the number of food groups considered

* CC = Canonical correlation coefficient, β = regression coefficient, DID = difference-in-difference estimator, VIP = variable importance in the projection. The magnitude of the relationships cannot be compared directly across studies as the methods and indicators used differ. Some indicators such as the Shannon diversity index cannot be compared across different locations as they depend on the total number of species. The type of regression model, number and types of crops and livestock species for example will all influence the result. The table shows selected results from each study as assumed relevant to the topic of this review.

1 9. Diversity and food security at the global scale

2 We found five studies study the relation of agricultural diversity to food security on the global scale.
3 Because of the low sample size, results are summarized in this separate section for all four food
4 security dimensions together. Since 1961, global crop diversity increased which may have influenced
5 national food supply overall. Crop diversity (H') increased by about 20% between 1961 and 2016 and
6 crop species richness increased more strongly than evenness in two studies using different national
7 agricultural data (Aizen et al., 2019; Khoury et al., 2014). In contrast to species richness, the results
8 for evenness were mixed between different world regions with Europe being the only region with a
9 decline in evenness but increase in richness. Dominance of the most abundant crop commodities
10 declined and agricultural production is increasingly homogeneous (Aizen et al., 2019; Khoury et al.,
11 2014). Going back even further in time, Nabhan et al. (2012) analysed how agrobiodiversity has
12 changed over time by comparing late 19th-c. to early 20th-c. records with their own fieldwork in 2005
13 in three regions of Tajikistan, Egypt, and the United States. They find that farmers adopt and
14 abandon crop varieties for different reasons in the three locations and that local and global factors
15 influence the conservation of agrobiodiversity. While for example diversity in the Tajikistan study
16 area remained roughly the same over time and only certain species changed their distribution in
17 space or time, diversity declined in the study area in the United States (northern Arizona). The
18 reason is that water scarcity led to a loss of varieties, and livelihoods shifted away from farming.

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

29 The diversity-stability hypothesis was tested for national crop yield between 1961 and 2010 across
30 the 100 most populous countries (Renard and Tilman, 2019). Crop diversity at the national level
31 ($\exp(H')$) is statistically associated with increased temporal stability of crop yield, irrespective of
32 aggregation to crop groups ($R^2 = 0.32 - 0.37$), and this stabilizing effect is similar in magnitude than
33 the destabilizing effect of rainfall variability. The study did not find any crop group contributing more
34 to yield stability than others. Troell et al. (2014) shows price indices for individual food sectors and
35 for food in the aggregate during the period 1990–2013. Cereal and oilseed prices have shown much
36 stronger variation than have price indices for meat, aquaculture, and capture fisheries. The
37 coefficient of variation for food in the aggregate is 0.33 over the entire period—substantially higher
38 than that of aquaculture (0.16), fisheries, and meat (0.21) but below that of grains and oils (0.4).
39 Lower volatility in the meat and fish sectors suggests a significant share of substitution possibilities
40 between various animal protein products and various feed ingredients.

41 **10. Synthesis and Recommendations**

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

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

		Food security dimension			
		Availability	Access	Stability	Utilisation
Spatial scale of data collection	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					

59

60

61 **Common reasons for positive and negative relationships**

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

86 **The different branches of literature**

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

99 **Recommendations for future research on diversity and food security**

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

- 102 ▪ The food dimension and indicators representing that dimension should be clearly stated and
103 explained. Where possible researchers should use established indicators. They have often been
104 tested or validated in several case studies and were developed and discussed by a commission of

105 experts. If new indicators are introduced, they should be validated and compared with existing
106 ones.

- 107 ▪ Some studies speak of “diversifying into” and it is important to clarify the nature of
108 diversification studied in this case. A new crop can be an addition to the existing crop portfolio
109 or a replacement for another crop. Specific crops such as cash crops can have benefits to
110 farmers also in the absence of overall diversification of the system.
- 111 ▪ When measuring the diversity-stability relationship, future studies should consider that the
112 relationship might be always positive for some measures of stability, but not for others. From a
113 statistical point of view the mean of variables is more stable as more variables and their
114 fluctuations are averaged (Doak et al., 1998).
- 115 ▪ When choosing a measure of diversity, consider that evenness in the distribution of different
116 food items or food groups is not necessarily desired from a nutritional perspective. A high score
117 only indicates health benefits if calculated from a list of healthy foods. Even then it is not
118 necessary to consume equal quantities of everything, but the amount required for a specific age
119 and sex group.
- 120 ▪ An element of scale-dependency should be introduced into diversity frameworks. Conclusions
121 on the benefits of agricultural diversity on the national or global scale might not be scalable to
122 the field scale and vice versa. The effect might be explained by a certain combination of
123 production / agroecological zones on a larger scale that cannot be reproduced on the field scale
124 and vice versa.
- 125 ▪ Several alternative strategies for increasing food security should be studied along with
126 diversification to compare the relative importance of each strategy for similar outcomes.

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

- 129 ▪ An interesting question is related to thresholds in achieving benefits from diversification. There
130 are three considerations here. Firstly, such a threshold is a probably a relative, rather than
131 absolute threshold, depending on the ecological and economic context of the farm and potential
132 benefits from diversification. High diversity in one context might be average in another.
133 Secondly, there might be a minimum requirement to achieve gains from diversification.
134 Achieving minimum dietary diversity of children through increasing agricultural diversity is a
135 good example. Thirdly, from a certain point, the benefits of diversity might diminish, which
136 suggests a challenge of “optimal” level of diversity.
- 137 ▪ The relationship between diversity, a characteristic of a farming system, and diversification, the
138 process of increasing diversity in a farming system, should be explored further. Existing diversity
139 can limit or enable further diversification. Already diversified systems might have characteristics
140 such as high level of flexibility in allocating resources, that enable even more diversification. On
141 the other hand, at already high levels of diversity there might be no further benefit from
142 diversification, or only at high costs, that may be diminishing returns. In some reviewed articles
143 80% of the farmers already practiced diversification so further diversification might not be their
144 priority.
- 145 ▪ The question of complementarity and redundancy between several species of crops for example
146 is understudied. This means that the benefits of diversification are not necessarily proportional

147 to the increase in diversity and relevant functions can on the other hand be maintained at lower
148 levels of diversity. Drought resilience for example can be achieved through the right species
149 composition irrespective of diversity (Dardonville et al., 2020).

- 150 ■ Apart from modelling and quantifying the diversity-food security relationships, more focus on
151 the pathways from diversification to food security should be researched. The most researched
152 pathway is perhaps through consumption of own production but there might also be market-
153 based agricultural diversification (Bellon et al., 2020). Consumption versus income-generating
154 pathways are for example discussed for India in Gillespie et al. (2012).
- 155 ■ There are noticeable gaps in understanding the relationship between diversity and food security;
156 on the national / global scale. On a national scale for example it would be interesting to know if
157 the prevalence of mal- or undernutrition change when the country decreased the number of
158 commodities produced nationally?

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

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167 Linkage scheme. KW designed the search syntax and pre-selected publications based on the initial
168 abstract screening. All authors either reviewed the pre-selected publications, extracted data from
169 the included publications and/or wrote parts of the manuscript with KW. KW and JPD reviewed and
170 cleaned data for the synthesis tables describing the magnitude of the observed effects and details of
171 methods. All authors read and reviewed the full articles included in the review after initial screening
172 to assess their relevance and contributed to revising the manuscript multiple times before
173 submission.

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