THE ROLE OF LEGUME TECHNOLOGIES IN THE AGRICULTURE-NUTRITION-FOOD SECURITY NEXUS: EVIDENCE FROM ZAMBIA

Christine M. Sauer, Michigan State University, sauerch3@msu.edu
Nicole M. Mason, Michigan State University, masonn@msu.edu
Mywish K. Maredia, Michigan State University, maredia@msu.edu
Rhoda Mofya-Mukuka, Indaba Agricultural Policy Research Institute (Zambia), rhoda.mukuka@iapri.org.zm

Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2

DRAFT
Please do not circulate or cite without authors' permission

Abstract

Despite the many potential benefits of legume cultivation, there is scarce empirical evidence on the effects of improved legume technologies on household food security and nutrition. This paper begins to fill that knowledge gap by empirically estimating the effects of adoption of cereal-legume intercropping and cereal-legume rotation on indicators of food security and nutrition for smallholder farm households in Zambia. The results indicate that cereal-legume rotation is positively and statistically significantly associated with household dietary diversity, months of adequate household food provisioning, and calorie and protein production, but is significantly negatively correlated with net crop income. In contrast, we find little evidence of statistically significant cereal-legume intercropping effects on the food security and nutrition status of Zambian smallholder farm households.

The Role of Legume Technologies in the Agriculture-Nutrition-Food Security Nexus: Evidence from Zambia

1. Introduction

In recognition of the myriad benefits of legume production, the Food and Agriculture Organization (FAO) of the United Nations has declared 2016 to be the International Year of Pulses.[1] Legume production and consumption impart several environmental, economic, and nutritional benefits. As natural nitrogen fixers, legumes reduce the need for inorganic fertilizer and can improve the environmental sustainability of cropping systems (Bohlool et al. 1992). Additionally, as a result of residual nitrogen left in the soil, legumes can enhance long-term soil fertility and crop productivity (Dakora and Keya 1997, Thierfelder et al. 2012). Legumes also help control cereal crop diseases and pests, which in turn reduces the need for costly pesticides (Bohlool et. al. 1992, Howieson et al. 2000).

In addition to the potential positive environmental effects of legume cultivation, legumes carry many potential economic and nutritional benefits for smallholder farm households. For example, these crops can be stored for long periods of time with no loss of nutritional value, which grants farmers the choice to consume or sell the legumes between harvests (FAO 2016). In addition, parts of the legume plant (e.g., the leaves of the cowpea [*Vigna unguiculata*] and bean [*Phaseolus vulgaris*] plants) can be eaten during the growing season, offering some insurance against food insecurity (Barrett 1990). Due to their high protein, mineral, and fiber content, legumes also have the potential to improve human health and nutrition and are a valuable supplement to a carbohydrate-based diet (Ojiewo et. al. 2015, Tharanathan and Mahadevamma 2003).

[1] Pulses are a subgroup of legumes that are harvested for dry grain. Examples include navy beans, kidney beans, chickpeas, and cowpeas.

Given this multi-faceted role that legumes play in the production and dietary systems of many developing countries, they are receiving increasing attention in the agricultural development funding strategies of international research organizations and donor agencies, such as the CGIAR, USAID, the Bill and Melinda Gates Foundation, the Australian Council of International Agricultural Research, and others (Murrell 2016). For example, under the U.S. Government's global hunger and food security initiative called Feed the Future (FTF), strategic investments on pulse crops are being promoted under two of the seven program areas—productivity enhancement and sustainable intensification. Similarly, under the aegis of 'Climate Smart Agriculture' (CSA), intercropping and rotating nitrogen-fixing legumes in the cropping system are also promoted as strategies to sustainably increase productivity and resilience (adaptation), reduce/remove greenhouse gases (mitigation), and enhance the achievement of national food security and development goals (FAO 2013).

A major focus of these international efforts and initiatives is to promote the integration of legumes into major farming systems to improve household incomes and nutrition. In fact, in response to the persistence of malnutrition as a global public health concern, legumes feature prominently as a strategic food group in the pathways linking agriculture to better nutritional outcomes. These agriculture-nutrition linkage pathways are conceptualized to include increased production of more and nutritious foods for self-consumption; increased agricultural income through increased production or productivity that can be used to purchase nutritious food and better health care; increased use of technologies and systems that improve or preserve the nutritional content of foods throughout the food supply chain—i.e., farm level, storage, marketing and processing; and increased empowerment of women to enhance their control over resources, knowledge and status (World Bank, 2007; Hawkes et al. 2012; Chung, 2012; Gillespie et al., 2012; Ruel et al., 2013; Herforth and Harris 2014).

These theoretically assumed linkages between agriculture and nutrition, and how legumes play a role (or not) in strengthening some of these linkages, are poorly understood. This study is thus designed to build an evidence base for these relationships by exploring pathways through which legumes can potentially enhance the agriculture-nutrition linkages. Specifically, we examine the link between the use of cereal-legume rotations or intercropping and some indicators of household food security and nutrition along the agricultural production and income pathways.

To the best of our knowledge, no study has explicitly analyzed the causal link between the use of cereal-legume rotations or intercropping and indicators of household food security and nutrition. This paper attempts to fill that gap by using nationally-representative panel survey data from smallholder households in Zambia. Specifically, we use instrumental variables and panel techniques including fixed effects and correlated random effects approaches to measure the impact of these two legume technologies on income (total income and crop income), per capita calorie and protein production, months of adequate household food provisioning (MAHFP), and household dietary diversity score (HDDS).[2] Some of these indicators such as income and production also influence household food security, which is considered a necessary condition for achieving nutrition outcomes. We thus explore the role of legume based technologies in this broader agriculture-nutrition-food security nexus.

As a preview of our results, we find that cereal-legume rotation has positive and statistically significant effects on HDDS, MAHFP, and per capita calorie and protein production,

---

[2] Legumes included in the study are groundnuts, soybeans, mixed beans, cowpeas, and velvet beans. Cereals include maize, sorghum, rice and millet.

and negative and statistically significant effects on net crop income. These results are robust to the estimator used. The results are more mixed for cereal-legume intercropping.

The remainder of this paper is organized as follows. Section 2 draws from the literature and builds a conceptual framework underlying the empirical analysis of this paper. In Sections 3 and 4 we describe the data and detail our empirical strategy. We present analysis results in Section 5, followed by conclusions in Section 6.

2. Conceptualizing the Role of Legumes in the Causal Pathways from Agriculture to Nutrition

There are different approaches used in the literature in conceptualizing causal pathways from agriculture to nutrition and health (see Webb 2013 for a review). Most of these approaches are based on theorized causal pathways that build on the understanding that agriculture can influence nutrition and health through multiple pathways (direct and indirect), and that food alone is not enough. For example, Headey et al. (2011) and Gillespie et al. (2012) talk of seven pathways, which include agriculture as the direct and indirect (via income) source of food at household level. Other pathways include macro-level agricultural policy as a driver of prices and agriculture as an entry-point for enhancing women's control over resources, knowledge and status. The frameworks by Hawkes et al. (2012) and Chung (2012) elaborate on elements not frequently highlighted, such as micronutrient deficiency versus anthropometry, nutrient quality/bioavailability, value chain, and demand creation for health services through knowledge and nutrition education.

The framework developed in a more recent study by Herforth and Harris (2014) highlights three main pathways linking agriculture to nutrition: food production, agricultural income, and women's empowerment (Figure 1). **Food production** impacts a household's nutritional status through the type, quantity, and seasonality of food available for consumption (Chung 2012, Herforth and Harris 2014). That is, the broader food market environment influences a household's decision of what to produce and consume. If a preferred food is not available or affordable in the local market, a household may instead choose to grow that crop on their farm (Herforth and Harris 2014). As a second pathway, an increase in **agricultural income** could result in increases in food expenditure, which could result in higher levels of dietary diversity and more food consumption overall. More agricultural income might also translate into higher non-food expenditure, including expenditure on health care, which could directly raise a household's nutrition status. **Women empowerment**, as a third pathway in this framework emphasizes women's combined roles in agriculture, dietary choices and healthcare, and how they influence the nutritional outcomes for both child and mother (Figure 1). Note that these are some of the same pathways that link agriculture to household food security, which is different but closely linked to nutrition security.

For a nutrition-focused agricultural strategy, legumes serve as a perfect conduit to unravel the linkages between agriculture and nutrition across all these three pathways. A production system that includes a greater variety of foods grants the household a greater diversity of food for own-consumption. For example, the study by Jones et al. (2014) indicates that a more diverse production system measured with a simple crop count, a crop and livestock count, and with Simpson's Index, was positively and significantly correlated with the dietary diversity indices, and with the number and frequency of legumes, fruits, and vegetable consumption. Thus, under the food production pathway, we expect that households that integrate legumes into the cropping system, either through monocropping, intercropping, or rotation, would have more and diverse availability of food.

Moreover, much of the research suggests a positive relationship between legume intercropping/rotation and crop yield. Legumes have a unique role in sustaining soil fertility through symbiotic biological nitrogen fixation, which serves as a mechanism for boosting crop yield in the system. There is extensive experimental evidence showing that the integration of grain legumes in the farming system significantly increases the yields of the subsequent crop in the rotation (Jeranyama *et al.*, 2007; Kamanga *et al.*, 2010; Lunze *et al.*, 2011; Odhiambo *et al.*, 2011; Chauhan *et al.*, 2012; Lunze & Ngongo, 2012; Thierfelder *et al.*, 2012). There are also impact studies based on observational data that support this linkage between legume intercropping or rotation and cereal productivity. For example, using plot-level data from a household panel survey of Zambian smallholders to model the impact of climate-smart agriculture practices (e.g., minimum soil disturbance, crop rotation, and legume intercropping), Arslan et al. (2015) show that legume intercropping had a positive and significant effect on maize yield. However, the effect of crop rotation on maize yield by this same study was shown to be negative. Kassie et al. (2015) used an endogenous switching regression (ESR) approach to examine the effects of maize-legume intercropping and rotation and minimum tillage on maize productivity in Malawi. Their results indicate that these practices had a positive and significant impact on maize yield. Similarly, Manda et al. (2016a) find a positive effect of maize-legume rotation, improved maize varieties, and residue retention on maize yield in rural Zambia.

Higher crop productivity caused by the presence of legumes in the cropping system as shown by the experimental and observational studies makes more food available for sale and consumption, thus influencing both the production pathway and income pathway. Additionally, since legume crops are often produced and managed by women, they also provide direct access to nutritious foods which can increase dietary choices available for themselves and for their children. Thus, legumes also pay an important role in the third pathway—women empowerment.

In this paper, we explore the role of two legume-based practices—intercropping and rotation—in influencing some intermediate indicators along these pathways linking agriculture to nutrition, as well as to food security. Specifically, we test the hypotheses that farm households that do cereal-legume intercropping or rotation would have: 1) more availability of food as measured by total production of calories and protein (production pathway); 2) more income from crop production and other sources (income pathway); and 3) longer period of adequate food availability and more diverse diet (a combination of production, income and women empowerment pathways).

3. Data

3.1. Data source and attrition

The data are from the Rural Agricultural Livelihoods Survey (RALS), a two-wave, nationally representative panel survey of Zambian smallholder farm households conducted in June-July 2012 and 2015 by the Indaba Agricultural Policy Research Institute.[3] The 2012 survey covered the 2010/11 agricultural year (October 2010-September 2011) and the associated crop marketing year (May 2011-April 2012). The 2015 survey covered the 2013/14 agricultural year and the 2014/15 crop marketing year. The RALS data include detailed information on household demographics, crop production (e.g., input use, area planted, and quantities harvested by plot and crop, as well as plot-level information on use of intercropping and the main crop that was planted on the plot in the previous agricultural year), crop sales, asset holdings, and access and distances to agricultural extension, *inter alia*. In addition, the data capture total household income,

[3] In Zambia, smallholder households are defined as those cultivating less than 20 ha of land. For details on the RALS sample design, see IAPRI (2012, 2015).

measured as net crop income (the gross value of crop production minus fertilizer costs) plus income from livestock and fisheries sales and consumption from own production, net income from formal and informal business activities, salaried/wage employment income, pensions, and remittances received. Both RALS survey waves also capture households' Months of Adequate Household Food Provisions (MAHFP; Bilinsky and Swindale, 2010), and the 2015 wave included the Household Dietary Diversity Score (HDDS; Swindale and Bilinsky 2006). These data allow us to analyze the effects of cereal-legume intercropping and rotations on six household-level welfare indicators: net total income, net crop income, calories produced/capita/day, protein produced/capita/day (in grams), MAHFP and HDDS.[4] The rationale for and more details on these outcome variables is provided in the next sub-section.

A total of 8,839 households were interviewed in the 2012 RALS. Of these, 7,254 (82.1%) were successfully re-interviewed in 2015. Given this non-trivial rate of attrition, we tested for attrition bias using the regression-based test recommended by Wooldridge (2010, p. 837). Based on these tests, we fail to reject the null hypothesis of no attrition bias (p>0.10) for four of the five outcome variables considered in this study that are observed in both survey waves. (Recall that HDDS is observed only in the 2015 RALS.) Only for the calories produced/capita/day outcome variable do we reject the null of no attrition bias at the 10% level or lower, but only marginally so (p=0.098). Therefore, the weight of the evidence suggests no attrition bias in our econometric estimates.

3.2. Outcome variables

[4] Total calories produced/capita/day and total protein produced/capita/day are calculated by multiplying the kg produced of each crop by the estimated calories/kg and protein/kg, respectively, then dividing by the number of household members and 365 days. Calorie and protein conversion factors are from FAO (1968).

The six outcome variables analyzed get at different dimensions of the agriculture-nutrition-food security nexus. MAHFP is a household-level indicator of food access (an important dimension of food security, along with availability, utilization, and stability), and HDDS is a household-level indicator of nutrition. By also analyzing household income (total and crop income) and household production of calories and protein, we can unpack the pathways through which cereal-legume intercropping and rotations affect household nutrition and food security in Zambia. (Recall the "agricultural income" and "food production" pathways in the conceptual framework, Figure 1.) In the remainder of this section, we describe the MAHFP and HDDS in more detail.

The MAHFP module in the 2012 and 2015 RALS asks households in which months, if any, it did not have enough food to meet its needs during the most recent crop marketing year (May-April). The resultant MAHFP outcome variable is an integer ranging from 0-12, with a higher value indicating more months with adequate household food provisions and thus greater household food security (Bilinsky and Swindale 2010).

The HDDS variable is constructed using data from a dietary diversity module included in the 2015 RALS. Interviewees were asked if anyone in the household consumed anything out of 16 different food groups (such as cereals, dark green leafy vegetables, and flesh meat) in the past 24 hours. Some of these categories were then combined for a total of 12 food categories as in the standard HDDS tool (Swindale and Bilinsky 2006). The HDDS is then an integer ranging from 0-12 that reflects a count of how many food groups were consumed by the household in the past day, with a higher number indicating greater dietary diversity. Hoddinott and Yohannes (2002) find that dietary diversity is positively associated with per capita consumption and per capita caloric availability from both staple foods and non-staples, suggesting that HDDS is a decent (and easy to implement) indicator of overall household food security. Although the HDDS provides a good measure of the breadth of food groups consumed by the household, it does not measure quantity consumed or the intra-household distribution, and it does not indicate a household's habitual dietary pattern (Kennedy et al. 2013).

4. Empirical Strategy

4.1. Estimation strategy

Despite the many potential benefits of cereal-legume rotations, intercropping, and other legume technologies, it is notoriously difficult to rigorously assess the impacts of agricultural technology adoption on smallholder welfare. Adoption of legume technologies is likely endogenous to household incomes, nutrition, and food security. A household that adopts a new technology usually does so voluntarily and the decision of whether or not to adopt is likely correlated with unobserved factors affecting household welfare (Alene and Manyong 2007, Khonje et al. 2015). An oft-cited explanation is that more motivated households or those with better management ability are more likely to adopt improved technologies. If this were the case and motivation or management ability were unobservable and also positively correlated with household crop income, for example, then ordinary least squares (OLS) estimates of the effects of cereal-legume intercropping or rotation on household crop income would be biased upward.

Randomly assigning technology *adoption* is also difficult, if not impossible, to achieve, although it may be possible to, for example, randomly assign exposure to or additional training in a given technology. However, in this study, we rely on observational data on the adoption of legume technologies and household welfare, and so must employ quasi-experimental techniques to identify the welfare effects of legume-cereal intercropping and rotation. More specifically, at present we use panel data methods (e.g., the fixed effects estimator and correlated random effects approach) or two-stage least squares to control/correct for different sources of endogeneity. We also report OLS estimates for all outcome variables.

For all outcome variables except for HDDS, which is only observed in the 2015 RALS, we estimate household fixed effects (FE) models of the welfare indicators regressed on measures of the household's adoption of cereal-legume intercropping and rotations, and a vector of control variables which are described in the next sub-section and are listed in Table 1. Cereal-legume intercropping (rotation) is measured as either: (i) a binary 'treatment' variable equal to one if the household practiced cereal-legume intercropping (rotation) on at least one plot, and equal to zero otherwise; or (ii) a continuous 'treatment' variable equal to the household's total hectares under cereal-legume intercropping (rotation). Under the key assumption of strict exogeneity of the observed covariates conditional on the unobserved time-constant household-level heterogeneity, the FE estimates of the cereal-legume intercropping and rotation effects will be unbiased and consistent. If, for example, a household's motivation and management ability did not vary between the 2012 and 2015 waves of the RALS, then the FE approach may largely solve the endogeneity problem.

Given the count-variable nature of the MAHFP, we also estimate correlated random effects negative binomial (CRE-NB) models for this outcome variable. The NB portion directly models the count dependent variable; it is also more flexible than a Poisson model in that it does not assume an equal mean and variance – a property that was rejected in our data. Combining NB with the CRE approach (Mundlak 1978; Chamberlain 1984) allows us to take advantage of the panel nature of the RALS data on MAHFP and control for time-constant unobserved household-level heterogeneity. Note that with nonlinear-in-parameters models like NB, using a fixed effects approach instead of CRE would result in biased estimates due to the so-called incidental parameters problem (Wooldridge, 2010). The key assumption for the CRE estimates to be unbiased is that the time-constant unobserved household-level heterogeneity is a linear function of the household time averages of the observed covariates, such that including these time averages as additional covariates in the regression effectively controls for the unobserved heterogeneity (ibid.).

We need to take a slightly different approach with the HDDS outcome variable, which is observed only in the 2015 RALS. Because of this, we cannot estimate household fixed effects models; however, because we observe all explanatory variables in both waves of the RALS, we can take a CRE-like approach to somewhat control for time invariant unobserved heterogeneity (ibid.). More specifically, we estimate linear CRE and CRE-NB models in which the RALS 2015 HDDS is regressed on the RALS 2015 levels of the covariates as well as the RALS 2012 and 2015 time averages of the covariates.

Finally, for all outcome variables, we estimate two-stage least squares (2SLS) regressions in which we instrument for the two main explanatory variables of interest, which we also suspect may be endogenous to household welfare: cereal-legume intercropping and rotation.[5] To do this, we need at least two instrumental variables (IVs), and these must be strongly partially correlated with the endogenous variables but uncorrelated with the idiosyncratic error term (i.e., uncorrelated with the dependent variable *except* through the endogenous variable). We use as IVs dummy variables for whether any member of the household received advice on "rotating cereals with legumes/nitrogen-fixing crops" and/or advice on "intercropping cereals with legumes/nitrogen-fixing crops". This advice must have been received during or prior to the agricultural year in question (i.e., 2010/11 and 2013/14 for RALS 2012 and 2015, respectively).

[5] These 2SLS models are estimated using the 2015 RALS data for HDDS, and the pooled 2012 and 2015 RALS data for the other outcome variables. We explored estimating fixed effects instrumental variables (FE-IV) models for the latter but were unable to identify sufficiently strong instruments.

First stage regression results of the suspected endogenous explanatory variables on the IVs and exogenous covariates suggest that cereal-legume intercropping and rotation advice dummies are strongly partially correlated with the use of these practices (Tables A1 to A3 in the Appendix). The partial F statistics for the excluded IVs exceed 10 in all of the binary treatment models and in the continuous treatment models when we use the 2012 and 2015 panel data (Table A3). It is only when we use the continuous treatment specifications and the 2015 RALS cross-section that the IVs are weaker (partial Fs of 7.31 and 9.56, Table A3). Note that these weaker IVs would affect only the HDDS continuous treatment regression. Therefore, overall, based on the Staiger and Stock (1997) rule of thumb of partial F>10, the first stage results suggest that the candidate IVs are sufficiently strong to be used in the 2SLS regressions. Moreover, because we control for distance to the nearest agricultural extension office, the advice variables should be uncorrelated with the error term. That is, conditional on a household's access to extension advice, receipt of specific advice about legume intercropping and rotation should be exogenous to household welfare.

Our analytical sample consists of all panel households that grew either a cereal crop and/or a legume crop in each survey wave. Standard errors in the regressions are clustered at the village level in the HDDS models and at the household level in the models for the other outcome variables.

4.2. Control variables

In all regressions, we control for household characteristics such as the age, gender, and education level of the household head, household size (number of members), household assets (landholding size, livestock owned, and farm equipment), and proxies for access to agricultural services and information (e.g., whether the household owns a radio or cell phone and the distance to the nearest agricultural extension office). We also include a variable measuring the total number of food groups produced by the household to control for overall farm production diversity.[6] In addition, we control for legume monocropping by the household (measured as either a binary or continuous variable as is done for the cereal-legume intercropping and rotation 'treatment' variables).[7] See Table 1 for more detailed variable descriptions and summary statistics for RALS 2015 panel households in our analytical sample.

5. Results

Table 2 provides information on the number of households who adopted either cereal-legume intercropping or cereal-legume rotation in 2012 and 2015. Tables 3 and 4 summarize the key findings from the regression analysis – i.e., the estimated effects of cereal-legume intercropping and cereal-legume rotation, respectively, on the six key outcome variables discussed above. (The full regression results are available from the authors upon request.) We begin with a brief descriptive analysis and then discuss each legume technology in turn.

Descriptive Analysis

The results in Table 2 suggest that adoption of cereal-legume intercropping is very low in both agricultural years under study. Just 240 households (3.4% of the total number of panel households that grew crops in both agricultural years) intercropped in 2010/2011; although this number rose to 318 households (4.8%) in 2013/2014, the overall status of adoption remains low. In contrast, cereal-legume rotation is much more common. A total of 2,520 households (36%)

[6] The food groups are the same as those used to compute the HDDS (cereals, vegetables, fruits, meat, eggs, etc.) (Kennedy et al. 2013).

[7] We acknowledge that legume monocropping may also be endogenous, but we were unable to identify a suitable IV for it.

rotated at least one plot in 2010/2011, and this figure also rose in the 2013/2014 agricultural year to 2,683 households (38%).

Despite the fact that the overall number of households that adopted either legume technology increased in the 2013/2014 agricultural year, a substantial number of households who adopted in 2010/2011 did not adopt again in 2013/2014. Of the 240 households who had at least one cereal-legume intercropped plot in 2010/2011, only 79 (33%) also cereal-legume intercropped in 2013/2014. Cereal-legume rotation seems to be a more consistent practice: 1,396 (55%) of the 2,520 households that rotated at least one plot in 2010/2011 rotated again in 2013/2014.

Cereal-legume Intercropping

Cereal-legume intercropping exhibits few statistically significant ($p<0.10$) effects on the food security, nutrition, and income indicators examined in this study (Table 3). For HDDS, for example, we only find a statistically significant cereal-legume intercropping effect when using a binary measure of the use of this legume technology, and only when the 2SLS estimator is used. This result suggests, on average and holding all else equal, that households that cereal-legume intercrop at least one plot had an HDDS that was 8.2 points *higher* than that of households that did not cereal-legume intercrop. Given that the maximum HDDS is 12 and the sample mean is 5.65, this estimate seems implausibly large in magnitude. Thus overall, the weight of the evidence suggests no statistically significant effect of legume-cereal intercropping on HDDS.

For MAHFP, three of the six estimates (POLS for binary and continuous treatment, and 2SLS for continuous treatment) suggest that cereal-legume intercropping *negatively* affects this measure of household food security;[8] however, once we control for time-constant unobserved heterogeneity using the FE estimator, we find no statistically significant effect of this legume technology on MAHFP.

The other results in Table 3 largely suggest no statistically significant effect of cereal-legume intercropping on household income (total or crop), nor on household calorie and protein production. While the POLS results suggest negative and statistically significant effects of this legume technology on the aforementioned indicators, once we correct for endogeneity via 2SLS or control for time invariant heterogeneity via FE, we find no evidence of statistically significant effects.

On balance, the econometric results suggest that cereal-legume intercropping has no statistically significant effects on the household nutrition and food security indicators examined here (HDDS and MAHFP). We also find little evidence of statistically significant cereal-legume intercropping effects on households' crop income and food production (calories and protein produced), which are two of the three main intermediate outcomes through which improved agricultural technologies are hypothesized to affect food security and nutrition (recall Figure 1).

Cereal-Legume Rotation

In contrast to cereal-legume intercropping, cereal-legume rotation has more statistically significant, and generally positive, effects on household welfare (Table 4). For example, the 2SLS results suggest that holding other factors constant, rotating cereals with legumes increases a household's HDDS by an average of 5.3 points, and each additional hectare of rotated crops increases HDDS by an average of 4.8 points. This result, however, is not robust to the estimator

[8] The 2SLS estimate for continuous treatment, for example, suggests that an additional hectare of cereal-legume intercrops reduces a household's MAHFP score by an average of 3.9 units, ceteris paribus. This is a large reduction in household food access given the sample mean MAHFP of 10.32.

used. In particular, once we control for time invariant heterogeneity via the CRE approach (both with a linear model and a negative binomial model), cereal-legume rotation has no statistically significant effect on HDDS.

Unlike the HDDS, the positive and statistically significant effects of cereal-legume rotation on MAHFP are robust to the estimator (and treatment variable) used. The magnitudes of the 2SLS estimates are perhaps too large to be plausible but the FE and CRE-NB results suggest that MAHFP increases by an average of 0.18 units with the use of cereal-legume intercropping, and by an average of 0.08 units given a one-hectare increase in cereal-legume intercrops, ceteris paribus.

The positive effects of cereal-legume rotation on MAHFP appear to be coming mainly through the food production pathway, as cereal-legume rotation significantly increases both household calorie and protein production but reduces household crop income (Table A6). However, cereal-legume rotation appears to have no statistically significant effect on household net total income. The statistical significance of these results is quite robust across estimators, although again the 2SLS estimates are much larger in magnitude than the POLS and FE estimates.

The FE results, for example, suggest that each additional hectare of cereal-legume rotated land increases calorie production by an average of 938 calories/capita/day and protein production by an average of 27 grams/capita/day, holding other factors constant. These are substantial increases vis-à-vis the sample means of 5,617 calories/capita/day and 146 grams of protein/capita/day. Although the adoption of rotation is positively correlated with MAHFP, it appears to have a negative and significant effect on household net crop income. For example, the FE results suggest that each additional hectare of cereal-legume rotated land reduces net crop income by an average of ZMW 621,944, or about 13% of mean household net crop income in our sample.

The effects of cereal-legume rotation on other indicators of household food security are more mixed. Although the adoption of rotation is positively correlated with MAHFP, it appears to have a negative and significant impact on household net crop income. The 2SLS results suggest that households that cereal-legume rotated at least one plot had almost 4.2 million fewer kwacha in net crop income than households that did not rotate, on average and holding other factors constant. Moreover, each additional hectare of cereal-legume rotated crops reduced average net crop income by a further 5 million kwacha, ceteris paribus. These results are robust to the estimator used. Cereal-legume rotation appears to have no statistically significant impact on household net total income.

Summary

Overall, the results suggest that intercropping cereals and legumes has no statistically significant effect on household welfare as measured by the indicators used here. In contrast, cereal-legume rotation is strongly positively associated with household MAHFP (and somewhat with HDDS). These effects appear to come mainly through increased calorie and protein production, i.e. the food production pathway, as opposed to the crop income pathway.

6. Conclusion

The results outlined in this paper suggest that not all cereal-legume technologies impact household food security and nutrition equally. Rotation of cereal crops with legumes positively affects most of the outcome variables considered except for net crop income. Households that rotate reap the benefits of having a greater range of food, and more calories and protein, to eat, and have sufficient food more often than households that do not adopt cereal-legume rotation. Intercropping cereals and legumes, on the other hand, generally appears to have no statistically significant effect on household welfare.

In addition to shedding light on the food security and nutrition impacts of cereal-legume intercropping and rotation, the results of this study suggest that increased food production rather than crop income is the main pathway through which cereal-legume rotation affects household food security and nutrition. In fact, the results suggest that rotation actually decreases net crop income. More research is needed to explore why this might be the case, and to determine if the legume technologies considered here have significant effects on household nutrition and food security through the pathway of women's empowerment. Furthermore, future analyses could use additional quasi-experimental methods such as propensity score matching and endogenous switching regression to correct for the potential endogeneity of cereal-legume intercropping and rotation to household welfare.

Acknowledgement

This study was supported by the USAID-funded Feed the Future Innovation Lab for Collaborative Research on Grain Legumes under the terms of Cooperative Agreement No. EDH-A-00-07-00005-00. The authors also gratefully acknowledge funding support from the USAID Mission to Zambia (grant number 611-A-00-11-00001-00). The opinions expressed in this paper are those of authors alone and should not be attributed to USAID or the Legume Innovation Lab.

References

Alene, A.D. and V.M. Manyong. 2007. "The Effects of Education on Agricultural Productivity Under Traditional and Improved Technology in Northern Nigeria: an Endogenous Switching Regression Analysis." *Empirical Economics* 32: 141-159.

Arslan, A., N. McCarthy, L. Lipper, S. Asfaw, A. Cattaneo, and M. Kokwe. 2015. "Climate Smart Agriculture? Assessing the Adaptation Impacts in Zambia." *Journal of Agricultural Economics* 66(3): 753-780.

Barrett, R.P. 1990. "Legume Species as Leaf Vegetables." In J. Janick and J.E. Simon (eds.), Advances in New Crops. 391-396. Retrieved May 23, 2016 from https://hort.purdue.edu/newcrop/proceedings1990/V1-391.html

Bilinsky, P. and A. Swindale. 2010. "Months of Adequate Household Food Provisioning (MAHFP) for Measurement of Household Food Access: Indicator Guide (v.4)." Washington, D.C.: FHI 360/FANTA.

Bohlool, B.B., J.K. Ladha, D.P. Garrity, and T. George. 1992. "Biological Nitrogen Fixation for Sustainable Agriculture: A Perspective." *Plant and Soil* 141: 1-11.

Chamberlain, G. (1984). *Panel data* in Handbook of Econometrics, Z. Griliches and M.D. Intriligator (eds.) Edition 1, Volume 2, Chapter 22, pages 1247-1318, Elsevier.

Chauhan, B.S., Mahajany, G., Sardanay, V., Timsina, J. & Jat, M.L. 2012. Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: problems, opportunities, and strategies. *Advances in Agronomy*, 117: 315–369.

Chung, K. 2012. "An Introduction to Nutrition-Agriculture Linkages." MINAG/DE Research Report 72E. Maputo, Mozambique: Directorate of Economics, Ministry of Agriculture.

Dakora, F.D. and S.O. Keya. 1997. "Contribution of Legume Nitrogen Fixation to Sustainable Agriculture in Sub-Saharan Africa." *Soil Biology and Biochemistry* 29(5): 809-817.

FAO. 1968. "Food Composition Table for Use in Africa." Rome, Italy: FAO. Retrieved February 20, 2016 from http://www.fao.org/docrep/003/x6877e/x6877e00.htm

FAO. 2013. *Climate-Smart Agriculture: Sourcebook.* Rome: FAO.

FAO. 2016. "2016 International Year of Pulses – Frequently Asked Questions." Rome, Italy: FAO. Retrieved May 23, 2016 from http://www.fao.org/pulses-2016/faq/en/

Gillespie S, Harris L, Kadiyala S. 2012. *The Agriculture-Nutrition Disconnect in India, What Do We Know?* Discussion Paper 01187, International Food Policy Research Institute, Washington, D.C.

Hawkes, C. R. Turner and J. Waage. 2012. *Current and Planned Research on Agriculture for Improved Nutrition: A Mapping and a Gap Analysis*. Report for the Department of International Development (DFID). London: Leverhulme Centre for Integrative Research on Agriculture and Health/University of berdeen/Center for Sustainable International Development.

Headey, D., Chiu, A., and Kadiyala S. 2011. *Agriculture's Role in the Indian Enigma: Help or Hindrance to the Undernutrition Crisis?* Discussion Paper 01085. Washington, DC: International Food Policy Research Institute.

Herforth, A. and J. Harris. 2014. "Understanding and Applying Primary Pathways and Principles. Brief #1." Improving Nutrition through Agriculture Technical Brief Series. Arlington, VA: USAID/Strengthening Partnerships, Results, and Innovations in Nutrition Globally (SPRING) Project.

Hoddinott, J. and Y. Yohannes. 2002. "Dietary Diversity as a Food Security Indicator." FCND Discussion Paper No. 136. Washington, D.C.: IFPRI.

Howieson, J.G., G.W. O'Hara, and S.J. Carr. 2000. "Changing Roles for Legumes in Mediterranean Agriculture: Developments from an Australian Perspective." *Field Crops Research* 65: 107-122.

IAPRI. 2012. "The 2012 Rural Agricultural Livelihoods Survey (for Small and Medium Scale Holdings) Interviewer's Instruction Manual." Lusaka, Zambia.

IAPRI. 2015. "The 2015 Rural Agricultural Livelihoods Survey (for Small and Medium Scale Holdings) Interviewer's Instruction Manual." Lusaka, Zambia.

Jeranyama, P., Waddington, S.R., Hesterman, O.B. and Harwood, R.R. 2007. Nitrogen effects on maize yield following groundnut in rotation on smallholder farms in sub-humid Zimbabwe. *African Journal of Biotechnology*, 6(13): 1503–1508.

Jones, A., A. Shrinivas, and R. Bezner-Kerr. 2014. "Farm Production Diversity is Associated with Greater Household Dietary Diversity in Malawi: Findings from Nationally Representative Data." *Food Policy* 46: 1-12.

Kassie, M., H. Teklewold, P. Marenya, M. Jaleta, and O. Erenstein. 2015. "Production Risks and Food Security under Alternative Technology Choices in Malawi: Application of a Multinomial Endogenous Switching Regression." *Journal of Agricultural Economics* 66(3): 640-659.

Kennedy, G., T. Ballard, and M. Dop. 2013. "Guidelines for Measuring Household and Individual Dietary Diversity." Rome, Italy: FAO.

Khonje, M., J. Manda, A. Alene, and M. Kassie. 2015. "Analysis of Adoption and Impacts of Improved Maize Varieties in Eastern Zambia." *World Development* 66: 695-706.

Lunze, L. and M. Ngongo. 2012. Potential nitrogen contribution of climbing bean to subsequent maize crop in rotation in South Kivu province of Democratic Republic of Congo. *In* A. Bationo, B. Waswa, J. Okeyo, F. Maina & J. Kihara, eds. *Innovations as key to the Green Revolution in Africa*, pp. 677–681. Dordrecht, The Netherlands, Springer Science.

Manda, J., A. Alene, C. Gardebroek, M. Kassie, and G. Tembo. 2016. "Adoption and Impacts of Sustainable Agricultural Practices on Maize Yields and Incomes: Evidence from Rural Zambia." *Journal of Agricultural Economics* 67(1): 130-153.

Mundlak, Y. 1978. "On the Pooling of Time Series and Cross Section Data." *Econometrica* 64: 69–85

Murrell, D. 2016. Global Research and Funding Survey on Pulse Productivity and Sustainability. Dubai: Global Pulse Confederation. Accessed (May 2016) : http://iyp2016.org/resources/documents/technical-reports/124-pulses-global-research-and-funding-survey/file

Ojiewo, C., D.J.D.H. Keatinge, J. Hughes, A. Tenkouano, R. Nair, R. Varshney, M. Siambi, E. Monyo, NVPR. Ganga-Rao, and S. Silim. 2015. "The Role of Vegetables and Legumes in Assuring Food, Nutrition, and Income Security for Vulnerable Groups in Sub-Saharan Africa." *World Medical and Health Policy* 7: 187-210.

Ruel M, H. Alderman, and the Maternal and Child Nutrition Study Group. 2013. Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? *Lancet*, June 6: doi:10.1016/S0140-6736(13)60843-0.

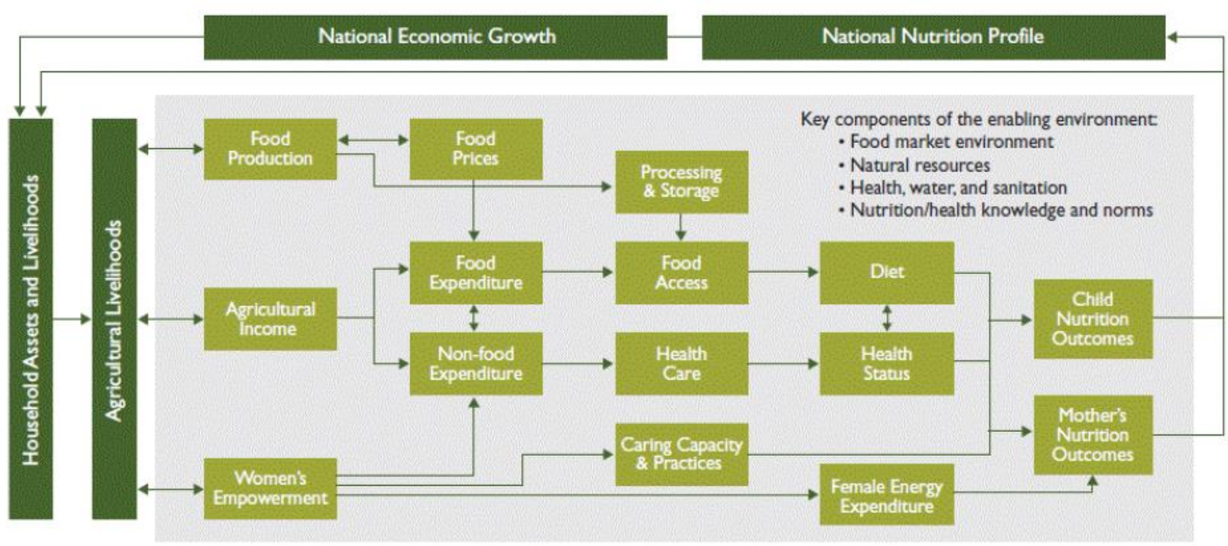
Staiger, D. and J.H. Stock. 1997. "Instrumental Variables Regression with Weak Instruments." *Econometrica* 65(3): 557-586.

Swindale, A. and P. Bilinksy. 2006. "Household Dietary Diversity Score (HDDS) for Measurement of Household Food Access: Indicator Guide (v.2)." Washington, D.C.: FHI 360/FANTA.

Tharanathan, R.N. and S. Mahadevamma. 2003. "Grain Legumes – a Boon to Human Nutrition." *Trends in Food Science and Technology* 14: 507-518.

Theirfelder, C., S. Cheesman, and L. Rusinamhodzi. 2012. "A Comparative Analysis of Conservation Agriculture Systems: Benefits and Challenges of Rotations and Intercropping in Zimbabwe." *Field Crops Research* 137: 237-250.
USAID (United States Agency for International Development). 2013. Agriculture-to-Nutrition Pathways. Background document for the Agriculture and Nutrition Global Learning and Exchange Event, Bangkok, March 19-23, 2013.
Webb, P. 2013. Impact Pathways from Agricultural Research to Improved Nutrition and Health: Literature Analysis and Research Priorities. Rome: FAO and WHO.
Wooldridge, J.M. (2010). Econometric Analysis of Cross Section and Panel Data, Second Edition. The MIT Press, Boston.
World Bank. 2007. *From Agriculture to Nutrition: Pathways, Synergies and Outcomes*. Agriculture and Rural Development Department. Washington, D.C.: World Bank.

Figure 1: Agriculture-Nutrition Conceptual Framework



Source: Herforth and Harris 2014.

Table 1. Summary Statistics (2014/15 agricultural year values)

Variable	Description	N	Mean	Std. Dev.
Dependent Variables				
HDDS	Household dietary diversity score (0-12)	6797	5.65	2.09
MAHFP	Months of adequate household food provisions (0-12)	6798	10.32	2.19
net_tot_income	Net household total income (real ZMW, 2014/15=100)	6798	12818.83	37028.2
net_crop_income	Net household crop income (real ZMW, 2014/15=100)	6798	4706.00	6312.65
tot_calories_PC_per_day	Total calories produced by household/capita/day	6798	5617.19	8812.5
tot_protein_PC_per_day	Total protein (grams) produced by household/capita/day	6798	146.47	248.61
Instrumental Variables				
intercropping_advice	=1 if household received advice on cereal-legume intercropping in the current year or previously	6797	0.26	0.44
rotation_advice	=1 if household received advice on cereal-legume rotation in the current year or previously	6797	0.54	0.5
Explanatory Variables (**'d variables are the key explanatory variables of interest)				
**cereal_legume_int	= 1 if household cereal-legume intercropped any plot	6798	0.05	0.21
**cereal_legume_rotation	= 1 if household rotated cereals and legumes between the previous and current agricultural year on any plot	6798	0.40	0.49
legume_mono	= 1 if household legume monocropped any plot	6798	0.59	0.49
**tot_ha_plant_clint	Total hectares cereal-legume intercropped	6798	0.05	0.33
**tot_ha_plant_clrot	Total hectares cereal-legume rotated	6798	0.36	0.93
tot_ha_plant_leg_mono	Total hectares legume monocropped	6798	0.27	0.48
Num_members	Number of household members	6798	6.02	2.64
eduhead	Education level of household head (years)	6795	5.69	3.57
malehead	= 1 if household head is male	6798	0.75	0.44
age_HH_head	Age of household head (years)	6798	48.24	15.16
chief_related	= 1 if household head or head's spouse is related to the village chief	6798	0.13	0.34
landholdsz	Total landholding size (hectares)	6798	4.21	9.09
radio	= 1 if household owns a radio	6797	0.56	0.5
cell_phone	= 1 if household owns a cell phone	6797	0.55	0.5
Dist_to_road	Distance (km) to nearest tarmac/tarred road	6798	28.9	34.89
Dist_to_ag_camp	Distance (km) to nearest agricultural camp or block office (extension)	6798	17.52	22.5
Dist_to_boma	Distance (km) to nearest market town	6798	40.51	32
assetall	Value of all non-land and non-livestock farm assets and equipment (real ZMW, 2014/15=100) [a]	6798	11537.46	136554.1
tot_food_groups	Total number of food groups grown by household	6798	4.1	1.46
tlu	Tropical Livestock Units owned [b]	6798	2.69	7.79

Note: The reference population is panel households who grew a cereal crop and/or legumes in 2014/15 (N=6,798). [a] This variable includes ox-drawn ploughs, disc ploughs, harrows, cultivators, rippers, ridgers/ weeders, planters, fitarelli (for zero tillage), tractors, hand driven tractors, scotch carts, wheel barrows, water pumps / treadle pumps, other irrigation equipment (e.g., irrigation pipes), knapsack sprayers, and boom sprayers. [b] TLU includes the following livestock types (conversion factors in parentheses): cattle (1), donkeys (0.6), pigs (0.4), goats and sheep, (0.2), ducks, geese, and turkey (0.06), rabbits (0.04), and chickens (0.02).

Table 2. Adoption of Cereal-Legume Intercropping and Rotation in 2010/2011 and 2013/2014 Agricultural Years

Cereal-legume intercropping

		2013/2014 ag. year (# HHs)		
		Adopted	Did not adopt	***Row Sum***
2010/2011 ag. year (# HHs)	Adopted	79	161	240
	Did not adopt	239	6,519	6,758
	Column Sum	318	6,680	6,998

Cereal-legume rotation

		2013/2014 ag. year (# HHs)		
		Adopted	Did not adopt	***Row Sum***
2010/2011 ag. year (# HHs)	Adopted	1,396	1,124	2,520
	Did not adopt	1,287	3,191	4,478
	Column Sum	2,683	4,315	6,998

.
Note: Reference population is panel households that raised crops in both 2012 and 2015 (N=6,998)

Table 3. Summary of Main Regression Results for the Effects of Cereal-Legume Intercropping on Household Welfare

Treatment variable:	**Binary (=1 if HH cereal-legume intercropped)**					**Continuous (total hectares cereal-legume intercropped)**				
Estimator:	OLS/POLS Coef.	2SLS Coef. †	FE Coef.	CRE Coef.	CRE-NB APE[a]	OLS/POLS Coef.	2SLS Coef. †	FE Coef.	CRE Coef.	CRE-NB APE[a]
Outcome Variable:										
HDDS	0.011	8.158		0.234	0.258	-0.011	2.058		0.095	0.103
	(0.154)	(3.080) *		(0.245)	(0.259)	(0.096)	(2.616)		(0.174)	(0.164)
MAHFP	-0.344	-1.314	-0.103		0.093	-0.131	-3.897	0.030		--[b]
	(0.126) ***	(2.227)	(0.173)		(0.286)	(0.077) *	(1.749) **	(0.094)		
Net total income	6155.396	-86,073.616	20,366.316			-1604.321	79280.085	4,627.593		
(‘000s ZMW)	(7,588.789)	(147246.433)	(17,091.346)			(1977.496)	(113222.774)	(6,027.785)		
Net crop income	-620.354	1,355.461	-240.018			-156.888	3,350.633	444.099		
(‘000s ZMW)	(153.203) ***	(2,554.711)	(295.496)			(142.343)	(2,276.287)	(363.533)		
Calorie	-1370.919	2,485.761	-507.677			-1299.641	-2,767.518	-404.576		
production/capita/day	(308.464) ***	(7,070.263)	(354.735)			(516.508) **	(4,155.424)	(386.380)		
Protein production/	-28.868	23.052	3.149			-30.056	-216.585	-6.986		
capita/day (grams)	(8.054) ***	(219.845)	(8.446)			(13.978) **	(132.887)	(10.312)		

Note: * $p<0.1$; ** $p<0.05$; *** $p<0.01$. Standard errors clustered at the household level in parentheses. APE = average partial effect. [a]All NB models assume a quadratic variance function except the binary MAHFP models, which assume a linear variance function. [b]NB-CRE did not converge. †Endogeneity tests suggested cereal-legume intercropping is endogenous.

Table 4: Summary of Main Regression Results for the Effects of Cereal-Legume Rotation on Household Welfare

Treatment variable:	**Binary (=1 if HH cereal-legume rotated)**					**Continuous (total hectares cereal-legume rotated)**				
Estimator:	OLS/POLS Coef.	2SLS Coef. †	FE Coef.	CRE Coef.	CRE-NB APE[a]	OLS/POLS Coef.	2SLS Coef. †	FE Coef.	CRE Coef.	CRE-NB APE[a]
<u>Outcome Variable</u>:										
HDDS	0.177 (0.072) **	5.275 (1.273) ***		-0.040 (0.107)	-0.046 (0.104)	0.139 (0.036) ***	4.754 (1.464) ***		0.036 (0.064)	0.020 (0.054)
MAHFP	0.299 (0.051) ***	4.616 (1.094) ***	0.179 (0.070) **		0.175 (0.105) *	0.119 (0.024) ***	4.458 (1.103) ***	0.082 (0.029) ***		--[b]
Net total income (‘000s ZMW)	11238.914 (19986.944)	-332,037.919 (251,132.920)	19,727.105 (34,883.502)			-2311.360 (2617.061)	-274,130.229 (209,740.902)	2,273.592 (3,327.842)		
Net crop income (‘000s ZMW)	146.911 (87.467) *	-4,205.714 (1,324.027) ***	-129.929 (137.843)			129.654 (108.467)	-5,021.606 (1,441.850) ***	-621.944 (209.392) ***		
Calorie production/ capita/day	557.782 (179.968) ***	7,921.271 (3,189.242) **	160.330 (204.889)			1803.969 (300.269) ***	5,321.388 (2,575.599) **	938.239 (326.058)***		
Protein production/ capita/day (grams)	31.017 (4.967) ***	394.762 (101.128) ***	5.926 (5.325)			55.966 (7.965) ***	303.879 (81.185) ***	27.054 (8.647)***		

Note: * $p<0.1$; ** $p<0.05$; *** $p<0.01$. Standard errors clustered at the household level in parentheses. APE = average partial effect. [a]All NB models assume a quadratic variance function except the binary MAHFP models, which assume a linear variance function. [b]NB-CRE did not converge. †Endogeneity tests suggested cereal-legume intercropping is endogenous.

APPENDIX

Table A1. First Stage Regression Results for Binary Treatment Variable Models (OLS)

Explanatory Variables	Cross-Sectional Data (OLS)		Panel Data (POLS)	
	Dependent (endogenous) variable:			
	Intercropping (=1)	Rotation (=1)	Intercropping (=1)	Rotation (=1)
intercropping_advice	0.051 (4.50)***	0.012 (0.62)	0.040 (4.96)***	0.008 (0.56)
rotation_advice	-0.035 (3.87)***	0.105 (6.21)***	-0.024 (4.74)***	0.059 (5.26)***
legume_mono	-0.080 (7.15)***	0.415 (21.97)***	-0.069 (11.11)***	0.417 (37.60)***
Num_members	-0.000 (0.24)	0.002 (0.79)	0.001 (1.20)	0.002 (1.19)
eduhead	0.001 (1.29)	-0.005 (2.19)**	0.001 (1.33)	-0.003 (1.72)*
1.malehead	-0.011 (1.23)	-0.009 (0.48)	-0.015 (2.24)**	-0.020 (1.55)
age_HH_head	0.002 (1.16)	0.006 (1.98)**	0.001 (0.57)	0.005 (2.48)**
age_HH_head_sq	-0.000 (1.03)	-0.000 (1.91)*	-0.000 (0.41)	-0.000 (2.32)**
1.chief_related	0.010 (0.84)	-0.026 (1.10)	0.013 (1.66)*	-0.021 (1.34)
landholdsz	0.000 (0.17)	0.000 (0.42)	0.000 (1.50)	0.001 (1.44)
1.radio	0.005 (0.65)	0.014 (0.89)	-0.004 (0.70)	0.008 (0.78)
1.cell_phone	-0.012 (1.31)	0.027 (1.56)	0.001 (0.14)	0.015 (1.37)
dist_to_road	0.001 (1.90)*	-0.000 (0.61)	0.001 (4.85)***	-0.000 (0.83)
dist_to_ag_camp	-0.000 (1.59)	0.000 (0.20)	-0.000 (0.70)	-0.000 (1.29)
dist_to_boma	-0.000 (2.01)**	-0.000 (1.19)	-0.000 (4.62)***	-0.000 (0.67)
assetall	-0.000 (1.71)*	0.000 (2.08)**	-0.000 (1.65)*	-0.000 (0.95)
tlu	-0.000 (0.22)	0.003 (3.33)***	-0.000 (1.45)	0.003 (5.05)***
tot_food_groups	0.024 (6.78)***	0.012 (1.84)*	0.022 (10.13)***	0.014 (3.66)***
_cons	-0.033 (0.96)	-0.075 (1.02)	-0.025 (1.07)	-0.047 (0.93)
Partial F (excluded IVs)	**11.65**	**24.00**	**15.32**	**19.22**
R^2	0.06	0.23	0.06	0.22
N	6,794	6,794	13,509	13,509

Note: * *p*<0.1; ** *p*<0.05; *** *p*<0.01. t-statistics in parentheses.

Table A2. First Stage Regression Results for Continuous Treatment Variable Models (OLS)

	Cross-Sectional Data (OLS)		Panel Data (POLS)	
	Dependent (endogenous) variable:			
Explanatory Variables	Intercropping (ha)	Rotation (ha)	Intercropping (ha)	Rotation (ha)
intercropping_advice	0.082	0.062	0.066	0.049
	(3.80)***	(1.67)*	(4.91)***	(2.06)**
rotation_advice	-0.042	0.076	-0.029	0.048
	(2.37)**	(2.47)**	(3.94)***	(2.89)***
tot_ha_plant_leg_mono	-0.049	0.930	-0.042	0.870
	(4.08)***	(10.09)***	(6.24)***	(15.93)***
Num_members	0.001	0.014	0.001	0.009
	(0.53)	(1.96)*	(0.82)	(2.18)**
eduhead	0.003	-0.002	0.002	0.001
	(1.72)*	(0.72)	(2.16)**	(0.59)
1.malehead	-0.007	-0.045	-0.006	-0.029
	(0.59)	(1.74)*	(0.73)	(1.82)*
age_HH_head	0.001	0.002	0.001	0.003
	(0.83)	(0.45)	(0.86)	(1.09)
age_HH_head_sq	-0.000	-0.000	-0.000	-0.000
	(0.80)	(0.35)	(0.78)	(0.74)
1.chief_related	0.011	-0.007	0.010	-0.004
	(0.73)	(0.18)	(1.01)	(0.18)
landholdsz	0.001	0.003	0.002	0.005
	(1.56)	(1.92)*	(3.45)***	(3.20)***
1.radio	0.010	0.042	-0.000	0.015
	(0.68)	(1.84)*	(0.02)	(1.18)
1.cell_phone	-0.004	0.066	0.009	0.052
	(0.26)	(2.60)***	(1.25)	(3.74)***
dist_to_road	0.001	0.001	0.001	0.000
	(1.95)*	(1.48)	(4.69)***	(1.64)
dist_to_ag_camp	-0.000	0.001	-0.000	0.000
	(1.12)	(1.21)	(0.09)	(1.48)
dist_to_boma	-0.000	-0.001	-0.000	-0.001
	(1.29)	(2.32)**	(3.98)***	(2.93)***
assetall	-0.000	0.000	-0.000	-0.000
	(0.88)	(2.23)**	(2.33)**	(2.59)***
tlu	0.002	0.008	0.001	0.008
	(1.59)	(2.95)***	(1.96)**	(3.91)***
tot_food_groups	0.008	-0.002	0.008	-0.002
	(2.45)**	(0.24)	(4.67)***	(0.32)
_cons	-0.035	-0.114	-0.044	-0.117
	(0.84)	(1.02)	(1.46)	(1.81)*
Partial F (excluded IVs)	**7.31**	**9.56**	**12.90**	**13.57**
R^2	0.03	0.28	0.03	0.27
N	6,794	6,794	13,509	13,509

Note: * $p<0.1$; ** $p<0.05$; *** $p<0.01$. t-statistics in parentheses.

Table A3. Summary of Main Results from the First Stage Regressions

	Binary treatment models				Continuous treatment models			
Data set:	Cross-sectional (OLS)		Panel (POLS)		Cross-sectional (OLS)		Panel (POLS)	
Endogenous variable:	Intercrop.	Rotation	Intercrop.	Rotation	Intercrop.	Rotation	Intercrop.	Rotation
Instruments:								
intercropping_advice	0.051	0.012	0.040	0.008	0.082	0.062	0.066	0.049
	(4.50)***	(0.62)	(4.96)***	(0.56)	(3.80)***	(1.67)*	(4.91)***	(2.06)**
rotation_advice	-0.035	0.105	-0.024	0.059	-0.042	0.076	-0.029	0.048
	(3.87)***	(6.21)***	(4.74)***	(5.26)***	(2.37)**	(2.47)**	(3.94)***	(2.89)***
Partial F statistic	**11.65**	**24.00**	**15.32**	**19.22**	**7.31**	**9.56**	**12.90**	**13.57**
N	6,794	6,794	13,509	13,509	6,794	6,794	13,509	13,509

Note: * *p*<0.1; ** *p*<0.05; *** *p*<0.01. t-statistics in parentheses.