# Smallholder Farming Households' Make-or-Buy Decisions: Linking Market Access, Production Risks, and Production Diversity to Dietary Diversity

Working Paper No. 360

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

Michael Keenan,
Stanley Karanja
Haki Pamuk
Ruerd Ruben

RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

CGIAR

CCAFS

Working Paper

# Smallholder Farming Households' Make-or-Buy Decisions: Linking Market Access, Production Risks, and Production Diversity to Dietary Diversity

Working Paper No. 360

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

Michael Keenan,
Stanley Karanja
Haki Pamuk
Ruerd Ruben

**To cite this working paper**
Keenan, M., Ng'ang'a Karanja S., Pamuk, H, Ruben, R. 2021. Smallholder Farming Households' Make-or-Buy Decisions Linking Market Access, Production Risks, and Production Diversity to Dietary Diversity CCAFS Working Paper no. 360. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

**About CCAFS working papers**
Titles in this series aim to disseminate interim climate change, agriculture and food security research and practices and stimulate feedback from the scientific community.

**About CCAFS**
The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is led by the International Center for Tropical Agriculture (CIAT), part of the Alliance of Bioversity International and CIAT, and carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For more information, please visit https://ccafs.cgiar.org/donors.

**Contact us**
CCAFS Program Management Unit, Wageningen University & Research, Lumen building, Droevendaalsesteeg 3a, 6708 PB Wageningen, the Netherlands. Email: ccafs@cgiar.org

# Abstract

Production risk and market access put pressure on agricultural household production and food consumption decisions. Improving market access and promoting production diversity have been proposed as solutions to better agricultural household nutritional outcomes. Particularly with regards to production diversity, the efficacy of these solutions has been called into question. We show that the effectiveness of increased production diversity translating into improved household nutrition is dependent on levels of market participation and access. To demonstrate these results, this paper develops a non-separable agricultural household model with multiple agricultural goods for consumption and/or production, production risk, and imperfect markets. Households jointly maximize production, consumption, and marketing decisions. The model's results are tested econometrically using nationally representative data from Tanzania. The paper contributes to a growing empirical literature concerning the relationships between production diversity, market access, and dietary diversity. We show that while on average a household needs to grow ten additional food groups to consume just one more food group, households not participating in markets need to grow just four more food groups to consume one more. This interaction explains why the literature typically finds weak correlations between dietary diversity and production diversity for typical households. The paper also contributes to the theoretical literature surrounding non-separable household models by providing a framework for understanding the role of markets and risk for household dietary diversity by developing. Our model provides economic theory consistent with existing empirical evidence and helps explain why most studies only find a small link between production diversity and dietary diversity.

## Keywords

Nutrition; Non-Separable Model; Production Diversity, Risk, Market Access.

# About the authors

**Michael Keenan**, Wageningen University and Research, Development Economics Group, P.O. Box 35,  6700 AA Wageningen, The Netherlands. Alliance of Bioversity International and CIAT Africa Hub Kasarani, Rd., ICIPE Complex, P.O. Box 823-00621, Nairobi, Kenya. Corresponding author, michael.keenan@wur.nl

**Stanley Karanja Ng'ang'a**. Alliance of Bioversity International and CIAT Africa Hub Kasarani, Rd., ICIPE Complex, P.O. Box 823-00621, Nairobi, Kenya.

**Haki Pamuk,**  Wageningen University and Research, Development Economics Group and Wageningen Economic Research, P.O. Box 35,  6700 AA Wageningen, The Netherlands.

**Ruerd Ruben**, Wageningen University and Research, The Netherlands.  Wageningen Economic Research and Development Economics Group, P.O. Box 35,  6700 AA Wageningen, The Netherlands.

# Acknowledgements

We thank Marcel van Asseldonk from Wageningen University and Research, Maarten Voors, Erwin Bulte, participants to the seminar in Wageningen University and Research for their comments about the study.

This working paper is part of the work conducted under the CSA/SuPER - Upscaling CSA with small-scale food producers organised via VSLAs under the CCAFS program project.  The authors acknowledge both financial and technical support from 4th Global Challenges Programme (GCP 4) – a joint climate smart agriculture scaling program implemented in Eastern and Southern AFRICA with the support from the Netherlands Organization for Scientific Research (NWO) and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) for East Africa, which is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors. The research also benefited from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), with support from CGIAR Fund Donors and through bilateral funding agreements. This study also benefits from the CGIAR Research Program on Policies Institutions and Markets which has provided funding for Michael Keenan's PhD dissertation, which includes this working paper.

# Contents

# Acronyms

| | |
|---|---|
| CSA | Climate smart agriculture |
| FAO | Food and Agriculture Organization |
| GHI | Global Hunger Index |
| SDGs | Sustainable Development Goals |

# 1 Introduction

Malnutrition is a significant challenge for the world. In the developing regions of the world, 780 million people are undernourished (FAO et al., 2018). The majority of undernourished people are smallholder farmers in rural areas of Africa and Asia (Pinstrup-Andersen, 2007; Sibhatu and Qaim, 2017). Despite the commitment of the Sustainable Development Goals (SDGs) in 2015 to end hunger, the share of undernourished people in Sub-Saharan Africa (SSA) has grown from 17.4% in 2017 to 19.1% in 2019 (FAO, IFAD, UNICEF, WFP, 2020). Studies show that improving dietary diversity may be a promising strategy to address undernourishment (Arimond et al., 2010; Kant et al., 1993; Popkin and Slining, 2013; Sibhatu et al., 2015). Smallholder farmers are particularly vulnerable to under-nutrition, as poverty rates among smallholders are typically much higher than national averages (Rapsomanikis, 2015). For this reason, many development initiatives introduce new crops and production methods to smallholder farmers to boost their production diversity and improve their dietary diversity. However, empirical evidence suggests that households need to grow nine more crops to increase the number of food groups they consume by one (Sibhatu and Qaim, 2018). Vast differences in smallholder market access and participation may be influencing the (in)effectiveness of production diversity as a means to improve dietary diversity (Sibhatu et al., 2015).

This study assesses the interaction of smallholders' production diversity, market access and participation, and dietary diversity. We develop a non-separable agricultural household model for multiple crops, involving joint decision making on consumption, production under risk, and market participation. Traditional models of agricultural households assume that food and production choices are separable under perfect markets. However, production and food choices in the context of rural farming households, particularly in developing regions, are non-separable because of market imperfections. Smallholder farmers usually face implicit and explicit transaction costs because they lack market information on prices, buyers, and sellers and can be far away from markets (Chamberlin and Jayne, 2013). These transaction costs can make consumption of on-farm produce for smallholder farmers cheaper than purchasing food products from the market. In addition, smallholder farmers are exposed to market and production risks with limited access to financial instruments (e.g. loans and insurance) to mitigate the effects of those risks. Instead, they diversify their agricultural production to reduce risk exposure and include both food and cash crops in their production mix (Makate et al., 2016).

Specifically, our model is a variant of the mean-variance portfolio optimization model, taking the non-separable production and consumption choices of smallholder farmers into account. In the full model, the farming household is endowed with a fixed amount of land and labor and can produce multiple crops. The household can consume its own food production, or as a price taker, it can sell and purchase food items at exogenous market prices. However, both purchasing and selling in the market involve transaction costs (e.g., transportation costs and costs of accessing market information). The household allocates its endowments to maximize jointly (i) the returns from the production while trying to minimize joint production risks, and (ii) household welfare from the consumption of food items. The household's consumption and production diversity are estimated endogenously by our model for given market transaction costs and prices, production risk, and food preferences. Three factors potentially drive production diversity: production risks, the love of consumption variety, and transaction costs (i.e. market acces).

Consistent with earlier theories (Finkelshtain and Chalfant 1990, Fafchamps 1992), the model predicts that risk increases production diversification and reduces specialization in the production of the crop with the highest financial return. This causes a fall in overall income. Moreover, the household prefers producing cash crops (or crops with high financial returns) to food crops when it is well integrated into markets (as in Omamo, 1998), but it prefers to produce food crops when transaction costs prohibit easy access to markets.

Our novel findings concern the interaction between market participation, production, and consumption diversity. We find that the influence of production risks and diversification on dietary diversity depends on the household's level of market access. The model shows that increasing market access (via reducing transaction costs) improves dietary diversity, allowing the household to specialize in producing (cash) crops with the highest (financial) returns. With those returns, the household can purchase and consume a diversified basket of food products from the market. When the household's level of market access is above a certain threshold, production diversity hinders consumption diversity. Increases in production risks incentivize the household to diversify their production to mitigate risk, causing a reduction in the returns from agriculture and consequently, dietary diversity. In contrast, production diversification positively contribute to the dietary diversity of a household with limited access to markets (under a given threshold of market access). Because of the household's love of variety, the household diversifies their production and grows multiple crops, which will primarily be consumed at home. The household aims to satisfy their preference for a diverse diet through a diverse production mix. However, growing more crops does not necessarily increase dietary diversity because it matters which crops are being grown, not just how many.

Finally, we test the predictions of the model through regression analysis. For this purpose, we use the nationally representative LSMS data for Tanzania in 2013. Rural Tanzania is a suitable and relevant context to test the predictions of the model, as nearly 68% of Tanzanian households work in the agricultural sector (FAO et al., 2018). Many of these smallholder farmers' diets are susceptible to climate shocks. Despite improvements over the last two decades, Global Hunger Index (GHI) reports that Tanzania has a serious hunger problem and ranks as one of the least food secure countries in the world, scoring 95th out of 117 countries in 2019 (Global Hunger Index, 2019).

In our regression analysis, we use the presence of village markets to measure market access, and we use past production shocks to proxy production risks. The results from the analysis show that increased production diversity is positively correlated with past production shocks and negatively correlated with the presence of markets, confirming our theoretical predictions. Further, we test whether market participation/access and production diversity are correlated with dietary diversity and anthropometric measures. Our findings give evidence to the theoretical model by showing that both market participation and production diversity are positively and significantly correlated with dietary diversity. Market participation plays a small mediating role in the correlation of production diversity with dietary diversity – production diversity is positively and significantly correlated with dietary diversity at low levels market participation, but has zero correlation at higher levels. The results do not hold for anthropometric outcomes, as in Chegere and Stage (2020).

Our study provides a consistent theoretical framework for the extensive empirical literature surrounding production diversity, market access, and household nutrition of smallholder farmers. The study also gives novel insights to the interaction between these factors. It also provides a clear set of policy implications on rural development and nutrition. Our findings show that improvements in market access of smallholder farmers while reducing their production risks enhances household nutrition. These suggest that improvements in the market participation of smallholders must be supported while introducing agricultural methods reducing production risk (e.g., new varieties and production methods). Their contribution depends on the market access, food choice, and risk exposure of smallholders. To this end, before introducing improved varieties or new crops, development practitioners should follow a participatory approach that involves smallholder households to understand their risks, food choices, market access challenges.

Related literature: Our study contributes to two strands of literature. First, we contribute to the agriculture household modeling literature. There is an extensive literature on agricultural household models that assess the responses of household supply and demand to changes in food prices (Taylor and Adelman, 2003). The majority of those models are so-called separable household models where households decide on production and consumption separately. The assumption of perfect markets, which allows for separable optimization, makes those models relatively easy to implement and find analytical results. However, still today, large portions of agricultural households in rural areas of developing countries are both consumers and producers of food. For this reason, several non-separable models have been developed to analyze smallholder farmer behaviour. Like their separable predecessors, these models address a variety of issues, particularly market access's role in crop diversification. For instance, Omamo (1998) shows that in the absence of risk, transaction costs explain the low-levels of specialization in agricultural production as a rational outcome. He suggests that in the case of two goods - a food crop and a cash crop - farmers with high transaction costs tend to inter-crop food and cash crops more, while farmers with low transaction cost specialize in the cash crop. de Janvry et al. (1991) introduced market imperfections (via transaction costs) for food and labour markets to analyze non-separable production decisions. Fafchamps (1992) uses a two-crop non-separable model to analyze the relationship between market access, risk, and crop allocations. The paper shows that small farms are food-crop oriented and large farms are cash crop oriented - a common observation in developing countries. Goetz (1992) illustrates a model whereby the households participate in markets based on fixed transaction costs. Key et al. (2000) extends this work by looking at the differences between the introduction of per-unit and fixed transaction costs on household market participation and supply response and by simultaneously solving the production, consumption, and market participation decisions.

The non-separable household models that are mentioned above cannot analyze the cases of many production and consumption goods, instead opting for two-good models. This omission makes it difficult to study household dietary diversity - a key component of household nutrition. This paper fills that gap in agricultural households modeling by introducing a non-separable household model with multiple goods produced under risk. For this purpose, we use the mean-variance framework that was originally proposed by Markowitz (1952) in the context of investors' portfolio allocation decisions in financial markets. The mean-variance approach and variants of it have been applied to farm planning in numerous studies (Collins 1988; Tauer 1983; Watts et al. 1984; Coyle 1992; Coyle 1999). Tzouvelekas (2011) uses a mean-variance approach with non-separability in labor markets. It tests the results for British farmers, in light of EU pricing policy support. In this study, we use the mean-variance approach with non-separable agricultural households models with imperfections in food markets in developing countries, for (to our knowledge) the first time. While our model is focused on the relationships between risk, market access, production and consumption diversification, it is also generalizable enough to potentially add other components.

Second, this relates to the empirical literature investigating the relationship between production diversity, market access, and household nutrition in developing countries. We contribute a theoretical framework for the empirical literature and empirically test the role of the interaction between production diversity and market access in determining dietary diversity. Several papers have found increases in consumption diversity associated with increases in production diversity. In Zimbabwe, crop diversification increased the dietary diversity of children and women during a nutrition education intervention (Murendo et al., 2018). Similar results are found in Malawi using nationally representative data, where crop and livestock diversification were associated with higher consumption diversity (Jones et al., 2014). While much of the research regarding the relationship between production diversity and nutrition is in Sub-Saharan Africa, these relationships have been observed in other regions, such as Bolivia (Jones, 2015) and India (Kumar et al., 2016). Despite the evidence that production diversity can improve household nutrition, the efficiency of production diversity as a lever to improve nutritional outcomes has been brought into question. In a meta-analysis of 45 studies in 26 countries analyzing this relationship, Sibhatu and Qaim (2018) find that the mean marginal effect of production diversity on household dietary diversity is quite low. In SSA, the review concludes that a household would need to cultivate nine additional crops just to increase consumption diversity by one food group (Sibhatu and Qaim, 2018).

Several other studies empirically analyse the effect of market access on household diversity. For instance, in a panel study in northern Ethiopia, being located closer to markets is associated with higher overall dietary diversity for children (Abay and Hirvonen, 2017). In Kenya, access to selling produce to supermarkets is found to improve household nutrition (Chege et al., 2015). Evidence even points towards market access being a more critical factor in improving household nutrition than production diversity in Malawi (Koppmair et al., 2017). Finally, cash income from produce is associated with higher dietary diversity and micro-nutrient consumption than production diversity in Uganda, Indonesia, and Kenya (Sibhatu and Qaim, 2016). Our theoretical model contributes to this literature by explaining how market access mediates the effect of product diversification on household dietary diversity by emphasizing the importance of the interaction between market access and production, and providing a consistent theoretical framework for existing empirical analysis.

The structure of the paper is as follows. Section 2 outlines the theoretical model and its implications. Section 3 introduces the econometric methods for testing the production outcomes of the model. Section 4 discusses the data used in the econometric approach, and Section 5 shows the results of the econometric analysis. We conclude the paper with a brief discussion on the findings. All proofs are shown in the appendices.

# 2 Theoretical Model

The proposed model is a non-separable household model (i.e. households maximize consumption, production, and market participation simultaneously) with N agricultural goods. The goods can either be produced and consumed at home or produced and sold on the market in exchange for other agricultural goods. On the production side, the household maximizes production while minimizing production risk according to a multi-good mean-variance function. On the consumption side, households maximize utility according to multi-good additive log utility function. The multi-good approach allows for the extrapolation of dietary diversity scores and can show how dietary diversity is related to market access and production risk (e.g. climate variability).

To simplify the model and focus on the linkages of consumption diversity and production diversity with production risk and market access, several assumptions are made. Households are price-takers in both supply and demand of agricultural goods. As consumers, households have a love of variety of goods. Further, households are risk-averse, and their production carries risk (in the form of climatic variation). Households are assumed to have no livestock holdings, cannot engage in off-farm labor, and land and labor costs are zero. These assumptions can be relaxed, but this is beyond the scope of this research.

This section first introduces the model's hypotheses, followed by a presentation of the model framework on both the consumption and production sides. The model framework culminates in a derivation of the household's value function. Then, the case of perfect markets in a risk-less setting is analyzed to understand the simplest case of the model. The next two sub-sections relax the assumption of a risk-free environment and of perfect markets, respectively. These specific cases of the model uncover the effects of production risk and market access on household production decisions and on household dietary diversity.

## 2.1 Hypotheses

The theoretical model is intended to explain the economic theory behind the empirical evidence linking production diversity, market access, and dietary diversity. Three main propositions are put forward in examining these relationships:

Proposition 1 Market access leads to greater specialization in production.

Proposition 2 Production risk leads to higher production diversity.

Proposition 3 Higher production diversity leads to higher dietary diversity if market access is low (and vice versa).

Proposition 4 Higher market access leads to higher dietary diversity through increased income.

We show that these four propositions hold using specific cases of a non-separable agricultural household model presented below.

## 2.2 Model Setup

Let there be a utility-maximizing agricultural household that both produces and consumes food crops during one period[1] The household can consume and produce up to $N$ different crops. Utility is gained through the consumption of crops and takes an additive log-utility functional form with decreasing marginal returns to each individual crop consumed and decreasing absolute risk aversion (DARA):

$$U = \sum_{i=1}^{N} w_i \ln(c_i + 1) \tag{1}$$

where $w_i$ is a preference parameter for good $i$ and $c_i$ is the consumption quantity of good $i$. Adding the constant 1 to consumption allows for zero consumption and ensures only positive consumption values can lead to positive

[1] By 'food' crops, we mean any agricultural good that can be consumed, including traditional cash crops like tea and coffee.

utility[2]. The household can consume any good $i$ through two different channels – by producing and selling crops on the market and using the resulting income to purchase and consume crop $i$ ("market consumption") or through producing crop $i$ at home and consuming the resulting home-production ("home consumption"). Consumption for good $i$ is defined as:

$$c_i = c_i^m + c_i^h \tag{2}$$

where $c_i^m$ is market consumption and $c_i^h$ is home consumption. We assume the household does not differentiate between consumption from the market and consumption from home production (i.e. both types of consumption yield equivalent amounts of utility). In both consumption channels, production of crops is required whether to sell on the market for income in the case of market consumption or to consume at home in the case of home consumption. Households are endowed with a productive asset and can allocate a proportion, $0 \leq s_i \leq 1$, of that productive asset to any good $i$ of the $N$ goods that can possibly be produced. This productive asset can be thought of as land and/or labor, and it may be a combination inputs. Further, these productive inputs are free[3] (i.e. there are no land or labor costs in the model). Production carries risk and is assumed to be log-normally distributed. Production, $q_i$, for any good $i$ is given by:

$$q_i = s_i \gamma_i \epsilon_i, \; \epsilon_i \sim \mathcal{N}(1, \sigma_i^2) \tag{3}$$

where $q_i$ is the quantity of good $i$ produced, $\gamma_i$ is a productivity parameter, and $\epsilon_i$ is the risk term following a log-normal distribution with mean 1 and variance $\sigma_i$. We assume all production risks are uncorrelated. This is a simplifying assumption and does not affect the mechanisms which we are trying to demonstrate In Appendix A, we show that the formulation in Equation 3 is compatible with a Cobb-Douglas production function for each crop $i$ if all crops have identical output elasticities for land and labor.

Under production risk, households are risk averse in their production decisions and choose to allocate their resources using a mean-variance approach that simultaneously maximises production and minimizes production variance. The expected quantity produced (using a common measure of quantity, e.g. calories) is given by:

$$q_i = E[q_i] - \frac{a}{2}\sigma^2 \; \forall \, i \, \in \, N \tag{4}$$

where $a$ is a non-negative constant determining the variance's contribution to utility. We restrict analysis to the domain in which $0 \leq q_i < \frac{1}{a}$ because this is the domain on which Equation 4 is monotonically increasing. Beyond this point, expected quantity of good $i$ decreases with more productive resources allocated to it (a common assumption when using quadratic utility functions).

Households choose how to allocate their productive resources to maximize their utility. For each crop $i$, they can allocate resources to production for sale on the market, $s_i^m$, or production for home consumption $s_i^h$. If the household produces crops for sale on the market, they receive an income of:

$$E[I] = \sum_{i=1}^{N} (p_i - t_i) E[q_i] \tag{5}$$

[2]This can be seen through the basic properties of the natural log function. ln$(x)$ is undefined when $x = 0$. Then, log utility is undefined for zero consumption. In contrast, ln$(x + 1) = 0$ when $x = 0$, indicating that utility is zero at zero consumption. The later is better suited in scenarios when zero consumption of an individual good is common. Since, ln$(x)$ is monotonically increasing and has global diminishing marginal returns, and ln$(x + 1)$ is defined for every values of $x \in -(1, \infty)$, then ln$(x)$ and ln$(x + 1)$ have the same proprieties for the range $[0, \infty)$, the possible range of consumption values.

[3]This is a simplifying assumption, but does not affect the relationship we are most interested in analyzing – the relationship between production risk, market access, and consumption diversity.

where $p_i$ is the market unit price for good $i$ and $t_i$ is the transaction cost for selling a unit of good $i$ on the market. Equation 5 serves as the budget constraints for market purchases as well, and combining Equation 4 and Equation 5, the full income constraint is:

$$\sum_{i=1}^{N}(p_i + t_i)c_i^m \leq \sum_{i=1}^{N}(p_i - t_i)(s_i\gamma_i - \frac{a}{2}s_i^2\sigma_i^2) \tag{6}$$

where the purchase price for good $i$ on the market is the market price, $p_i$, plus the per unit transaction cost $t_i$. Home consumption does not need to be purchased, but it is constrained by home production. The household cannot consume more of a crop from home production than it produces for home consumption. Assuming there are no post-harvest losses, the home consumption is constrained by:

$$E[c_i^h] = s_i^h E[\gamma_i] - \frac{a}{2}s_i^2\sigma_i^2 \,\forall\, i \,\in\, N \tag{7}$$

Putting the utility, income constraints, and home-consumption constraints together, the household's utility maximization problem is:

$$\begin{aligned} \max E[U] &= \sum_{i=1}^{N} w_i \ln(E[c_i^m] + E[c_i^h] + 1) \\ \text{s.t.} \sum_{i=1}^{N}(p_i + t_i)c_i^m &\leq \sum_{i=1}^{N}(p_i - t_i)(s_i E[\gamma_i] - \frac{a}{2}s_i^2\sigma_i^2) \\ E[c_i^h] &= s_i^h E[\gamma_i] - \frac{a}{2}s_i^2\sigma_i^2 \end{aligned} \tag{8}$$

The maximization problem in Equation 8 is specified in terms of both $c$ terms (in the utility function) and $s$ terms (in the constraints). The problem states that households maximize their utility from consuming $N$ goods (from home and/or the market) subject to their market consumption of all goods being constrained by their income and their home consumption of any being constrained by the production of that good for home consumption. To simplify the problem and specify it only in terms of $s$ terms, the utility function can be expressed as an indirect utility function (which shows the maximum attainable utility given prices and income) via the principle of duality in optimization problems. Appendix B shows how each $c_i^m$ term can be written in terms of prices and income and the utility maximization problem can be converted into the value function maximization problem in Equation 9 whereby the household only chooses $s$ values to maximize utility, and optimal $c$ values are obtained ex-post. In the resulting value function maximization problem, home production is simply substituted for home consumption to get:

$$\begin{aligned} \max E[V] = \sum_{i=1}^{N} w_i \ln([\frac{w_i}{(p_i + t_i)\sum_{j=1}^{N} w_j}\sum_{j=1}^{N}(p_j - t_j)(s_j^m E[\gamma_j] - \frac{a}{2}s_j E[\gamma_j]^2 + \sigma_j^2)] + [s_i^h E[\gamma_i] - \frac{a}{2}s_i\sigma_i^2] + 1) \\ \text{s.t.} \sum_{i=1}^{N} s_i^h + s_i^m \leq 1 \end{aligned} \tag{9}$$

where the constraint ensures that the proportion of productive resources allocated to all crops (for home and market production) is equal to one (i.e. the household cannot allocate more resources than it has).

Equation 9 describes the entire model. The household chooses production levels and marketing decisions of $N$ goods to maximize their additive log utility of consumption of $N$ goods either at home or from the market. The two terms in brackets are the contributions to utility of consumption from the market place and from home production, respectively, for each good $i$. The constraint on Equation 9 indicates that the household can only use their endowment of productive inputs for production.

Market consumption is defined by the first term in brackets in Equation 9. There are two components to total market consumption. The first is household income from producing and selling goods on the market: $\sum_{j=1}^{N}(p_j - t_j)(s_j^m E[\gamma_j] - \frac{a}{2} s_j E[\gamma_j]^2 + \sigma_j^2)$. This follows directly from the income constraint in Equation 8. The second term is the relative preference of good $i$ divided by the purchase price: $\frac{w_i}{(p_i+t_i)\sum_{j=1}^{N} w_j}$. Income and the relative preference/price parameter a multiplied together to give this total consumption of a good $i$ from the market place. Intuitively, this shows that households choose their consumption behavior in markets by spending all of their income while consuming more of goods they prefer, consuming less of expensive goods, and balancing these two attributes. Further, The household operates under imperfect markets, whereby it pays a per-unit transaction cost of $t$ to participate in both production and consumption markets.

The second term in brackets is the consumption from home production, which follows directly from the second constraint in Equation 8. Households must consume from home production only the total food they produce for home consumption. The final term inside the natural log function is the constant, 1, which ensures that zero consumption of any good is possible and leads to zero utility.

The value function is monotonically increasing on the interval of $q_i^{h,m} \in [0, \frac{1}{a}]$, the range which we defined the production function above. Using Equation 9, the next subsections focus on specific cases of this model which can show two motivations for production diversity and their differential effects on consumption diversity.

## 2.3 The Base Case: Perfect Market without Production Risk

In the "base case" of the model, the household engages in perfect markets without risk. Understanding how the household behaves under these assumptions, sets the comparison for the model with imperfect markets and/or risk. These comparisons will show how risk affects household outcomes (Propositions 2 and 3), and how market access affects household outcomes (Propositions 1 and 4).

In the case of perfect output markets, there are no transaction costs ($t_i = 0 \, \forall \, i$), and as a result, households can seamlessly sell their production on the market and exchange it for consumption goods. Households do not engage in home production in this case since home production is equivalent to selling a unit of good $i$ on the market and buying it back at the same price, $p_i$. The scenario leads to a separable model, whereby households can maximize their income and consumption separately. Since the value function represents the maximized utility for a given level of income and prices, at this stage, the household only needs to maximize its income to maximize the value function.

In the case, we also assume that there is no production risk ($\sigma_i = 0 \, \forall \, i$). No production risk also implies that the production function is linear instead of quadratic, and expected production simplifies to: $E[q_i] = q_i$. Combining these assumptions, Equation 9 becomes:

$$\max E[V] = \sum_{i=1}^{N} w_i \ln\left(\frac{w_i \sum_{j=1}^{N} p_j (s_j^m \gamma_j)}{p_i \sum_{j=1}^{N} w_j}\right) \quad \text{s.t.} \sum_{i=1}^{N} s_i^m \leq 1 \tag{10}$$

Since $\ln(.)$ is monotonically increasing on the domain specified for the value function, the function is maximized by maximizing the argument of Equation 10. Without production risk, the household chooses to invest in the highest returning productive activity, determined by the term $p_j\gamma_j$, which maximizes utility.

Proposition 1: Market access leads to greater specialization in production.

$$\begin{cases} \text{arg max}\, E[V] = s_k^* = 1 \\ s_i^* = 0\, \forall\, i \neq k \end{cases} \tag{11}$$

where good $k$ is the good that has the highest return, $p_k\gamma_k$ and yields the highest utility after taking into account fixed costs. Consumption can be calculated ex-post and becomes the optimal consumption values found in Appendix B. From these optimal consumption values, it is easy to see how dietary diversity improves with income. Let dietary diversity be defined by the Herfindahl-Hershman Index (HHI):

$$\text{HHI} = \sum_{i=1}^{N} c_i^2/C \tag{12}$$

where $C$ is total consumption. The HHI measures the level of concentration in a diet. A lower HHI indicates a less concentrated diet (or a more diverse diet) while a higher HHI indicates a more concentrated (less diverse) diet. In Appendix C, we show that the comparative static of HHI with respect to income is negative, indicating that dietary diversity improves with increases in income:

$$\frac{\partial \text{HHI}}{\partial I} < 0 \tag{13}$$

Therefore, increasing dietary diversity for the household with perfect market access and no risk requires only increasing household income. Production diversity away from the most profitable crop will reduce income and consequently, reduce dietary diversity.

## 2.4 Perfect Markets with Production Risk

To understand why risk increases production diversity (Proposition 2), the assumption of risk-less production is dropped, but the assumption of perfect markets is maintained for simplicity. Equation 9 becomes:

$$\begin{gathered} \max E[V] = \sum_{i=1}^{N} w_i \ln\left(\frac{w_i \sum_{j=1}^{N}(p_j s_j^m E[\gamma_j] - \frac{a}{2} s_j^2 \sigma_j^2)}{(p_i + t_i)\sum_{j=1}^{N} w_j}\right) \\ \text{s.t.} \sum_{i=1}^{N} s_i^m \leq 1 \end{gathered} \tag{14}$$

Since there are perfect markets, the household can optimize consumption and production separately, and the production choices that maximize income will also maximize utility from consumption. The household solves:

$$\begin{gathered} \frac{\sum_{j=1}^{N}(p_j - t_j)(s_j^m E[\gamma_j] - \frac{a}{2} s_j \sigma_j^2)}{(p_i + t_i)\sum_{j=1}^{N} w_j} \\ \text{s.t.} \sum_{i=1}^{N} s_i^m \leq 1 \end{gathered} \tag{15}$$

Proposition 2: Production risk leads to higher production diversity.

This is the standard mean-variance problem and it leads to the well-known optimal solution:

$$\mathsf{s}^{m*} = {}^{-1}(\mathsf{r} - \mathsf{1}\frac{\mathsf{r}'^{-1}\mathsf{1} - 1}{\mathsf{1}'^{-1}\mathsf{1}}) \tag{16}$$

where $\mathsf{s}^{m*}$ is an $N$-length vector and the return vector (with respect to $\mathsf{s}^{m*}$), r, is given by:

$$\mathsf{r} = \begin{pmatrix} p_1\gamma_1 \\ p_2\gamma_2 \\ \vdots \\ p_n\gamma_n \end{pmatrix} \tag{17}$$

, the (co)variance matrix, is given by:

$$= \begin{pmatrix} \sigma_1^2 & 0 & \dots & 0 \\ 0 & \sigma_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_n^2 \end{pmatrix} \tag{18}$$

In the optimal solution, the household diversifies to reduce exposure to risk. While risk is reduced, the income is necessarily lower than in the risk-less case because the household has diversified away from producing only the most profitable good in exchange for producing less profitable crops (and higher return is associated with higher risk). As in the case of perfect markets and no risk, the optimal consumption parameters fall directly from the optimal solution. However, since income is lower in the case involving risk than no risk, and the comparative static of HHI with respect to income is negative (see Equation 13) then diversification caused by risk also has a negative effect on HHI.

Proposition 3 (Part 1): Higher production diversity leads to lower dietary diversity if the market access is high.

$$\text{HHI}_{\text{risk}} > \text{HHI}_{\text{no risk}} \tag{19}$$

Equation 19 shows part of Proposition 4. Agricultural households with high market access who diversify production to mitigate risk have lower dietary diversity. This means that production diversity is not necessarily associated with higher consumption diversity and can depend on the level of market access. The next sub-sections show the role of production diversity when market access is low.

## 2.5 Imperfect Markets without Production Risk

To show the other side of Proposition 3, imperfect markets are introduced (i.e. transaction costs are present). For simplicity of demonstration, let each transaction cost be $t_i = p_i$, such that the household cannot earn any income from selling crops. The budget constraint collapses to zero and the household can only consume its own production. Equation 9 becomes:

$$\max E[V] = \sum_{i=1}^{N} w_i \ln(s_i^h \gamma_i + 1)$$
$$\text{s.t.} \sum_{i=1}^{N} s_i^h \leq 1 \tag{20}$$

The solution to Equation 9 is given by:

$$s_i^* = \frac{w_i \gamma_i N - \sum_{j=1, j\neq i}^{N} w_j \gamma_j}{\sum_{j=1}^{N} w_j \gamma_j} \; \forall \; i \in N \tag{21}$$

In the optimal solution, the household's production decisions depend only on their consumption preferences $w$ and productivity parameters $\gamma$. Therefore, a second source of production diversification is market access – when a household loses market access, then they diversify their production mix in order to meet their demand for different types of food consumption, and they do it in a way that is aligned with their consumption preferences and productive capacity. This is in contrast to the case where the household has perfect market access and no risk, as this household specializes its production completely in the most profitable crop. The result in Equation 21 shows the second source of production diversification: lack of output market access.

Proposition 3 (Part 2): Higher production diversity leads to higher dietary diversity if the market access is low.

It is trivial to show that a decrease in production HHI is equivalent to a decrease in consumption HHI:

$$\text{HHI}_{\text{production}} = \text{HHI}_{\text{consumption}} \text{ if } t_i = p_i \; \forall \; i \tag{22}$$

The effects of autarky on dietary diversity are negative. This result can be logically extended to less extreme cases of imperfect markets, such that $0 < t_i < p_i$. When transaction costs are 0, then the there are perfect markets, and when they are equal to $p_i$, then the household operates in autarky for a given good, $i$. In the "in between" cases, $t_i \rightarrow p_i$ is equivalent to a decrease price and results in a decrease in income (this trivially follows from the definition of income in Equation 5) . Further, this relationship is linear by definition. Appendix C shows that a loss in income is associated with a loss in dietary diversity. Therefore, an increase in transaction costs (or a decrease in market access) is also associated with a decrease in dietary diversity. This results in Proposition 4:

Proposition 4: Higher market access leads to higher dietary diversity despite being associated with lower production diversification

$$\text{HHI}_{\text{Market Access}} < \text{HHI}_{\text{No Market Access}} \tag{23}$$

The result in Equation explains why the empirical literature has found that households with higher market access have higher dietary diversity. They have higher incomes and can purchase a diverse range of foods from the markets. However, these households have lower production diversity than households without market access. This shows that market access is a mediating factor for the effect of production diversity (from production risk) on dietary diversity.

Additionally, the difference between the range of goods offered on the market may also mean that the household operating in autarky has lower dietary diversity than the household operating in perfect markets. Let there by $N$ crops that are able to be produced - $\gamma_i > 0 \; \forall \; i \in N$ and let there by $N + M$ foods that can be purchased on the market. The difference in the goods able to be produced and able to be purchased can occur for a myriad of reasons, e.g. on-farm limitations to the range of crops that can be produced and imports of foods grown in different climates from other areas. By default, the household operating in autarky will have a less diverse diet than if it operated under perfect market access.

# 3 Empirical Methodology

The empirical analysis tests whether the propositions put forth in Section 2.1 hold among smallholder farmers in rural Tanzania. To better understand how the empirical analysis links with the model's propositions, the propositions can be re-stated using empirical terminology. The terminology in the propositions below draws on the variables used in the analysis (Section 4). The propositions to be tested empirically are:

Proposition 1 Market participation and/or living in a village with market is negatively correlated with production diversity.

Proposition 2 Households experiencing negative production shocks in the past ten years have higher production diversity than households not experiencing production shocks.

Proposition 3 Production diversity is positively correlated with dietary diversity for households with low market participation and negatively correlated with dietary diversity for households with higher market participation (or with village markets).

Corollary to Proposition 3 Overall, production diversity is positively correlated with dietary diversity in rural Tanzanian households because market participation is low[4].

Proposition 4 Market participation and/or living in a village with market is positively correlated with higher dietary diversity.

## 3.1 The Production Side: Testing Propositions 1 and 2

Section 2 shows that production diversity can be driven by market access and risk exposure.

To test Propositions 1 and 2, we follow an empirical strategy similar to Asante et al. (2018). The following regression model is estimated:

$$\text{pd}_i = \beta_0 + \beta_1 \sigma_j + \beta_2 \text{shock}_i + \beta_3 \text{market}_i + \beta X_i + \epsilon_i \tag{24}$$

where $\text{pd}_i$ is a production diversity outcome (discussed in Section 4), $\text{shock}_i$ is an indicator of whether the household experienced a negative production shock in the past ten years (a proxy for perceived risk), $\text{market}_i$ is the market participation or access variable, $X_i$ is a vector of household-level controls, $\alpha_j$ is a district fixed effects term, $\beta_0$ is a constant, and $\epsilon_i$ is the error term.

Standard errors in the models which use count variables (e.g. Agricultural Diversity Score) as dependent variables are estimated assuming a Poisson distribution. The models with HHI (i.e. Simpson's Index) are estimated with a GLM model using a logistic functional link and binomial distribution of the outcome variable, as all values of Simpson's Index fall between 0 and 1. Marginal effects are calculated and reported in each model.

The main independent variables of interest are $\text{shock}_i$ and $\text{market}_i$, whose coefficients, $\beta_2$ and $\beta_3$ respectively, indicate whether Propositions 1 and 2 hold.

[4] This corollary is added because we test for the overall correlation of production diversity with dietary diversity in addition to correlations based on market participation, in line with previous studies

### 3.2 The Consumption-Side: Testing Propositions 3 and 4

To test Proposition 4 and the Corollary to Proposition 3, we use models that are commonly run in the empirical literature surrounding production diversity, market access, and dietary diversity (Sibhatu and Qaim 2016, Jones (2017a), Jones 2017b, Koppmair et al. 2017). The model is given by:

$$\text{dd}_i = \beta_1 \text{pd}_i + \beta_2 \text{market}_i + \beta X_i + \alpha_j + \text{month}_i + \epsilon_i \tag{25}$$

where $\text{dd}_i$ is a household measure of dietary diversity (either HDDS or HHI), $\text{pd}_i$ is a measure of crop diversity (Agricultural Diversity Score or Simpson's Index), $\text{market}_i$ is a measure for market participation or market access, $X_i$ is a vector of control variables, $\alpha_j$ is the distric fixed effects, and $\text{month}_i$ is a fixed effects variable for the month the survey was conducted (included because of seasonal variation in dietary diversity), and $\epsilon_i$ is the error term.

As in the production diversity models, standard errors with models using HDDS as an outcome variable are estimated using an assumed Poisson distribution (as HDDS is a count variable). Standard errors in models with Consumption HHI as an outcome are estimated with GLM with a logistic link and binomial distribution. Marginal effects are reported in each of the specifications.

To test the Corollary to Proposition 3, an interaction term between production diversity and market access/participation is added to Equation . The model becomes:

$$\text{dd}_i = \beta_1 \text{pd}_i + \beta_2 \text{market}_i + \beta_3 \text{pd}_i \times \text{market}_i + \beta X_i + \alpha_j + \text{month}_i + \epsilon_i \tag{26}$$

The coefficient $\beta_3$ of the interaction term, $\text{pd}_i \times \text{market}_i$ indicates whether market participation has a moderating or exacerbating influence on the relationship between production diversity and dietary diversity. A negative $\beta_3$ indicates that crop diversity is less important for households with high access/participation in markets, while a positive $\beta_3$ indicates that crop diversity is more important for households with high market access/participation.

Due to well-known issues issues with the interpretation of coefficients for interaction terms in non-linear models (Shang et al., 2018), we calculate the marginal effects of crop diversity for different levels of market-participation and create margins plots to graphically understand and interpret the interaction effects (as in the analysis of Equation 26).

## 4 Data, Variables, and Summary Statistics

### 4.1 Data Sources

The empirical analysis uses data from the third wave of the Tanzanian National Panel Survey (NPS), which forms part of the World Bank's Living Standards and Measurement Studies (LSMS). Tanzania's National Bureau of Statistics (NPS) implemented the survey from October 2012 to September 2013. We restrict the analysis to 1,050 rural households engaging in agriculture and having less than two hectares of land, which is a cutoff for small-scale farmers (Lowder et al., 2016).

The NPS survey contains instruments regarding household demographics, household characteristics (e.g. income, assets), household consumption on 59 food items for the seven days prior to the survey, household plot-level agricultural information, and community-level data. We link the household food consumption data with nutrition tables for Tanzania from the Harvard School of Public Health (Lukmanji et al., 2008). We test the propositions in Section 2.1 using the combination of the NPS household and community surveys and Harvard School of Public Health nutrition tables.

## 4.2 Variables

### 4.2.1 Outcome Variables

Production diversity is measured using two common measures of production diversity: the Agricultural Diversity Score (ADS) and Simpson's Index of diversity (SI), which is the HHI applied to an agricultural setting. The ADS is a simple count of the number of food crops grown by the household, according to the same twelve food groups used in the Household Dietary Diversity Score (HDDS) (see below). The ADS is a useful measure, but is unable to assess the evennesss' of production across different crops. The SI captures this evenness and for a household, $i$, is calculated as $\text{SI}_i = \sum_{j=1}^{N} 1 - s_j^2$, where $s_j$ is the area share of cultivation for crop $j$. SI corresponds directly to the diversification measures used in Section 2.

On the consumption side, dietary diversity is the main outcome variable of interest. Dietary diversity is measured in two ways - the HDDS index (Koppmair et al. 2017, (Jones, 2017a), Sibhatu and Qaim 2016) and the HHI for food consumption (Akerele et al., 2017). These are analogous to the production outcomes. HDDS is a simple count of the twelve food groups consumed by the household in the past seven days. The consumption HHI is a concentration index of the different foods consumed by the household. Using the Harvard School of Public Health nutrition tables, we calculate the total number of calories consumed by the household in the past seven days and the number of calories coming from each food item. We then calculate the percentage of calories coming from individual food items. The consumption HHI for household $i$ is given by $HHI_i = \sum_{j=1}^{N} 1 - s_j^2$, where $s_j$ is the percentage share of calories coming from food item $j$[5]

As additional analysis presented in Appendix H, we test whether these results translate to children's anthropometric outcomes. Measures of children's anthropometric outcomes can be used as an indicator of overall household nutrition (WFP, 2005). Three anthropometric outcomes for children under five are used to proxy household nutrition. Wasting is measured by a low weight-for-height z-score (WHZ); stunting is measured by a low height-for-age z-score (HAZ); being underweight is measured by a low-weight-for-age z-score (WAZ). As in Chegere and Stage (2020), we create indicator variables for each of these measures. If the z-scores fall below -2 for WHZ, HAZ, or WAZ for any child in the household then a household is considered to have a stunted, wasted, or underweight child, respectively.

### 4.2.2 Main Independent Variables

Depending on the econometric model, the main independent variables of interest are producer market participation and access indicators, the presence of production shocks in the past 10 years, and crop production diversity indicators (discussed in Section 3).

Market participation is measured by a weighted average of the percent of crops sold, where the weight is the area of a crop under cultivation[6]. This measure follows the logic of the maize and non-maize market participation variables used in Koppmair et al. (2017), but combines all crops into one and applies weights based on the area of production for each crop.

The primary market access indicator is the presence of a daily or weekly markets in a given household's village. This measure is chosen because we make the assumption that market access should be positively correlated with market participation. The presence of a daily or weekly market has the highest positive relationship with market participation of all the considered market access indicators (see Appendix F).

Production risk is proxied by whether a household experienced a negative production shock (either drought or pests) in the past ten year. This measure provides a subjective perception of the risk levels of a household's production environment.

[5]The HHI is constructed using food items, not food groups because individual food items within a food group can also have important micronutrients (Steyn et al., 2006).

[6]Mathematically this is: $\sum_{i=1}^{N} \frac{\text{Kgs. Sold}_i}{\text{Kgs. Harvested}_i} \times \frac{\text{area}_i}{\text{total area}}$

### 4.2.3 Control Variables

Each specification includes a series of household and community-level control variables. Household-level demographic variables include the household head's age, sex, an indicator for whether the household head is literate or not, and household size. These variables are related to the labor endowment available to households in Section 2. In relation to households' land endowment, the number of acres devoted to agriculture is included as a control variable. To control for effects livestock on dietary diversity the number of tropical livestock units is included as a control. Outside income and wealth effects are controlled for using log annual non-agricultural income, log value of loans received, log agricultural input value, an indicator for mobile phone ownership, and indicator for use of mobile money. Finally, we include the survey-month fixed effects to capture seasonal variation in consumption and district fixed effects to capture geographic variation in both production and consumption.

## 4.3 Descriptive Statistics

Table 1 displays the descriptive statistics for the households considered in the analysis of the 2012/2013 wave of the NPS. In terms of production diversity, every household cultivates a crop from at least one food group (Agricultural Diversity Score), with the average household cultivating around 3 food groups and the maximum cultivating seven. The average production concentration, measured by Simpson's Index, is 0.51 meaning that most households have a somewhat diverse crop mix. The average household sells only 19% of their crop production, indicating that most households are primarily engaged in subsistence agriculture.

The typical household consumed seven food groups (out of twelve possible groups) in the seven days prior to the survey, but this measure is fairly variable with a standard deviation of almost two food groups. The dietary HHI also shows that households have fairly diverse diets (more diverse than their production), but there is considerable variation with some households having a diet concentrated in only one food item. In terms of anthropometric measures, 28% of households have at least one child under five who is stunted, 3% have at least one wasted child, and 10% have an underweight child. However, only about half of the households have any children under the age of five.

The average household has 5.66 members, and the average household head is 46 years old. 77% of household heads are men, and 68% of household heads are literate. In terms of household agriculture, the average household owns about two acres of land[7].

Financially, the average household earns 606,649 TZS ($\approx$ 382 USD using January, 2013 exchange rates). The average household received 37,480 TZS ($\approx$ 24 USD) in the past twelve months and has 30,406 ($\approx$ 19 USD) in outstanding loans. Households use 97,225 ($\approx$ 61 USD) in agricultural inputs on average. Finally, 63% of households have mobile phones, but only 27% have access to mobile money.

[7] Only households with fewer than 4.95 acres (two hectares) are considered.

Table 1: Descriptive Statistics

| | (1) | | | | |
|---|---|---|---|---|---|
| | Mean | Standard Deviation | Median | Minimum | Maximum |
| ADS | 3.01 | 1.39 | 3.00 | 1.00 | 7.00 |
| Simpson's Index | 0.51 | 0.32 | 0.50 | 0.00 | 1.00 |
| HDDS | 7.11 | 1.91 | 7.00 | 0.00 | 10.00 |
| Dietary HHI | 0.34 | 0.20 | 0.29 | 0.00 | 1.00 |
| Stunting = 1 | 0.28 | 0.45 | 0.00 | 0.00 | 1.00 |
| Wasting = 1 | 0.03 | 0.18 | 0.00 | 0.00 | 1.00 |
| Underweight = 1 | 0.10 | 0.30 | 0.00 | 0.00 | 1.00 |
| Presence of Village Market | 0.38 | 0.48 | 0.00 | 0.00 | 1.00 |
| % of Crops Sold | 18.76 | 25.85 | 0.00 | 0.00 | 100.00 |
| Production Shock = 1 | 0.43 | 0.50 | 0.00 | 0.00 | 1.00 |
| HH Head Age | 46.34 | 16.60 | 44.00 | 18.00 | 108.00 |
| HH Head Literate = 1 | 0.68 | 0.47 | 1.00 | 0.00 | 1.00 |
| Male HH Head | 0.73 | 0.44 | 1.00 | 0.00 | 1.00 |
| HH Size | 4.66 | 2.34 | 4.00 | 1.00 | 16.00 |
| Total HH Acres | 1.98 | 1.24 | 2.00 | 0.10 | 4.90 |
| Annual Outside Income | 606649.58 | 7724138.65 | 0.00 | 0.00 | 2.40e+08 |
| Agricultural Input Value (Past 12 Months) | 97225.02 | 282138.74 | 16000.00 | 0.00 | 2422800.00 |
| Outstanding Loan Quantity | 30406.38 | 298730.14 | 0.00 | 0.00 | 6200000.00 |
| Remittances Received (Past 12 Months) | 37480.76 | 166852.91 | 0.00 | 0.00 | 3000000.00 |
| HH Tropical Livestock Units | 1.40 | 5.19 | 0.04 | 0.00 | 102.56 |
| Own Mobile Phone | 0.55 | 0.50 | 1.00 | 0.00 | 1.00 |
| Access to Mobile Money | 0.21 | 0.41 | 0.00 | 0.00 | 1.00 |
| Observations | 1050 | | | | |

# 5 Empirical Results

The results show evidence for each of the four propositions put forth in Section 2. First, the production-side propositions are tested (Propositions 1 and 2), and then the consumption-side results are shown (Propositions 3 and 4 and the Corollary to Proposition 3).

## 5.1 The Production-Side: Evidence for Propositions 1 and 2

To test Propositions 1 and 2, Equation 24 is estimated using the ADS and SI as outcomes variables. The results using perception of production shocks and market participation are presented in Table 2.

Proposition 1: Proposition 1 states that households with higher market access grow fewer crops because of gains from specialization. The empirical results related to Proposition 2 are presented in Table 2 (using market participation) and Table 3 (using the presence of village markets).

Table 2 shows that more market-oriented households grow fewer crops – a 1 percentage point increase in the percentage of crops old on the market is correlated with a decrease in the number of crops produced by 0.006. This suggests that a household moving from complete home production to complete market participation (a 100 percentage point increase in the percent of crops sold) would reduce the number of crops they grow by 0.6 on average. The specification without fixed effects and controls gives evidence that Proposition 1 holds. However, the results are not robust to the inclusion of district and interview month fixed effects (Column 2) and controls (Column 3).

When using Simpson's Index as an outcome variable, market participation appears to play a statistically significant role in determining production diversity. The unconditional correlation presented in Table 2 Column 4 shows that a one percentage point increase in the percentage of crops sold is correlated with 0.0015 point increase in SI. A household moving from complete autarky to complete market participation (a 100 percentage point increase) would increase SI by 0.15 points, which is a reduction of production diversity of nearly 0.5 standard deviations. These results are robust to the inclusion of district and interview month fixed effects (Column 5) and household controls (Column 6). The outcomes is stronger when using Simpson's Index (which is used in Section 2) as an outcome variable.

Proposition 2: Proposition 2 states that households with higher production risk will diversify their production as a risk mitigation mechanism. The empirical results for this proposition are presented in Tables 2 and 3 which show the estimated coefficients from Equation 24. Production risk is proxied using the number of production shocks experienced in the past ten years. Column 1 of Table 2 shows that households experiencing a production shocks in the past ten years grow 0.38 crops more on average than households not experiencing a shock, conditional only on market participation. This coefficient is attenuated to 0.13 (and statistically significant at the 90% level) when controlling for district fixed effects and interview month fixed affects (Column 2). The result is not robust to the inclusion of controls (Column 3).

The correlations between Simpson's Index and the main independent variables are stronger and more robust than for ADS. This could be because the ADS measurement is relatively less variable than SI (see Table 1). Column 4 in Table 2 shows that households that experienced production shocks in the past ten years have more diverse production mixes than households not experiencing production shocks (by 0.06 points in SI, or 0.2 standard deviations). This correlation is attenuated to -0.04 (or 0.12 standard deviations), but robust at the 90% significance level when including fixed effects, and the result is robust to the inclusion of household controls. These results are also robust to using the presence of a market in the village as a control instead of the rate of market participation (see Table 3). The evidence shows that Proposition 2 generally holds, and is strongest evidence is found when considering Simpson's Index as an outcome variable (as the theoretical model does) rather than ADS.

Table 2: Correlates of Production Diversity (Market Participation)

| | (1)<br>ADS | (2)<br>ADS | (3)<br>ADS | (4)<br>SI | (5)<br>SI | (6)<br>SI |
|---|---|---|---|---|---|---|
| Production Shock = 1 | 0.377$^{***}$ | 0.126$^{*}$ | 0.0952 | -0.0573$^{***}$ | -0.0375$^{*}$ | -0.0373$^{**}$ |
| | (0.0986) | (0.0764) | (0.0722) | (0.0199) | (0.0196) | (0.0183) |
| % of Crops Sold | -0.00620$^{***}$ | -0.00248 | -0.00287 | 0.00148$^{***}$ | 0.00101$^{**}$ | 0.00164$^{***}$ |
| | (0.00206) | (0.00175) | (0.00175) | (0.000413) | (0.000399) | (0.000392) |
| HH Head Age | | | 0.0108$^{***}$ | | | -0.000753 |
| | | | (0.00237) | | | (0.000611) |
| HH Head Literate = 1 | | | 0.129 | | | 0.0344 |
| | | | (0.0879) | | | (0.0226) |
| Male HH Head | | | 0.0113 | | | 0.00491 |
| | | | (0.0844) | | | (0.0212) |
| HH Size | | | 0.0479$^{***}$ | | | 0.00155 |
| | | | (0.0124) | | | (0.00414) |
| Total HH Acres | | | 0.0879$^{***}$ | | | -0.101$^{***}$ |
| | | | (0.0277) | | | (0.00746) |
| Visited by Agr. Extension = 1 | | | 0.0949 | | | -0.0398 |
| | | | (0.137) | | | (0.0393) |
| Improved Crops = 1 | | | 0.120 | | | -0.0186 |
| | | | (0.0748) | | | (0.0211) |
| Log Non-Agr. Income Past 12 Months | | | -0.00145 | | | -0.00178 |
| | | | (0.00608) | | | (0.00166) |
| Log Agr. Input Value | | | 0.0672$^{***}$ | | | -0.00574 |
| | | | (0.0256) | | | (0.00667) |
| Log Loan Value | | | -0.00236 | | | 0.000375 |
| | | | (0.0122) | | | (0.00333) |
| Log Remittances Value | | | 0.00149 | | | 0.00384$^{*}$ |
| | | | (0.00784) | | | (0.00206) |
| HH Tropical Livestock Units | | | -0.00598 | | | 0.00342$^{**}$ |
| | | | (0.0109) | | | (0.00170) |
| Elevation | | | 0.000450$^{**}$ | | | 0.0000194 |
| | | | (0.000209) | | | (0.0000447) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-3 are estimated using a Poisson model
Columns 4-6 are estimated using a GLM model using a logistic functional link and binomial distribution.

Table 3: Correlates of Production Diversity (Market Access)

| | (1) ADS | (2) ADS | (3) ADS | (4) SI | (5) SI | (6) SI |
|---|---|---|---|---|---|---|
| Production Shock = 1 | 0.417$^{***}$ | 0.135$^{*}$ | 0.101 | -0.0668$^{***}$ | -0.0417$^{**}$ | -0.0416$^{**}$ |
| | (0.0994) | (0.0759) | (0.0724) | (0.0196) | (0.0195) | (0.0183) |
| Village Market = 1 | -0.360$^{**}$ | -0.137 | -0.112 | 0.0792$^{***}$ | 0.0290 | 0.0399$^{*}$ |
| | (0.148) | (0.0992) | (0.0989) | (0.0245) | (0.0235) | (0.0214) |
| HH Head Age | | | 0.0112$^{***}$ | | | -0.00106$^{*}$ |
| | | | (0.00235) | | | (0.000608) |
| HH Head Literate = 1 | | | 0.128 | | | 0.0342 |
| | | | (0.0884) | | | (0.0223) |
| Male HH Head = 1 | | | 0.00709 | | | 0.0102 |
| | | | (0.0850) | | | (0.0214) |
| HH Size | | | 0.0493$^{***}$ | | | 0.000827 |
| | | | (0.0125) | | | (0.00412) |
| Total HH Acres | | | 0.0837$^{***}$ | | | -0.0975$^{***}$ |
| | | | (0.0278) | | | (0.00756) |
| Visited by Agr. Extension = 1 | | | 0.0987 | | | -0.0402 |
| | | | (0.138) | | | (0.0389) |
| Improved Crops = 1 | | | 0.113 | | | -0.0140 |
| | | | (0.0750) | | | (0.0213) |
| Log Non-Agr. Income Past 12 Months | | | 0.000275 | | | -0.00267 |
| | | | (0.00603) | | | (0.00169) |
| Log Agr. Input Value | | | 0.0612$^{**}$ | | | -0.00278 |
| | | | (0.0258) | | | (0.00665) |
| Log Loan Value | | | -0.00346 | | | 0.00102 |
| | | | (0.0124) | | | (0.00334) |
| Log Remittances Value | | | 0.00233 | | | 0.00345$^{*}$ |
| | | | (0.00778) | | | (0.00202) |
| HH Tropical Livestock Units | | | -0.00580 | | | 0.00316$^{*}$ |
| | | | (0.0109) | | | (0.00177) |
| Elevation | | | 0.000431$^{**}$ | | | 0.0000214 |
| | | | (0.000213) | | | (0.0000473) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-3 are estimated using a Poisson model
Columns 4-6 are estimated using a GLM model using a logistic functional link and binomial distribution.

## 5.2 The Consumption-Side: Evidence for Propositions 3 and 4

Proposition 3: Proposition 3 states that production diversity is negatively correlated with dietary diversity in households with high market access and positively correlated with dietary diversity in households with low market access. Figure 1 to Figure 4 display the results of the estimation of Equation 26, which tests whether there is a significant interaction between market participation/access and production diversity. The results suggest that there is an interaction term, but there is only weak evidence for this.

Figure 1 plots the coefficient of ADS at different levels of market participation. At zero market participation, an increase in the number of food groups produced is correlated with a 0.25 increase in the number of food groups consumed (Panel 1). This suggests that a household would need to grow only four more food groups to consume one more food group[8]. This coefficient steadily decreases as market participation increases. Households selling 80-100% of their crops do not realize any statistically significant benefits to dietary from growing one more food group. These results are robust at the 90% confidence level to the inclusion of district and interview month fixed effects (Panel 2) and household controls (Panel 3). However, the coefficients are attenuated when including controls and fixed effects. The full specification suggests, that households with no market participation, still need to grow nine more food groups to consume just one more food group (a correlation of 0.11), and households selling over 40% of their crops do not gain any dietary diversity by growing more crops.

The results in Figure 2 show weaker evidence of an interaction effect. The results in Panel 1 suggest that increases in Simpson's Index are negatively correlated with HDDS for houseolds with low market participation (0-40%). However, the results are only robust at the 90% level to the inclusion of district and interview month fixed effects for households with 20% and 40% market participation (Panels 2 and 3). These dynamics provide weak support for the results in Figure 1.

When using consumption HHI as an outcome, the results are similar. Figure 3 shows that an increase in ADS is correlated with an reduction in consumption HHI for households selling 40% or less of their crops. For households who sell low levels of their production (20%-40%), the results are robust at the 90% level to the inclusion of district and interview month fixed effects (Panels 2 and 3). The full specification in Panel 3 suggests that a one unit increase in the number of food groups produced, decreases dietary concentration by around 0.01 point (or 0.05 standard deviations) for with relatively low levels of market participation (i.e. selling 20% to 40% of their crops).

Figure 4 shows the results using Simpson's Index as an independent variable and consumption HHI as the dependent variable. The results in Panel 1, which does not include fixed effects or controls, shows that a one unit increase in Simpson's Index (a decrease production diversity) is associated with 0.05 increase in consumption HHI (a decrease in consumption diversity) for households operating in autarky. For households selling more than 0% of their crops, production diversity does not have a statistically significant relationship with consumption diversity. When including district and interview month fixed effects (Panel 2) and controls (Panel 3), there are no statistically significant relationships, although the curve of the margins plot slopes in the direction that Proposition 4 predicts. The findings are much weaker when using market access (Appendix G), but this is likely because market access and market participation are only weakly correlated (Appendix F).

The results do not hold when using Anthropometric measures (results shown in Appendix H). As with dietary diversity outcomes, the results even appear to be in contrast to the expected outcomes. However, this can be due to relatively low incidences of malnutrition and half of the households not having children under five (and therefore, by default, having values of zero for malnutrition).

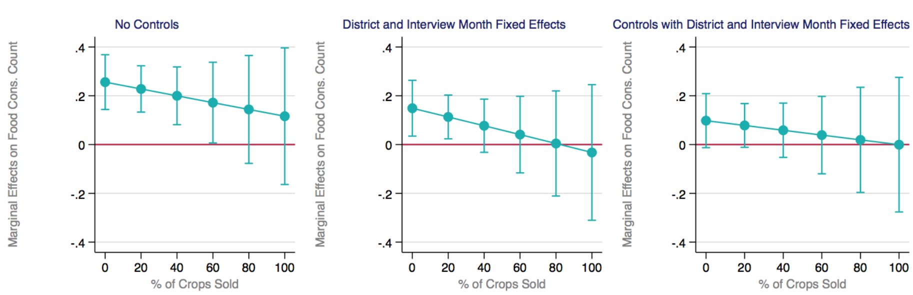


Figure 1: Correlates of HDDS: Interaction between ADS and Producer Market Participation (95% Confidence Intervals)

[8]The overall sample needs to produce about ten food groups to consume one more. See Table 4

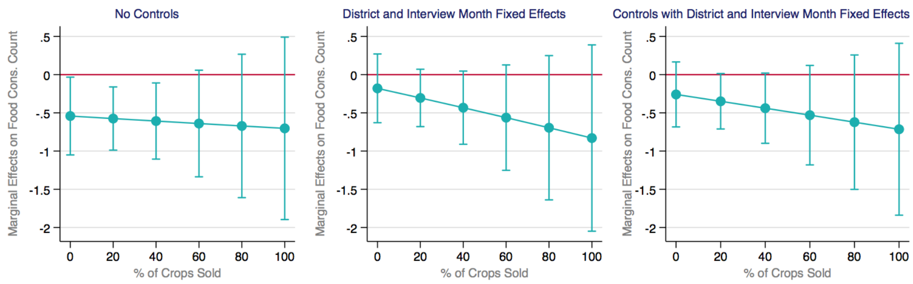


Figure 2: Correlates of HDDS: Interaction between SI and Producer Market Participation (95% Confidence Intervals)

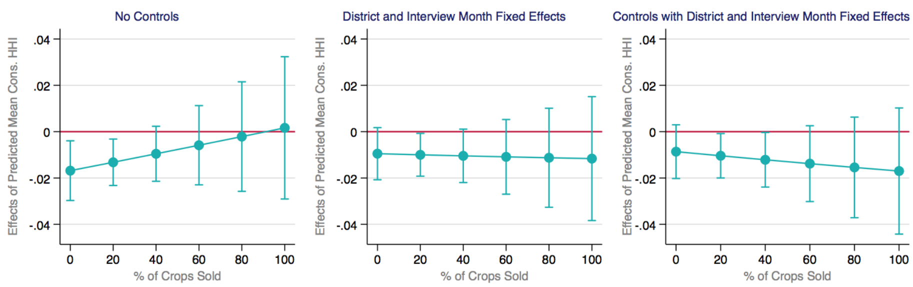


Figure 3: Correlates of HDDS: Interaction between ADS and Producer Market Participation (95% Confidence Intervals)

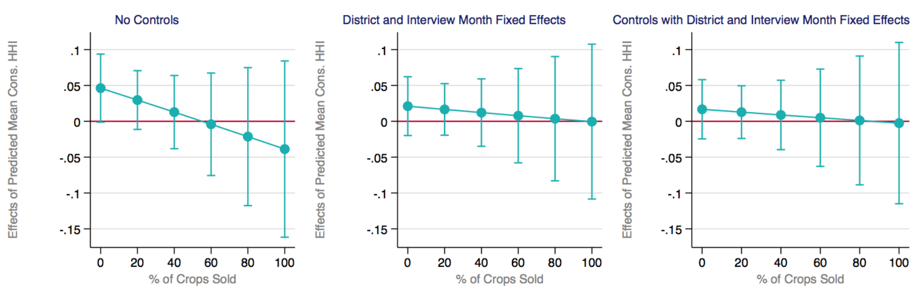


Figure 4: Correlates of HHI: Interaction between SI and Producer Market Participation (95% Confidence Intervals)

The Corollary to Proposition 3: The Corollary to Proposition 3 states that production diversity should be positively correlated with consumption diversity in the overall sample because the overall sample has low market orientation (an average of 19% of crops sold on the market). This proposition is tested using Equation 3.2, the results are presented in Table 4 and Table 5. Table 4 shows that there is robust evidence of Proposition 4a holding when using HDDS as an outcome variable. Column 1 suggests that if a household cultivates an additional food group, then they will consume 0.16 additional food groups. This correlation is weaker (but still statistically significant) when including district and interview month fixed effects in Column 2. Column 3 shows that, conditional on household controls and district and interview month fixed effects, an increase in the production of one food group is correlated with the consumption of an additional 0.08 food groups. This finding is in line with Sibhatu and Qaim (2018), which finds in a meta-analysis of the literature that households need to grow 10 additional food groups to consume just one more.

Higher concentration of production is associated with lower HDDS, as seen in Columns 4-6 of Table 4. A one point increase in Simpson's Index is correlated with a reduction of 0.006 in the number of food groups consumed.

Conditional on district and interview month fixed effects, this correlation is only 0.003 (and statistically significant at the 90% level). While these results are statistically significant and indicative that Proposition 4a holds, they are not practically significant. If a household has perfect production concentration (an SI of 1), and changes their production system to perfect diversification (an SI of 0), they will consume 0.33 food groups more on average. In practical terms, gaining an extra food group of consumption from increasing production diversity can be an extremely costly solution.

Table 5 corroborates these results by showing that increases in the number of food groups grown are significantly correlated with higher dietary diversity. However, the results are small in absolute terms. Column 1 of 5 shows that an increase of production diversity by one food group is correlated with a reduction in consumption HHI of 0.014 (or 0.07 standard deviations). The result is robust to the inclusion of district and interview month fixed effects (Column 2) and household controls (Column 3). The full specification in Column 3 suggests that an increase in production of one food group reduces consumption concentration by 0.01 points (or 0.05 standard deviations). Columns 4-6 suggest that when using Simpson's Index as the explanatory variable related to production diversity, there are no statistically significant relationships between production diversity and dietary diversity. 5 supports the results in 4 indicating that there relationships between production and dietary diversity, but they are extremely small in practical terms.

In terms of anthropometric outcomes, the correlations are much weaker. Food production does not appear to have a statistically significant correlation with the probability of malnutrition in Table 9, although the coefficient of food production is negative in seven of the nine specifications. Similarly, the coefficient of Simpson's Index is not statistically significant for the probability of being underweight and wasting, but it is significantly and negatively correlated the probability of stunting.This suggests that less production diversity leads to a lower probability of stunting (contrary to proposition 4a). However, there are only 35 observations with recorded stunting, so these results should be interpreted with caution. As with the correlation of market participation and anthropometric measures, this result does not disprove the proposition, but rather shows that the same factors driving household dietary diversity are not necessarily driving anthropometric malnutrition outcomes.

Proposition 4: Proposition 4 states that households with higher market access, have higher dietary diversity. Table 4 shows the estimates of Equation 3.2 using HDDS as the outcome variable. Across all specifications, there is no evidence in Table 4 that the percentage of crops sold has a statistically significant correlation with HDDS. However, when using the consumption HHI as an outcome variable, the percentage of crops sold is significantly and negatively correlated with consumption HHI (Table 5). These relationships are only observed when including district and interview month fixed effects (Columns 2, 3, 5, and 6). The results in Columns 2 and 5 of Table 5 suggest that a shift from autarky to complete market participation (a 100 percentage point increase in the percent of crops sold) results in a 0.057 decrease in consumption HHI. This is equivalent to a 0.29 standard deviation increase in consumption diversity. The observed relationship is lower when controlling for household characteristics (Columns 3 and 6), where the results suggest that a shift from autarky to complete market orientation is correlated with 0.038 decrease in the consumption HHI. This is equivalent to a 0.19 standard deviation increase in dietary diversity.

The results for Proposition 4 are weak, but there is ample evidence for Proposition 4 in the existing literature, as is highlighted in a comprehensive review of the literature on this topic (Sibhatu and Qaim, 2018). The weak evidence could be a result of the low levels of marketing in Tanzania (the weighted average of crops sold is only 19%). The results are also in-line with other studies from Tanzania – Chegere and Stage (2020) finds no statistically significant correlation between market orientation and dietary diversity outcomes, but does not use a dietary concentration index. This could highlight the importance of looking beyond count variables in dietary diversity outcomes and also analyzing concentration indices.

Further, the results do not hold when using anthropometric measures as outcome variables (presented in Table 9 and Table 10. This is consistent with Chegere and Stage (2020). The results even suggest that an increase in market participation is associated in an increase probability of a child under five being underweight. However, this result does not hold for wasting or stunting, and the coefficients are small – a 100 percentage point increase in the percentage of crops sold is correlated with an 8% increase in the probability of stunting. This result is contrary to the results presented above, but does not disprove the the theoretical model's propositions because the theoretical model focuses on dietary diversity. However, this result may open a discussion of whether dietary diversity is the best measure of household nutrition or whether anthropometric outcomes represent a better measure for household nutrition.

Table 4: Correlates of Household Dietary Diversity Score (Market Participation)

| | (1) HDDS | (2) HDDS | (3) HDDS | (4) HDDS | (5) HDDS | (6) HDDS |
|---|---|---|---|---|---|---|
| ADS | 0.162$^{***}$ | 0.114$^{**}$ | 0.0790$^{*}$ | | | |
| | (0.0505) | (0.0461) | (0.0458) | | | |
| SI | | | | -0.568$^{***}$ | -0.279 | -0.328$^{*}$ |
| | | | | (0.213) | (0.192) | (0.185) |
| % of Crops Sold | -0.00206 | 0.00226 | 0.000529 | -0.00225 | 0.00227 | 0.000775 |
| | (0.00257) | (0.00250) | (0.00249) | (0.00260) | (0.00249) | (0.00249) |
| HH Head Literate = 1 | | | 0.609$^{***}$ | | | 0.626$^{***}$ |
| | | | (0.139) | | | (0.139) |
| Male HH Head | | | 0.0315 | | | 0.0306 |
| | | | (0.137) | | | (0.137) |
| HH Size | | | 0.0322 | | | 0.0372 |
| | | | (0.0249) | | | (0.0250) |
| Total HH Acres | | | -0.111 | | | -0.171 |
| | | | (0.171) | | | (0.174) |
| Total HH Acres Squared | | | 0.0367 | | | 0.0443 |
| | | | (0.0338) | | | (0.0342) |
| HH Tropical Livestock Units | | | 0.0139 | | | 0.0150$^{*}$ |
| | | | (0.00879) | | | (0.00886) |
| Log Non-Agr. Income Past 12 Months | | | 0.0132 | | | 0.0122 |
| | | | (0.00808) | | | (0.00807) |
| Log Non-Farm Enterprise Asset Val. | | | 0.0373$^{***}$ | | | 0.0374$^{***}$ |
| | | | (0.00963) | | | (0.00952) |
| Access to Mobile Money | | | 0.564$^{***}$ | | | 0.571$^{***}$ |
| | | | (0.144) | | | (0.143) |
| Own Mobile Phone | | | 0.477$^{***}$ | | | 0.479$^{***}$ |
| | | | (0.140) | | | (0.141) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-6 are estimated using a Poisson model

Table 5: Correlates of Consumption HHI (Market Participation)

| | (1)<br>HHI | (2)<br>HHI | (3)<br>HHI | (4)<br>HHI | (5)<br>HHI | (6)<br>HHI |
|---|---|---|---|---|---|---|
| ADS | -0.0139$^{***}$<br>(0.00524) | -0.00999$^{**}$<br>(0.00472) | -0.0103$^{**}$<br>(0.00491) | | | |
| SI | | | | 0.0322<br>(0.0209) | 0.0174<br>(0.0181) | 0.0136<br>(0.0184) |
| % of Crops Sold | 0.0000551<br>(0.000267) | -0.000570$^{**}$<br>(0.000238) | -0.000387$^{*}$<br>(0.000231) | 0.0000957<br>(0.000266) | -0.000566$^{**}$<br>(0.000238) | -0.000382$^{*}$<br>(0.000231) |
| HH Head Literate = 1 | | | -0.0330$^{***}$<br>(0.0123) | | | -0.0343$^{***}$<br>(0.0122) |
| Male HH Head | | | -0.0165<br>(0.0136) | | | -0.0164<br>(0.0136) |
| HH Size | | | 0.0111$^{***}$<br>(0.00252) | | | 0.0105$^{***}$<br>(0.00248) |
| Total HH Acres | | | 0.00348<br>(0.0167) | | | 0.00481<br>(0.0170) |
| Total HH Acres Squared | | | -0.00286<br>(0.00350) | | | -0.00312<br>(0.00353) |
| HH Tropical Livestock Units | | | -0.00122<br>(0.000788) | | | -0.00125<br>(0.000773) |
| Log Non-Agr. Income Past 12 Months | | | -0.00121<br>(0.000955) | | | -0.00115<br>(0.000947) |
| Log Non-Farm Enterprise Asset Val. | | | -0.00156<br>(0.00111) | | | -0.00158<br>(0.00111) |
| Access to Mobile Money | | | -0.0367$^{**}$<br>(0.0163) | | | -0.0367$^{**}$<br>(0.0165) |
| Own Mobile Phone | | | -0.0400$^{***}$<br>(0.0135) | | | -0.0400$^{***}$<br>(0.0135) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-6 are estimated using a GLM model using a logistic functional link and binomial distribution.

# 6 Discussion and Conclusion

Nutrition-sensitive agriculture has become a center-piece of many government programs and agricultural interventions in recent decades as the development community aims to meet the SGDs. A central component of many of these programs is the link between production diversity and dietary diversity. As governments, NGOs, and international organizations become more focused on climate change, production diversity among smallholders is taking an even more central role because of its potential to build resilience to climate change and mitigate smallholder effects on climate change. Despite production diversity's assumed linkage with dietary diversity, the empirical evidence is not promising. Sibhatu and Qaim (2018) finds in a review of empirical studies that a smallholder farmer would need to grow nine more crops to consume one more food group. These results indicate that practitioners and researchers alike should rethink the link between dietary diversity and production diversity.

Our paper provides the first theoretical economic model to demonstrate the link between production diversity and dietary diversity, and we provide empirical evidence validating the predicted outcomes from our model. Much of the empirical literature has treated smallholder production diversity as exogenous, but smallholders choose which crops to grow and at what levels. When taking into account why farmers may diversify, the linkage between production diversity and dietary diversity becomes more clear and we can better see which farmers benefit from production diversity (in terms of dietary diversity) and which ones do not. Our empirical estimates show that in order to increase consumption by one food group, the average household needs to produce six more food groups (unconditional on other factors). However, the households that do not participate in markets only need to grow four more food groups to consume an additional food group.

From a policy perspective, two major themes come from this research. First,there is not a ”one size fits all” approach to nutrition-sensitive agriculture. Households with and without access to output markets have very different requirements to improve their nutrition and respond to different incentives. In order to be effective, agricultural programs must take this into account or there will continue to be weak linkages between interventions and nutrition outcomes. In particular, programs seeking to promote new crops or climate smart agriculture (e.g. improved seeds or improved practices that build resilience to climate change), must carefully think about which crops and practices to promote for different households in different market access regimes. In other words, programs must be targeted based on market access to be effective. Second, both the links between production diversity and consumption diversity and market participation and consumption diversity are empirically weak, despite being theoretically strong. This suggests that policymakers should explore other avenues to improve household nutrition, such as improving mobile infrastructure, road infrastructure, reducing gender gaps in agriculture production, and increasing overall farm production.

Since the proliferation of non-separable agricultural household models in the 1990s, there has not been much development in theoretical models of the agricultural household. The literature has become increasingly empirical for a myriad of reasons. However, non-separable agricultural household models can provide many insights that the empirical literature may over-look. Further research should continue building on non-separable household models to explore other issues. Our model does not explore reasons for diversification beyond market access and risk mitigation. For example, these could be joint production or differences in output elasticities. Models looking at these motivations for diversification could also lead to important insights on household nutritional outcomes. Non-separable models should also be expanded to look at climate change mitigation efforts, adoption of technology, access to finance, access to labor markets, and various other topics.

Empirically, future research should explore the mediation effect of market access on production and dietary diversity. RCTs introducing new crops should also include survey modules on dietary diversity in order to explore the causal effects of increasing production diversity on dietary diversity. More broadly, future research should focus on the mechanisms of production diversity and their links to dietary diversity, as production diversity is driven by a number of factors that may have differential effects on dietary diversity.

# References

Abay, K. and Hirvonen, K. (2017). Does Market Access Mitigate the Impact of Seasonality on Child Growth? Panel Data Evidence from Northern Ethiopia. Journal of Development Studies, 53(9):1414–1429.

Akerele, D., Sanusi, R. A., Fadare, O. A., and Ashaolu, O. F. (2017). Factors Influencing Nutritional Adequacy among Rural Households in Nigeria: How Does Dietary Diversity Stand among Influencers? Ecology of Food and Nutrition, 56(2):187–203.

Arimond, M., Wiesmann, D., Becquey, E., Carriquiry, A., Daniels, M. C., Deitchler, M., Fanou-Fogny, N., Joseph, M. L., Kennedy, G., Martin-Prevel, Y., and Torheim, L. E. (2010). Simple food group diversity indicators predict micronutrient adequacy of women's diets in 5 diverse, resource-poor settings1-7. Journal of Nutrition, 140(11):2059–2069.

Asante, B. O., Villano, R. A., Patrick, I. W., and Battese, G. E. (2018). Determinants of farm diversification in integrated crop-livestock farming systems in Ghana. Renewable Agriculture and Food Systems, 33(2):131–149.

Chamberlin, J. and Jayne, T. S. (2013). Unpacking the Meaning of 'Market Access': Evidence from Rural Kenya. World Development, 41(1):245–264.

Chege, C., Andersson, C., and Qaim, M. (2015). Impacts of supermarkets on farm household nutrition in Kenya. World Development, 72:394–407.

Chegere, M. J. and Stage, J. (2020). Agricultural production diversity, dietary diversity and nutritional status: Panel data evidence from Tanzania. World Development, 129(December 2019):104856.

Collins, R. A. (1988). Risk Analysis with Single-Index Portfolio Models: An Application to Farm Planning: Reply. American Journal of Agricultural Economics, 70(1):195.

Coyle, B. T. (1992). Risk Aversion and Yield Uncertainty in Duality Models of Production: A Mean-Variance Approach. American Journal of Agricultural Economics, 74(4):849–859.

Coyle, B. T. (1999). Agricultural & Applied Economics Association Risk Aversion and Yield Uncertainty in Duality Models of Production : A Mean-Variance Approach. 81(3).

de Janvry, b. A., Fafchamps, M., and Sadoulet, E. (1991). Department of Agricultural and Resource Economics Division of Agriculture and Natural Resources University of California At Berkeley.

Fafchamps, M. (1992). Cash Crop Production, Food Price Volatility,and Rurual Market Integration in the Third World.

FAO, IFAD, UNICEF, WFP, and WHO (2018). The State of Food Security and Nutrition in the World 2018: Building climate resilience for food security and nutrition. Technical report, Rome.

FAO, IFAD, UNICEF, WFP, W. (2020). The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Technical Report 3, Rome.

Finkelshtain, I. and Chalfant, J. A. (1990). Marketed Surplus Under Risk: Do Peasants Agree with Sandmo?

Global Hunger Index (2019). Global Hunger Index 2019: Tanzania. (October).

Goetz, S. J. (1992). A Selectivity Model of Household Food Marketing Behavior in Sub-Saharan Africa. American Journal of Agricultural Economics, 74(2):444.

Jones, A. D. (2015). The production diversity of subsistence farms in the Bolivian Andes is associated with the quality of child feeding practices as measured by a validated summary feeding index. Public Health Nutrition, 18(2):329–342.

Jones, A. D. (2017a). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. Nutrition Reviews, 75(10):769–782.

Jones, A. D. (2017b). On-Farm Crop Species Richness Is Associated with Household Diet Diversity and Quality in Subsistence- and Market-Oriented Farming Households in Malawi. The Journal of Nutrition, 147(1):86–96.

Jones, A. D., Shrinivas, A., and 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.

Kant, A. K., Schatzkin, A., Harris, T. B., Ziegler, R. G., and Block, G. (1993). Dietary diversity and subsequent mortality in the First National Health and Nutrition Examination Survey Epidemiologic Follow-up Study. The American Journal of Clinical Nutrition, 57(3):434–440.

Key, N., Sadoulet, E., and De de Janvry, A. (2000). Transactions costs and agricultural household supply response. American Journal of Agricultural Economics, 82(2):245–259.

Koppmair, S., Kassie, M., and Qaim, M. (2017). Farm production, market access and dietary diversity in Malawi. Public Health Nutrition, 20(2):325–335.

Kumar, A., Saroj, S., Singh, R., and Jee, S. (2016). Agricultural Diversity, Dietary Diversity and Nutritional Intake: An Evidence on Inter-linkages from Village Level Studies in Eastern India. Agricultural Economics Research Review, 29(conf):15.

Lowder, S. K., Skoet, J., and Raney, T. (2016). The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. World Development, 87:16–29.

Lukmanji, Z., Hertzmark, E., Mlingi, N., and Assey, V. (2008). Tanzania food composition tables. muhimbili university of allied science,Tanzania food and nutrition centre and Havard school of public health, (November):259.

Makate, C., Wang, R., Makate, M., and Mango, N. (2016). Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change. SpringerPlus, 5(1).

Markowitz, H. (1952). Portfolio Selection. The Journal of Finance, 7(1):77–91.

Murendo, C., Nhau, B., Mazvimavi, K., Khanye, T., and Gwara, S. (2018). Nutrition education, farm production diversity, and commercialization on household and individual dietary diversity in Zimbabwe. Food and Nutrition Research, 62:1–13.

Omamo, S. W. (1998). Farm-to-market transaction costs and specialisation in small-scale agriculture: Explorations with a non-separable household model. Journal of Development Studies, 35(2):152–163.

Pinstrup-Andersen, P. (2007). Agricultural research and policy for better health and nutrition in developing countries: A food systems approach. Agricultural Economics, 37(S1):187–198.

Popkin, B. M. and Slining, M. M. (2013). New dynamics in global obesity facing low- and middle-income countries. Obesity Reviews, 14(S2):11–20.

Rapsomanikis, G. (2015). The economic lives of smallholder farmers: An analysis based on household data from nine countries. Technical report, FAO, Rome.

Shang, S., Nesson, E., and Fan, M. (2018). Interaction Terms in Poisson and Log Linear Regression Models. Bulletin of Economic Research, 70(1):E89–E96.

Sibhatu, K. T., Krishna, V. V., and Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. Proceedings of the National Academy of Sciences of the United States of America, 112(34):10657–10662.

Sibhatu, K. T. and Qaim, M. (2016). Farm production diversity and dietary quality:Linkages and measurement issues. GlobalFood Discussion Papers, 80(March):34.

Sibhatu, K. T. and Qaim, M. (2017). Rural food security, subsistence agriculture, and seasonality. PLoS ONE, 12(10):1–15.

Sibhatu, K. T. and Qaim, M. (2018). Review: The association between production diversity, diets, and nutrition in smallholder farm households. Food Policy, 77(October 2017):1–18.

Steyn, N., Nel, J., Nantel, G., Kennedy, G., and Labadarios, D. (2006). Food variety and dietary diversity scores in children: are they good indicators of dietary adequacy? Public Health Nutrition, 9(5):644–650.

Tauer, L. W. (1983). Target MOTAD. American Journal of Agricultural Economics, 65(3):606–610.

Taylor, J. E. and Adelman, I. (2003). Agricultural Household Models : Genesis , Evolution , and Extensions. Review of Economics of the Household, 1:33–58.

Tzouvelekas, V. (2011). Production and Consumption Decisions of Rural Households under Price Risk : A Mean-Variance Approach. 5th Conference of Research in Economic Theory and Econnometrics (CRETE), (022653):1–26.

Watts, M. J., Held, L. J., and Helmers, G. A. (1984). A Comparison of Target MOTAD to MOTAD. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, 32(1):175–186.

WFP (2005). A manual: Measuring and interpreting malnutrition and mortality. Technical report, WFP, Rome.

# A Combining Cobb-Douglas and Mean-Variance

In the two good case, we will show that at each efficient allocation of land and labour to crops 1 and 2, $\frac{a_i^*}{A_T} = \frac{l_i^*}{L_T}$, where $a_i^*$ and $l_i^*$ are efficient allocations and $L_T$ and $A_T$ are the total amounts of labour and land endowed.

We note that since there are no monetary costs associated with land and labor, maximizing revenue and profit are the same. We also note that the $L_T$ term refers to labour that has been allocated to agriculture, excluding labour allocated to off-farm activities.

The revenue function is given by:

$$R = p_1 q_1 + p_2 q_2 = p_1 \phi_1 l_1^{\alpha} a_1^{1-\alpha} \epsilon_1 + p_2 \phi_2 l_2^{\alpha} a_2^{1-\alpha} \epsilon_2$$

We can see that we have an additive Cobb-Douglas framework, whereby each crop takes the same functional form (i.e. has the same $\alpha$ terms). This assumption is key to the proof.

The household faces the problem:

max $E[R] = p_1 \phi_1 l_1^{\alpha} a_1^{1-\alpha} + p_2 \phi_2 l_2^{\alpha} a_2^{1-\alpha}$ s.t $l_1 + l_2 = L_T$ $a_1 + a_2 = A_T$

The error terms go away in the case of maximizing the expectation. The constraints indicate that all labour and must be allocated.

The Lagrangian becomes: $\mathcal{L} = p_1 \phi_1 l_1^{\alpha} a_1^{1-\alpha} + p_2 \phi_2 l_2^{\alpha} a_2^{1-\alpha} + \lambda_l (L_T - l_1 - l_2) + \lambda_A (A_T - a_1 - a_2)$

The first order conditions are:

1. $\frac{\partial \mathcal{L}}{\partial l_1} = \alpha p_1 \phi_1 l_1^{\alpha-1} a_1^{1-\alpha} - \lambda_L = 0$
2. $\frac{\partial \mathcal{L}}{\partial l_2} = \alpha p_2 \phi_2 l_2^{\alpha-1} a_2^{1-\alpha} - \lambda_L = 0$
3. $\frac{\partial \mathcal{L}}{\partial a_1} = (1-\alpha) p_1 \phi_1 l_1^{\alpha} a_1^{-\alpha} - \lambda_A = 0$
4. $\frac{\partial \mathcal{L}}{\partial a_2} = (1-\alpha) p_2 \phi_2 l_2^{\alpha} a_2^{-\alpha} - \lambda_A = 0$
5. $\frac{\partial \mathcal{L}}{\partial \lambda_L} = L_T - l_1 - l_2 = 0$
6. $\frac{\partial \mathcal{L}}{\partial \lambda_A} = A_T - a_1 - a_2 = 0$

We cannot explicitly solve for our choice variables, but we can demonstrate key relationships between them: we will show that $\frac{a_i^*}{A_T} = \frac{l_i^*}{L_T}$.

We note that in the optimal case, from standard microeconomic theory, the marginal revenue from labour allocations to crops 1 and 2 must equal, and the marginal revenue from land allocations to crops 1 and 2 must equal.

As a result, we set FOC 1 equal to FOC 2, and we set FOC 3 equal to FOC 4. This is equivalent to setting the marginal revenues equal to each other (because FOC's 1-4 are marginal revenues excepting the lambda term which drops out of the analysis in any case when we set FOC's 1 and 2 equal to each other FOC's 3 and 4 equal to each other).

We start with FOC 1 = FOC 2:

$$\alpha p_1 \phi_1 l_1^{\alpha-1} a_1^{1-\alpha} - \lambda_L = \alpha p_2 \phi_2 l_2^{\alpha-1} a_2^{1-\alpha} - \lambda_L$$

Simplifying:

$$p_1 \phi_1 l_1^{\alpha-1} a_1^{1-\alpha} = p_2 \phi_2 l_2^{\alpha-1} a_2^{1-\alpha}$$

Rearranging:

$\frac{p_1\phi_1 a_1^{1-\alpha}}{p_2\phi_2 a_2^{1-\alpha}} = \frac{l_2^{\alpha-1}}{l_1^{\alpha-1}}$

Simplifying: $\frac{p_1\phi_1 a_1^{1-\alpha}}{p_2\phi_2 a_2^{1-\alpha}} = \frac{l_2}{l_1}$

Rearranging:

$\frac{l_1}{l_2}\frac{p_1\phi_1 a_1^{1-\alpha}}{p_2\phi_2 a_2^{1-\alpha}} = 1$

Now we perform the same analysis on FOC's 3 and 4 (the FOC's for the $a$ terms):

We start with FOC 3 = FOC 4:

$(1-\alpha)p_1\phi_1 l_1^{\alpha} a_1^{-\alpha} - \lambda_A = (1-\alpha)p_2\phi_2 l_2^{\alpha} a_2^{-\alpha} - \lambda_A$

Simplifying:

$p_1\phi_1 l_1^{\alpha} a_1^{-\alpha} = p_2\phi_2 l_2^{\alpha} a_2^{-\alpha}$

Rearranging:

$\frac{p_1\phi_1 l_1^{\alpha}}{p_2\phi_2 l_2^{\alpha}} = \frac{a_2^{-\alpha}}{a_1^{-\alpha}}$

Simplifying:

$\frac{p_1\phi_1 l_1^{\alpha}}{p_2\phi_2 l_2^{\alpha}} = \frac{a_2}{a_1}$

Rearranging:

$\frac{a_1}{a_2}\frac{p_1\phi_1 l_1^{\alpha}}{p_2\phi_2 l_2^{\alpha}} = 1$

Now, we can see that we have two equations that are both equal to 1. So, we can set these equations equal to each other:

$(\frac{l_1}{l_2})\frac{p_1\phi_1 a_1^{1-\alpha}}{p_2\phi_2 a_2^{1-\alpha}} = (\frac{a_1}{a_2})\frac{p_1\phi_1 l_1^{\alpha}}{p_2\phi_2 l_2^{\alpha}}$

Cross-multiplying to get $a$ terms and $l$ terms on same side, and we get:

$\frac{a_2}{a_1}\frac{p_1\phi_1 a_1^{1-\alpha}}{p_2\phi_2 a_2^{1-\alpha}} = \frac{l_2}{l_1}\frac{p_1\phi_1 l_1^{\alpha}}{p_2\phi_2 l_2^{\alpha}}$

Cross multiply to cancel out constants:

$\frac{a_2}{a_1}\frac{a_1^{1-\alpha}}{a_2^{1-\alpha}} = \frac{l_2}{l_1}\frac{l_1^{\alpha}}{l_2^{\alpha}}$

Rearrange by cross multiplying:

$\frac{l_1 a_1^{1-\alpha}}{l_2 a_2^{1-\alpha}} = \frac{a_1 l_1^{\alpha}}{a_2 l_2^{\alpha}}$

Cross multiply the $l$ terms and simplify:

$\frac{l_2^{\alpha} a_1^{1-\alpha}}{l_2 a_2^{1-\alpha}} = \frac{a_1 l_1^{\alpha}}{a_2 l_1}$

$\frac{l_2^{\alpha-1} a_1^{1-\alpha}}{a_2^{1-\alpha}} = \frac{a_1 l_1^{\alpha-1}}{a_2}$

Cross-multiply by $a$ terms and simplify:

$\frac{l_2^{\alpha-1} a_2}{a_2^{1-\alpha}} = \frac{a_1 l_1^{\alpha-1}}{a_1^{1-\alpha}}$

$l_2^{\alpha-1} a_2^{-\alpha} = l_2^{\alpha-1} a_1^{-\alpha}$

Rearrange:

$(\frac{l_2}{a_2})^{\frac{\alpha-1}{\alpha}} = (\frac{l_1}{a_2})^{\frac{\alpha-1}{\alpha}}$

Simplify:

$\frac{l_2}{a_2} = \frac{l_1}{a_1}$

Rearrange:

$\frac{a_1}{a_2} = \frac{l_1}{l_2}$

So, we have shown that the ratios of allocations must equal, but we need to show that proportion of total allocations equal each other. So we use the definitions of total allocations: $l_1 + l_2 = L_2$ and $a_1 + a_2 = A_T$. The proof from here is quite trivial.

Let us substitute for $a_2$ and $l_2$:

$\frac{a_1}{A_T - a_1} = \frac{l_1}{L_T - l_1}$

Cross multiplying:

$a_1(L_t - l_1) = l_1(A_T - a_1)$

Expanding:

$a_1 L_T - a_1 l_1 = l_1 A_T - a_1 l_1$

Adding $a_1 l_1$ to both sides:

$a_1 L_T = l_1 A_T$

Rearranging:

$$\boxed{\frac{a_1^*}{A_T} = \frac{l_1^*}{L_T}}$$

We denote $a_1$ and $l_1$ as $a_1^*$ and $l_1^*$ because these are efficient solutions. Now, we have proved that under efficient allocations, the proportion of total land and labour allocated to a crop are equal.

Because this result holds, the term $s_i = \frac{l_i}{L} = \frac{a_i}{A}$. We can then write:

$s_i \phi_i A^\alpha L^{1-\alpha} = \phi_i (\frac{a_i}{A})^\alpha (\frac{l_i}{L})^{1-\alpha}$

This concludes the proof for why $s_i$ can be used in the mean variance model while maintaining the Cobb-Douglas production function for each good.

# B Derivation of Optimal Market Consumption

This appendix derives the optimal consumption levels for goods consumed on the market. To demonstrate this, we present the utility function using only market consumption and an exogonous income constraint for simplicity. At the end of the derivation, we can plug in the income constraint specified in Section 2.

$$\begin{aligned} \max U &= \sum_{i=1}^{N} w_i \ln(c_i + 1) \\ \text{s.t.} \sum_{i=1}^{N} p_i c_i &= I \end{aligned} \tag{27}$$

The Lagrangian becomes:

$$\mathcal{L} = \sum_{j=1}^{N} w_j \ln(c_j + 1) - \lambda(I - \sum_{j=1}^{N} p_j c_j) \tag{28}$$

The FOCs are given by:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial c_i} &= \frac{w_i}{c_i + 1} - \lambda p_i = 0 \,\forall\, i \in\ N \\ \frac{\partial \mathcal{L}}{\partial \lambda} &= I - \sum_{j=1}^{N} p_j c_j = 0 \end{aligned} \tag{29}$$

Solve for $c_i$ in terms of exogenous variables and $\lambda$:

$$c_i = \frac{w_i}{\lambda p_i} - 1 \,\forall\, i \in\ N \tag{30}$$

Plug solution of $c_i$ into $\frac{\partial \mathcal{L}}{\partial \lambda}$ and solve for $\lambda^*$:

$$\lambda^* = \frac{\sum_{j=1}^{N} w_j}{I + \sum_{j=1}^{N} p_j} \tag{31}$$

Plug solution of $\lambda^*$ into $c_i$ to get $c_i^*$:

$$c_i^* = \frac{w_i(I + \sum_{j=1}^{N} p_j)}{p_i \sum_{j=1}^{N} w_j} - 1 \,\forall\, i \in\ N \tag{32}$$

$c_i^*$ can be plugged into the utility function to obtain the value function in Equation 9.

# C Proof that HHI Decreases with Income

The optimal consumption was derived in Appendix B and is given by:

$$c_i^* = \frac{w_i(I + \sum_{j=1}^{N} p_j)}{p_i \sum_{j=1}^{N} w_j} - 1 \; \forall \, i \in \; N \tag{33}$$

The consumption share of good $i$ is equal to the proportion of good $i$ consumed over total consumption: $c_i/C$ where $C$ is total consumption. Written out, this is:

$$\frac{c_i}{C} = \frac{\frac{w_i(I+\sum_{j=1}^{N} p_j)}{p_i \sum_{j=1}^{N} w_j} - 1}{\sum_{k=1}^{N} \frac{w_k(I+\sum_{j=1}^{N} p_j)}{p_k \sum_{j=1}^{N} w_j} - 1} \tag{34}$$

Rearranging:

$$\frac{c_i}{C} = \frac{[w_i(I + \sum_{j=1}^{N} p_j) - p_i \sum_{j=1}^{N} w_j]}{[\sum_{k=1}^{N} w_k(I + \sum_{j=1}^{N} p_j) - p_k \sum_{j=1}^{N} w_j]} \frac{[\sum_{k=1}^{N} p_k \sum_{j=1}^{N} w_j]}{[p_i \sum_{j=1}^{N} w_j]} \tag{35}$$

Distributing $w$ terms in the first term's numerator and denominator:

$$\frac{c_i}{C} = \frac{[w_i I + w_i \sum_{j=1}^{N} p_j - p_i \sum_{j=1}^{N} w_j]}{[\sum_{k=1}^{N} w_k I + w_k \sum_{j=1}^{N} p_j - p_k \sum_{j=1}^{N} w_j]} \frac{[\sum_{k=1}^{N} p_k \sum_{j=1}^{N} w_j]}{[p_i \sum_{j=1}^{N} w_j]} \tag{36}$$

Recall the definition of consumption diversity is:

$$\text{HHI} = \sum_{i=1}^{N} \frac{c_i}{C} \tag{37}$$

So, HHI becomes:

$$\text{HHI} = (\frac{[w_i I + w_i \sum_{j=1}^{N} p_j - p_i \sum_{j=1}^{N} w_j]}{[\sum_{k=1}^{N} w_k I + w_k \sum_{j=1}^{N} p_j - p_k \sum_{j=1}^{N} w_j]} \frac{[\sum_{k=1}^{N} p_k \sum_{j=1}^{N} w_j]}{[p_i \sum_{j=1}^{N} w_j]})^2 \tag{38}$$

Rearranging:

$$\text{HHI} = (\frac{[w_i I + w_i \sum_{j=1}^{N} p_j - p_i \sum_{j=1}^{N} w_j]}{[\sum_{k=1}^{N} w_k I + w_k \sum_{j=1}^{N} p_j - p_k \sum_{j=1}^{N} w_j]})^2 (\frac{[\sum_{k=1}^{N} p_k \sum_{j=1}^{N} w_j]}{[p_i \sum_{j=1}^{N} w_j]})^2 \tag{39}$$

We want to know if $\frac{\partial \text{HHI}}{\partial I} \gtrless 0$. The second term is simply a positive constant and can be ignored because it is irrelevant for determining the sign of the comparative static of HHI with respect to $I$.

For simplicity in taking the derivative, we expand the first term:

$$
\begin{aligned}
&(\frac{[w_i I]}{[\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j]} \\
&+\frac{[w_i \sum_{j=1}^N p_j]}{[\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j]} \\
&-\frac{[p_i \sum_{j=1}^N w_j]}{[\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j]})^2
\end{aligned} \tag{40}
$$

We will apply the chain rule. We take the derivative of the "inside" function first and obtain:

$$
\begin{aligned}
&\frac{-w_i I \sum_{k=1}^N w_k}{(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)^2} + \frac{w_i}{\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j} \\
&-\frac{w_i \sum_{j=1}^N p_j}{(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)^2} \\
&+\frac{p_i \sum_{j=1}^N w_j}{(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)^2}
\end{aligned} \tag{41}
$$

Simplifying:

$$
\frac{p_i \sum_{j=1}^N w_j - w_i \sum_{j=1}^N p_j - w_i I \sum_{k=1}^N w_k}{(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)^2} + \frac{w_i}{\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j} \tag{42}
$$

Getting a common denominator:

$$
\frac{(p_i \sum_{j=1}^N w_j - w_i \sum_{j=1}^N p_j - w_i I \sum_{k=1}^N w_k) + w_i(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)}{(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)^2} \tag{43}
$$

Notice that the sign of the "inside" portion of the derivative relies only on the numerator. The denominator is positive (as it is a square), and thus if the numerator is positive (negative), the "inside" portion is positive (negative):

$$
(p_i \sum_{j=1}^N w_j - w_i \sum_{j=1}^N p_j - w_i I \sum_{k=1}^N w_k) + w_i(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j) \gtrless 0 \tag{44}
$$

Rearranging:

$$
(p_i \sum_{j=1}^N w_j - w_i \sum_{j=1}^N p_j - w_i I \sum_{k=1}^N w_k) \gtrless -(w_i(\sum_{k=1}^N w_k I + w_k \sum_{j=1}^N p_j - p_k \sum_{j=1}^N w_j)) \tag{45}
$$

Simplifying:

$$(p_i \sum_{j=1}^{N} w_j - w_i \sum_{j=1}^{N} p_j) \gtreqless -(w_i \sum_{k=1}^{N} w_k \sum_{j=1}^{N} p_j - p_k \sum_{j=1}^{N} w_j) \tag{46}$$

Rearranging:

$$(p_i \sum_{j=1}^{N} w_j - w_i \sum_{j=1}^{N} p_j) \gtreqless w_i(\sum_{k=1}^{N} p_k \sum_{j=1}^{N} w_j - w_k \sum_{j=1}^{N} p_j) \tag{47}$$

$$\frac{(p_i \sum_{j=1}^{N} w_j - w_i \sum_{j=1}^{N} p_j)}{\sum_{k=1}^{N}(p_k \sum_{j=1}^{N} w_j - w_k \sum_{j=1}^{N} p_j)} \gtreqless w_i \tag{48}$$

Assuming that prices and preferences differ across crops, the LHS takes must be less than one. If $w_i$ values are normalized such that $w_i >= 1 \, \forall \, i$, then the LHS is always less than the RHS and the "inside" of the chain rule derivative is negative.

To complete the derivation of the comparative static of HHI with respect to $I$, we note that the "outside" part of the chain rule is:

$$2(\frac{[w_i I + w_i \sum_{j=1}^{N} p_j - p_i \sum_{j=1}^{N} w_j]}{[\sum_{k=1}^{N} w_k I + w_k \sum_{j=1}^{N} p_j - p_k \sum_{j=1}^{N} w_j]} \frac{[\sum_{k=1}^{N} p_k \sum_{j=1}^{N} w_j]}{[p_i \sum_{j=1}^{N} w_j]}) \tag{49}$$

Since the "outside" is positive and the "inside" portion is negative, then then:

$$\frac{\partial \text{HHI}}{\partial I} < 0 \tag{50}$$

This means that as income increases, the concentration of consumption decreases. In other words, dietary diversity increases.

# D Derivation of Solution of Imperfect markets Without Risk

The maximization problem is given by:

$$\begin{aligned} \max E[V] &= \sum_{i=1}^{N} w_i \ln(s_i^h \gamma_i + 1) \\ \text{s.t.} \sum_{i=1}^{N} s_i^h &\leq 1 \end{aligned} \tag{51}$$

The Lagrangian becomes:

$$\mathcal{L} = \sum_{i=1}^{N} w_i \ln(s_i^h \gamma_i + 1) + \lambda(1 - \sum_{i=1}^{N} s_i^h) \tag{52}$$

The FOCs are given by:

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial s_i^h} &= \frac{w_i}{s_i^h \gamma_i + 1} - \lambda = 0 \,\forall\, i \in N \\ \frac{\partial \mathcal{L}}{\partial \lambda} &= 1 - \sum_{i=1}^{N} s_i^h) = 0\end{aligned} \tag{53}$$

Put $s_i^h$ in terms of $\lambda$:

$$s_i^h = \frac{w_i \gamma_i}{\lambda} - 1 \tag{54}$$

Plug $s_i^h$ into $\frac{\partial \mathcal{L}}{\partial \lambda}$:

$$\sum_{i=1}^{N} \frac{w_i \gamma_i}{\lambda} - 1 = 1 \tag{55}$$

After some basic algebra, we get:

$$\lambda^* = \frac{\sum_{i=1}^{N} w_i \gamma_i}{N+1} \tag{56}$$

Using $\lambda^*$ to obtain $s_i^*$:

$$s_i^* = \frac{w_i \gamma_i}{\frac{\sum_j w_j \gamma_j}{N+1}} \tag{57}$$

This simplifies to:

$$s_i^* = \frac{w_i \gamma_i N - \sum_{j=1, j \neq i}^{N} w_j \gamma_j}{\sum_{j=1}^{N} w_j \gamma_j} \tag{58}$$

The comparative statics are consistent with economic theory – an increase in the preference parameter $w_i$ or the production parameter $\gamma_i$ leads to an increase in $s_i$, while an increase $w_j$ or $\gamma_j$ for another good $j \neq i$ leads to a decrease in the allocation to $s_i$.

# E Derivation of Mean-Variance Solution

For simplicity in this derivation, we denote $s_i^m$ as $s_i$ for all values of $i$.

The maximization problem is given by:

$$\max \sum_{i=1}^{N} s_i p_i \gamma_i - \frac{a}{2} \sum_{i=1}^{N} (s_i^2 \sigma_i^2 + \sum_{j \neq i}^{N} s_i s_j \sigma_i \sigma_j \rho_{ij}) \qquad \text{s.t.} \sum_{i=1}^{N} s_i = 1 \tag{59}$$

The Lagrangian is:

$$\mathcal{L} = \sum_{i=1}^{N} s_i p_i \gamma_i - \frac{a}{2} \sum_{i=1}^{N} (s_i^2 \sigma_i^2 + \sum_{j \neq i}^{N} s_i s_j \sigma_i \sigma_j \rho_{ij}) + \lambda (1 - \sum_{i=1}^{N} s_i) \tag{60}$$

The FOCs are given by:

$$\frac{\partial \mathcal{L}}{\partial s_i} = p_i \gamma_i - a(s_i \sigma_i^2 + \sum_{j=1, j \neq i} s_j \sigma_i \sigma_j \rho_{ij}) - \lambda = 0 \, \forall \, i \, \in \, N \qquad \frac{\partial \mathcal{L}}{\partial \lambda} = 1 - \sum_{i=1}^{N} s_i = 0 \tag{61}$$

Rearranged, the FOCs become:

$$\frac{\partial \mathcal{L}}{\partial s_i} = a(s_i \sigma_i^2 + \sum_{j=1, j \neq i} s_j \sigma_i \sigma_j \rho_{ij}) = p_i \gamma_i - \lambda \, \forall \, i \, \in \, N \qquad \frac{\partial \mathcal{L}}{\partial \lambda} = 1 - \sum_{i=1}^{N} s_i = 0 \tag{62}$$

Let s be the following N-length vector:

$$\text{r} = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_N \end{pmatrix} \tag{63}$$

Let r be the following N-length vector:

$$\text{r} = \begin{pmatrix} p_1 \gamma_1 \\ p_2 \gamma_2 \\ \vdots \\ p_n \gamma_n \end{pmatrix} \tag{64}$$

Let  be the following $N \times N$ matrix:

$$= \begin{pmatrix} \sigma_1^2 & \sigma_1 \sigma_2 \rho_{12} & \dots & \sigma_1 \sigma_n \rho_{1n} \\ \sigma_2 \sigma_1 \rho_{21} & \sigma_2^2 & \dots & \sigma_2 \sigma_n \rho_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_n \sigma_1 \rho_{n1} & \sigma_n \sigma_2 \rho_{n1} & \dots & \sigma_n^2 \end{pmatrix} \tag{65}$$

The FOCs can then be written as the following system of equation:

$$\begin{aligned} \mathsf{s} &= \mathsf{r} - 1'\lambda \\ \mathsf{s}'1 &= 1 \end{aligned} \tag{66}$$

Solving the first matrix equation:

$$\mathsf{s} = {}^{-1}\mathsf{r} - {}^{-1}1'\lambda \tag{67}$$

where ${}^{-1}$ is the inverse of the covariance matrix, known as the precision matrix.

Using s to solve for $\lambda$, we can show that:

$$\lambda^* = \frac{\mathsf{r}'^{-1}1 - 1}{1'^{-1}1} \tag{68}$$

Plugging $1\lambda$ into s, the optimal production shares can be given by:

$$\mathsf{s}^* = {}^{-1}(\mathsf{r} - 1\frac{\mathsf{r}'^{-1}1 - 1}{1'^{-1}1}) \tag{69}$$

Notice that when $a \to \infty$ (i.e. the household becomes extremely risk averse), then solution is the result of the well-known minimum variance portfolio:

$$\mathsf{s}^*_{\text{extreme}} = \frac{{}^{-1}1}{1'^{-1}1} \tag{70}$$

# F Correlates of Market Participation: Choosing a Market Access Variable

In Table 6, the measure that is most positively correlated with market participation is the presence of a daily or weekly market in a village. While log distance to the market (from either household or plots) is significantly correlated with market participation, the direction of the correlation suggests that household further from markets, participate in markets more frequently. This relationship runs contrary to theory, and the market access variable should correlated theoretically and empirically with increased participation. As a result, the presence of any market in a village is chosen (despite not being robust to the inclusion of fixed effects). This exercise underscores the need for careful and better measurement of market access variables.

Table 6: Correlates of Market Participation

| | (1) % of Crops Sold | (2) % of Crops Sold | (3) % of Crops Sold | (4) % of Crops Sold | (5) % of Crops Sold | (6) % of Crops Sold | (7) % of Crops Sold | (8) % of Crops Sold | (9) % of Crops Sold | (10) % of Crops Sold |
|---|---|---|---|---|---|---|---|---|---|---|
| Log Plot Distance to Market | 0.0133 | | | | | 0.0156** | | | | |
| | (0.00872) | | | | | (0.00775) | | | | |
| Log Household Distance to Market | | 0.0250** | | | | | 0.0122 | | | |
| | | (0.0115) | | | | | (0.0193) | | | |
| Presence of Weekly Village Market | | | 0.0361 | | | | | -0.0361* | | |
| | | | (0.0244) | | | | | (0.0216) | | |
| Presence of Daily Village Market | | | | 0.0187 | | | | | 0.0234 | |
| | | | | (0.0241) | | | | | (0.0257) | |
| Presence of Any Village Market | | | | | 0.0364* | | | | | 0.00777 |
| | | | | | (0.0220) | | | | | (0.0213) |
| District Fixed Effects | No | No | No | No | No | Yes | Yes | Yes | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-10 are estimated using a GLM model using a logistic functional link and binomial distribution.

# G Consumption Diversity and Market Access

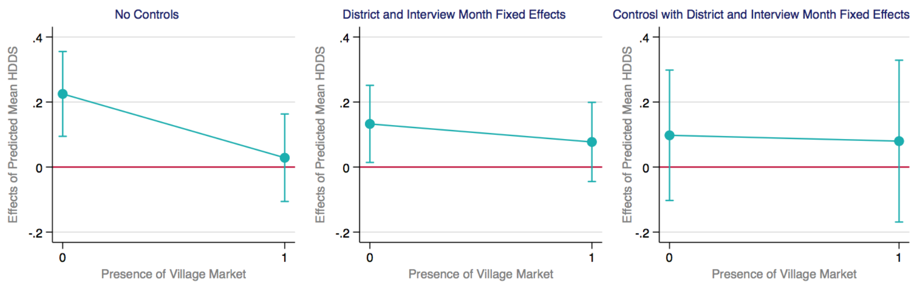


Figure 5: Correlates of HDDS: Interaction between ADS and Producer Market Participation (95% Confidence Intervals)

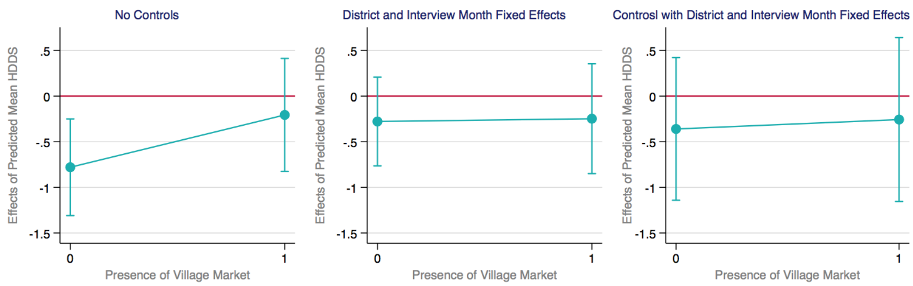


Figure 6: Correlates of HDDS: Interaction between SI and Producer Market Participation (95% Confidence Intervals)

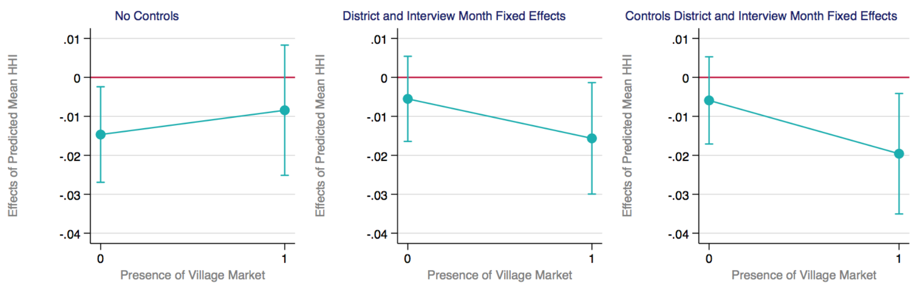


Figure 7: Correlates of HDDS: Interaction between ADS and Producer Market Participation (95% Confidence Intervals)

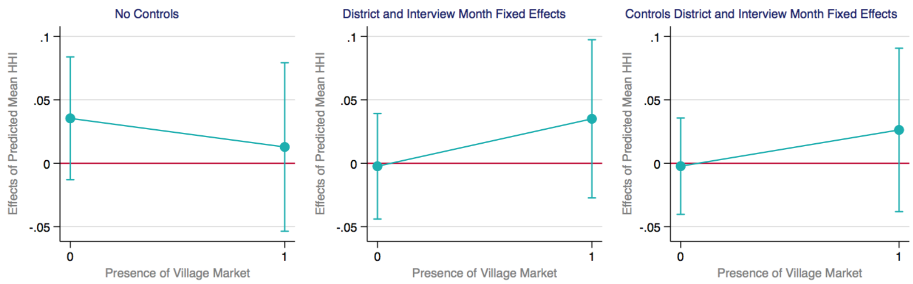


Figure 8: Correlates of HHI: Interaction between SI and Producer Market Participation (95% Confidence Intervals)

Table 7: Correlates of Household Dietary Diversity Score (Market Access)

| | (1)<br>HDDS | (2)<br>HDDS | (3)<br>HDDS | (4)<br>HDDS | (5)<br>HDDS | (6)<br>HDDS |
|---|---|---|---|---|---|---|
| Food Crop Count | 0.159*** | 0.112** | 0.0777* | | | |
| | (0.0500) | (0.0466) | (0.0453) | | | |
| Crop HHI | | | | -0.555*** | -0.266 | -0.318* |
| | | | | (0.206) | (0.191) | (0.182) |
| Daily or Weekly Market = 1 | -0.194 | 0.0722 | -0.0393 | -0.206 | 0.0646 | -0.0399 |
| | (0.156) | (0.174) | (0.152) | (0.155) | (0.173) | (0.151) |
| HH Head Literate = 1 | | | 0.611*** | | | 0.628*** |
| | | | (0.139) | | | (0.139) |
| Male HH Head | | | 0.0329 | | | 0.0332 |
| | | | (0.138) | | | (0.137) |
| HH Size | | | 0.0317 | | | 0.0365 |
| | | | (0.0250) | | | (0.0251) |
| Total HH Acres | | | -0.108 | | | -0.164 |
| | | | (0.168) | | | (0.170) |
| Total HH Acres Squared | | | 0.0363 | | | 0.0436 |
| | | | (0.0336) | | | (0.0338) |
| HH Tropical Livestock Units | | | 0.0139 | | | 0.0149* |
| | | | (0.00878) | | | (0.00884) |
| Log Non-Agr. Income Past 12 Months | | | 0.0132* | | | 0.0122 |
| | | | (0.00800) | | | (0.00800) |
| Log Non-Farm Enterprise Asset Val. | | | 0.0374*** | | | 0.0374*** |
| | | | (0.00963) | | | (0.00952) |
| Access to Mobile Money | | | 0.566*** | | | 0.574*** |
| | | | (0.143) | | | (0.142) |
| Own Mobile Phone | | | 0.477*** | | | 0.480*** |
| | | | (0.141) | | | (0.141) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-6 are estimated using a GLM model using a logistic functional link and binomial distribution.

Table 8: Correlates of Consumption HHI (Market Access)

| | (1) HHI | (2) HHI | (3) HHI | (4) HHI | (5) HHI | (6) HHI |
|---|---|---|---|---|---|---|
| Food Crop Count | -0.0126** | -0.00925* | -0.00973** | | | |
| | (0.00511) | (0.00472) | (0.00487) | | | |
| Crop HHI | | | | 0.0267 | 0.0130 | 0.00829 |
| | | | | (0.0200) | (0.0182) | (0.0185) |
| Daily or Weekly Market = 1 | 0.0351* | 0.00990 | 0.0196 | 0.0373** | 0.0103 | 0.0199 |
| | (0.0184) | (0.0175) | (0.0167) | (0.0182) | (0.0175) | (0.0168) |
| HH Head Literate = 1 | | | -0.0348*** | | | -0.0358*** |
| | | | (0.0121) | | | (0.0121) |
| Male HH Head | | | -0.0176 | | | -0.0174 |
| | | | (0.0139) | | | (0.0139) |
| HH Size | | | 0.0114*** | | | 0.0108*** |
| | | | (0.00253) | | | (0.00249) |
| Total HH Acres | | | 0.00100 | | | 0.00138 |
| | | | (0.0165) | | | (0.0168) |
| Total HH Acres Squared | | | -0.00257 | | | -0.00272 |
| | | | (0.00347) | | | (0.00349) |
| HH Tropical Livestock Units | | | -0.00115 | | | -0.00117 |
| | | | (0.000807) | | | (0.000793) |
| Log Non-Agr. Income Past 12 Months | | | -0.00120 | | | -0.00116 |
| | | | (0.000963) | | | (0.000953) |
| Log Non-Farm Enterprise Asset Val. | | | -0.00152 | | | -0.00154 |
| | | | (0.00109) | | | (0.00109) |
| Access to Mobile Money | | | -0.0373** | | | -0.0372** |
| | | | (0.0163) | | | (0.0165) |
| Own Mobile Phone | | | -0.0407*** | | | -0.0407*** |
| | | | (0.0134) | | | (0.0134) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes |
| Observations | 1050 | 1050 | 1050 | 1050 | 1050 | 1050 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Columns 1-6 are estimated using a GLM model using a logistic functional link and binomial distribution.

# H Anthropometric Measures

Table 9: Correlates of Anthropometric Measures (Market Paricipation)

| | (1) Under-weight = 1 | (2) Under-weight = 1 | (3) Under-weight = 1 | (4) Wasting = 1 | (5) Wasting = 1 | (6) Wasting = 1 | (7) Stunting = 1 | (8) Stunting = 1 | (9) Stunting = 1 |
|---|---|---|---|---|---|---|---|---|---|
| Food Crop Count | 0.00483 | 0.00372 | -0.00406 | -0.00701 | -0.0146 | -0.0286$^{***}$ | -0.00108 | -0.00452 | -0.00856 |
| | (0.00727) | (0.00983) | (0.00945) | (0.00967) | (0.0107) | (0.0101) | (0.00368) | (0.00703) | (0.00661) |
| % of Crops Sold | 0.000737$^{**}$ | 0.000866$^{**}$ | 0.000851$^{**}$ | 0.000445 | 0.000283 | 0.000364 | 0.000209 | 0.000207 | 0.000143 |
| | (0.000367) | (0.000430) | (0.000409) | (0.000595) | (0.000607) | (0.000544) | (0.000175) | (0.000288) | (0.000264) |
| HH Head Literate = 1 | | | -0.0278 | | | 0.0415 | | | -0.0219 |
| | | | (0.0226) | | | (0.0303) | | | (0.0170) |
| Male HH Head | | | 0.0827$^{***}$ | | | 0.0852$^{**}$ | | | 0.109$^{***}$ |
| | | | (0.0275) | | | (0.0343) | | | (0.0306) |
| HH Size | | | 0.0294$^{***}$ | | | 0.0615$^{***}$ | | | 0.0103$^{***}$ |
| | | | (0.00364) | | | (0.00575) | | | (0.00347) |
| Total HH Acres | | | -0.0406 | | | -0.0545 | | | 0.0530$^{*}$ |
| | | | (0.0376) | | | (0.0409) | | | (0.0303) |
| Total HH Acres Squared | | | 0.00868 | | | 0.0104 | | | -0.0127$^{**}$ |
| | | | (0.00780) | | | (0.00858) | | | (0.00637) |
| HH Tropical Livestock Units | | | -0.00129 | | | -0.00447 | | | -0.000209 |
| | | | (0.00186) | | | (0.00321) | | | (0.00103) |
| Log Non-Agr. Income Past 12 Months | | | -0.000661 | | | 0.00102 | | | 0.00115 |
| | | | (0.00177) | | | (0.00236) | | | (0.00140) |
| Log Non-Farm Enterprise Asset Val. | | | -0.00172 | | | -0.00113 | | | -0.00232 |
| | | | (0.00207) | | | (0.00253) | | | (0.00148) |
| Access to Mobile Money | | | -0.0914$^{***}$ | | | -0.147$^{***}$ | | | -0.0313 |
| | | | (0.0335) | | | (0.0358) | | | (0.0222) |
| Own Mobile Phone | | | -0.0117 | | | -0.0333 | | | 0.00973 |
| | | | (0.0211) | | | (0.0286) | | | (0.0169) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Observa-tions | 1050 | 875 | 875 | 1050 | 1050 | 1050 | 1050 | 672 | 672 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-9 are estimated using a Probit model
The numbers of observations in Columns 2, 3, 8, and 9 are lower because the Probit model predicts some cases perfectly with fixed effects.

Table 10: Correlates of Anthropometric Measures (Market Paricipation)

| | (1) Under-weight = 1 | (2) Under-weight = 1 | (3) Under-weight = 1 | (4) Wasting = 1 | (5) Wasting = 1 | (6) Wasting = 1 | (7) Stunting = 1 | (8) Stunting = 1 | (9) Stunting = 1 |
|---|---|---|---|---|---|---|---|---|---|
| Crop HHI | -0.0213 | -0.0260 | -0.0128 | -0.0506 | -0.0497 | -0.0564 | -0.0299$^{*}$ | -0.0604$^{**}$ | -0.0685$^{**}$ |
| | (0.0301) | (0.0367) | (0.0380) | (0.0422) | (0.0423) | (0.0432) | (0.0175) | (0.0290) | (0.0321) |
| % of Crops Sold | 0.000734$^{**}$ | 0.000875$^{**}$ | 0.000897$^{**}$ | 0.000578 | 0.000412 | 0.000590 | 0.000262 | 0.000264 | 0.000262 |
| | (0.000374) | (0.000430) | (0.000411) | (0.000598) | (0.000608) | (0.000563) | (0.000191) | (0.000293) | (0.000285) |
| HH Head Literate = 1 | | | -0.0279 | | | 0.0417 | | | -0.0209 |
| | | | (0.0224) | | | (0.0299) | | | (0.0162) |
| Male HH Head | | | 0.0826$^{***}$ | | | 0.0860$^{**}$ | | | 0.105$^{***}$ |
| | | | (0.0275) | | | (0.0344) | | | (0.0304) |
| HH Size | | | 0.0292$^{***}$ | | | 0.0602$^{***}$ | | | 0.0103$^{***}$ |
| | | | (0.00361) | | | (0.00567) | | | (0.00354) |
| Total HH Acres | | | -0.0441 | | | -0.0731$^{*}$ | | | 0.0378 |
| | | | (0.0388) | | | (0.0419) | | | (0.0302) |
| Total HH Acres Squared | | | 0.00905 | | | 0.0125 | | | -0.0110$^{*}$ |
| | | | (0.00788) | | | (0.00866) | | | (0.00620) |
| HH Tropical Livestock Units | | | -0.00123 | | | -0.00429 | | | 0.0000955 |
| | | | (0.00191) | | | (0.00335) | | | (0.00115) |
| Log Non-Agr. Income Past 12 Months | | | -0.000749 | | | 0.000775 | | | 0.000650 |
| | | | (0.00176) | | | (0.00236) | | | (0.00134) |
| Log Non-Farm Enterprise Asset Val. | | | -0.00173 | | | -0.00120 | | | -0.00234 |
| | | | (0.00208) | | | (0.00255) | | | (0.00148) |
| Access to Mobile Money | | | -0.0913$^{***}$ | | | -0.150$^{***}$ | | | -0.0312 |
| | | | (0.0336) | | | (0.0356) | | | (0.0236) |
| Own Mobile Phone | | | -0.0112 | | | -0.0313 | | | 0.0121 |
| | | | (0.0209) | | | (0.0289) | | | (0.0168) |
| District Fixed Effects | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Survey Month Fixed Effects | No | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Observa-tions | 1050 | 875 | 875 | 1050 | 1050 | 1050 | 1050 | 672 | 672 |

Marginal effects; Standard errors in parentheses
(d) for discrete change of dummy variable from 0 to 1
$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Columns 1-9 are estimated using a Probit model
The numbers of observations in Columns 2, 3, 8, and 9 are lower because the
Probit model predicts some cases perfectly with fixed effects.

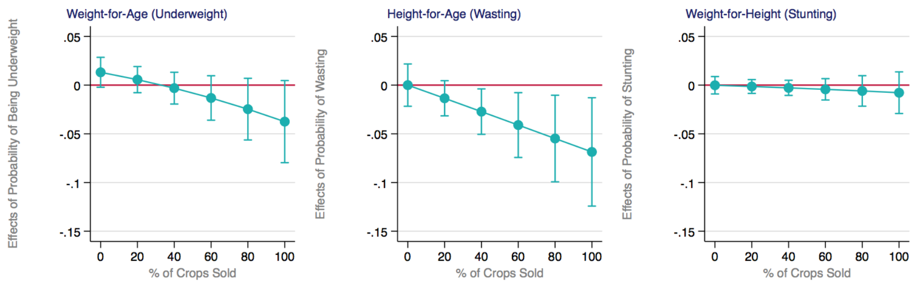


Figure 9: Correlates of Anthropometric Measures: Interaction between ADS and Producer Market Participation (95% Confidence Intervals)

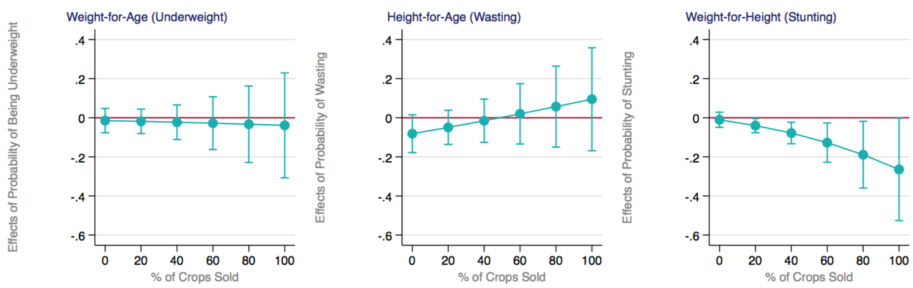


Figure 10: Correlates of Anthropometric Measures: Interaction between SI and Producer Market Participation (95% Confidence Intervals)

RESEARCH PROGRAM ON
**Climate Change, Agriculture and Food Security**

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) brings together some of the world's best researchers in agricultural science, development research, climate science and Earth system science, to identify and address the most important interactions, synergies and tradeoffs between climate change, agriculture and food security. For more information, visit us at **https://ccafs.cgiar.org/.**

Titles in this series aim to disseminate interim climate change, agriculture and food security research and practices and stimulate feedback from the scientific community.

CCAFS is led by:

Alliance

CCAFS research is supported by: