Climate Change and Crop Choice in Zambia:
A Mathematical Programming Approach

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Abstract

While climate change is widely regarded as a threat to food security in southern Africa, few studies attempt to link the science of climate change impacts on agriculture with the specificities of smallholder livelihoods. In this paper, we build a series of linear programming (LP) farm-household models in Zambia in order to assess the impact of climate change on rural households and likely changes in land use and crop management. The LP models represent three household types (smallholders, emergent farmers, and female-headed households) in three agro-ecological zones with divergent cropping patterns and climate trends. Model parameters are drawn from several nationally representative rural household surveys, local meteorological records, and downscaled climate predictions of the Hadley (HadCM3) and CCSM models for the year 2050. The calorie-maximizing LP models are calibrated to best reflect baseline crop distributions at each site. Statistical analyses of crop yields over nine years reveal that crops in Zambia exhibit varying levels of sensitivity to climate shocks, and under climate change scenarios, the LP models indicate that farmers will shift their choices of technologies and crops. Among smallholder farms, calorie production from field crops changes by -13.56 to +5.13% under the Hadley predictions and -10.61 to +9.79% under the CCSM predictions. Although farm-households are expected to meet their consumption requirements even under climate change scenarios, the probability of falling below a minimum threshold of calorie production increases in two of our three study sites, and this is particularly true for smallholder farmers who face binding land constraints. Given the current choice set, autonomous on-farm adaptation generally will not be enough to offset the negative yield effects of climate change. Zambia therefore needs larger-scale institutional developments and agricultural research to provide farmers with additional adaptation options.

Key Words: climate change, mathematical programming, farm-households, Zambia
JEL Codes: C61; O13; Q12; Q54

1. Introduction

Inter-annual variability in climatic conditions is an important determinant of crop output in Zambia. Over 90% of smallholder crop production is rain-fed, making yield shortfalls from unpredictable rainfall a major risk for farmers (Siegel and Alwang 2005). Maize production has been consistently poor in seasons with low rainfall (Jain 2006), although Zambia also experiences heavy localized floods that threaten agricultural production. The general climate outlook for southern Africa is characterized by rising temperatures and an increased frequency and severity of extreme weather events (IPCC 2013a).

Studies of the food security impacts of climate change often assume zero or complete adaptation, either predicting food production changes with cropping choices held constant, or estimating regional yield potential without consideration of the likely choices to be made by farmers (Seo and Mendelsohn 2008). Yet farmers do select adaptation strategies from within their choice set, including the adoption of new crops, cultivars, and management regimes. It has been found that warmer temperatures are already prompting the abandonment of mono-cropping systems in lieu of multiple cropping and mixed crop-livestock systems (Hassan and Nhemachena 2008). While acknowledging the potential for adaptation, it is important to note that such strategies are not always available: Food insecure households face a limited choice set due to the costs and perceived risks of adaptation, imperfect access to input and output markets, and lack of insurance and credit. A decision to switch varieties or crops will depend, not only on each crop's sensitivity to climate, but also on the crops' relative profitability.

Smit et al. (1999) distinguishes between autonomous and planned adaptations to climate change: Autonomous adaptations include the farm-level selection of a new crop mix from existing choices, while planned adaptations include agricultural research and development of new crop varieties suited to a changing climate. It is imperative to understand the likelihood and impact of autonomous adaptation in order to identify the most beneficial planned adaptations.

Most studies of climate change impacts on agriculture have been carried out at relatively low spatial resolution, such as the national, regional, or global scale (Thornton et al. 2010). Yet the household level is where food scarcity is ultimately experienced and where decisions about production, investment, risk management, and consumption are made in most rural societies (Ziervogel et al. 2006). Thornton et al. (2010) observe that there remain "real difficulties in making the connections between relatively coarse climate models and the spatial and temporal scales at which appropriate adaptation information is really needed." The IPCC has therefore stressed the importance of assessing the effects of climate change and possible adaptation strategies at the agricultural system or household level. However, in a recent literature review, Van Wijk et al. (2012) find that only 3% of the publications considered were smallholder- or farm-household-level studies of climate change adaptation. Morton (2007) similarly observes that few studies connect the science of climate change impacts on agriculture with “the specificities of smallholder and subsistence systems”. We hope to fill this gap in the literature.

In this paper, we construct a series of farm-household models of representative household types (smallholders, emergent farmers, and female-headed households) from three agro-ecological regions in Zambia, and then simulate household behavior with the expected yields predicted under climate change scenarios. Households maximize calorie production, and model results include the objective function value, the amount of land and labor devoted to different crop activities, and the binding constraints that drive results. We identify how adaptation patterns differ across different household types and quantify the extent to which simple farm-level measures will be enough to offset expected losses. To capture the probabilistic nature of agricultural production, we further explore the probability distributions of crop production with a stochastic simulation of climate variables.

The paper is organized as follows: Section 2 provides a brief literature review related to mathematical programming models and climate variability/ change. Sections 3 and 4 summarize the data sources and introduce our study sites. Section 5 describes the LP model, and section 6 explains the statistical method used to estimate the yield impacts of climate change across Zambia. Section 7 compares the model solutions at baseline to present-day conditions at each site. Section 8 presents the results and discussion of the model solutions under climate change scenarios, and section 9 contains concluding remarks.

2. Mathematical programming farm-household models

A mathematical programming (MP) farm-household model is able to integrate the multiple objectives, activity options, and obstacles faced by smallholder farmers in order to better understand the trade-offs that drive farmer decisions under a changing climate. When the objective function is linear, this is known as a linear programming (LP) model. A LP model solves for optimal resource allocations within a typical farm-household, subject to a set of constraints. These may include available cash and land, seasonal labor constraints, and the level of available technology. This type of whole-firm optimization model acknowledges that new crops or cultivars are not adopted solely on the basis of productive potential. By including a realistic set of activities and constraints, it is able to consider the opportunity costs of different activity mixes in order to account for the likelihood of on-farm adaptation (Hazell and Norton 1986).

Several studies have combined MP models with a stochastic simulation of climate variables. Keil et al. (2009) study the impact of El Niño oscillations on agricultural incomes in Indonesia, combining climate and hydrologic models, statistical crop yield functions, the stochastic simulation of weather variables, and a LP model. The probability distributions of model outcomes are then used to quantify a representative household's vulnerability to El Niño impacts. Heidecke and Heckelei (2010) also build a stochastic optimization model to analyze the impact of changing water inflows on the distribution of farm income in Morocco. The authors feed random water quantities into statistical crop models and then run a Monte Carlo simulation of a regional model, as though a social planner first observes the water flow outcome and then optimizes among cropping activities.

Hansen et al. (2009) examine the value of seasonal rainfall forecasts in Kenya and use a Monte Carlo simulation with GCM-sourced weather predictions, so that the farmer observes a random climate outcome for the upcoming season and then optimizes among farm activities. Letson et al. (2005) also consider the value of forecasts of El Niño oscillation phase in Argentina. The authors enter synthetically-generated stochastic weather outcomes into a set of crop simulation models, and the LP model is solved iteratively, given the oscullation phase along with random prices and yields. Once the farm model is solved for optimal land allocations, the authors constrain the model to these settings to simulate the outcomes over many years. The authors then estimate of certainty equivalences of utility with and without seasonal forecasts.

3. Data

This study references several household-level data sets for rural Zambia. These include a series of Supplemental Surveys (SS) conducted in 2000/01, 2004, and 2008 by the Zambian Central Statistical Office (CSO), the Ministry of Agriculture and Livestock (MAL), and the Michigan State University Food Security Research Project (FSRP); the Rural Agricultural Livelihoods Survey (RALS) conducted in 2012 by the CSO, the Indaba Agricultural Policy Research Institute (IAPRI), and the FSRP; and the Crop Forecast Survey (CFS) conducted annually by the MAL and CSO for the years 2001 to 2012. The latter is a nationally representative household survey focused on expected crop production that takes place before or during harvest, once farmers are able to estimate their crop yields. Labor requirements for some crops are taken from a secondary source (Siegel and Alwang 2005), and the timing of labor inputs is drawn from focus group discussions that were held in 2012/2013 in each study site. Monetary values are inflated to 2011/2012 values using the consumer price index, and because the Zambian currency has since been rebased (1,000 old kwacha = 1 new kwacha), monetary values in this paper do reflect this adjustment. The exchange rate for 2011/12 was 1 U.S. dollar = 5.01 ZMK. No effort was made to impute missing data points for the household surveys.

Historical monthly rainfall and temperature data are obtained from records collected by 35 meteorological stations run by the Zambian Meteorological Department (ZMD). While data availability differs at each station, rainfall records are often available from approximately 1950/51-2010/11, and temperature records are available from 1979/80-2010/11. Missing weather observations are imputed with an average of nearby meteorological stations of similar altitude. For future climate predictions, we reference the predictions published by the Intergovernmental Panel for Climate Change (IPCC 2013b) for two general circulation models (GCMs). We assume the A1B emissions scenario, in which future energy sources are balanced across renewable and nonrenewable sources. Future predictions are downscaled to a 6 km^2 resolution and then averaged over the area of our study sites. Future monthly predictions are downscaled to a resolution of 6 km^2 and then averaged over the area of our study sites.

4. Study sites

The farm-household models are intended to reflect conditions in three study sites across Zambia (Figure 1). These sites are selected based on their location entirely within a given agro-ecological region and livelihood zone (with the exception of site 3, which spans two such zones) (Zambia VAC 2004), and their proximity to a meteorological station with consistent historical record-keeping.

Study site 1 in the south is characterized by a hot and dry climate with average rainfall of approximately 600-700 mm/ year, although the area is prone to weather extremes of both droughts and floods. The site is populated by Tonga people, and livestock-rearing plays a prominent role in the local economy, with cattle widely used for plowing. Site 2, located in agro-ecological zone (AEZ) IIa, is characterized by high rainfall and relatively fertile soil. This is also the most densely populated of our three sites, and approximately one quarter of households self-identify as being female-headed. Site 3 is located in AEZ III, with fertile soils and rainfall of over 1,000 mm/ year. Livestock-keeping is limited due to the high burden of livestock disease. Unlike other regions in Zambia, the staple crops in this zone include both maize and cassava, and site 3 experiences the fewest average months per year without food stocks. This area is sparsely populated and characterized by a particularly poor road network (Zambia VAC 2004). Descriptive statistics of the three sites are provided in Table 1.

5. The farm-household model

5.1 Overview

The model links economic and crop models by combining several techniques: regression analysis for crop production functions, linear programming for farm-level decision making, and stochastic simulation for the incorporation of an uncertain climate. The LP model is built in Microsoft Excel, and it incorporates basic household characteristics, crop budgets, timelines of crop management, and yield functions that capture crop sensitivities to climate.

All farm-level decisions on land preparation and planting are assumed to be made at the beginning of the agricultural season (or in the case of cassava production, the first season), with no contingency plan based on weather outcomes partway through the season. Following Siegel and Alwang (2005), we assume that non-crop production activities occur only during nonworking times, with no trade-off between on-farm work and off-farm household and income-generating activities. We further assume that economic factors and government policies are fixed, such that climate is the only variable driver of the production process. While not realistic, this condition prevents the model from growing too complex and limits the need for assumptions about future price trends. This study intends to capture the impact of climate change only as it is experienced through changes in crop yield.

The household's objective is assumed to be the maximization of calorie production:

$$Max\ calories\ = \sum_{j=1}^{n} K_j\, X_j$$

subject to input requirements for each crop activity and the household's resource constraints:

$$\sum_{j=1}^{m} a_{ij}\, X_j\ \le\ b_i$$

and the non-negativity constraint:

$$X_j\ \ge 0$$

where X_j = level of the j^{th} cropping activity (hectares allocated to crop regime j)

C_{ij} = cost of input i used for one hectare of production of activity j

a_{ij} = quantity of resource i required for one hectare of production of activity j

b_i = amount of resource i available to the farm-household

K_j = calories produced from one hectare of production of activity j

The model assumes that crop production is of the Leontief functional form, such that all inputs can be scaled up proportionally to produce more of a given crop activity. The "calorie content" of cotton is translated through the market to equal the amount of maize grain that can be purchased at local prices with the monetary value of cotton sales. This is the only crop for which the sales price implicitly enters the objective function. The model is solved using the simplex LP method.

It should be noted that we have considered numerous variations of the model and alternate objective functions in the model validation process. These include the maximizations of profit and the weighted ratio of calories-to-cost, which can also be thought of as a maximization of the rate of return (a “bang for buck” strategy). A nonlinear mean-variance analysis of profit was also conducted. In these cases, a safety-first constraint was included in which the household must produce or acquire a minimum number of calories per adult equivalent. In addition, we have considered the use of flexibility constraints, which ensure the inclusion of specific non-cash crops in model solutions. For the emergent farmer, we included the options to rent land and hire in labor at the market rate, with local agricultural wages derived from survey data. Among these variations of the model, we select the maximization of calories without any flexibility constraints in order to best mirror baseline patterns in each site, and to allow the model to adjust freely to new climate conditions. The other baseline results are not reported here.

5.2 Model components

Crop activities

Activities included in the model for each site are listed in Table 2. To select these activities, we first reference the CFS to identify the common crops and crop regimes in each study site. A regime is defined as a combination of cultivar and management choices, including seed type (local or hybrid/ improved), tillage method (hand or plough), fertilizer use (fertilizer applied or not applied), and time of land preparation (before or after the start of rainy season). Because the common regimes do not necessarily represent a diverse range of management practices, we also include some less common regimes. This loosely follows the model construction of Siegel and Alwang (2005).

Crop yields

Average and median yields for each crop regime are presented in Table 3, though the model is parameterized with median values. Cases of zero yield, as when a farmer is not able to harvest anything from a field, are dropped for yield estimates and all analyses in this paper. When fewer than 30 observations can be found within a study site, the geographic range is expanded to the province. In the model, we do not account for expected losses in storage.

Labor requirements

For maize, cassava, and rice, the amount of time required for different activities (land preparation, planting, fertilizer application, weeding, harvest, and post-harvest activities) is estimated from the CFS, while estimates for the remaining crops are taken from a secondary source (Siegel and Alwang 2005). The timeline of these tasks for a "typical year" was produced in a series of focus group discussions with farmers at each site. An example of the labor timeline from site 2 is given in Table 4.

Crop budgets

Table 5 contains an example of variable costs for site 2, with all costs reported at farmgate prices and only median values reported. Herbicides and pesticides are omitted, as they are used by only a small proportion of Zambian households (4.36% and 12.22%) (source: RALS 12). Both variable costs and median sales prices are averaged over the years for which information is available, and gross margins of all crop activities are given in Table 6. For cotton and cassava, which are thought to quickly deplete the soil of nutrients (Howeler 1991), we impose an additional requirement that the household leave fallow an area of land equal to what is planted to these crops. For example, the model may select 0.5 ha of cotton but must also leave 0.5 ha of land in fallow. This captures farmers' concerns about the maintenance of soil fertility, a factor that would not be reflected in the model without this condition.

Household composition and endowments

The models are constrained by the average landholding size in each site for specific household types (Table 7). Smallholders are defined as those with landholdings (excluding rented/ borrowed land) below 5 ha, while emergent famers are those with landholdings between 5 and 20 ha. A female-headed household (FHH) is defined as any household that self-identifies as being headed by a woman, and this group therefore overlaps with the other two categories. The models also include a budget constraint, and these are estimated with reference to available information on household expenditures in each study site (Table 8), as well as the budget that drives the model to the most "valid" solutions at baseline. The composition of a typical household determines the labor endowment of the representative household, along with its consumption needs. Assuming that each household member between the ages of 15 and 59 is able to contribute 20 seven-hour workdays per month to farm labor (following Siegel and Alwang 2005), we also estimate the household labor available for each two-week interval (Table 9).

6. Yield effects of climate change

6.1 Climate predictions

To understand the baseline climate conditions in each site, we match districts to nearby meteorological stations and summarize the historical data collected by the Zambia Meteorological Department. We average the records of Choma and Kafue meteorological stations (site 1), Chipata and Petauke stations (site 2), and Mbala and Kasama stations (site 3). These cover precipitation records for 50 or 60 years (1960/61 or 1950/51-2009/10) and temperature records for 31 years (1979/80-2009/10). The average temperature, rainfall, and monthly coefficient of variation of rainfall over the growing season are given in Table 10.

We refer to the IPCC (2013b) for predictions of rainfall and temperature around the year 2050 for one relatively "wet" climate model that predicts rainfall increases in Zambia (CCSM) and one relatively "dry" model (Hadley). CCSM also predicts a slight decrease in intra-seasonal variation in rainfall, as measured by the coefficient of variation across months. Future predictions are converted into a proportion change from baseline with reference to WorldCLIM, a climate grid that represents baseline climate conditions (Table 10).

6.2 Statistical yield models and climate impacts

Statistical yield functions are used to capture crop sensitivity to seasonal rainfall and temperature variation, and these are based on field-level data collected over nine years for which we have both seed type and weather data. We first aggregate the yield observations from field- to district-level, as such spatial aggregation has been found to produce more reliable results. This is because noise in the explanatory variables induces attenuation bias, whereas aggregation to broader spatial scales cancels out the measurement errors at individual locations (Lobell and Burke 2010). In this study, measurements errors are found in yield estimates of farmers and climate measures that do not capture microclimatic variations. We train the model on yield data from all of Zambia rather than construct a time-series model for each site. Although this restricts all sites to the same yield-climate relationship, this approach expands the sample size and exploits the wider variation in both temperature and rainfall found across the country.

The linear yield models are of the form:

$$ln\left(Mean\ yield_{tdcsf}\right) = f\left(rain_{dt},\ rain_{dt}^{2},\ average\ temp_{dt}, temp_{dt}^{2},\ CVrain_{dt},\ districts\right) \quad (1)$$

where yield = kgs/ha, *t* = year, *d* = district, *c* = crop, *s* = seed type (improved vs. local), *f* = fertilizer use (yes vs. no), $rain_{dt}$ = total rainfall in district *d* and year *t* over the November-March period, $CVrain_{dt}$ = the coefficient of variation in monthly rainfall over the five-month season in district *d* and year *t*, average $temperature_{dt}$ = the average of nighttime lows and daytime highs over the five-month season in district *d* and year *t*, and districts = district dummy variables. No time trend is included because we do not expect to find meaningful technological changes during the eleven-year study period. Furthermore, the latter years are all characterized by unusually high rainfall, making it difficult to isolate the impact of technological advances.

Regressors are selected with a (forward) stepwise variable selection procedure based on the Akaike Information Criterion (AIC) (Rowhani et al. 2011; Holzkämper et al. 2012). All season-level variables and district fixed effects included in equation (1) are candidate regressors. For local cassava, with a growing period that extends over two seasons, the model includes both the previous and current years' weather outcomes as candidate climate regressors. Goodness of fit is based on the AIC in order to minimize the number of climate predictors, as too many variables may lead to over-fitting and a model that is difficult to interpret (Lobell et al. 2007). Once the yield functions are specified, yield estimates under alternate seasonal climate conditions can be calculated. For a given crop regime, these may differ across sites when baseline conditions differ and/or when the predicted changes in climate variables differ between sites. The estimated yield changes based on the Hadley and CCSM climate predictions are given in Table 11, with an example of the yield functions for site 2 in Table 12.

Note that these point estimates do not account for uncertainty in both the GCMs and the statistical models. While statistical yield models are able to capture poorly understood processes related to climate, such as erosion, pest behavior, and pollination dynamics, they do have several drawbacks. They are necessarily simple and unable to capture interactive effects of multiple climate variables; there is an assumption of stationarity when used to project the yield impacts of future climate change; and it is uncertain how well they can project beyond the historical range of observed climate conditions (Lobell and Burke 2010; Lobell et al. 2007). However, statistical models are able to provide yield estimates across the entire range of field crops that are relevant to farmers in Zambia.

Although the estimated yield impacts of climate change differ under the Hadley and CCSM predictions, the relative impacts across crops are similar under both scenarios. Furthermore, the yield impacts occur mostly through changes in temperature rather than precipitation. Several crops seem to be particularly robust to climate change. Sunflower and cassava are generally unaffected by climate, while cotton seems to benefit from increased temperatures. These results are not surprising, as cassava has elsewhere been found to be neutral or even to benefit from climate change in Africa (Blanc 2012; Jarvis et al. 2012; Liu et al. 2008). Cotton yields are elsewhere predicted to increase with climate change in Cameroon (Gerardeaux et al. 2013). Other crops appear quite sensitive to climate change in Zambia, including millet and sorghum, and similar results are seen in other studies (Blanc 2012; Butt et al. 2005).

7. Validation of baseline model

To select the appropriate objective function and ensure that the model reflects baseline crop choices in reality, we first run the model with a variety of objectives and constraints. Annual budget constraints are chosen to both reflect actual input expenditures (Table 8) and to direct the model to reflect baseline levels of welfare in each site. We validate the model by comparing results to the actual crop distribution (inclusive of fallow land) for each household type, as seen in the household surveys (Table 13). The percent of land that is "re-directed" away from the actual crop distribution is calculated for each model solution, and we aim to minimize this value, i.e. to best mirror reality. We also validate the model by comparing results to the average gross value of crop production, as well as calorie production from field crops (excluding cotton) for each household type (Table 14).

Based on this exercise, we determine that the objective of all households should be the maximization of total calorie production, subject to the constraints of household labor and owned land. The model omits any flexibility constraints, as this allows the model to respond freely to a shock. The budget constraints for the smallholder and FHH models differ at each site, and the FHH is allotted 25 ZMK less than the smallholder in order to reflect FHHs' lesser expenditure on cash inputs, as well as the institutional constraints on income generation for FHHs. Baseline results are found in Table 15. Some models produce quite favorable results of the validation tests, notably the smallholder model in site 2 and emergent farmer in site 3.

It is somewhat surprising that the smallholder household consistently produces the fewest calories/ AE/ day, rather than the category of FHHs. However, while FHHs have tighter labor constraints and less land, they also have lower calorie requirements than other household types. Table 14 provides empirical support for the validity of our model results. T-tests for significance of the difference in crop calories/ AE/ day between the categories of FHHs and smallholders show no significant difference (site 1 p-value = 0.833, site 2 p-value = 0.119, site 3 p-value = 0.579). In site 2, FHHs are seen to produce *more* calories/AE/day from field crops, although this is not significant at the 10% level.

While this paper does not include the baseline results across all variations of the model, we observe in this step in model construction that profit-maximization does not necessarily characterize the behavior of smallholder farmers in Zambia. Instead, the maximization of either calorie production or the rate of return drives the model to make choices that better mirror reality. At the same time, profit-maximization does seem to adequately characterize emergent farmers that are presumably more oriented to the market. This step also provides insight into the labor bottleneck for Zambian farmers: While the smallholder is often constrained at the time of land preparation, the emergent farmer is also constrained at the time of weeding or harvesting, particularly during the cotton harvest.

8. Results and discussion

8.1 Crop choice under climate change scenarios

To determine the optimal cropping choices under climate change, we next shock the models with a new set of expected yields for each activity, as calculated in Tables 11 and 12. All other parameters and constraints are held constant, and results are given in Table 16. Although yields under the Hadley and CCSM predictions do differ, the cropping choices under each scenario are extremely similar. This is probably because the crop yields respond in a parallel fashion under both scenarios. Thus, a preferred crop under the Hadley scenario is also preferred under the wetter CCSM scenario.

Figure 2 illustrates the shifts in crop choice made by the representative farm-households under the Hadley scenario. (Results are extremely similar to the CCSM scenario.) In site 1, the smallholder household shifts almost entirely from maize to cotton. This is not surprising, as cotton yields are predicted to rise dramatically with higher temperatures, particularly in site 1. (Note that the temperature-yield relationship for cotton is quadratic, so that the yield effect depends on both the baseline temperature and predicted temperature change at a given site.) Both the smallholder and emergent farmers shift their maize production toward MZ10 (hybrid without fertilizer), which is the maize regime that is least sensitive to climate change. Interestingly, the FHH does not alter its cropping pattern because it already produces cotton at baseline. In site 2, there is a similar shift toward cotton (emergent and smallholder farmers) and sunflower (emergent farmer). This is because sunflower yields are predicted to remain unchanged while cotton yields are predicted to increase. In addition, the production costs of cotton are lower than maize. In site 3, the smallholder shifts from paddy rice to groundnuts, and both the smallholder and emergent farmers shift their maize production regimes to early tillage. This accommodates the labor requirements of other crops at the start of the growing season. Interestingly, although hybrid cassava (CAS2) yields are unaffected by climate change, the emergent farmer does not shift in that direction. The model does allocate slightly more land to groundnuts, sweet potato, and mixed beans.

Given these adjustments in cropping choices, farmers are able to reclaim or even gain calories that would otherwise be lost if the baseline cropping choices were maintained under climate change scenarios (Table 17). For example, under the Hadley scenario, the smallholder in site 2 would lose 7.17% of crop calories produced if they did not adapt to the new set of expected yields. By allocating more land toward cotton production, the farmer is able to recover 4.97% of calories and ultimately loses just 2.21% of calories.

The emergent farmer in site 1 would lose 8.69% of calories with baseline choices held constant, but with adaptation the farmer gains 1.44% of calories to achieve an even higher level of welfare.

8.2 Vulnerability to food shortfalls

We next estimate the probability that a smallholder household or FHH falls below an arbitrary threshold of 3,000 calories/AE/day of field crop production, as a function of variable climate outcomes each year. The optimal cropping choices of each representative household are frozen, both at baseline and under each climate change scenario. We then run a Monte Carlo simulation in which climate variables enter the yield functions stochastically. For baseline, these climate variables are drawn randomly from the baseline fitted distributions of each climate variable (Figure 3), and we assume that climate regressors are independent of one another. For future scenarios, we shift the baseline distributions to the new expected values while preserving the spread. These expected values are derived from the proportion changes of the Hadley and CCSM predictions relative to WorldCLIM (Table 11). The changes in proportion are then applied to the baseline average values in order to estimate a level change in rainfall amount, rainfall variation, and average temperature at each site. Climate variables are drawn randomly from these new distributions.

Table 18 presents the average calorie production (or in the case of cotton, calorie acquisition) and probability of falling below the 3,000 calorie threshold. In sites 2 and 3, average calorie levels fall and vulnerability increases under climate change, with the most severe outcomes occurring under the Hadley climate predictions. This is not surprising, as Hadley predicts higher temperatures, lower rainfall, and a higher level of intra-seasonal rainfall variation, which generally result in lower crop yields. Thus, the vulnerability of a smallholder household in site 3 increases from 6.6% at baseline to 15.9% under CCSM and 20.3% under Hadley, even as cropping choices are optimized in each scenario. These results are also illustrated in Figure 4 with a series of cumulative density functions for the smallholder and emergent farmer in each site. For the emergent farmer in site 1, both climate change scenarios first-order stochastically dominate the baseline scenario. However, the opposite pattern is found in sites 2 and 3.

8.3 Site-level changes in crop output

An estimation of expected changes in aggregate crop production must account for the heterogeneous impacts of climate change on each household type. The final exercise in this paper is a back-of-the-envelope calculation of predicted changes in total calories produced/acquired and total kgs of maize produced in each site, with the number of households and proportion of smallholders and emergent farmers held constant (Table 19). Under the Hadley predictions, the shift away from maize results in a decrease in maize production of 70.48% (site 1), 67.38% (site 2), and 18.79% (site 3). However, because the representative farms adjust to climate change by selecting non-maize crops, total calorie production (or acquisition through cotton sales) increases by 3.69% (site 1) and decreases by just 9.38% (site 2) and 15.73% (site 3).

9. Conclusions

Several caveats should first be noted. This paper does not attempt to capture the other changes that will surely occur in Zambia, including population growth or an increasing commercial orientation of farmers. While we aim to consider only the cropping options currently available to farmers, new options will undoubtedly be introduced within the next several decades. Although agriculture in site 3 is currently limited by a lack of animal draught power in the north, future technological advances may include better management of livestock disease or the widespread use of tractors in the region. As well, results in sites 1 and 2 are largely driven by increased yields of cotton, which is a cash crop that can only be translated into calories through the market. We implicitly hold constant the relative prices of maize and cotton. However, the future price of cotton will be affected by conditions in cotton-growing regions worldwide, and this is not captured in the model. Furthermore, the model does not contain a safety-first constraint that would have restricted the household to produce adequate calories from non-cash crops. With such a constraint, the models would not be able to shift so freely toward cotton. Several additional caveats regarding the limitations of statistical yield models have been covered in section 6. Finally, our yield models only consider monthly precipitation. However, the relative cross-crop estimates of yield change may have differed had we been able to capture daily or dekadal intra-season variation in rainfall.

With these caveats in mind, several conclusions can be gleaned from this study. First, labor constraints seem to be an important baseline determinant of cropping decisions among emergent farmers, who, in reality, tend to leave fallow 23-60% of their land across the three sites. Second, FHHs do not necessarily experience lower calorie production from field crops, as compared with the larger category of smallholder farmers. While this focus on FHHs should not be conflated with a gender analysis of climate change impacts, it seems that FHHs are not necessarily the most vulnerable to climate shocks among Zambian households.

Third, the likely yield impacts of climate change will differ across crops and management in Zambia. For example, our statistical analysis indicates that sunflower and cassava will be relatively unaffected, while cotton may even benefit from rising temperatures. Farmers are therefore likely to adjust their cropping choices under a changing climate, and because the agricultural landscape differs from one region to another, rural households across Zambia will undoubtedly experience climate change differently. Interestingly, maize grown with fertilizer seems to be more sensitive to climate shocks, thereby reducing the benefit of fertilizer use. While fertilizer can considerably improve yields, it may not be a solution to the threat of climate change.

Fourth, the potential for on-farm adaptation to offset the negative effects of climate change should not be ignored. Farmers in sub-Saharan Africa regularly cope with climate variability by adjusting their management strategies (Twomlow et al. 2008), and it should be expected that they will adapt to a changing climate in the same manner. Under the Hadley predictions, representative smallholder farmers are able to mitigate the negative yield effects of climate change by recovering or gaining 4.92 to 7.39% of calories (2.95 to 9.79% under CCSM) that would otherwise be lost without adaptation. Fifth, while the benefits of autonomous adaptation are non-negligible, it is not enough to completely negate the negative effects of climate change in sites 2 and 3. This underscores the importance of larger-scale changes such as the design of heat-tolerant crop varieties, development of irrigation infrastructure, and agricultural policies that reduce risk for smallholder farmers. Under a changing climate, farmers will require new and better options within their choice set.

Sixth, results of this study suggest that farmers will still be able to meet their food needs in the future. However, farm-households will experience heightened vulnerability to food shortfalls under climate change, particularly in site 3. Furthermore, it is generally expected that climate extremes will become more common in the future (IPCC 2013). In other words, the distribution of climate variables will gain "fatter tails", which renders our calculation an underestimate of future vulnerability. The implication seems to be that households will be more secure with a more diverse agricultural or livelihood portfolio.

Future directions for research may include the incorporation of uncertainty into the estimates of yield change. The Monte Carlo simulation can be improved with a more nuanced understanding of how climate variables are correlated. For example, rather than treating them as independent, they might be selected from a copula. We also hope to use the farm-household models to investigate the potential for minimum tillage techniques to offset the negative yield effects of climate change. This will shed light on the present-day constraints on adoption of these management strategies. Finally, we will explore the impact of government policies to promote maize production in light of the expected cross-crop yield effects of climate change.

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TABLES AND FIGURES

Figure 1. *Study sites*

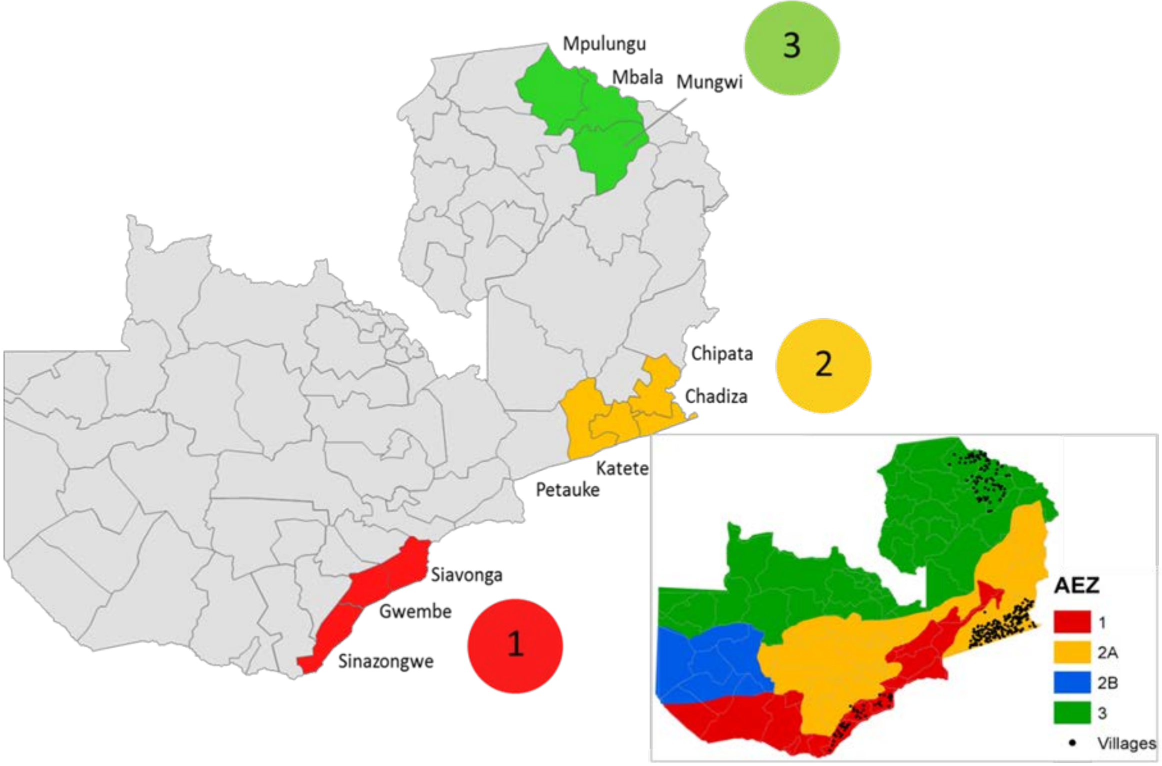


Table 1. *Characteristics of study sites, 2008*

	Site 1		**Site 2**		**Site 3**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Population density (Population/ km^2)	14.01		42.20		12.47	
Village distance to main road (km)	9.34	(6.60)	13.00	(11.73)	20.37	(20.80)
Proportion FHH	0.15	(0.36)	0.27	(0.44)	0.16	(0.37)
HH Size	5.87	(2.63)	5.55	(2.73)	5.49	(2.39)
HH member completed primary school	0.46	(0.50)	0.31	(0.46)	0.48	(0.50)
Income per capita (ZMK)	1,438.49	(2,052.59)	762.83	(1,165.14)	1,475.17	(2,586.21)
Poor (below $1/per capita)	0.80	(0.40)	0.92	(0.27)	0.82	(0.38)
Proportion off-farm income	0.49	(0.36)	0.22	(0.26)	0.45	(0.42)
Tropical Livestock Units (excluding oxen)	4.77	(7.91)	3.03	(5.11)	0.65	(1.69)
Value of equipment/ machines/ oxen	1,739.65	(2,855.25)	1,570.87	(3,628.68)	725.64	(2,858.84)
Calories/adult equivalent/day	3,510.03	(3,244.41)	3,554.71	(3,560.38)	2,655.19	(2,858.47)
Months without food stocks	3.09	(3.03)	2.32	(2.30)	1.36	(2.44)
No. obs.	173		1,044		424	

Of cropping households						
No. cropping HHs	24,809.25		194,675.30		74,309.99	
Proportion smallholder HHs	0.82	(0.39)	0.91	(0.28)	0.69	(0.46)
Land area cultivated (ha)	1.68	(1.13)	1.78	(1.43)	1.60	(1.37)
No. field crops planted	2.03	(1.03)	2.66	(1.13)	2.62	(1.14)
HH sold crops	0.60	(0.49)	0.77	(0.42)	0.82	(0.38)
Uses fertilizer	0.12	(0.32)	0.39	(0.49)	0.31	(0.46)
Owns water pump	0.02	(0.13)	0.00	(0.07)	0.00	0.00
No. obs.	161		1,032		395	

Source: SS 2008

Table 2. *Crop activities*

	Crop	Seed Type	Tillage Method	Fertilizer	Time of Tillage	Code
SITE 1	Maize	Hybrid	Ox	No	Late	MZ10
	Maize	Local	Hand	No	Early	MZ1
	Maize	Local	Ox	No	Late	MZ6
	Maize	Hybrid	Ox	Yes	Late	MZ8
	Groundnuts	Local	Hand	No	Late	GR2
	Groundnuts	Improved	Ox	No	Late	GR10
	Groundnuts	Local	Ox	No	Late	GR6
	Sunflower	Local	Ox	No	Late	SUN6
	Sunflower	Improved	Ox	No	Late	SUN10
	Millet	Local	Ox	No	Late	MIL6
	Millet	Local	Hand	No	Early	MIL1
	Sweet potatoes	Local	Ox	No	Late	SP6
	Sweet potatoes	Improved	Hand	No	Late	SP12
	Sorghum	Local	Ox	No	Late	SOR6
	Sorghum	Improved	Ox	No	Late	SOR10
	Cotton	Improved	Ox	No	Late	COT10
	Cotton	Improved	Hand	No	Late	COT12
SITE 2	Maize	Local	Hand	No	Early	MZ1
	Maize	Hybrid	Hand	Yes	Late	MZ4
	Maize	Local	Hand	Yes	Early	MZ9
	Maize	Local	Ox	No	Late	MZ6
	Groundnuts	Local	Hand	No	Early	GR1
	Groundnuts	Local	Hand	No	Late	GR2
	Groundnuts	Improved	Hand	No	Late	GR12
	Groundnuts	Local	Ox	No	Late	GR6
	Sunflower	Improved	Ox	No	Late	SUN10
	Sunflower	Local	Hand	No	Late	SUN2
	Sweet potatoes	Improved	Hand	No	Late	SP12

	Sweet potatoes	Local	Hand	No	Late	SP2
	Cotton	Improved	Hand	No	Late	COT12
	Cotton	Improved	Ox	No	Late	COT10
SITE 3	Maize	Local	Hand	No	Late	MZ2
	Maize	Hybrid	Hand	Yes	Early	MZ3
	Maize	Local	Hand	No	Early	MZ1
	Maize	Hybrid	Ox	Yes	Late	MZ4
	Groundnuts	Local	Hand	No	Early	GR1
	Groundnuts	Local	Hand	No	Late	GR2
	Groundnuts	Hybrid	Hand	Yes	Late	GR12
	Groundnuts	Local	Ox	No	Late	GR6
	Cassava	Local	---	---	---	CAS1
	Cassava	Improved	---	---	---	CAS2
	Millet	Local	Hand	No	Early	MIL1
	Millet	Local	Hand	No	Late	MIL2
	Sweet potatoes	Local	Hand	No	Late	SP2
	Sweet potatoes	Improved	Ox	No	Early	SP12
	Mixed Beans	Local	Hand	No	Late	MB2
	Mixed Beans	Local	Hand	No	Early	MB1
	Paddy rice	Local	Hand	No	Early	PR1
	Paddy rice	Local	Hand	No	Late	PR2

Table 3. *Crop yields (kgs/ha)*

SITE 1					**SITE 2**					**SITE 3**				
Crop	Mean	SD	Median	No. obs.	Crop	Mean	SD	Median	No. obs.	Crop	Mean	SD	Median	No. obs.
MZ10	1,294.37	(994.88)	1,150.00	1,011	MZ1	1,144.14	(832.24)	946.50	1,769	MZ2	1,549.44	(1,273.04)	1,206.00	1,074
MZ1	1,241.70	(1,142.08)	920.00	136	MZ4	2,354.86	(1,461.00)	2,129.63	1,374	MZ3	3,298.81	(1,592.96)	3,162.50	495
MZ6	1,064.91	(810.10)	920.00	555	MZ9	1,619.67	(1,081.54)	1,419.75	1,012	MZ1	1,627.78	(1,116.18)	1,380.00	499
MZ8	1,854.10	(1,303.86)	1,437.50	680	MZ6	1,239.81	(884.72)	1,064.82	1,456	MZ4	3,399.39	(1,737.38)	3,101.85	994
GR2	541.23	(638.97)	320.00	199	GR1	581.60	(448.71)	474.07	710	GR1	872.06	(823.52)	699.20	596
GR10	619.52	(813.36)	349.60	845	GR2	513.48	(439.55)	395.06	2,422	GR2	785.68	(2,909.58)	512.00	1,990
GR6	492.01	(498.08)	320.00	287	GR12	459.92	(410.66)	395.06	1,030	GR12	609.44	(599.81)	431.60	84
SUN6	505.52	(856.63)	300.00	289	GR6	527.03	(554.62)	384.00	1,670	GR6	572.71	(504.87)	456.00	136
SUN10	459.10	(451.27)	300.00	483	SUN10	516.28	(357.25)	444.48	715	CAS1	5,294.17	(7,323.68)	3,570.00	529
MIL6	454.84	(511.10)	307.50	390	SUN2	490.17	(352.09)	411.56	987	CAS2	8,560.72	(12,051.69)	4,764.80	232
MIL1	365.49	(295.95)	303.70	41	SP12	3,622.19	(5,304.85)	2,508.00	138	MIL1	1,044.75	(787.74)	880.00	711
SP6	2,678.69	(6,119.28)	1,856.00	613	SP2	3,385.78	(5,744.97)	2,291.36	188	MIL2	1,058.77	(1,276.41)	792.00	901
SP12	3,575.36	(5,225.84)	2,520.00	190	COT12	914.22	(539.78)	823.05	2,405	SP12	4,470.66	(5,933.44)	3,024.69	293
SOR6	700.56	(779.05)	454.32	719	COT10	1,015.95	(1,732.11)	840.00	1,237	SP2	3,942.35	(5,330.55)	2,864.20	440
SOR10	400.60	(379.13)	264.00	338						MB1	676.28	(821.27)	533.33	356
COT10	798.72	(460.22)	720.00	614						MB2	635.68	(651.69)	433.20	2,298
COT12	631.14	(405.14)	540.00	96						PR1	1,425.47	(1,194.50)	1,213.33	248
										PR2	1,116.56	(866.81)	978.67	150

Source: CFS 2008-2010 (cassava), CFS 2003-12 (all other cassava)

Table 4. *Labor requirements for crop regimes (site 2)*

		MZ1	MZ4	MZ9	MZ6	GR1	GR2	GR12	GR6	SUN10	SUN2	SP12	SP2	COT16	COT10
September	1														
	2	9.87													
October	1	9.87													
	2	9.87				26.00	20.00	19.00							4.50
November	1	5.29				26.00	20.00	19.00						15.00	5.50
	2	5.29			7.41	5.83	4.00	4.00	19.00					15.00	1.00
December	1	14.80	5.71	14.81	13.05	16.49	4.00	4.00	23.00					1.00	3.20
	2	17.30	15.00	23.38	25.44	10.66	2.00	2.00	16.19	8.00	8.00	30.00	30.00	1.00	3.20
January	1	17.30	15.24	14.91	19.80	10.56	10.33	9.19	7.19	10.60	13.20	34.00	34.00	7.50	3.20
	2		13.84	13.08	14.80		8.33	7.19	7.19	2.60	9.32			7.50	
February	1		11.28	10.96			8.33	7.19		11.99	9.32	7.99	7.99		3.20
	2	2.50	2.75	2.50		1.83				11.99	9.32	7.99	7.99	7.50	3.20
March	1	2.50	2.75	2.50		1.83	2.00	2.00		11.99		7.99	7.99	7.50	
	2		2.75	2.50		1.83	2.00	2.00							
April	1					7.83	2.00	2.00							
	2					6.00				6.80					
May	1		5.87	6.26		6.00	10.80	18.00	11.99	9.80		18.00	8.00		
	2	9.88	5.87	6.26	12.35	6.00	10.80	18.00	11.99	3.00		31.32	14.66	16.65	14.15
June	1	17.16	5.87	6.26	20.10	16.00	14.40	14.40	19.18		10.80	13.32	6.66	18.25	15.22
	2	7.28	7.92	7.83	7.75	16.00	14.40	14.40	19.18		10.80	13.32	6.66	18.25	15.22
July	1	7.28	7.92	7.83	7.75	16.00	14.40	14.40	19.18		4.00			1.60	1.07
	2		7.92	7.83		16.00	14.40	14.40	19.18		4.00				

Sources: CFS 2011 and 2012 (maize, cassava, and rice), Siegel and Alwang (2005) (other crops), focus groups (timeline of agricultural tasks)

Table 5. *Variable costs of crop activities (site 2)*

	Basal Fert	Top Fert	Seed/ planting material	Plough	Basal Fert	Top Fert	Seed/ planting material	Plough	Total Variable Costs
	Kg/Ha	Kg/Ha	Kg/Ha	Yes/No	ZMK/Kg	ZMK/Kg	ZMK/Kg	ZMK/Ha	ZMK/Ha
MZ1			28.08				1.07		30.00
MZ4	123.46	133.33	28.64		2.67	2.82	6.90		929.29
MZ9	123.46	133.33	23.11		2.67	2.82	1.07		756.45
MZ6			26.96	Yes			1.07	40.00	68.81
GR1			39.01				3.16		123.46
GR2			39.01				3.16		123.46
GR12			39.51				4.22		166.69
GR6			39.01	Yes			3.16	40.00	163.46
SUN10			10.27	Yes			7.33	40.00	115.33
SUN2			10.27				7.14		73.37
SP12			583.92				0.41		240.00
SP2			583.92				0.20		116.78
COT12			20.00				3.00		60.00
COT10			24.69	Yes			3.00	40.00	114.07

Sources: SS 2004 and 2008, and RALS 12 (fertilizer); CFS 2012 (seed, plough prices); RALS 12 (seed/ha)
Note: Cassava kgs/ha in site 3 estimated from the value for sweet potato.

Table 6. *Productivity and rate of return for crop activities*

SITE 1			**SITE 2**			**SITE 3**		
Crop	Calories/ha (1,000s)	Calories/ZMK (1,000s)	Crop	Calories/ha	Calories/ ZMK	Crop	Calories/ha	Calories/ ZMK
MZ10	4,105.50	19,523.48	MZ1	3,379.01	112,633.76	MZ2	4,305.42	173,701.44
MZ1	3,284.40	107,495.31	MZ4	7,602.78	8,181.29	MZ3	11,290.13	10,887.26
MZ6	3,284.40	51,318.75	MZ9	5,068.52	6,700.41	MZ1	4,926.60	199,527.32
MZ8	5,131.88	7,085.90	MZ6	3,801.39	55,247.47	MZ4	11,073.61	10,187.29
GR2	1,756.80	10,980.00	GR1	2,602.67	21,081.60	GR1	3,838.61	16,196.66
GR10	1,919.30	11,995.65	GR2	2,168.89	17,568.00	GR2	2,810.88	15,616.00
GR6	1,756.80	10,980.00	GR12	2,168.89	13,011.30	GR12	2,369.51	11,255.18
SUN6	1,458.00	16,311.88	GR6	2,108.16	12,897.35	GR6	2,503.44	14,726.12
SUN10	1,458.00	12,968.30	SUN10	2,160.17	18,731.17	CAS1	5,319.30	53,803.46
MIL6	1,048.58	16,383.98	SUN2	2,000.16	27,261.81	CAS2	7,099.55	47,312.77
MIL1	1,035.63	47,504.90	SP12	3,034.68	12,644.50	MIL1	3,000.80	128,471.75
SP6	2,245.76	19,055.12	SP2	2,772.54	23,740.78	MIL2	2,700.72	115,624.58
SP12	3,049.20	19,057.50	COT12	7,197.53	119,958.85	SP12	3,659.88	11,437.11
SOR6	1,590.12	22,716.05	COT10	7,345.80	64,395.00	SP2	3,465.68	22,256.98
SOR10	924	13,200.00				MB1	1,957.33	13,805.04
COT10	5,401.44	63,546.35				MB2	1,589.84	11,213.15
COT12	4,051.08	90,024.00				PR1	4,173.87	51,026.63
						PR2	3,366.61	37,378.81

Sources: SS 2004 and 2008, RALS 12 (sales prices); Calories estimated from Wu Leung et al. (1968)
Note: Cotton harvest is translated into calories through the site-specific cotton sales price and retail price of maize meal.

Table 7. *Household land size*

		Landholdings (ha)	
Site		Mean	Median
1	Smallholders	1.80	1.67
	Emergent farmers	6.76	6.41
	FHHs	1.68	1.25
2	Smallholders	1.92	1.62
	Emergent farmers	6.48	7.31
	FHHs	1.74	1.34
3	Smallholders	1.23	1.00
	Emergent farmers	7.89	6.13
	FHHs	1.30	0.63

Source: SS 2008

Note: Site 2 exhibits an active land rental market, with an average land size accessed by emergent farmers of 7.32 ha.

Table 8. *Input expenditures*

		Fertilizer expenditure, including transport cost			Seed expenditure		
Site		Mean	SD	Median	Mean	SD	Median
1	Smallholders	16.98	(139.76)	0.00	86.30	(186.04)	12.00
	Emergent farmers	83.89	(298.73)	0.00	236.78	(309.38)	160.00
	FHHs	0.00	(0.00)	0.00	48.67	(80.78)	0.00
2	Smallholders	131.04	(363.27)	0.00	105.68	(143.53)	55.00
	Emergent farmers	799.13	(2,319.98)	0.00	400.71	(475.47)	250.00
	FHHs	98.68	(307.37)	0.00	91.60	(152.87)	45.00
3	Smallholders	143.05	(367.67)	0.00	108.01	(151.62)	80.00
	Emergent farmers	358.62	(846.47)	0.00	217.03	(280.30)	160.00
	FHHs	94.78	(345.82)	0.00	86.23	(120.05)	40.00

Sources: SS 2008 and CFS 2012

Table 9. *Household composition*

Site		HH members	Adult equivalents	Prime-age individuals	Labor endowment
1	Smallholders	5.77	4.75	2.94	29.40
	Emergent farmers	6.7	5.51	3.31	33.10
	FHHs	3.99	3.30	2.07	20.70
2	Smallholders	5.49	4.57	2.65	26.50
	Emergent farmers	6.51	5.43	3.17	31.70
	FHHs	4.14	3.44	2.09	20.90
3	Smallholders	5.42	4.53	2.8	28.00
	Emergent farmers	6.16	5.22	2.95	29.50
	FHHs	4.08	3.45	2.12	21.20

Source: SS 2008

Note: Labor endowment = workdays per two-week interval

Table 10. *Climate predictions of Hadley and CCSM*

		Baseline		**Future**	
		Met station data		Expected proportion Δ	
	Site	Mean	SD	Hadley	CCSM
Rainfall (mm)	1	708.34	(171.56)	-0.07	+0.04
	2	948.77	(220.95)	-0.08	+0.04
	3	1,021.21	(220.02)	-0.01	+0.07
Avg. temp (°C)	1	23.10	(0.53)	+0.10	+0.10
	2	24.07	(0.55)	+0.10	+0.09
	3	20.79	(0.50)	+0.11	+0.10
CV rain	1	0.50	(0.19)	+0.11	-0.04
	2	0.48	(0.18)	+0.02	+0.00
	3	0.37	(0.18)	+0.09	+0.04

Sources: IPCC (2013b) and ZMD records

Note: All variables refer to the November-March growing season.

Table 11. *Estimated yield changes under climate change scenarios*

SITE 1			**SITE 2**			**SITE 3**		
	Expected proportion Δ			Expected proportion Δ			Expected proportion Δ	
Regime	Hadley	CCSM	Regime	Hadley	CCSM	Regime	Hadley	CCSM
MZ10	-0.06	+0.02	MZ1	-0.08	-0.03	MZ2	-0.07	-0.04
MZ1	-0.11	-0.02	MZ4	-0.24	-0.16	MZ3	-0.21	-0.15
MZ6	-0.11	-0.02	MZ9	-0.02	0.01	MZ1	-0.07	-0.04
MZ8	-0.26	-0.15	MZ6	-0.08	-0.03	MZ4	-0.21	-0.15
GR2	-0.33	-0.27	GR1	-0.44	-0.36	GR1	-0.05	-0.02
GR10	-0.22	-0.15	GR2	-0.44	-0.36	GR2	-0.05	-0.02
GR6	-0.33	-0.27	GR12	-0.20	-0.15	GR12	-0.20	-0.15
SUN6	-0.02	0.00	GR6	-0.44	-0.36	GR6	-0.05	-0.02
SUN10	-0.03	0.01	SUN10	-0.01	0.00	CAS1	-0.08	-0.04
MIL6	-0.60	-0.54	SUN2	0.03	-0.02	CAS2	0.00	0.00
MIL1	-0.60	-0.54	SP12	-0.45	-0.41	MIL1	-0.33	-0.31
SP6	-0.18	-0.15	SP2	-0.16	-0.15	MIL2	-0.33	-0.31
SP12	-0.43	-0.43	COT16	+0.07	+0.07	SP12	-0.43	-0.39
SOR6	-0.48	-0.45	COT10	+0.07	+0.07	SP2	-0.17	-0.16
SOR10	-0.23	-0.16				MB1	-0.15	-0.12
COT10	+0.22	+0.27				MB2	-0.15	-0.12
COT12	+0.22	+0.27				PR1	-0.36	-0.32
						PR2	-0.36	-0.32

Source: Author's calculation based on CFS (2003-2011)

Table 12. *Derivation of expected yield changes (site 2)*

Baseline temp (°C)	24.07	
Baseline rain (mm)	948.77	
	Hadley	CCSM
Δ temp	+2.34	+2.22
Δ rain	-77.25	+35.55
Δ CV rain	+0.01	0.00

	Coefficients					**Proportion Δ**	
Regime	**Rain**	**Rain^2**	**Temp**	**Temp^2**	**CVrain**	**Hadley**	**CCSM**
MZ1	1.58E-03	-6.87E-07	-0.02		-0.61	-0.08	-0.03
MZ4	1.86E-03	-7.28E-07	-0.08		-0.60	-0.24	-0.16
MZ9	1.68E-04				-0.71	-0.02	0.01
MZ6	1.58E-03	-6.87E-07	-0.02		-0.61	-0.08	-0.03
GR1	6.65E-04	-2.67E-07	1.05	-0.02	-0.50	-0.44	-0.36
GR2	6.65E-04	-2.67E-07	1.05	-0.02	-0.50	-0.44	-0.36
GR12	1.92E-04		-0.07		-0.86	-0.20	-0.15
GR6	6.65E-04	-2.67E-07	1.05	-0.02	-0.50	-0.44	-0.36
SUN10					-0.55	-0.01	0.00
SUN2	-4.85E-04				-0.90	0.03	-0.02
SP12			-0.19			-0.45	-0.41
SP2	-8.80E-05		-0.07		-0.45	-0.16	-0.15
COT16	-1.93E-04		2.16	-0.04	-0.88	0.07	0.07
COT10	-1.93E-04		2.16	-0.04	-0.88	0.07	0.07

Note: Significant district dummies not shown

Table 13. *Crop distributions by area*

	Site 1			**Site 2**			**Site 3**		
Crop	Small-holder	Emergent	FHH	Small-holder	Emergent	FHH	Small-holder	Emergent	FHH
Maize	0.46	0.37	0.38	0.56	0.46	0.52	0.23	0.14	0.16
Cassava	0	0	0	0	0	0	0.28	0.10	0.17
Sorghum	0.20	0.18	0.26	0	0	0	0	0	0
Cotton	0.10	0.13	0.07	0.15	0.18	0.12	0	0	0
Millet	0.05	0.03	0.05	0	0	0	0.06	0.03	0.04
Groundnuts	0.01	0.01	0.02	0.09	0.07	0.10	0.05	0.03	0.05
Mixed Beans	0	0	0	0	0	0	0.13	0.08	0.10
Sweet Potatoes	0	0	0	0	0	0	0.02	0.01	0.01
Sunflower	0	0	0	0.06	0.06	0.05	0	0	0
Rice	0	0	0	0	0	0	0	0.01	0.01
Fallow	0.17	0.28	0.23	0.13	0.23	0.21	0.22	0.61	0.45

Sources: SS 2004 and 2008, CFS 2008-2010

Table 14. *Production from field crops*

		Crop calories (1,000s)		Crop calories/AE/day		Gross value crop production (1,000s ZMK)		Gross value/AE	
Site		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	Smallholder	4,363.62	(4,369.03)	3,263.19	(3,658.73)	1,389.11	(1,346.61)	370.42	(386.26)
	Emergent	9,198.29	(10,620.42)	5,179.78	(7,822.59)	3,114.46	(3,106.36)	631.48	(794.36)
	FHHs	2,157.83	(1,583.44)	2,975.43	(4,590.64)	765.03	(698.99)	341.81	(457.84)
2	Smallholder	5,222.10	(5,546.82)	3,955.10	(3,988.61)	1,913.66	(1,803.45)	523.49	(493.89)
	Emergent	19,307.61	(26,467.66)	13,045.67	(21,951.67)	6,604.52	(7,435.96)	1,568.78	(2,343.96)
	FHHs	4,310.13	(7,919.03)	4,751.35	(8,064.16)	1,436.01	(2,259.97)	580.08	(964.65)
3	Smallholder	5,374.83	(5,538.02)	4,126.58	(4,622.29)	1,996.27	(1,741.84)	572.26	(577.99)
	Emergent	17,441.56	(18,071.22)	11,548.00	(13,314.61)	6,278.57	(5,946.95)	1,554.74	(1,898.07)
	FHHs	3,344.55	(5,500.63)	3,642.16	(7,406.00)	1,340.49	(2,122.02)	550.72	(1,147.77)

Source: SS 2008

Note: "Calories" does not include the calories that purchased through cash crop (cotton) production.

Table 15. *Baseline results*

SITE 1		**Smallholder**	**FHH**	**Emergent**
Budget constraint		75	50	1,500
Net revenue (ZMK)		1,684.13	1,362.43	3,614.59
Returns per AE per day (ZMK)		0.97	1.13	1.8
Returns to land (ZMK/ha)		935.63	810.97	534.7
Cash spent on inputs		75	50	1,500
% cash inputs of gross value of production		4.26	3.54	29.33
Calories per AE per day		3,226.70	3,581.00	8,123.88
Calories (1,000s) per ZMK		74.59	86.27	10.89
Land cultivated (ha)		1.53	1.09	4.31
Land binding?		Yes	Yes	No
Labor binding (months)		Dec	June	Dec, Jan, May, June
Ha crop activity	MZ10	0	0	0.2
	MZ1	0.85	0.51	0
	MZ6	0.4	0	0
	MZ8	0	0	1.71
	SUN6	0	0	1.29
	SUN10	0	0	0.28
	SOR6	0.27	0.2	0
	COT10	0	0	0.82
	COT12	0	0.38	0
	Fallow	0.27	0.59	2.45
VALIDATION TESTS				
Total % land "misplaced"		28.92	40.57	31.45
% deviation (gross value of		26.64	84.62	64.22

production)			
% deviation (calories produced - no cotton)	5.48	23.11	29.49

SITE 2		Smallholder	FHH	Emergent
Budget		350	325	1,500
Net revenue (ZMK)		2,119.20	1,916.04	5,099.73
Returns per AE per day (ZMK)		1.27	1.53	2.57
Returns to land (ZMK/ha)		1,103.75	1,101.17	787
Cash spent on inputs		350	325	1,500
% cash inputs of gross value of production		14.17	14.5	22.73
Calories per AE per day		4,938.24	5,967.49	10,995.20
Calories per 1,000 ZMK		23.53	23.05	14.53
Land cultivated (ha)		1.53	1.28	4.72
Land binding?		Yes	Yes	No
Labor binding (months)		Dec	June	Jan, June
Ha	MZ4	0.29	0.28	1.37
crop activity	MZ6	0.86	0.54	0
	SUN10	0	0	0.61
	COT12	0.39	0.46	0
	COT10	0	0	1.37
	Fallow	0.39	0.46	3.13
VALIDATION TESTS				
Total % land misplaced		15.56	20.26	32.16
% deviation (gross value of production)		29.03	56.06	0.07
% deviation (calories produced - no cotton)		4.31	2.92	39.24

SITE 3		Smallholder	FHH	Emergent
Budget		200	175	1,500
Net revenue (ZMK)		1,988.27	2,273.20	6,006.97
Returns per AE per day (ZMK)		1.2	1.81	3.15
Returns to land		1,616.48	1,748.62	761.34
Cash spent on inputs		200	175	1,500
% cash inputs of gross value of production		9.14	7.16	20.56
Calories per AE per day		3,868.88	4,476.52	9,740.07
Calories per 1,000 ZMK		31.98	32.21	12.37
Land cultivated (ha)		1.23	1.26	3.19
Land binding?		Yes	Yes	No
Labor binding (months)		N/A	Oct, Nov	Oct-Jan, April, June, July
Ha	MZ2	0.4	0.27	0

crop activity	MZ3	0.14	0.05	0.29
	MZ1	0.26	0.27	0
	MZ4	0	0	0.86
	GR1	0	0.35	0.05
	GR2	0	0	0.04
	GR6	0	0.03	0.77
	CAS1	0	0	0.29
	CAS2	0	0.04	0.2
	MIL2	0	0	0.09
	SP2	0	0	0.29
	MB1	0	0	0.07
	MB2	0	0	0.12
	PR1	0.43	0.25	0.1
	Fallow	0	0.04	4.7
VALIDATION TESTS				
Total % land misplaced		71.41	71.67	11.82
% deviation (gross value of production)		9.62	82.64	19.56
% deviation (calories produced)		19.02	68.54	6.4

Table 16. *Cropping choices under climate change scenarios*

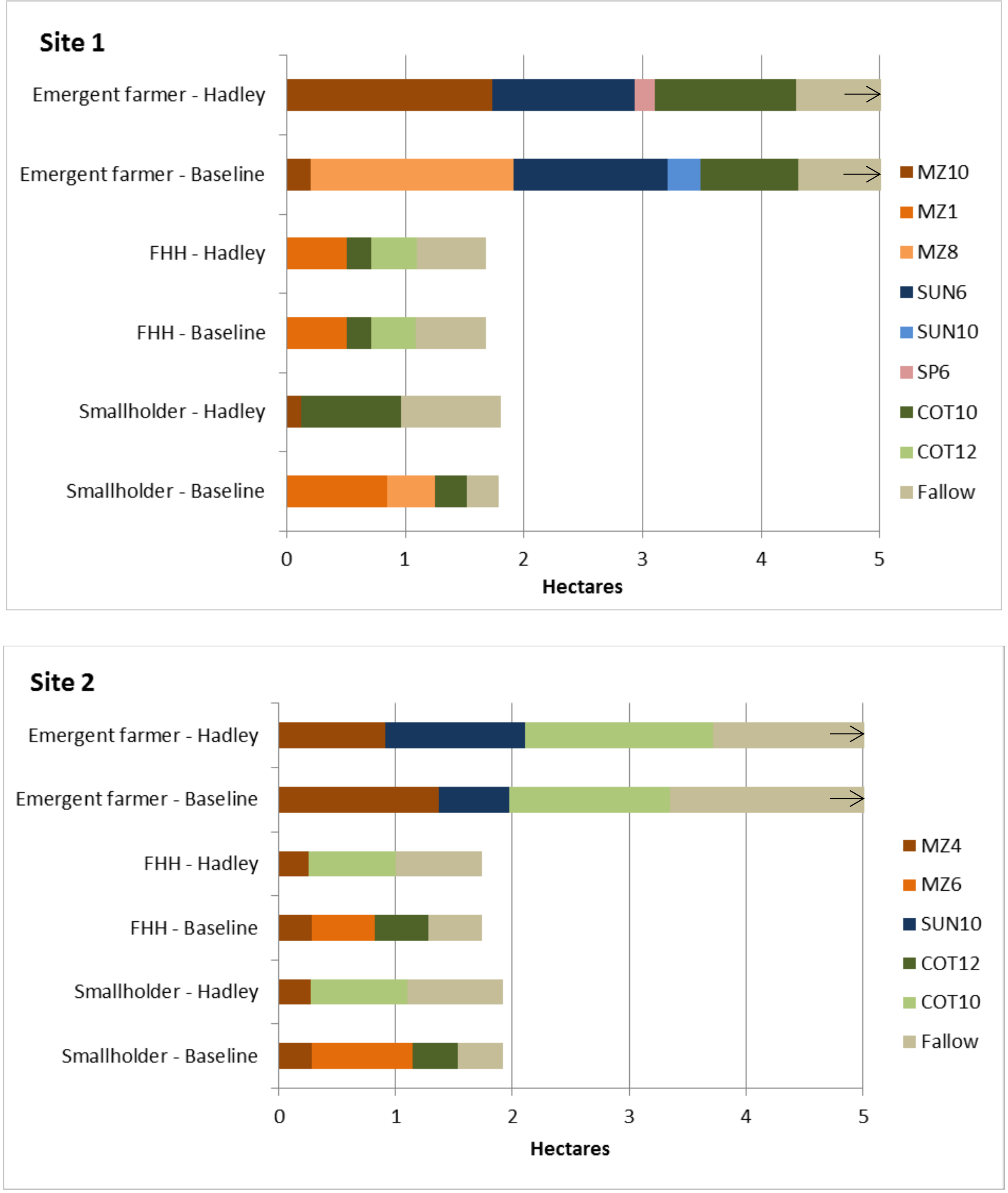
		HADLEY			**CCSM**		
SITE 1		**Smallholder**	**FHH**	**Emergent**	**Smallholder**	**FHH**	**Emergent**
Net revenue (ZMK)		1,920.81	1,506.32	4,827.13	2,008.37	1,597.74	5,131.73
Returns per AE per day (ZMK)		1.11	1.25	2.40	1.16	1.33	2.55
Cash spent on inputs		75.00	50.00	592.89	75.00	50.00	592.89
% cash inputs of gross value of production		3.76	3.21	10.94	3.60	3.03	10.36
Calories per AE per day		5,881.49	4,715.04	8,241.21	6,141.91	4,999.21	8,714.96
Calories (1,000s) per ZMK		78.42	94.30	27.95	81.89	99.98	29.56
Land cultivated (ha)		0.96	1.10	4.29	0.96	1.10	4.29
Returns to land (ZMK/ha)		1,067.12	896.62	714.07	1,115.76	951.04	759.13
Ha crop activity	MZ10	0.13	0.51	1.73	0.13	0.51	1.73
	SUN6	0	0	1.20	0	0	1.20
	SP6	0	0	0.17	0	0	0.17
	COT10	0.84	0.20	1.19	0.84	0.20	1.19
	COT12	0	0.38		0	0.38	0
	Fallow	0.84	0.59	2.47	0.84	0.59	2.47

	HADLEY			**CCSM**		
SITE 2	**Smallholder**	**FHH**	**Emergent**	**Smallholder**	**FHH**	**Emergent**
Net revenue (ZMK)	2,040.48	1,846.60	5,095.76	2,091.67	1,894.70	5,276.14
Returns per AE per day (ZMK)	1.22	1.47	2.57	1.25	1.51	2.66

Cash spent on inputs		350.00	325.00	1,167.45	350.00	325.00	1,167.45
% cash inputs of gross value of production		14.64	14.97	18.64	14.33	14.64	18.12
Calories per AE per day		4,829.29	5,827.37	10,326.06	4,930.85	5,954.17	10,624.57
Calories (1,000s) per ZMK		23.02	22.51	17.53	23.50	23.00	18.04
Land cultivated (ha)		1.10	1.00	3.72	1.10	1.00	3.72
Returns to land (ZMK/ha)		1,062.75	1,061.26	786.38	1,089.41	1,088.91	814.22
Ha	MZ4	0.28	0.26	0.91	0.28	0.26	0.91
crop activity	SUN10	0	0	1.20	0	0	1.20
	COT12	0	0	0	0	0	0
	COT10	0.82	0.74	1.61	0.82	0.74	1.61
	Fallow	0.82	0.74	2.76	0.82	0.74	2.76

		HADLEY			**CCSM**		
SITE 3		**Smallholder**	**FHH**	**Emergent**	**Smallholder**	**FHH**	**Emergent**
Net revenue (ZMK)		2,217.62	1,952.67	4,869.08	2,298.92	2,001.80	5,172.18
Returns per AE per day (ZMK)		1.34	1.55	2.56	1.39	1.59	2.71
Cash spent on inputs		200.00	175.00	1,500.00	200.00	175.00	1,500.00
% cash inputs of gross value of production		8.27	8.23	23.95	8.00	8.05	22.88
Calories per AE per day		3,344.28	4,003.93	8,045.53	3,458.32	4,117.37	8,477.96
Calories per 1,000 ZMK		27.65	28.81	10.22	28.59	29.63	10.77
Land (ha)		1.23	1.30	3.22	1.23	1.29	3.21
Returns to land		1,802.94	1,502.05	617.12	1,869.04	1,539.85	655.54
Ha	MZ3	0.07	0.02	0.53	0.07	0.02	0.50
crop activity	MZ1	0.70	0.52	0.01	0.70	0.53	0.01
	MZ4	0	0	0.61	0	0	0.64
	GR1	0.45	0.36	0.04	0.45	0.35	0.04
	GR6	0	0.04	0.93	0	0.03	0.91
	CAS1	0	0	0.20	0	0	0.22
	CAS2	0	0	0.19	0	0.01	0.19
	MIL1	0	0.06	0.06	0	0.04	0.06
	SP2	0	0.30	0.39	0	0.31	0.38
	MB1	0	0	0.01	0	0	0.02
	MB2	0	0	0.24	0	0	0.22
	PR1	0.01	0.01	0.01	0.01	0.01	0.02
	Fallow	0	0	4.67	0	0.01	4.68

Figure 2. *Crop distributions under climate change*



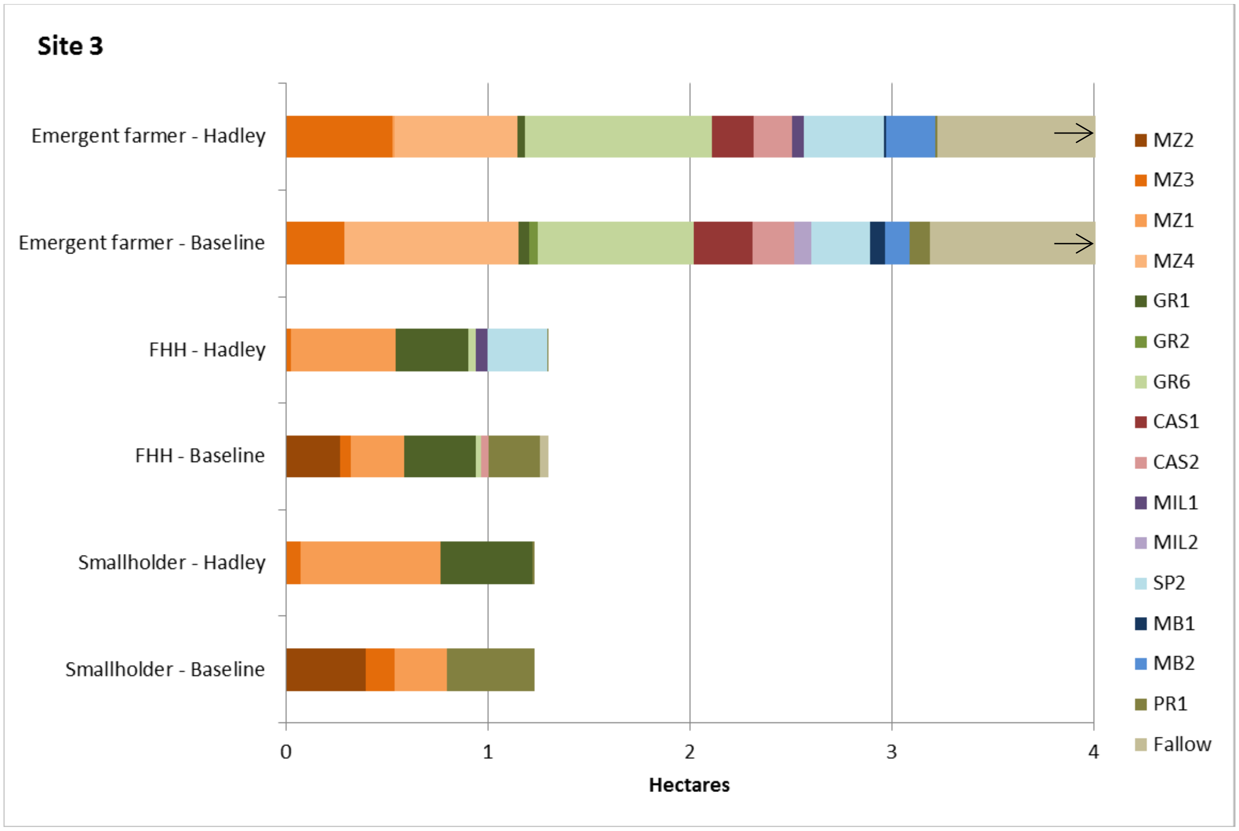
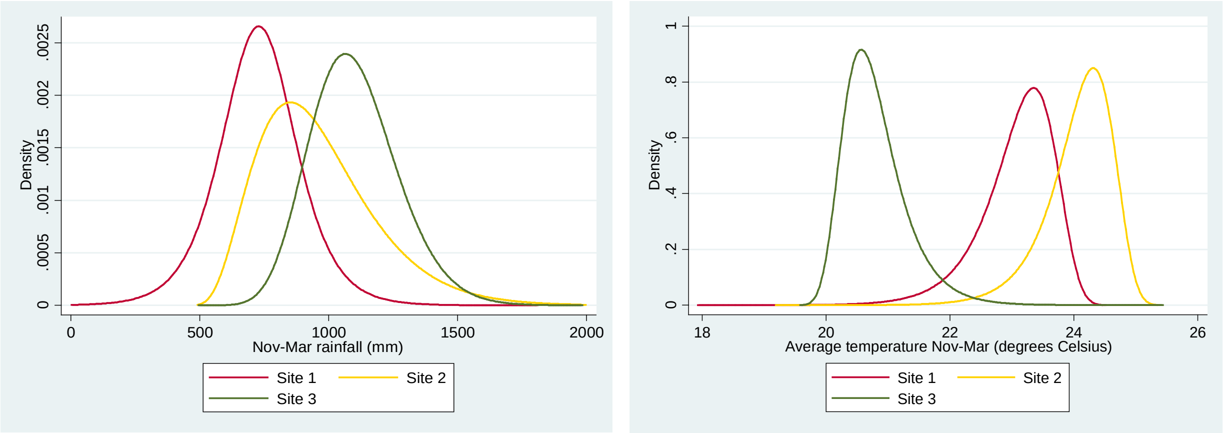


Table 17. *Calories reclaimed or gained through adaptation*

		Smallholder	FHH	Emergent
SITE 1	Baseline (calories/AE/day)	3,226.70	3,581.00	8,123.88
Hadley	Without adaptation	3,153.96	3,914.52	7,417.73
	With adaptation	3,392.35	3,914.52	8,241.21
	% change in calories with adaptation	5.13	9.31	1.44
	% calories reclaimed/ gained through adaptation	7.39	0.00	10.14
CCSM	Without adaptation	3,416.09	4,150.45	8,070.45
	With adaptation	3,542.56	4,150.45	8,714.96
	% change in calories with adaptation	9.79	15.90	7.28
	% calories reclaimed/ gained through adaptation	3.92	0.00	7.93
SITE 2	Baseline	4,938.24	5,967.49	10,995.20
Hadley	Without adaptation	4,583.93	5,614.06	10,081.91
	With adaptation	4,829.29	5,827.37	10,326.06
	% change in calories with adaptation	-2.21	-2.35	-6.09
	% calories reclaimed/ gained through adaptation	4.97	3.57	2.22
CCSM	Without adaptation	4,785.24	5,831.27	10,521.46
	With adaptation	4,930.85	5,954.17	10,624.57

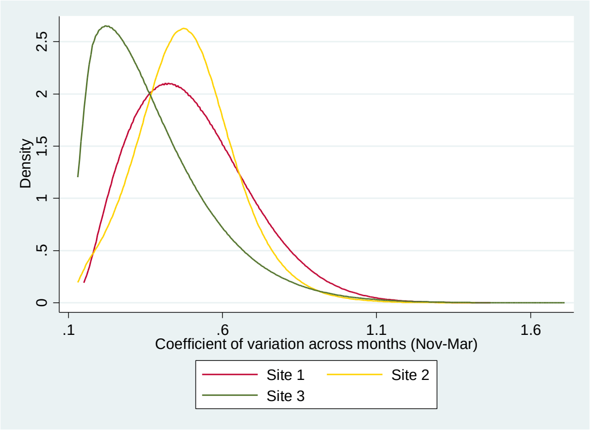
	% change in calories with adaptation	-0.15	-0.22	-3.37
	% calories reclaimed/ gained through adaptation	2.95	2.06	0.94
SITE 3	Baseline	3,868.88	4,476.52	9,740.07
Hadley	Without adaptation	3,153.94	3,904.81	8,023.53
	With adaptation	3,344.28	4,003.93	8,045.53
	% change in calories with adaptation	-13.56	-10.56	-17.40
	% calories reclaimed/ gained through adaptation	4.92	2.21	0.23
CCSM	Without adaptation	3,300.87	4,049.94	8,466.45
	With adaptation	3,458.32	4,117.37	8,477.96
	% change in calories with adaptation	-10.61	-8.02	-12.96
	% calories reclaimed/ gained through adaptation	4.07	1.51	0.12

Figure 3. *Fitted probability distributions of climate variables*



Growing season rainfall

Average temperature



Coefficient of variation of rainfall

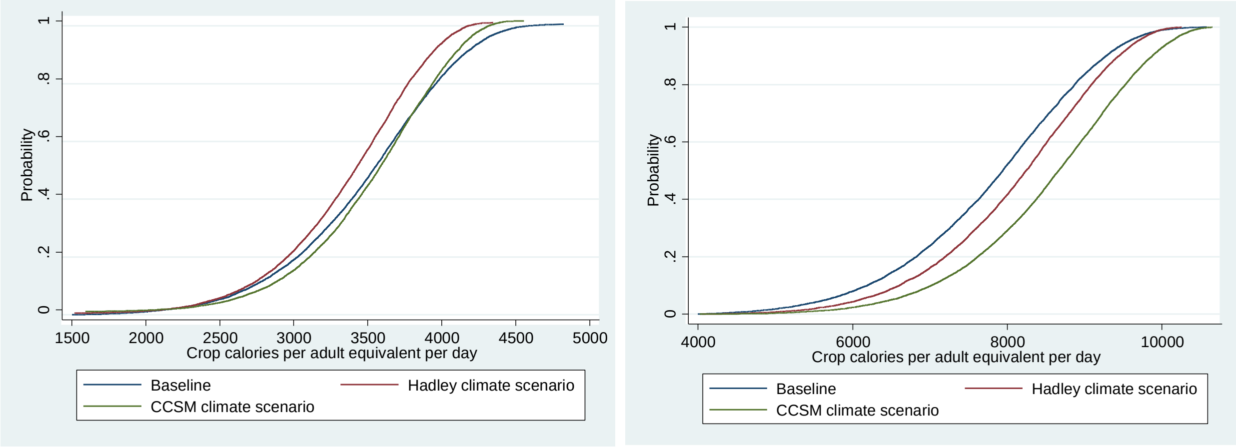
Source: ZMD records

Table 18. *Vulnerability to food shortfalls*

		Baseline		**Hadley**		**CCSM**	
		Mean calories	Vulnerability	Mean calories	Vulnerability	Mean calories	Vulnerability
Site 1	Smallholder	3,475.97	19.1%	3,362.73	21.6%	3,525.79	14.3%
	FHH	3,444.08	21.9%	3,853.50	7.1%	4,057.97	4.1%
	Emergent	7,818.77		8,117.66		8,536.93	
Site 2	Smallholder	4,880.81	0.2%	4,807.54	0.3%	4,919.05	0.2%
	FHH	5,912.73	0.2%	5,800.57	0.3%	5,938.74	0.2%
	Emergent	10,920.15		10,294.28		10,591.04	
Site 3	Smallholder	3,828.86	6.6%	3,305.54	20.3%	3,397.20	15.9%
	FHH	4,543.61	1.1%	3,899.87	5.3%	4,022.42	3.9%
	Emergent	10,456.87		8,591.50		9,000.53	

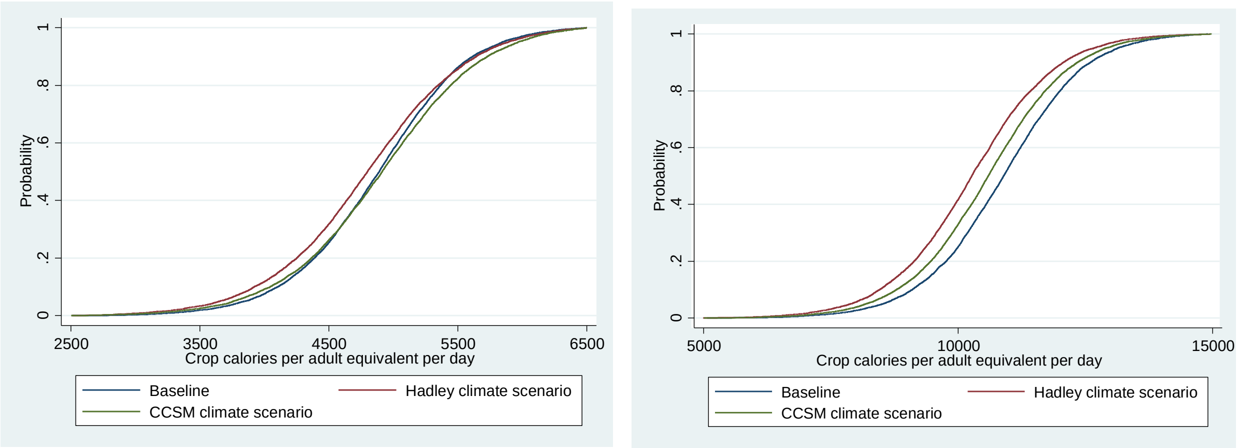
Note: Vulnerability is the probability of falling below 3,000/AE/day from field crop production.

Figure 4. *Cumulative density functions of calories/AE/day*



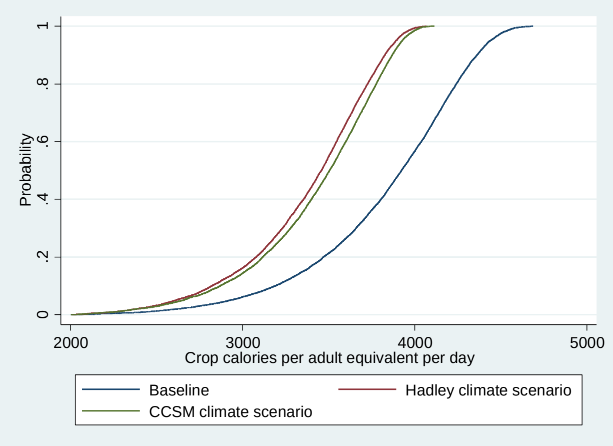
Smallholder (site 1)

Emergent farmer (site 1)

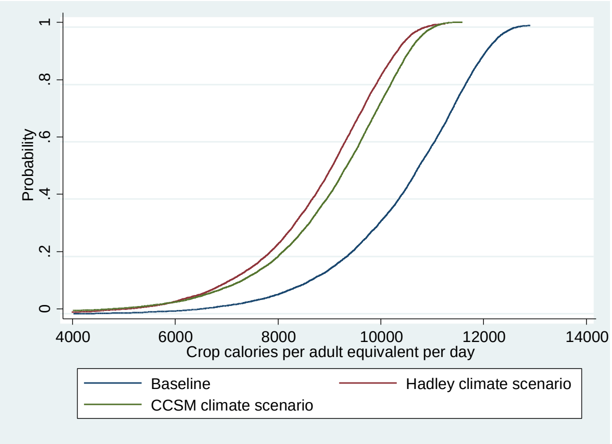


Smallholder (site 2)

Emergent farmer (site 2)



Smallholder (site 3)



Emergent farmer (site 3)

Table 19. *Aggregate impact of climate change on crop production*

		Site 1		**Site 2**		**Site 3**	
		Smallholder	**Emergent**	**Smallholder**	**Emergent**	**Smallholder**	**Emergent**
Baseline	Calories produced/ acquired (1,000s)	5,594.29	16,338.33	8,237.23	21,791.93	6,396.99	18,557.75
	Kgs maize produced	1,155.35	2,691.71	1,525.75	2,919.27	1,284.59	3,582.46
	No. households	20,340.10	4,464.90	177,154.52	17,520.78	51,273.89	23,036.10
Hadley	Calories (1,000s)	5,881.49	16,574.30	7,393.70	20,465.73	5,529.60	15,329.15
	Kgs maize produced	102.96	1,879.09	446.24	1,473.41	1,076.69	2,834.72
	% Δ calories	3.69%		-9.38%		-15.73%	
	% Δ kgs maize produced	-70.48%		-67.38%		-18.79%	
CCSM	Calories (1,000s)	6,141.91	17,527.09	8,224.90	21,057.36	5,718.16	16,153.06
	Kgs maize produced	113.67	2,041.31	495.04	1,634.52	1,114.14	3,033.12
	% Δ calories	8.81%		-0.82%		-11.94%	
	% Δ kgs maize produced	-67.83%		-63.81%		-14.42%	