Production diversity and dietary diversity in smallholder farm households

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Undernutrition and micronutrient malnutrition remain problems of significant magnitude in large parts of the developing world. Improved nutrition requires not only better access to food for poor population segments, but also higher dietary quality and diversity. Because many of the poor and undernourished people are smallholder farmers, diversifying production on these smallholder farms is widely perceived as a useful approach to improve dietary diversity. However, empirical evidence on the link between production and consumption diversity is scarce. Here, this issue is addressed with household-level data from Indonesia, Kenya, Ethiopia, and Malawi. Regression models show that on-farm production diversity is positively associated with dietary diversity in some situations, but not in all. When production diversity is already high, the association is not significant or even turns negative, because of foregone income benefits from specialization. Analysis of other factors reveals that market access has positive effects on dietary diversity, which are larger than those of increased production diversity. Market transactions also tend to reduce the role of farm diversity for household nutrition. These results suggest that increasing on-farm diversity is not always the most effective way to improve dietary diversity in smallholder households and should not be considered a goal in itself. Additional research is needed to better understand how agriculture and food systems can be made more nutrition-sensitive in particular situations.

nutrition-sensitive food systems | small-scale farmers | food security | Africa | Asia

Hunger and malnutrition are complex global problems. Despite improvements in food and nutrition security over the last few decades, the prevalence of undernutrition remains high, especially in Africa and Asia (1–3). Close to 800 million people are still classified as chronically hungry, meaning that they do not have sufficient access to calories (4). An estimated 2 billion people suffer from micronutrient malnutrition, mostly due to low intakes of vitamins and minerals such as iron and zinc (3). Nutritional deficiencies are responsible for a large health burden in terms of lost productivity, impaired physical and mental human development, susceptibility to various diseases, and premature deaths (5). Nutritional deficiencies are not only the result of low food quantities consumed, but also of poor dietary quality and diversity. In fact, the level of dietary diversity was shown to be a good indicator of people's broader nutritional status in many situations (6–12). More diverse diets tend to be associated also with lower rates of overweight and obesity—other nutritional problems of rising magnitude in many parts of the world (13). Increasing dietary diversity is therefore an important strategy to improve nutrition and health. This implies that agricultural production also needs to be diversified, so that a wide range of different types of foods are available and accessible also to poor population segments (14). Over the last 50 y, agricultural modernization has contributed to narrowing global production patterns with a focus on a limited number of major crop plants (15).

In Africa and Asia, the majority of the undernourished people live in rural areas. Many of them are smallholder farmers (16). Against this background, further diversifying production on these smallholder farms is often perceived as a useful approach to improve dietary diversity and nutrition (17–20). Several recent development initiatives have promoted smallholder diversification through introducing additional crop and livestock species with the intention to improve household nutrition (21, 22). Because farm diversity can help to increase agrobiodiversity too, this approach is also welcome from environmental perspectives (21, 23, 24). But is there really such a clear link between production diversity on the farm and consumption diversity in the farm household? What are other factors that influence this relationship and dietary diversity in smallholder farm households more generally? These are under-researched questions of relevance for improving agriculture and nutrition in the small-farm sector (25, 26). Here, we address these questions empirically with data from several developing countries.

A positive relationship between farm production diversity and dietary diversity is plausible, because much of what smallholder farmers produce is consumed at home (27). However, assuming that all smallholders are pure subsistence farmers and do not sell and buy any food is too simplistic. Taking into account market transactions, the relationship between production diversity and dietary diversity becomes more complex. Instead of producing everything at home, households can buy food diversity in the market when they generate sufficient income (17). Farm diversification may contribute to income growth and stability up to a certain point, but beyond that point further diversification may reduce household income due to foregone benefits from specialization (28). Because lower household incomes tend to be associated with lower dietary quality, the relationship between production and consumption diversity may even turn negative in some situations. Beyond farming, the majority of smallholder households in developing countries also have off-farm income sources (29), further adding to the complexity. When relying on markets, nutrition effects in farm households will also depend on how well the markets function and

Significance

Given that hunger and malnutrition are still widespread problems in many developing countries, the question of how to make agriculture and food systems more nutrition-sensitive is of high relevance for research and policy. Many of the undernourished people in Africa and Asia are small-scale subsistence farmers. Diversifying production on these farms is often perceived as a promising strategy to improve dietary quality and diversity. This hypothesis is tested with data from smallholder farm households in Indonesia, Kenya, Ethiopia, and Malawi. Higher farm production diversity significantly contributes to dietary diversity in some situations, but not in all. Improving small farmers' access to markets seems to be a more effective strategy to improve nutrition than promoting production diversity on subsistence farms.

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Table 1. Descriptive statistics by country

Household characteristics	Pooled	Indonesia	Kenya	Ethiopia	Malawi
Farm size, ha	1.26 (2.60)	4.50 (7.42)	0.71 (0.94)	1.63 (1.91)	0.74 (0.60)
Production diversity (no. of crop/livestock species produced)	6.13 (4.75)	1.74 (0.91)	7.82 (2.58)	10.19 (5.81)	4.80 (3.08)
Food crop production diversity (no. of food crop species produced)	3.62 (2.96)	0.29 (0.76)	4.72 (1.51)	6.30 (3.64)	2.90 (1.90)
Margalef species richness index	0.44 (0.47)	0.16 (0.10)	0.79 (0.28)	0.85 (0.65)	0.28 (0.25)
Food variety score (no. of food items consumed)	15.94 (8.43)	29.58 (8.11)	24.68 (4.64)	7.91 (2.31)	16.68 (6.72)
Dietary diversity score (no. of food groups consumed)	7.99 (2.48)	10.02 (1.29)	11.40 (0.97)	5.42 (1.70)	8.48 (2.02)
Market distance, km	21.27 (33.37)	6.55 (7.41)	3.09 (3.58)	63.53 (47.50)	8.17 (5.71)
Off-farm income (dummy)	0.36	0.48	0.51	0.32	0.35
No. of observations	8,230	674	397	2,045	5,114

Mean values are shown with SDs in parentheses. Additional variables are shown in Table S1.

who within the household controls the income from commercial farm sales and off-farm employment (28, 30, 31). As is well known, gender aspects can play important roles in determining household food and nutrition security (32). Hence, the direction and strength of the production–consumption diversity relationship will be situation-specific. Although recent case studies of the nutritional impacts of smallholder farm diversification projects exist (33–35, *), linkages and influencing factors have not been analyzed from a broader perspective.

We analyze the relationship between production and consumption diversity in smallholder farm households with data from four developing countries: Indonesia, Kenya, Ethiopia, and Malawi. These four countries were chosen because recent household-level data suitable for the analysis were available, which is not the case for many other countries. Moreover, these four countries cover different situations in terms of farm structures, market access, culture, and levels of poverty and malnutrition, so that the data may be useful to derive some broader conclusions that are relevant beyond a particular case. The data from Indonesia and Kenya refer to specific regions within these countries, where smallholder farmers grow cash crops for the market (*Materials and Methods*). The data from Ethiopia and Malawi are nationally representative.

Results

Descriptive statistics for key variables used in this analysis are shown in Table 1 (additional variables are shown in Table S1). The average size of farms in the pooled sample covering all four countries is 1.3 ha, but farm sizes and other socioeconomic characteristics vary significantly within and across countries. There are also wide variations in terms of production diversity and dietary diversity. We use the number of crop and livestock species produced on a farm as the measure of production diversity (in a robustness check we also use other measures). Farmers in the Indonesian sample have very low production diversity with only 1.7 species produced on average. The sample from Indonesia refers to one province in Sumatra, where many farmers do not produce any food but have specialized in rubber and oil palm as plantation crops. In the other countries, production diversity is considerably higher. The highest production diversity is observed in Ethiopia, where farms produce 10.2 different crop and livestock species on average.

There are different ways to measure dietary diversity; the two most common indicators are the food variety score and the dietary diversity score (7, 17). The dietary diversity score, which measures the number of food groups consumed over a given period, is considered more suitable for international comparisons (*Materials and Methods*). Table 1 shows that household dietary diversity is higher in Indonesia and Kenya than in Ethiopia and Malawi. This is interesting, because the sample farms in Indonesia and Kenya are more specialized in the production of cash crops. Evidently, specialization and lower production diversity are not necessarily associated with lower dietary diversity, when diverse types of foods can be purchased from the market. These relations are analyzed in more detail in the following.

Association Between Production Diversity and Dietary Diversity. Table 2 shows results of regression models where dietary diversity is used as a dependent variable and farm production diversity as an explanatory variable (see *Materials and Methods* for details of model specification). Farm production diversity is positively associated with dietary diversity, but the effect is relatively small. In the pooled sample, producing one additional crop or livestock species leads to a 0.9% increase in the number of food groups consumed.

The magnitude of this effect varies by country. In Kenya and Ethiopia, the coefficient estimates are very small and not statistically significant. In these two countries, average production diversity is quite high; further increasing farm diversity would hardly contribute to higher dietary diversity. In Indonesia, the estimated coefficient is larger, which is due to the low average production diversity observed. Many farmers in the Indonesian sample only grow rubber. Those that grow an additional crop usually adopt oil palm, which contributes to higher household incomes. Hence, the improvement in dietary quality in Indonesia is attributable primarily to rising incomes from cash crop sales rather than more diverse subsistence production.

The models in Table 2 also include a square term for farm production diversity, which is negative in most cases. This means that the effect on dietary diversity diminishes, probably because foregone benefits from specialization become more relevant for farms that are already highly diversified.

Role of Market Access. We now analyze more explicitly how access to markets affects dietary diversity by including additional explanatory variables into the regression models. One indicator of market access is the geographic distance from the farm household to the closest market where food can be sold or bought. The estimated coefficients are negative in all models (Table 3), implying that households in remoter regions have lower dietary diversity. Better market access through reduced distances could therefore contribute to higher dietary diversity. Comparing the magnitude of the estimated coefficients in the pooled model reveals that reducing market distance by 10 km has the same effect on dietary diversity as increasing farm production diversity by one additional crop or livestock species.

The interaction term between production diversity and market distance is insignificant in most cases (Table 3). The positive and significant interaction coefficient in the Malawi model suggests that the role of production diversity is more important in remoter regions where farms tend to be more subsistence-oriented. This effect is expected.

*Rajendran S, Afari-Sefa V, Bekunda M, Dominick I, Lukumay PJ, 88th Annual Conference of the Agricultural Economics Society, AgroParisTech, April 9–11, 2014, Paris.

Table 2. Association between production diversity and dietary diversity

Explanatory variables	Pooled	Indonesia	Kenya	Ethiopia	Malawi
Production diversity	0.009*** (0.002)	0.054*** (0.015)	0.003 (0.010)	0.002 (0.004)	0.015*** (0.002)
Production diversity squared	−1.4E-04* (8.6E-05)	−0.007*** (0.003)	1.4E-04 (5.7E-04)	1.3E-04 (1.5E-04)	−3.2E-04** (1.4E-04)
Model intercept	1.613*** (0.012)	2.238*** (0.018)	2.403*** (0.038)	1.653*** (0.024)	2.074*** (0.009)
No. of observations	8,230	674	397	2,045	5,114

The dependent variable in all models is the dietary diversity score of households, including 12 food groups. Models were estimated with a Poisson estimator. Coefficient estimates are shown with robust SEs in parentheses. The pooled data model was estimated with country fixed effects. See Table S3 for full results. *, **, *** Statistically significant at the 10%, 5%, and 1% level, respectively.

Another indicator of market access is the availability of off-farm income sources. Many smallholders complement their farm income with off-farm income when employment opportunities in other sectors arise. Results in Table 3 show that off-farm income is associated with higher dietary diversity. Cash earnings from off-farm activities increase the households' ability to buy diverse foods from the market. Interestingly, this effect is much larger than the effect from increasing farm production diversity. The interaction term between off-farm income and production diversity shows mixed results. The negative coefficients in some of the models imply that the availability of off-farm income reduces the role of farm production diversity for household nutritional quality.

The result that market access improves dietary diversity is interesting, but a relevant question is whether this also leads to more healthy diets. Depending on the type of food outlets available in a particular context, buying food may possibly be associated with rather unhealthy dietary diversification, for instance, through increased consumption of fats, sweets, or sugary beverages. To examine this further, we reestimated the models by using alternative dietary diversity scores as dependent variables, only including more healthy food groups (*Materials and Methods*). The finding that better market access tends to increase dietary diversity also holds with this alternative specification (Table S2).

Role of Selling and Buying Food. The role of markets can also be assessed by looking more directly at what households sell and buy. This information is only available for the samples from Ethiopia and Malawi, but this part of the analysis is also more interesting for these countries, because sample farmers in Indonesia and Kenya are much more commercialized anyway. We proceed with a pooled sample from Ethiopia and Malawi only. In the second column of Table 4 we include a dummy as additional explanatory variable that takes a value of one if the household sells at least parts of its farm produce to the market. The estimated coefficient is positive and significant. It is also much larger than the production diversity coefficient. This comparison suggests that facilitating the commercialization of smallholder farms may be a better strategy to improve nutrition than promoting more diversified subsistence production. Furthermore, the negative and significant interaction term confirms that market participation reduces the role of production diversity for dietary quality.

In the third column of Table 4, we use a different dependent variable and now look at dietary diversity only with respect to the food purchased in the market. The farm production diversity coefficient in this model is significantly negative, meaning that more diversified farms tend to buy less diversified foods in the market. This is perhaps not surprising: If the farm produces diverse foods itself, diversity from the market may not be needed to the same extent. However, diversified own production can substitute for diversity from the market only partially, because more than half of all of the food consumed in sample households is purchased (Table S1). The negative interaction terms between farm production diversity, distance to market, and harvest sold suggest that subsistence orientation tends to reduce the diversity of foods purchased in the market. The other coefficients in the third column of Table 4 are as expected. Better market access in terms of shorter distance and more off-farm income opportunities increase the level of purchased food diversity.

Robustness Checks. There are several other factors that may influence dietary diversity in smallholder farm households. The objective of this study is to better understand the role of farm production diversity in different situations, not to fully explain dietary diversity and all its influencing factors. Nevertheless, farm production diversity may be correlated with some of the omitted factors, which could potentially bias the estimation results. To test for such bias, we reestimated the regression models, this time including socioeconomic and demographic characteristics—such as farm and household size, as well as age, education, and gender of the household head—as additional explanatory variables. Some of these other factors are significant, but the estimation coefficients for farm production diversity and market access do not change much (Tables S3 and S4). We interpret this as evidence that the main results do not suffer from omitted variable bias.

In other sets of robustness checks, we used alternative measures of production diversity, namely the Margalef species richness index, which weights by the area grown with different crops, and a species count only including food crops as opposed to

Table 3. Production diversity, market access, and dietary diversity

Explanatory variables	Pooled	Indonesia	Kenya	Ethiopia	Malawi
Production diversity	0.010*** (0.002)	0.048*** (0.016)	0.001 (0.010)	0.006 (0.004)	0.011*** (0.003)
Production diversity squared	−1.5E-04 (9.7E-05)	−0.008*** (0.003)	2.0E-04 (0.001)	1.1E-04 (1.5E-04)	−1.5E-04 (1.5E-04)
Market distance	−0.001*** (2.6E-04)	−0.002 (0.002)	−0.006 (0.005)	−0.001* (3.1E-04)	−0.014*** (0.002)
[Production diversity] × [market distance]	1.6E-05 (2.0E-05)	−6.9E-05 (0.001)	5.0E-04 (5.5E-04)	−2.0E-05 (2.6E-05)	4.3E-04* (2.2E-04)
Off-farm income	0.039*** (0.008)	−0.009 (0.020)	0.059** (0.029)	0.073** (0.029)	0.083*** (0.013)
[Production diversity] × [off-farm income]	−0.002* (0.001)	0.020** (0.010)	−0.002 (0.003)	−3.5E-04 (0.002)	−0.004* (0.002)
Model intercept	1.662*** (0.014)	2.250*** (0.021)	2.425*** (0.043)	1.652*** (0.031)	2.111*** (0.015)
No. of observations	8,230	674	397	2,045	5,114

The dependent variable in all models is the dietary diversity score of households, including 12 food groups. Models were estimated with a Poisson estimator. Coefficient estimates are shown with robust SEs in parentheses. The pooled data model was estimated with country fixed effects. See Table S3 for full results. *, **, *** Statistically significant at the 10%, 5%, and 1% level, respectively.

Table 4. Production diversity, market participation, and dietary diversity in Ethiopia and Malawi (pooled sample)

Explanatory variables	Dietary diversity score with respect to all foods	Dietary diversity score with respect to purchased foods
Production diversity	0.010*** (0.002)	−0.013*** (0.003)
Production diversity squared	6.2E-06 (1.1E-04)	0.001*** (1.5E-04)
Market distance	−4.4E-04* (2.7E-04)	−0.002*** (4.7E-04)
[Production diversity] × [market distance]	−2.6E-05 (2.2E-05)	−9.1E-05** (3.8E-05)
Produce sold to market	0.045*** (0.016)	0.020 (0.021)
[Production diversity] × [produce sold]	−0.005*** (0.002)	−0.007*** (0.002)
Off-farm income	0.075*** (0.011)	0.099*** (0.015)
[Production diversity] × [off-farm income]	−0.001 (0.001)	0.001 (0.002)
Malawi (dummy)	0.479*** (0.011)	0.572*** (0.017)
Model intercept	1.613*** (0.016)	1.450*** (0.023)
No. of observations	7,159	7,159

For the calculation of the dietary diversity scores, 12 food groups were included. Models were estimated with a Poisson estimator. Coefficient estimates are shown with robust SEs in parentheses. *, **, *** Statistically significant at the 10%, 5%, and 1% level, respectively.

nonfood cash crops (*Materials and Methods*). We reestimated the different regression models with these alternative measures (Tables S5–S10). The findings are largely in line with those discussed above. Hence, the results do not seem to be driven by the way production diversity is measured. Interestingly, when only including food crops the effect of production diversity on dietary diversity is even smaller and insignificant in most cases (Tables S8 and S9), whereas the negative effect on food diversity purchased from the market gets stronger (Table S10). These results underline the importance of market interactions and strengthen the statement that nonfood cash crop production can also contribute to improved dietary quality through the income pathway.

Discussion

Increasing people's dietary diversity is an important strategy to improve nutrition and health. At aggregate level, this also requires diversification of agricultural systems. A research and policy focus on only a few cereal crops, as was sometimes observed during past decades, may have been useful to address issues of calorie undersupply but seems less suitable to deal with problems of various nutritional deficiencies. Whereas sustainably increasing the productivity of cereal crops remains a continuous challenge, agricultural research and policy efforts need to be broadened and also include the promotion of plant and animal species that were rather neglected in the past. Improved technologies and market potentials for a broader set of agricultural species would increase farmers' incentives to adopt alternatives best suited to their conditions. The optimal mix will vary from one location to another. More diverse agricultural systems are also good for biodiversity and the environment.

However, this plea for more diverse agriculture should not be misunderstood in a way that every individual farm should increase the level of production diversity. Especially in smallholder systems of Africa, the number of different species produced is often quite high anyway. Resource-poor farmers diversify their sources of food and income as a risk-coping strategy. Our analysis with data from different African and Asian countries showed that farm production diversity is positively associated with dietary diversity in some situations, but not in all. The results also revealed that the effect is not linear. When production diversity is already high, the dietary diversity relationship is not significant, or it even turns negative, because of foregone income resulting from farm diversification beyond optimal levels.

We also showed that smallholder access to agricultural markets and off-farm employment have positive effects on household dietary diversity. These market effects are larger than those of increased production diversity in most cases. Comparisons show that more commercialized farms that produce cash crops for the market have more diverse diets than subsistence farms on average. Households with higher cash incomes tend to buy more diverse foods from the market. This food diversity from the market cannot be fully substituted through diverse subsistence production.

Whereas improved market access often provides incentives for farmers to specialize, actual outcomes depend on many factors, not all of which were analyzed here. Where properly functioning markets for various commodities exist, commercial orientation of farms and high levels of production diversity are not necessarily a contradiction. More research is needed to better understand how agriculture and food systems can be made more nutrition-sensitive in particular situations. This also needs to take into account institutional and cultural aspects at the local level. Promoting production diversity may help in some situations, but our results suggest that increasing on-farm diversity among smallholders is not always the most effective way to improve dietary diversity and should not be considered a goal in itself.

In conclusion, the common assumption that higher farm production diversity is always conducive to household nutrition needs adjustment. The most suitable policy mix to improve nutrition in smallholder farm households will vary from case to case. In many situations, facilitating market access through improved infrastructure and other policies to reduce transaction costs and price distortions seems to be more promising than promoting further production diversification as such.

Materials and Methods

Data. The data used in this study are from cross-section surveys of farm households in Indonesia, Kenya, Ethiopia, and Malawi. The surveys were carried out for different purposes and by different research teams. The surveys in Indonesia and Kenya were initiated and carried out by us. Cash crop producers in specific regions were sampled, as is further described below. Prior to starting each interview, the procedures of data collection and anonymity were explained, and respondents were asked for their verbal informed consent to participate. Socioeconomic surveys that are not associated with any risk for participants do not require approval by an institutional review board at the University of Goettingen. The samples from Indonesia and Kenya are not nationally representative. The surveys in Ethiopia and Malawi were obtained from the World Bank's Living Standards Measurement Study – Integrated Surveys on Agriculture (LSMS-ISA) (36). The samples from Ethiopia and Malawi are nationally representative. In all four country surveys, a wide array of household socioeconomic information was captured, including details of agricultural production and food consumption at the household level. All four surveys used a 7-d consumption recall for a large number of food items, which we used to calculate measures of dietary diversity.

The data from Indonesia include 674 observations from farm households in the province of Jambi, Sumatra. The data were collected in 2012 through multistage random sampling to capture the province's regional diversity (37).

In Jambi, farmers primarily grow rubber and oil palm as plantation crops. Most farms do not grow other crops, although a few are involved in rice cultivation, horticulture, livestock keeping, and aquaculture. The data from Kenya include 397 observations of smallholder farmers in Kiambu County, Central Kenya, that produce vegetables and other horticultural crops for markets in Nairobi. The data were collected in 2012 through multistage random sampling (28). In addition to horticultural crops, sample farmers in Kenya cultivate maize, other staple food crops, as well as nonfood cash crops such as tea and coffee. Many farms also keep livestock on a small scale.

The data for Ethiopia are taken from the 2010/2011 Ethiopia Socioeconomic Survey supported by LSMS-ISA (36). The total dataset includes close to 4,000 household observations from rural areas and small towns. Out of this total, we excluded those that were not involved in own agricultural production and that had missing data for relevant variables, leaving 2,045 observations. The data for Malawi are taken from the 2010/2011 Malawi Integrated Household Survey supported by LSMS-ISA (17, 36). The total dataset includes over 12,000 households, of which we use 5,114 observations after excluding nonfarm households and those with missing data. Farmers in Ethiopia and Malawi are mostly subsistence-oriented, growing various food crops and keeping livestock primarily for home consumption. In some regions, farmers also grow cash crops such as cotton, tea, coffee, and sugarcane.

Measurement of Dietary Diversity. Dietary diversity is usually measured using two indicators: the food variety score and the dietary diversity score (6, 7, 38, 39). The food variety score is a simple count of the different food items consumed during the recall period. This is a useful indicator for nutritional assessments within one setting. However, owing to cultural differences in dietary habits the food variety score is less suitable for comparisons across countries. Moreover, the item count depends much on the level of food group disaggregation in the questionnaire, which varies by survey. Hence, for cross-country analyses and comparisons the dietary diversity score is preferred (18, 39). The dietary diversity score is the number of food groups consumed by the household during the recall period.

There is no international consensus on which food groups to include in the calculation of dietary diversity scores. Many studies classify all foods consumed into 12 groups (38, 39), an approach that we follow for the main part of the analysis. The following 12 food groups are included to calculate household dietary diversity scores: cereals; white tubers and roots; legumes, nuts, and seeds; vegetables; fruits; meat; eggs; fish and fish products; milk and milk products; sweets and sugars; oils and fats; and spices, condiments, and beverages. However, research has shown that the last three food groups contribute little to the micronutrient density of the diet, so that—depending on the purpose—there are also studies that have calculated dietary diversity scores only based on the remaining nine food groups (12, 39). We use dietary diversity scores only including the nine more healthy food groups in a sensitivity analysis.

Measurement of Production Diversity. In the main part of the analysis, we use the number of crop and livestock species produced on a farm as the measure of production diversity. This is a simple, unweighted count measure. In a set of robustness checks, we use two alternative measures to examine whether this influences the results significantly. First, we use the Margalef species richness index. The Margalef index is often used in the agrobiodiversity literature and accounts for the area cultivated with different crop species on the farm (40, 41). Second, we use a simple, unweighted count of only the food crop species produced on a farm (food crop production diversity). Because some of the farms also produce nonfood cash crops (e.g., rubber, oil palm, tea, and coffee) that do not directly contribute to household dietary diversity, this differentiation may be important from a nutrition perspective. Mean values of these alternative measures of production diversity are shown in Table 1.

Regression Models. To analyze the relationship between on-farm production diversity and dietary diversity we use regression models of the following form:

$$DD_i = \alpha_0 + \alpha_1 PD_i + \alpha_2 PD_i^2 + \varepsilon_i, \quad [1]$$

where DD_i is the dietary diversity score and PD_i is production diversity in farm household i. A positive and significant estimate for α_1 implies that higher production diversity is associated with higher dietary diversity, as is commonly assumed. Inclusion of PD_i^2 as the square term of production diversity tests whether the relationship is linear. A negative and significant estimate for α_2 implies that the strength of the association is diminishing at higher levels of production diversity. ε_i is a random error term.

DD_i is a count variable that can take values between 1 and 12 (or between 1 and 9 when only including the more healthy food groups) and is not normally distributed. We use a Poisson estimator with a maximum-likelihood procedure for model estimation (42). With the Poisson distribution, the coefficient estimates can be interpreted as semielasticities. That is, a coefficient estimate states by what percentage the dietary diversity score changes when the explanatory variable changes by one unit.

In extended model specifications, we add additional explanatory variables to analyze the role of market access for dietary diversity as follows:

$$DD_i = \alpha_0 + \alpha_1 PD_i + \alpha_2 PD_i^2 + \alpha_3 \boldsymbol{MA}_i + \alpha_4 (PD_i \times \boldsymbol{MA}_i) + \varepsilon_i, \quad [2]$$

where $\boldsymbol{MA}_i$ is a vector or market access indicators such as distance to the closest market and the availability of off-farm income sources for household i. Market distance refers to the number of kilometers farmers have to cover to reach the next marketplace to sell their produce. This is usually the next town where they can also buy food and other goods. We use the distance as reported by survey respondents. Data on travel time or road quality were not consistently available across the surveys. Off-farm income is measured with a dummy variable that takes a value of one if the household has any income from off-farm employment or self-employed nonfarm activities.

Market access tends to improve household income, so α_3 is expected to be positive (negative for market distance, because larger distance means worse market access). With the interaction term between PD_i and $\boldsymbol{MA}_i$ we test whether market access influences the effect of production diversity on household dietary diversity. Increasing market transactions are expected to reduce the role of production diversity. As a robustness check, we extend the model in Eq. **2** by including additional variables that may affect dietary diversity, such as farm and household size, as well as age, education, and gender of the household head.

The regression models are estimated separately for each country and also with the data pooled for all four countries. In the pooled data models, we include dummy variables to control for country fixed effects, such as unobserved socioeconomic or cultural differences. The data within and across countries cover a wide spectrum of conditions; all models are estimated with robust SEs to account for heteroscedasticity (42).

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1. Godfray HCJ, et al. (2010) Food security: The challenge of feeding 9 billion people. *Science* 327(5967):812–818.
2. Dubé L, Pingali P, Webb P (2012) Paths of convergence for agriculture, health, and wealth. *Proc Natl Acad Sci USA* 109(31):12294–12301.
3. IFPRI (2014) *Global Nutrition Report 2014: Actions and Accountability to Accelerate the World's Progress on Nutrition* (International Food Policy Research Institute, Washington, DC).
4. FAO, IFAD, WFP (2015) *The State of Food Insecurity in the World 2015* (Food and Agriculture Organization of the United Nations, Rome).
5. Lim SS, et al. (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 380(9859):2224–2260.
6. Kant AK, Schatzkin A, Harris TB, Ziegler RG, Block G (1993) Dietary diversity and subsequent mortality in the First National Health and Nutrition Examination Survey epidemiologic follow-up study. *Am J Clin Nutr* 57(3):434–440.
7. Ruel MT (2003) Operationalizing dietary diversity: A review of measurement issues and research priorities. *J Nutr* 133(11, Suppl 2):3911S–3926S.
8. Headey D, Ecker O (2013) Rethinking the measurement of food security: From first principles to best practice. *Food Security* 5(3):327–343.
9. Steyn NP, Nel JH, Nantel G, Kennedy G, Labadarios D (2006) Food variety and dietary diversity scores in children: Are they good indicators of dietary adequacy? *Public Health Nutr* 9(5):644–650.
10. Moursi MM, et al. (2008) Dietary diversity is a good predictor of the micronutrient density of the diet of 6- to 23-month-old children in Madagascar. *J Nutr* 138(12): 2448–2453.
11. Arimond M, Ruel MT (2004) Dietary diversity is associated with child nutritional status: Evidence from 11 demographic and health surveys. *J Nutr* 134(10):2579–2585.
12. Arimond M, et al. (2010) Simple food group diversity indicators predict micronutrient adequacy of women's diets in 5 diverse, resource-poor settings. *J Nutr* 140(11): 2059S–2069S.
13. Popkin BM, Slining MM (2013) New dynamics in global obesity facing low- and middle-income countries. *Obes Rev* 14(Suppl 2):11–20.
14. Pingali P (2015) Agricultural policy and nutrition outcomes – getting beyond the preoccupation with staple grains. *Food Security* 7(3):583–591.

AGRICULTURAL SCIENCES

SUSTAINABILITY SCIENCE

15. Khoury CK, et al. (2014) Increasing homogeneity in global food supplies and the implications for food security. *Proc Natl Acad Sci USA* 111(11):4001–4006.
16. Pinstrup-Andersen P (2007) Agricultural research and policy for better health and nutrition in developing countries: A food systems approach. *Agric Econ* 37:187–198.
17. Jones AD, Shrinivas A, Bezner-Kerr R (2014) Farm production diversity is associated with greater household dietary diversity in Malawi: Findings from nationally representative data. *Food Policy* 46:1–12.
18. Pellegrini L, Tasciotti L (2014) Crop diversification, dietary diversity and agricultural income: Empirical evidence from eight developing countries. *Can J Dev Stud* 35(2): 211–227.
19. Remans R, et al. (2011) Assessing nutritional diversity of cropping systems in African villages. *PLoS One* 6(6):e21235.
20. Powell B, et al. (2015) Improving diets with wild and cultivated biodiversity from across the landscape. *Food Security* 7:535–554.
21. Burlingame B, Dernini S, eds (2012) *Sustainable Diets and Biodiversity: Directions and Solutions for Policy, Research and Action* (Food and Agriculture Organization and Bioversity International, Rome).
22. Fanzo J, Hunter D, Borelli T, Mattei F, eds (2013) *Diversifying Food and Diets: Using Agricultural Diversity to Improve Nutrition and Health* (Routledge, London).
23. Frison EA, Smith IF, Johns T, Cherfas J, Eyzaguirre PB (2006) Agricultural biodiversity, nutrition, and health: Making a difference to hunger and nutrition in the developing world. *Food Nutr Bull* 27(2):167–179.
24. Deckelbaum RJ, Palm C, Mutuo P, DeClerck F (2006) Econutrition: Implementation models from the Millennium Villages Project in Africa. *Food Nutr Bull* 27(4):335–342.
25. Pinstrup-Andersen P (2013) Nutrition-sensitive food systems: From rhetoric to action. *Lancet* 382(9890):375–376.
26. Gómez MI, et al. (2013) Post-green revolution food systems and the triple burden of malnutrition. *Food Policy* 42:129–138.
27. World Bank (2007) *From Agriculture to Nutrition: Pathways, Synergies, and Outcomes* (World Bank, Washington, DC).
28. Chege CGK, Andersson CIM, Qaim M (2015) Impacts of supermarkets on farm household nutrition in Kenya. *World Dev* 72:394–407.
29. Haggblade S, Hazell PBR, Reardon T, eds (2007) *Transforming the Rural Nonfarm Economy: Opportunities and Threats in the Developing World* (Johns Hopkins Univ Press, Baltimore).
30. Fischer E, Qaim M (2012) Gender, agricultural commercialization, and collective action in Kenya. *Food Security* 4(3):441–453.
31. von Braun J, Kennedy E, eds (1994) *Agricultural Commercialization, Economic Development, and Nutrition* (Johns Hopkins Univ Press, Baltimore).
32. Sraboni E, Malapit MJ, Quisumbing AR, Ahmed A (2014) Women's empowerment in agriculture: What role for food security in Bangladesh? *World Dev* 61:11–52.
33. Olney DK, Talukder A, Iannotti LL, Ruel MT, Quinn V (2009) Assessing impact and impact pathways of a homestead food production program on household and child nutrition in Cambodia. *Food Nutr Bull* 30(4):355–369.
34. Herforth A (2010) Promotion of traditional African vegetables in Kenya and Tanzania: A case study of an intervention representing emerging imperatives in global nutrition. PhD thesis (Cornell Univ, Ithaca, NY).
35. Keding GB, Msuya JM, Maass BL, Krawinkel MB (2012) Relating dietary diversity and food variety scores to vegetable production and socio-economic status of women in rural Tanzania. *Food Security* 4:129–140.
36. World Bank (2013) Living Standards Measurement Study: Integrated Surveys on Agriculture. Available at econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/EXTLSMS/0,,contentMDK:23512006~pagePK:64168445~piPK:64168309~theSitePK:3358997,00.html. Accessed January 2, 2015.
37. Krishna VV, Euler M, Siregar H, Fathoni Z, Qaim M (2015) Farmer heterogeneity and differential livelihood impacts of oil palm expansion among smallholders in Sumatra, Indonesia. EFForTS Discussion Paper 13 (Univ of Goettingen, Goettingen, Germany).
38. Swindale A, Bilinsky P (2006) *Household Dietary Diversity Score (HDDS) for Measurement of Household Food Access: Indicator Guide* (Academy for Educational Development, Washington, DC).
39. FAO (2011) *Guidelines for Measuring Household and Individual Dietary Diversity* (Food and Agriculture Organization, Rome).
40. Smale M, Hartell J, Heisey PW, Senauer B (1998) The contribution of genetic resources and diversity to wheat production in the Punjab of Pakistan. *Am J Agric Econ* 80: 482–493.
41. Di Falco S, Chavas JP (2009) On crop biodiversity, risk exposure, and food security in the highlands of Ethiopia. *Am J Agric Econ* 91:599–611.
42. Greene WH (2012) *Econometric Analysis* (Prentice Hall, Upper Saddle River, NJ), 7th Ed.