

# Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries

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*The declining diversity of agricultural production and food supplies worldwide may have important implications for global diets. The primary objective of this review is to assess the nature and magnitude of the associations of agricultural biodiversity with diet quality and anthropometric outcomes in low- and middle-income countries. A comprehensive review of 5 databases using a priori exclusion criteria and application of a systematic, qualitative analysis to the findings of identified studies revealed that agricultural biodiversity has a small but consistent association with more diverse household- and individual-level diets, although the magnitude of this association varies with the extent of existing diversification of farms. Greater on-farm crop species richness is also associated with small, positive increments in young child linear stature. Agricultural diversification may contribute to diversified diets through both subsistence- and income-generating pathways and may be an important strategy for improving diets and nutrition outcomes in low- and middle-income countries. Six research priorities for future studies of the influence of agricultural biodiversity on nutrition outcomes are identified based on gaps in the research literature.*

## INTRODUCTION

The composition of global food supplies has become increasingly similar in recent decades.<sup>1</sup> These changes have been paralleled by the emergence of modern intensive agriculture, which explicitly aims to simplify biological diversity and promote uniformity for the purpose of facilitating economies of scale.<sup>2</sup> Yet, agricultural biodiversity serves multiple beneficial ecological and societal roles. Species diversity within agroecosystems supports a variety of ecosystem services and can enhance the productivity and stability of these systems.<sup>3</sup> Agricultural biodiversity also contributes to defining

and maintaining cultural identities and livelihood diversity.<sup>4,5</sup> Furthermore, biodiversity within agricultural systems is necessary for preservation of plant genetic resources that are essential for future adaptation to environmental change.<sup>6</sup> The declining diversity of agricultural production and food supplies worldwide may have important implications for global diets.

In spite of the abundance of food produced by modern intensive agricultural systems, poor quality diets, commonly manifested as diets lacking diversity, remain a widespread challenge around the globe. Diet diversity is thought to be essential for optimum human nutrition. Diverse diets contribute to overall macro-

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and micronutrient adequacy,<sup>7–9</sup> are associated with improved nutritional status of individuals,<sup>10</sup> and may help individuals meet dietary needs that are as of yet unknown (eg, through intake of any of thousands of bioactive phytochemicals contained within plant foods that may help to prevent chronic disease).<sup>11</sup> Yet, monotonous, staple-based diets deficient in essential micronutrients continue to characterize the diets of most low-income households in low- and middle-income countries (LMICs).<sup>12</sup> At the same time, in nearly all countries globally, diets that are highly differentiated, characterized by a diversity of energy-dense, ultraprocessed packaged foods, yet lacking in sufficient fruits, vegetables, and pulses, have emerged as a new manifestation of poor diet quality.<sup>13</sup>

Despite an intuitive connection between the diversity of agricultural production and the diversity of diets, there has been no comprehensive synthesis of the empirical evidence for these associations. Understanding this relation, particularly in LMICs, is critically important given the concurrent challenges of persistent undernutrition and the rise in the prevalence of obesity and diet-related noncommunicable disease facing these countries.<sup>14</sup> Changes in global food systems (ie, food production, distribution, trade, and marketing) are principally responsible for this emerging landscape of chronic illness.<sup>15</sup> However, little evidence is available to understand how specific components of food systems, including agricultural production diversity, may be contributing to poor-quality diets and adverse nutrition outcomes. This evidence is essential to designing policies and interventions that appropriately leverage agricultural biodiversity, in concert with components of other food systems, to address the multiple burdens of malnutrition in LMICs.

The objectives of this review are to (1) assess the nature and magnitude of the associations of agricultural biodiversity with diet quality and nutritional status in LMICs and (2) determine the factors that lead to heterogeneity in these associations, as well as the potential causal pathways linking agricultural diversification with nutrition outcomes, particularly considering the influence of market access and participation.

## LITERATURE SEARCH

Articles in PubMed, Web of Science, Scopus, Agris, and Google Scholar were reviewed using a standard set of search terms. Studies were excluded if they (1) were not in English; (2) did not include at least 1 metric of farm-, village-, or regional-level terrestrial, cultivated agricultural biodiversity; (3) did not explicitly measure at least 1 diet or nutrition outcome; or (4) were exclusively centered on homestead gardens or biofortified crops rather

than entire farm systems. Both homestead gardens and biofortified crops contribute in important ways to on-farm agricultural biodiversity and have been shown through experimental research to improve diet quality, micronutrient status, and health outcomes<sup>16,17</sup>; however, these approaches do not account for how farm- or regional-scale changes in agricultural biodiversity may affect nutrition outcomes. Such scales are the focus of this review given the importance of on-farm ecological interactions for influencing farm productivity and resilience<sup>18</sup>; the role of the entire farm system in influencing farmers' decisions related to crop choice, use, and management<sup>19</sup>; and plausible connections between regional-scale agricultural biodiversity and the diversity of foods in regional markets.<sup>20</sup>

The findings of this review build on those of a previous review that examined the association of agricultural biodiversity and diet outcomes in a smaller set of studies as part of a broader series of research questions.<sup>21</sup> The current review includes 15 new studies not previously reported. Because several of these studies were published within the timeframe of the previous review, a publication year exclusion criterion was not applied to this review. The limited size of the empirical literature assessing the association of agricultural biodiversity with diet and nutrition outcomes and the need for a comprehensive review examining the magnitude and nature of this association, as well as modifying factors and mechanisms, warrant inclusion of all published studies to date.

Given the heterogeneity observed in measurement approaches, indicators, analytic models, and correlation measures presented, a quantitative meta-analysis was not conducted; instead, findings were qualitatively compared and contrasted across the reviewed studies. In addition, few of the reviewed studies directly measured diet quality. Most studies assessed diet diversity as a proxy for diet quality. Therefore, the evidence presented for the first objective of the review is largely centered on assessing the association between agricultural biodiversity and diet diversity. Furthermore, for the second objective of the review, those studies that assessed market access measured only simple proxies of market access (eg, distance to nearest town, market or road; ownership of mode of transport). Therefore, the specific nature of markets accessed by households was not assessed.

## MEASUREMENT APPROACHES

In total, 23 studies that showed an association between at least 1 indicator of agricultural biodiversity and an indicator of diet quality, diversity, or nutritional status were identified (Table 1<sup>19,20,22–36,37–42</sup>). The analyses

**Table 1 Summary of studies examining the association between agricultural biodiversity and nutrition outcomes**

Reference	Location	Sample size	Nutritional indicator(s) <sup>a</sup>	Indicator(s) of agricultural biodiversity <sup>a</sup>	Indicator(s) of market access	Association between agricultural biodiversity and nutrition outcomes <sup>b</sup>
Dewey (1981) <sup>24</sup>	Mexico	149 children	DD (ie, proportional calories contributed by 46 food categories) (24 h; children 2–4 y); child height, weight-for-height DDS (10), FVS, MAR (7 d; adults)	Number of HH crops (additional information not provided)	N/A	+: Number of HH crops vs DD (adjusted $r = 0.25$ for $HH \geq 5$ crops); number of HH crops vs child height (adjusted $r = 0.29$ )
Torheim et al. (2004) <sup>22</sup>	Mali	319 HH	DDS (7 d; preschool-aged children)	Crop count	N/A	+: MAR vs crop count ( $\beta = 0.002$ ); null association DDS vs crop count
Ekasa et al. (2008) <sup>37</sup>	Kenya	144 HH	FVS (7 d; preschool-aged children)	Count of food crops, domesticated animals, and wild collected food items combined	N/A	+: FVS vs ABD (unadjusted $R^2 = 0.485$ )
Herforth (2010) <sup>36</sup>	Kenya, Tanzania	Kenya: 169 HH (87 HH w/children 2–5 y); Tanzania: 207 HH with children 2–5 y	DDS (12), FVS (24 h; HH); DDS (8), FVS (24 h; child); number of fruits and vegetables consumed (24 h; HH)	Crop count (past 12 months); crop and animal species raised on farm	N/A	+: FVS (HH) vs crop count ( $\beta = 0.171$ ) (Kenya); crop count vs DDS (HH) ( $\beta = 0.067$ ), DDS (child) ( $\beta = 0.049$ ), FVS (HH) ( $\beta = 0.141$ ), FVS (child) ( $\beta = 0.165$ ) (Tanzania)
Gonder (2011) <sup>25</sup>	Philippines	844 individuals from 261 HH	DDS (8), FVS (24 h; all individuals in HH and combined for HH); child (<60 mo) HAZ, WAZ, WHZ	Crop and livestock species count; “production group” count (ie, fruits, vegetables, grains, livestock, and miscellaneous items)	N/A	Null: no associations observed
Remans et al. (2011) <sup>31</sup>	Kenya, Malawi, Uganda	170 HH	DDS (15) (24 h; HH); serum iron, retinol among women	Edible species count (measured directly, not via survey); 4 nutritional functional diversity metrics	N/A	Null: DDS vs edible species count or nutritional functional diversity not associated; associations not reported for serum iron/retinol; +: DDS vs village-level edible species richness (ANOVA, $F$ value not reported)
Ecker et al. (2012) <sup>38</sup>	Ghana	3976 HH	“Micronutrient-sensitive dietary diversity score” (similar to DDS, but not defined) (HH)	Food production activities count	N/A	+: DDS vs food production activities count ( $\beta = 0.206$ ) (all HH), ( $\beta = 0.199$ ) (market-oriented HH), ( $\beta = 0.203$ ) (subsistence-oriented HH)
Powell (2012) <sup>23</sup>	Tanzania	274 HH	DDS (6, 14) (24 h and 7 d; children 2–5 y), FVS (24 h and 7 d; children 2–5 y); MAR (2 d 24 h)	Crop species count	N/A	+: DDS (6) (7 d) vs crop count (unadjusted $r = 0.15$ ); DDS (14) (7 d) vs crop count (unadjusted $r = 0.29$ ); FVS (7 d) vs crop count (unadjusted $r = 0.33$ ); MAR vs crop count (unadjusted $r = 0.18$ )
Oyarzun et al. (2013) <sup>32</sup>	Ecuador	51 HH	FVS (24 h; HH aggregated across each individual)	Margalef Index; Shannon Index; crop species richness (measured directly, not via survey)	N/A	+: FVS vs crop species richness (unadjusted $R^2 = 0.194$ )

(continued)

Table 1 Continued

Reference	Location	Sample size	Nutritional indicator(s) <sup>a</sup>	Indicator(s) of agricultural biodiversity <sup>a</sup>	Indicator(s) of market access	Association between agricultural biodiversity and nutrition outcomes <sup>b</sup>
Walingo and Ekesa (2013) <sup>26</sup>	Kenya	164 HH	FVS (23) (24 h; child 12–60 mo); child stunting, wasting, and underweight; recent diarrhea, malaria, or acute respiratory infections in children	Count of crop and livestock species; Shannon-Wiener Index for species diversity	N/A	+: FVS vs crop and livestock species count (unadjusted $r = 0.496$ )
Jones (2015) <sup>39</sup>	Bolivia	251 HH	Child feeding index (7 components) including DDS (24 h, 7 d; children 6–23 mo)	Crop species count	N/A	+: Composite child feeding index for children 6–23 mo vs crop species count ( $\beta = 0.04$ )
Jones et al. (2014) <sup>33</sup>	Malawi	6623 HH	DDS (12), FCS (7 d; HH)	Crop species count; crop and livestock count; Simpson's Index	N/A	+: DDS vs crop species count ( $\beta = 0.23$ ); DDS vs Simpson's Index ( $\beta = 0.68$ )
Pellegrini and Tasciotti (2014) <sup>35</sup>	Albania, Indonesia, Malawi, Nepal, Nicaragua, Pakistan, Panama, Vietnam	33 119 HH (pooled)	DDS (13), FVS (recall period not specified; HH)	Crop count	N/A	+: DDS vs crop count ( $\beta = 0.01$ ) (pooled sample)
Dillon et al. (2015) <sup>40</sup>	Nigeria	2154 HH	DDS (12) (7 d; HH)	Food crop group count (5) (unspecified groups; non-food crops excluded)	N/A	+: DDS vs food crop group count (log $\beta = 0.24$ )
Kumar et al. (2015) <sup>27</sup>	Zambia	3040 HH	DDS (7) (24 h; 6–23 mo children); DDS (12); (recall period not specified; HH); child HAZ, WAZ, WHZ (and corresponding stunting, underweight, wasting prevalences)	Crop count (ie, field crops and vegetables), crop group count (7), number of agricultural activities (field crops, horticultural crops, animal rearing, and products) (all HH level); cluster-level maximum production diversity	Household ownership of mode of transport	+: Crop count vs DDS (child) ( $\beta = 0.22$ ), DDS (HH) ( $\beta = 0.25$ ); crop count vs HAZ (24–59 mo) ( $\beta = 0.03$ ), HAZ (6–23 mo) ( $\beta = -0.08$ )
Malapit et al. (2015) <sup>28</sup>	Nepal	3332 HH	DDS (9) (24 h; maternal); DDS (7) (24 h; children 6–59 mo); maternal BMI; child HAZ, WAZ, WHZ	Crop group count (9) (aligned with DDS food groups)	N/A	+: Crop group count vs DDS (maternal) ( $\beta = 0.1$ ), DDS (child) ( $\beta = 0.06$ ), maternal BMI (HH with female decision makers and absent male decision makers) ( $\beta = -0.762$ ), child HAZ (HH with women as decision makers, absent male decision makers) ( $\beta = 0.14$ ), child WAZ/WHZ ( $\beta = 0.03/0.03$ )

(continued)

Table 1 Continued

Reference	Location	Sample size	Nutritional indicator(s) <sup>a</sup>	Indicator(s) of agricultural biodiversity <sup>a</sup>	Indicator(s) of market access	Association between agricultural biodiversity and nutrition outcomes <sup>b</sup>
Shively and Sununtnasuk (2015) <sup>29</sup>	Nepal	1769 children 0–59 mo	Child HAZ (<24 mo, 24–59 mo)	Crop count; share of each food group within total crop diversity; any production of eggs, milk or meat	N/A	–: Crop count vs child HAZ (<24 mo) ( $\beta = 0.05$ ), child HAZ (24–59 mo) ( $\beta = 0.03$ )
Sibhatu et al. (2015) <sup>34</sup>	Indonesia, Kenya, Ethiopia, Malawi	8230 HH	DDS (12) (7 d, HH)	Crop and livestock species count; food crop species count; Margalef species richness index	Self-reported distance to nearest market-place where produce can be sold	–: DDS vs crop and livestock species count (pooled) ( $\beta = 0.01$ ), Indonesia ( $\beta = 0.05$ ), Malawi ( $\beta = 0.02$ ); $\beta$ s interpreted as semielasticities
Snapp and Fisher (2015) <sup>41</sup>	Malawi	9189 HH	DDS (12), FCS (9) (7 d; HH)	Count of cultivated non-maize crop groups (10); count of cultivated nonmaize crop groups intercropped with maize (10)	Distance of household to nearest major road (km); presence of bus stop in community; household bicycle ownership; presence of daily market in community	–: DDS vs both indicators of ABD (IRR = 1.019); FCS vs count of cultivated nonmaize crop groups (IRR = 0.333)
Bellon et al. (2016) <sup>20</sup>	Benin	652 HH	DDS (10) (24 h; maternal) (food groups counted only if individual consumed at least 15 g of foods from the group)	Count of plant species grown and collected during the previous agricultural season	Self-reported travel time to main market town (minutes)	–: DDS vs plant species count ( $\beta = 0.04$ )
Jones (2017) <sup>19</sup>	Malawi	3000 HH	DDS (10) (7 d; HH); daily energy, protein, iron, zinc, and vitamin A intake per adult equivalent (7 d; HH)	Species richness of cultivated crops; crop varietal richness; crop nutritional functional richness (count of crop groups based on food groups included in DDS) (10)	Household distance (Euclidean) to the nearest town with population >20 000; household distance to nearest road	–: DDS vs crop species richness ( $\beta = 0.08$ ), crop varietal richness ( $\beta = 0.09$ ), crop nutritional functional richness ( $\beta = 0.13$ )
Koppmair et al. (2017) <sup>42</sup>	Malawi	408 HH	DDS (12) (24 h; household, under-5 child, maternal)	Production diversity score (count of crop groups based on crop groups included in DDS) (12); crop species count	Presence of a local village market; reported walking hours to district-level market	–: DDS for household, child, mother vs production diversity score ( $\beta = 0.15$ , 0.19, 0.13)
M’Kaibi et al. (2016) <sup>30</sup>	Kenya	525 HH	DDS (9) (24 h; children 24–59 mo); child HAZ, WAZ, WHZ	Count of food crops, domesticated animals, and wild collected food items combined	N/A	–: DDS vs ABD (ANOVA: $F = 14.791$ ); no associations observed with anthropometric indicators

<sup>a</sup>Number in parentheses immediately following nutritional or agricultural biodiversity indicator indicates the maximum number of foods or crop groups used for the indicator. The information in parentheses (ie, 24 h, 7 d, etc) following the nutritional indicators indicates the recall period for the indicator used, as well as the level at which the data were collected (ie, household-level; child-level, etc).

<sup>b</sup> $r$  is the Pearson product-moment correlation coefficient.  $\beta$  is the partial regression coefficient from adjusted regression model unless otherwise specified. + indicates a positive association between the agricultural biodiversity indicator and the nutrition indicator. Crop count refers to a count of distinct crop species. All agricultural biodiversity indicators were assessed based on respondent recall and were at the level of the household or farm unless otherwise specified. All associations reported were statistically significant at  $P < 0.05$ .

Abbreviations: ABD, agricultural biodiversity; ANOVA, analysis of variance; BMI, body mass index; DD, dietary diversity; DDS, dietary diversity score (ie, count of food groups); FCS, food consumption score; FVS, food variety score (ie, count of food items); HAZ, height-for-age Z score; HH, household; IRR, incident rate ratio; MAR, mean adequacy ratio; N/A, not applicable; WAZ, weight-for-age Z score; WHZ, weight-for-height Z score.

were predominantly carried out using data from sub-Saharan African countries (17 studies), and nearly all were cross-sectional, with only 1 study using a longitudinal analysis.<sup>19</sup> All studies that assessed diet used 1 or more indicators of diet diversity (ie, either a count of food groups or food items). Only 3 studies assessed diet quality (ie, estimating nutrient intakes). Two studies assessed the mean ratio of intake to recommended intake of energy and 9 micronutrients,<sup>19,22,23</sup> and another estimated daily intakes per adult equivalent of energy, protein, iron, zinc, and vitamin A within households.<sup>19</sup> Overall, measurement instruments used to collect dietary data and the exact specifications of the dietary indicators varied widely across the studies. Few studies assessed metrics of nutritional status beyond diet diversity. Seven studies measured anthropometry among preschool-aged children,<sup>24–30</sup> 1 assessed maternal body mass index (BMI),<sup>28</sup> and 1 assessed serum indicators of micronutrient status (ie, iron and retinol) among women.<sup>31</sup>

Agricultural biodiversity was assessed in all studies reviewed using simple count indicators of the number of distinct crop species on farms or managed by households (ie, crop species richness) or by assessing richness of edible crop species, crop groups, or crop and livestock species. One study further assessed crop varietal richness (ie, subspecies distinctions),<sup>19</sup> and 4 studies<sup>26,32–34</sup> assessed the equality of distribution of crop species on farms using indicators of crop species evenness (eg, Margalef Species Richness Index, Simpson's Index, Shannon-Wiener Index). Two studies further assessed nutritional functional diversity or richness.<sup>19,31</sup> Functional diversity measures the number of distinct species in a population that have unique functional traits. Nutritional functional diversity as applied to assessing agricultural biodiversity thus indicates those crop species that provide a unique combination of nutrients or a unique nutritional functional group (eg, legume, dark green leafy vegetable) to the farm system.

#### ASSOCIATIONS OF AGRICULTURAL BIODIVERSITY AND DIET DIVERSITY

In total, 19 of 21 studies observed a positive association between agricultural biodiversity and diet diversity (Table 1). In most of these studies, the magnitude of the association was small. For example, in adjusted analyses, a 1-unit increase in crop species richness was associated with a 0.01,<sup>34,35</sup> 0.07,<sup>36</sup> 0.08,<sup>19</sup> 0.23,<sup>33</sup> and 0.25<sup>27</sup> unit increase, respectively, in the number of food groups consumed by households. This implies that potentially large and unrealistic increases in crop species richness may be required to have a nutritionally meaningful impact on the diversity of household diets. These

7 studies that produced adjusted associations between crop species richness and food group diet diversity are comparable in many respects (ie, the coefficients noted are from household-level analyses; food group counts as opposed to food variety scores are used; and crop species richness is reported, as opposed to counts of crops and animals or counts of just fruits and vegetables). However, there is still heterogeneity in the indicators assessed and the underlying data used to calculate those indicators. For example, 7, 10, 12, or 13 food groups are used in the diet diversity indicators in these studies, 3 use dietary data based on a 7-day recall period,<sup>19,33,34</sup> 1 uses data based on a 24-hour recall period,<sup>36</sup> 2 studies did not provide information on the recall period used,<sup>27,35</sup> and 1 study did not specify the methodology used to collect dietary data.<sup>35</sup> Diet assessment method, recall period, and definition of food group diversity may all influence observed associations. Seven-day recall periods, for example, may misleadingly inflate diversity scores from indicators that are based on 24-hour recall data<sup>43,44</sup> by capturing a longer recall period. Longer recall periods may also limit variability in observed diversity scores. Selection of food groups will also alter observed associations between agricultural biodiversity and diet diversity, particularly if the selected food groups do not align with those crops or crop groups used to define agricultural biodiversity.<sup>45</sup>

In those few studies that assessed the linearity of the association between agricultural biodiversity and diet diversity, the square term for agricultural biodiversity was negative in regression models that used diet diversity as a dependent variable.<sup>34,35</sup> This suggests an inverse U relationship such that at very low levels of agricultural biodiversity, a marginal increase in agricultural biodiversity is associated with precipitously higher diet diversity, whereas, at moderate and high levels of agricultural biodiversity, the same marginal increase is associated with no change and lower diet diversity, respectively. Both subsistence- and market-oriented mechanisms may explain this observed threshold effect. For example, one hypothesis suggests that the declining marginal dietary benefits of agricultural diversification at high levels of agricultural biodiversity may be due to foregone income from specialization in one or only a few cash crops.<sup>34</sup> In contrast, an elegant assessment of the nutritional functional diversity of farms in Kenya, Malawi, and Uganda provides evidence that the capacity of farms to supply dietary nutrients for consumption has a threshold at high levels of agricultural biodiversity.<sup>31</sup> Across these 3 countries it was observed that on-farm richness of edible crop species was associated with a greater diversity of potential dietary nutrients supplied by farms. This association was not strictly linear however. For example, beyond 25 cultivated species, there

was minimal improvement in total farm nutrient output. This threshold, a markedly high level of species diversity, suggests that the potential dietary benefits of agricultural diversification (using available nutrient supply as a proxy) are maintained across an impressive range of on-farm species diversity. When examining the nutritional functional diversity of vitamins only (ie, thiamin, riboflavin, folate, niacin, and vitamins A and C), the authors observed that the linearity of the relationship was much less clear and that nutritional functional diversity depended greatly on the existence of only a few species. The impact of agricultural diversification on the availability of limiting nutrients in diets may be of greater public health importance than the supply of any or all nutrients from agricultural production, particularly in low-income regions where even moderate deficiencies of specific nutrients (eg, iron, vitamin A) can have profound health and developmental impacts on children and other vulnerable groups. However, no studies to date have examined the human health impacts of on-farm nutritional functional diversity.

Considering the increasing marginal dietary benefits of agricultural diversification on farms with low agricultural biodiversity, both subsistence- and market-oriented mechanisms may play important roles. Sibhatu et al<sup>34</sup> hypothesize that the larger magnitude of relationship between agricultural biodiversity and diet diversity that they observed among farmers in Indonesia as compared with farmers from sub-Saharan Africa is because most of the Indonesian farmers in their sample grew only rubber. Those farmers that diversified within these low biodiversity systems often adopted oil palm as an additional cash crop, and therefore dietary gains were realized through increased income and the purchase of more diverse foods. Other evidence points to agricultural diversification among farms with low agricultural biodiversity benefiting diets via a subsistence pathway. In Ecuador, for example, households with farms of low agricultural biodiversity consumed fewer on-farm food items than households with highly agrobiodiverse farms, and on-farm species richness was positively associated with the number of food items consumed from own production.<sup>32</sup> Similar trends were observed in Mexico, where greater crop diversity was associated with less dependence on purchased foods.<sup>24</sup> Dewey<sup>24</sup> suggests that less reliance on purchased foods was a distinct advantage in regions where food prices were higher than wages. However, it is difficult to identify discrete mechanisms for this threshold effect given the reliance of the reviewed studies on observational data and the lack of analysis explicitly examining effect heterogeneity. Households with more biodiverse farms that rely less on purchased foods may also be poorer households, with fewer employment opportunities and

social connections and less access to robust markets. For these households, greater consumption of own production and fewer food purchases may function as a coping mechanism against food insecurity rather than as a derived benefit of greater agricultural biodiversity. Alternatively, households cultivating only 1 or 2 crops may earn substantial income from off-farm sources—an important independent determinant of household diet quality<sup>34,38</sup>—thus limiting the importance of agricultural production as a source of either revenue or subsistence for the household. Therefore, analysis of food sourcing behaviors provides only a partial understanding of the potential mechanisms linking agricultural biodiversity and diet diversity, if the association can, in fact, be interpreted as causal. The confounding influence of poverty, wealth, and food insecurity cannot be fully accounted for in the reviewed studies.

### **ROLE OF MARKETS IN UNDERSTANDING THE POTENTIAL NUTRITIONAL BENEFITS OF AGRICULTURAL DIVERSIFICATION**

On-farm nutrient provisioning does not comprehensively explain the nonlinear relationship between agricultural biodiversity and diet quality. The role of agricultural input and output markets as well as consumer food markets as driving forces motivating the selection and use of crop species and access to diverse foods for consumption must also be considered. Only 6 of the reviewed studies examined the importance of market access, concurrent with agricultural biodiversity, for diet quality.<sup>19,20,27,34,41,42</sup> All of these studies observed a positive association between market access and diet diversity, although for 1 of the studies,<sup>20</sup> this association was consistent with random variation. These studies did not differentiate between types of markets (eg, agricultural input, agricultural output, or consumer food markets) but rather used proxy indicators of market access such as vehicle ownership or distance to a nearby road or population center. In all 6 studies, agricultural biodiversity remained significantly correlated with diet diversity even after adjusting for market access. Jones<sup>19</sup> assessed the statistical interaction between agricultural biodiversity and market access on diet diversity in a longitudinal sample from Malawi and found no evidence of effect modification. Sibhatu et al<sup>34</sup> assessed this same interaction and found that the association between agricultural biodiversity and diet diversity among Malawian households further from the nearest market was less than that among households closer to the nearest market. However, this heterogeneity was not observed in their analysis of samples from Indonesia, Kenya, or Ethiopia or in a pooled sample across all countries. Koppmair et al<sup>42</sup> assessed samples

from Malawi that were stratified by market access and also observed that the association between agricultural biodiversity and diet diversity was stronger in households further from district markets. This effect heterogeneity seems intuitive. Households with less access to markets depend less on market-purchased food and more on own production as a source of diet diversity. Indeed, across all studies, the largest associations observed between agricultural biodiversity and diet diversity were from studies in Zambia<sup>27</sup> and Malawi,<sup>33</sup> countries with poorly functioning markets and where subsistence agriculture dominates. However, it is clear from the evidence that there is not a consistent interaction between market access and agricultural biodiversity on diet diversity, and these dynamics certainly vary across contexts. Households in more remote or subsistence settings may simply have less diverse production systems overall, reflecting the stronger magnitude of association between agricultural biodiversity and diet diversity among farms of low biodiversity noted earlier. Further research is needed to elucidate these dynamics and to understand the contextual factors that may influence the role of markets in moderating the relationship between agricultural biodiversity and diets.

Assessing access to markets using indicators of proximity (eg, self-reported travel time or Euclidean distance to nearest markets) likely does not capture the complex construct of market access, nor does market access, even measured rigorously, necessarily equate to market participation. Assessing the market orientation of farms is perhaps a more direct proxy indicator of household participation in certain markets and is an alternative approach to understanding how markets may intersect with agricultural biodiversity to influence diets. Evidence from the reviewed studies suggests that households with farms that are at least partly market oriented have more diverse diets than less market-oriented farms.<sup>19,33,34,42</sup> No consistent definition of or threshold for market orientation was defined among these studies. Market orientation was modeled either as a dichotomous variable (ie, selling any share of farm production)<sup>34</sup> or as a continuous variable (ie, proportion of cultivated area devoted to nonfood cash crops<sup>42</sup> or to crops that are at least in part sold<sup>33</sup>; proportion of total harvest sold<sup>19</sup>; proportion of total maize production or other food crop production sold<sup>42</sup>). Market-oriented crops may provide greater income from agriculture that can be used to purchase diverse foods but may also be consumed directly if they are only partly sold (eg, by saving a share of market-oriented horticultural crops for home consumption). Despite the importance of market-oriented production for diet diversity, the relationship between agricultural biodiversity and diet diversity appears to be consistent across

farms with varying degrees of market orientation.<sup>19,20,38</sup> This observation is consistent with evidence that suggests that greater diversification, especially in high subsistence settings, may reflect greater, and not foregone, opportunities for market engagement by smallholder farmers who maintain a foundation of subsistence staple crop production but have also diversified into one or more cash crops.<sup>33</sup> This same trend was noted in Burkina Faso where local markets were observed to enhance agricultural biodiversity by providing an outlet for household production.<sup>20</sup> Furthermore, more highly diversified farms are commonly associated with higher household agricultural revenues, indicating the importance of diversification for not only subsistence production but also commercial production.<sup>35,40</sup> Nonetheless, the evidence to date is not sufficient to disentangle the direction or causal nature of these associations. Increased access to markets may incentivize diversified production to meet new market demands. Alternatively, agricultural diversification may serve as a demand-generating force in its own right that stimulates creation of new markets.

Although agricultural diversification may in some contexts facilitate greater commercial production and increased income from agriculture, the quality of consumer food markets in a region may limit the ability of households to translate greater income into more diverse, nutritious diets. In settings where access to consumer food markets is limited overall, where high food price-to-wage ratios limit accessibility, or where highly processed, nutrient-poor foods predominate markets, diversification into nutrient-dense, edible species may provide greater nutritional benefits than diversification into cash crops. Indeed, poorly functioning consumer markets may be a primary motivating factor that incentivizes farmers to maintain greater in situ inter- and intraspecific diversity of edible crops.<sup>46</sup> Agricultural biodiversity is also consistently more strongly associated with diet diversity than is agricultural income.<sup>27,40,41</sup> This suggests that in many rural regions access to adequate consumer food markets may limit the dietary benefits of increased agricultural income. Importantly, none of the studies reviewed identified the nature of the markets in question (eg, agricultural input, agricultural output, consumer food). Although different kinds of markets may be spatially clustered, access to agricultural output markets (where farmers can sell produced food and/or nonfood commodities) and consumer food markets (where consumers may purchase local, regional, and/or imported food items) may vary considerably within regions. Additional evidence is needed to understand the nature of markets to which households have access in analyses that examine the role of markets in moderating or mediating the relation between agricultural biodiversity and diet.



In total, the evidence indicates that proximity to markets and market orientation of agricultural crop production are likely important determinants of diet diversity. Although reducing distance to markets in some contexts may lessen the influence of agricultural biodiversity on diet diversity, this trend is not universally observed, and the positive association of agricultural biodiversity with diet diversity, independent of market proximity, is highly consistent. Perhaps most important, agricultural diversification and enhancement of market access may be synergistic strategies for increasing diet diversity. Policy prescriptions for which strategy or combination of approaches may have the largest impact on nutrition outcomes must be crafted while accounting for local contexts. For example, 1 study found that decreasing the distance to a nearby market by 10 km would have a similar impact on household diet diversity as increasing farm production diversity by 1 crop or livestock species.<sup>34</sup> The feasibility, cost, and social desirability of either option will differ substantially in different settings. The potential nutritional impact of diversification will further exhibit heterogeneity based on (1) the type of species introduced, (2) its use by the household, and (3) trade-offs with household labor and other income-generating crops or activities. Similarly, the nutritional implications of enhanced market access will likely vary based on (1) the type of market (eg, agricultural input, agricultural output, or consumer food), (2) seasonality of operation, (3) institutional barriers to the proper functioning of the market, (4) regional price-to-wage ratios, (5) availability of specific food items, and (6) consumer preferences and purchasing behaviors. Over and above these considerations, in certain contexts, substituting one approach for the other may result in missed opportunities for achieving even stronger dietary benefits by drawing upon the synergies between incentivizing diversified production and strengthening market linkages.

#### **HETEROGENEITY IN THE RELATIONSHIP BETWEEN AGRICULTURAL BIODIVERSITY AND DIET DIVERSITY**

Beyond market access and participation, other sources of heterogeneity in the relationship between agricultural biodiversity and diet diversity, as well as complementary determining factors that shape understanding of this relationship, were observed in the reviewed studies. Access to land is of particular interest as a potential determinant of agricultural biodiversity given trends of diminishing farm sizes in sub-Saharan Africa and concurrent debates surrounding international land transactions on the continent.<sup>47,48</sup> More arable land available for production may allow farmers to diversify their production. Yet the associations between land size and agricultural biodiversity observed in the reviewed studies are mixed. In

eastern Africa, on-farm species richness was independent of farm size.<sup>31</sup> In Ecuador, the same trend was observed, although metrics of crop evenness (eg, Shannon Index and fraction of land occupied by a given agricultural species) all decreased with increasing farm size.<sup>32</sup> In Malawi, however, cultivated land area was strongly positively associated with on-farm crop species richness, independent of household wealth, despite the fact that household wealth alone showed no relationship with agricultural biodiversity.<sup>19</sup> Households with greater cultivated land area in Malawi were also larger. It is possible that among larger households, subdivision of inherited agricultural land among male children still living with their parents had yet to occur.<sup>19</sup> Therefore, intrafamilial land subdivision may play a role in limiting the capacity of households to diversify production where maize cultivation is prioritized to safeguard household consumption. This same trend was observed in Burkina Faso where on-farm crop species richness was greater among larger households.<sup>20</sup> Overall, few studies have examined farm size as a determinant of agricultural biodiversity, and none have assessed its potential as an effect modifier of the relationship between agricultural biodiversity and diet diversity or quality.

Women's control of decision making and resource use is also an important determinant in understanding household-level influences on diet diversity. Jones et al (2014)<sup>33</sup> observed that the relationship between agricultural biodiversity and household diet diversity was more positive among households headed by women than households headed by men. In another study, agricultural income controlled by women had a greater positive impact on household diet diversity as compared with income controlled by men.<sup>41</sup> These findings align with those from previous studies across many different contexts that indicate that women's control of income and decision making has important benefits for child- and household-level nutrition outcomes.<sup>49,50</sup> When women control income, they often purchase foods and other health-related inputs that directly benefit the health and nutritional status of household members. Women's differential purchasing behaviors, as well as their selection and use of cultivated crops that may reflect nutrition priorities, could underlie the role of women's empowerment as a modifying factor in the relationship between agricultural biodiversity and diet diversity. This finding, however, needs to be confirmed through replication in different contexts.

#### **ASSOCIATIONS OF AGRICULTURAL BIODIVERSITY AND CHILD ANTHROPOMETRY**

Among the 6 studies for which data on child anthropometry was reported, 4 observed at least 1 positive association between agricultural biodiversity and an

indicator of child anthropometric status (Table 1). Agricultural biodiversity was consistently positively associated with height-for-age Z score (HAZ) of preschool-aged children.<sup>27–29</sup> A 1-unit increase in crop species count was associated with a 0.03<sup>27</sup> and 0.05<sup>29</sup> increase in HAZ, respectively, among children 24–59 months of age. Increasing crop group count (aligned with the food groups used to measure diet diversity) was associated with a 0.14 increase in HAZ among children 6–59 months of age from households with women as decision makers.<sup>28</sup> The linear growth stature of severely stunted children ( $HAZ < -3$ ) was most strongly associated with greater household production diversity.<sup>27</sup> Severely stunted children commonly have profound dietary deficiencies, and therefore, even marginal improvements to diet quality could have a positive influence on their growth trajectory. Nonetheless, the magnitude of the association between agricultural biodiversity and child HAZ is small (ie, approximately 0.05 standard deviations). For comparison, the most successful infant and child feeding intervention trials have improved child HAZ by approximately 0.7.<sup>51</sup> Among the reviewed studies, other indices of child anthropometric status (ie, weight-for-age Z score, weight-for-height Z score) showed variable or null associations with agricultural biodiversity.

Compared with analyses of diet diversity, few studies have assessed the potential impact of agricultural diversification on the anthropometric status of individuals. Interpreting the causal nature of such analyses is especially challenging given the multifactorial determinants of body composition, particularly among young children, for whom many nonfood factors contribute to undernutrition (eg, access to improved water and sanitation, hygiene of home environments). Furthermore, timing of intervention exposure is crucially important. Most child linear growth faltering takes place prior to 24 months of age. Therefore, to prevent linear growth deficits, the potential dietary benefits of diversified agricultural production would need to occur between approximately 6 and 24 months of age, when many children are receiving complementary foods. Given that children in these age groups are commonly fed by a caregiver, an entire suite of feeding behaviors are also involved in shaping the diets of young children. These behaviors must also be accounted for when considering the potential for agricultural diversification to change the diets and growth of young children through increased access to diverse foods.

It is plausible that agricultural biodiversity may influence the nutritional status of adults as well as children. The single study that examined anthropometry in adults observed that agricultural biodiversity in Nepal

was associated with lower BMI among women.<sup>28</sup> The authors hypothesize that greater agricultural production diversity may lead to higher workloads for women, especially in households with low labor availability. Such workloads could contribute to higher energy expenditures and deleterious effects on women's nutritional status. The association between women's workloads and nutritional status has been observed in many other contexts<sup>52,53</sup>; however, further studies are needed to substantiate the linkage between agricultural biodiversity and women's nutritional status.

## CONCLUSION

The most recent evidence to date suggests that agricultural biodiversity has a clear and consistent association with more diverse household- and individual-level diets. However, the magnitude of this association is small. Furthermore, the relationship is not linear. Its magnitude depends on the extent of existing diversification of farms. Marginal increases in agricultural biodiversity among farms of low biodiversity are associated with larger increases in diet diversity than highly biodiverse farms for which incremental increases in agricultural biodiversity may, in fact, yield decreases in diet diversity. Few studies assessed the influence of agricultural biodiversity on anthropometric outcomes. Greater crop species richness was associated with small, positive increments in child HAZ (a 1-unit increase in crop species richness was associated with approximately 0.05 higher HAZ), but other anthropometric indices showed variable associations. Importantly, nearly three quarters of the studies reviewed were conducted in sub-Saharan Africa. Therefore, the results observed may not necessarily be applicable to all LMIC contexts.

The summary evidence captured in this review also provides some indication of the pathways by which agricultural biodiversity may influence nutrition outcomes. Agricultural diversification may contribute to diversified diets through both subsistence and income-generating pathways. Maintaining at least a partial market orientation to farms is associated with more diverse diets in some contexts, and overall, household access to markets has an important independent association with diet diversity. However, the context-specific factors that facilitate the functioning or prioritization of subsistence or income pathways, or their combination, for improving diets and nutrition outcomes remain unclear. Agricultural diversification may enhance smallholder farmers' engagement with markets if cash crops are added to production systems and well-functioning markets are accessible that allow farmers to translate market-oriented production into new income. Highly diversified systems

may, however, also increase the risk of potential income losses through foregone benefits of specialization. Regardless, the evidence reviewed in this study, as well as in previous reviews,<sup>54,55</sup> suggests that agricultural interventions that solely aim to increase households' agricultural revenues may have limited nutritional impacts. Agricultural diversification may be an important complementary strategy to improving nutritional status and the diversity of diets, especially in regions of LMICs where access to and institutional support for markets are poor.

Based on gaps in the available evidence to date, 6 principal research priorities are identified that should be emphasized in future studies of the influence of agricultural biodiversity on nutrition outcomes: (1) assessment of diet quality; (2) research design and reporting; (3) effect heterogeneity and pathway analysis; (4) scale of assessment; (5) measurement and indicators; and (6) assessment of health impacts.

First, nearly all of the research in this area to date has measured diet diversity as a proxy for diet quality. Although diet diversity has been shown to be associated with more adequate nutrient intakes and improved nutritional status of adults and children, it is a summary indicator that potentially masks important variation in nutrient intakes. It may also amplify nutritionally meaningless differences in diets or provide misleading interpretations of outcomes by including food groups that negligibly improve diet quality or even detract from it (eg, by including food groups such as spices, condiments, beverages, sweets, and sugars—food groups commonly included in the indicators used in the reviewed studies). Furthermore, the relevance of diet diversity for diet quality may depend on the underlying level of diet diversity in the population. Incremental increases in diet diversity may have less impact on diet quality in regions with higher background levels of diet diversity. Future studies should rigorously assess diet quality using standard approaches that allow for estimation of nutrient intakes from specific food groups and items. Those studies that are unable to directly assess diet quality, and that instead measure diet diversity with the intent of it serving as a proxy for diet quality, should ensure that they use indicators validated for such a use.<sup>56</sup> To the author's knowledge, only 2 diet diversity indicators have been validated as indicators of diet quality. The Minimum Dietary Diversity for Women indicator<sup>43</sup> is a valid indicator of the micronutrient adequacy of women's diets, and the World Health Organization (WHO) Minimum Dietary Diversity indicator<sup>57</sup> is a valid indicator of the micronutrient density adequacy of complementary foods for children 6–23 months of age.<sup>8</sup> Alternative diet diversity metrics that have not been validated as

indicators of individual diet quality cannot be interpreted as such.

Second, nearly all of the studies reviewed generated inferences from analysis of cross-sectional data. Point estimates from these analyses may over- or underestimate the true association between agricultural biodiversity and diet outcomes due to confounding bias. Therefore, although many of the reviewed studies adjusted for potential confounding variables in their analyses, the causal inference from these studies remains limited. Longitudinal designs are needed to identify the temporal sequence of exposure and outcome and to adjust for time-variant factors. Experimental and quasi-experimental designs may also be warranted, although experimental studies are needed beyond the level of home gardens. These studies should examine changes at the scale of farms, communities, or regions. Interventions that strategically select new crop species as part of an agricultural diversification scheme to improve diet diversity might require far fewer new crop species to achieve diversified diets than the number of crops indicated in the associations produced among the reviewed observational studies. Such evidence, however, must be generated through intervention research that includes carefully designed control or comparison groups or perhaps even natural experiments with reasonable comparison regions. Rigorous research designs are especially needed given the long and potentially nonlinear causal pathways in many contexts linking agricultural production diversity to diets. The complexity in these systems enhances the opportunity for threats from confounding bias and model misspecification. Fundamentally, comprehensive reporting of measurement approaches and indicator specification is needed when reporting data, and explicit design efforts should be made to minimize selection bias, ensure adequately powered samples, and rigorously measure exposures, outcomes, and covariates.

Third, there is little evidence explaining heterogeneity in the relationship between agricultural biodiversity and nutrition outcomes. Assessments of effect modification are critical for understanding the context-specific factors that facilitate or prevent agricultural diversification from influencing diets and nutrition outcomes (eg, agroecological conditions, policy and institutional environments, and sociocultural influences). The nonlinearity of the association between agricultural biodiversity and diets also needs to be examined with respect to households' existing levels of diet diversity. It is likely that households with more diverse diets will benefit less from marginal increases in production diversity. However, this has not been examined to date. Furthermore, the causal pathways that underlie the relation between agricultural biodiversity and nutrition

outcomes and their relative importance in different contexts are poorly understood. More research is needed to understand how agricultural diversification influences subsistence- and market-oriented production and how these pathways in turn affect nutrition. Other well-recognized gender-sensitive pathways between agriculture and nutrition,<sup>58</sup> including women's time, workload, caregiving capacities, and control of income and decision making, have also received almost no attention in the agricultural biodiversity literature. Disaggregated analyses are likely to be most effective in elucidating mediating pathways and effect modifiers of the relationship between agricultural biodiversity and diet outcomes. Pooling data across multiple country contexts can obscure important regional-level variability and, most important, may prevent meaningful policy recommendations from being drawn. As discussed above, the extent to which agricultural diversification may influence the diversity of diets and the nature of heterogeneity in this relationship depends on multiple context-specific factors, including local agroecological conditions, the extent to which households depend on agriculture as a source of food and livelihood, access to and opportunities for participation in different kinds of markets, the level of development of transportation infrastructure, and the strength and reliability of local institutions. Indeed, the smallest associations observed between agricultural biodiversity and diet diversity were from pooled analyses across diverse contexts.<sup>34,35</sup> A clear accounting of the settings of future studies is important, as is an expanded geographic focus of the evidence base, which currently emphasizes sub-Saharan Africa.

Fourth, only 2 of the reviewed studies examined agricultural biodiversity beyond the scale of the household.<sup>27,31</sup> In descriptive analyses applying no statistical tests, Remans et al<sup>31</sup> found that households in villages with greater crop species richness had higher diet diversity and food security than households in villages with lower crop species richness. Kumar et al<sup>27</sup> concluded that differences in child diet diversity were driven predominantly by household- and not village-level production diversity. Although some research has examined relationships between national-level agricultural production diversity and the diversity of country food supplies,<sup>59</sup> overall, there is a dearth of analyses of the nutritional impacts of agricultural biodiversity at village or regional scales that warrants further research. The influence of landscape- and regional-scale agricultural specialization on broader food environments and consumption patterns may be of particular policy relevance,<sup>60</sup> given that food available in markets in LMICs is commonly sourced from nearby regions. Therefore, regional agricultural diversification could support

diversity in local markets and, in turn, enhance diet diversity among households in the same region.<sup>20</sup>

Fifth, only 1 of the reviewed studies assessed agricultural biodiversity at the subspecies level. This study observed that the association of on-farm varietal diversity (reported for 5 crops) with diet diversity was similar to that observed for crop species diversity.<sup>19</sup> Heterogeneity in the nutritional content of different varieties within the same species is well documented. Biofortification programs exploit this genetic diversity to breed micronutrient-rich varieties of common staple crops. However, it is unclear whether increased varietal diversity may have nutritional impacts above and beyond potential dietary benefits of species richness or whether such diversity may even be deleterious if varietal diversity substitutes for species diversity that could contribute more substantively to improved nutrition.<sup>61</sup> New research that assesses varietal diversity is needed, in concert with direct measurement of agricultural biodiversity to complement survey-based approaches. Only 2 of the reviewed studies directly assessed species diversity through observation of farmers' fields.<sup>31,32</sup> Anecdotal evidence suggests that intraspecific agricultural biodiversity is underestimated using recall-based approaches. Therefore, direct observation may substantively improve estimates of the relationship between agricultural biodiversity and nutrition. Similarly, assessments of market access would benefit from more rigorous measurement approaches. In the few studies that assessed access to markets, proxy indicators that are likely highly error prone (eg, proximity to a major road, ownership of own transportation, proximity to nearest population center) were used.<sup>27,34,41</sup> None of these indicators directly measures market access or differentiates between market type, which may be critical for analyzing pathways between agricultural diversification and nutrition. Aggregate indicators may be needed that apply data reduction techniques to create indices that capture the multiple domains of this complex concept. Careful reporting of information on market participation is also warranted. As noted above, indicators of market participation reported in the reviewed studies were widely varying. Given heterogeneity across countries in the proportion of agricultural production sold, it is likely that defining a meaningful, cross-national threshold for market orientation of production may be impossible. Yet efforts to standardize market participation indicators across studies based on robust production data would help to facilitate cross-study comparisons. At a minimum, the methodology used to assess market orientation of farms and the mean and variance of the indicator(s) should be clearly presented and compared when possible with other studies to allow for critical interpretation.

Finally, the downstream health impacts of agricultural diversification are largely unknown. The few studies that have assessed anthropometric outcomes have suggested that agricultural biodiversity has a small positive association with child linear stature. However, impacts on prevention of anemia, child illness, optimum child development, manifestations of nutritional deficiencies, mental health and well-being, or community-level health outcomes have not been studied. Additional research is also needed to understand the potential impacts of agricultural diversification on overweight and obesity, whether through healthy additions to energy-dense, nutrient-poor diets or through substitutions of biodiverse foods for less healthy options (eg, highly processed snack foods and beverages).

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