Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty

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Prepared by Eric Crawford, Jennifer Olson, and Ayala Wineman

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Table of Contents

Abbreviations iv

Executive Summary 1

Project Purpose 1
Questions Addressed 1
Highlights of Results 2
Implications for Policy and Programs 4
Kenya versus Zambia 4
Conclusions and implications (climate and crop modeling) 4
Conclusions and implications (household modeling) 5
Lessons Learned 6
Overall successes of the modeling approach 6
Data and methodological challenges 6
Possible Next Steps 7

1. Introduction 8

2. Scope of the Report 8

3. Purpose of Award 8

3.1 Proposed project activities 8
3.2 Differences in implemented versus proposed project activities 9

4. Summary of Activities and Results 10

4.1 Zambia 10
4.1.1 Climate and crop modeling and analysis 11
4.1.2 Focus groups 16
4.1.3 Household modeling 17
4.2 Kenya 19
4.2.1 Climate and crop modeling analysis 20
4.2.2 Focus Groups 24
4.2.3 Household modeling 25

5. Implications for Policy and Programs 28

5.1 Kenya versus Zambia 28
5.2 Conclusions and implications (climate and crop modeling) 28
5.2.1 Implications for irrigation 29
5.2.2 Implications for crop choice and crop breeding 29
5.2.3 Implications for nutrient management 29
5.3 Conclusions and implications (household modeling) 29

6. Lessons Learned About Methods 30

6.1 Overall successes of the modeling approach 30
6.2 Methodological challenges 30
6.2.1 Data requirements. 30
6.2.2 Linking climate, crop, and household models 30
6.3 Possible next steps 31

References **33**

Annex A: Program Description **35**

Annex B: Performance Indicators and Targets, FY 2012 to 2014 ..... **39**

Annex C: Project Reports and Publications **40**

Annex D: Project PowerPoint Presentations **44**

Annex E: Project-related Trips **47**

Annex F: Figures **48**

Figure 1. Study Sites in Zambia 48

Figures 2 and 3: Nine-year moving average trend line in annual precipitation in Livingstone and Kasama, Zambia. 49

Figures 4 and 5: Simulated maize yield in Zambia in 2050 with low (5 kg/ha, on left) and moderate (85 kg/ha, on right) nitrogen fertilizer application. Maize cultivar: 700 series. GCM: HadCM3. 49

Figure 6. Basic Structure of the Farm Household Model 50

Figure 7. Study Sites in Kenya 51

Figures 8, 9 and 10. Simulated maize yield in East Africa in 2000 and 2050, and change in yield between 2000 and 2050. Maize cultivar H614, 85 kg/ha N, GCM HadCM3 52

Figures 11 and 12. Simulated potential maize yield in East Africa in 2000 and 2050, with supplemental irrigation (maize cultivar H614, 85 kg/ha N, GCM HadCM3). 53

Abbreviations

AFRE	Agricultural, Food, and Resource Economics
CCSM	The "Community Climate System Model" GCM developed by the National Center for Atmospheric Research in Boulder, Colorado.
CERES	Crop Estimation through Resource and Environment Synthesis
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data1
CSIRO	A GCM developed by the Commonwealth Scientific and Industrial Research Organization of Australia.
DSSAT	The Decision Support System for Agrotechnology Transfer is a process-based crop model (i.e., models the entire phenology or life-span of the crop) that has inputs such as soil characteristics, radiation, fertilizer inputs, planting date, crop cultivar characteristics and daily temperature and rainfall. It thus facilitates comparing simulated crop yields across different locations, climate, management, and/or cultivar characteristics.
ECHAM	A GCM developed by the Max Planck Institute for Meteorology in Hamburg, Germany.
FEWSNET	Famine Early Warning System Network
FSRP	The Food Security Research Project, funded by USAID as an associate award under the Michigan State University Food Security III cooperative agreement.
GART	The Golden Valley Agricultural Research Trust, a public/private organization of the Zambian Ministry of Agriculture and the Zambia Farmers Union. It conducts research and promotes agricultural methods for small-scale farmers including conservation farming.
GCM	Global Climate Model, or General Circulation Model (used interchangeably). This is the general term for climate models developed to simulate global atmospheric circulation patterns over space and time including the impact of enhanced GHG.
GHG	Greenhouse gases, including water vapor, carbon dioxide, methane, nitrous oxide and ozone, which absorb and emit radiation in the atmosphere.
HadCM3	A "Hadley Centre Coupled Model," a GCM developed by the UK Meteorology Office in Exeter, UK.
IAPRI	Indaba Agricultural Policy Research Institute, Zambia
KALRO	Kenya Agricultural and Livestock Research Organisation
KARI	Kenya Agricultural Research Institute (now KALRO)

[1] Produced by researchers at the University of California, Santa Barbara.

MODIS	Moderate-resolution Imaging Spectroradiometer[2]
MSU	Michigan State University
NASA POWER	NASA Prediction of Worldwide Energy Resource
RFE	African Rainfall Estimation Algorithm
SRES A1B	"Special Report on Emissions Scenarios" (SRES) refers to levels of greenhouse gas emissions that are used in GCM scenarios to make projections of possible future climate change. SRES levels were established by the Intergovernmental Panel for Climate Change (IPCC, the international body preparing consensus scientific reports on climate change). A1B represents a moderately aggressive level of enhanced GHG (some adoption of reduced GHG emissions and eventual slowing of population growth).
UCSB	University of California, Santa Barbara
UNZA	The University of Zambia.
WISE	World Inventory of Soil Emission Potentials. A global (including the tropics) database of soil profile information developed by the Consultative Group on International Agricultural Research (CGIAR). The Food and Agriculture Organization (FAO) and the International Soil Reference and Information Centre (ISRIC) have combined WISE with other data to form a spatially explicit soils database.
WorldClim	A spatially explicit global database representing the "average" monthly climate based on modeling several years (1950-2000) of available meteorological station data. In our project, it represents current climate.
ZARI	The Zambia Agricultural Research Institute, under the Zambian Ministry of Agriculture and Livestock
ZMD	Zambia Meteorological Department

[2] A payload scientific instrument launched into Earth orbit by NASA in 1999 on board the Terra (EOS AM) Satellite, and in 2002 on board the Aqua (EOS PM) satellite.

Executive Summary

Project Purpose

This project, entitled "Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty," originally spanned a three-year period from October 1, 2011, through September 30, 2014. It was granted a seven-month extension to April 30, 2015. The report presented here covers the entire project period. The amount of the award provided by USAID/BFS/ARP was $698,865. Project Co-Principal Investigators are Eric W. Crawford, Professor, Department of Agricultural, Food, and Resource Economics (AFRE), and Jennifer M. Olson, Associate Professor, Department of Media and Information, both of Michigan State University (MSU).

The purpose of the activities supported under this Award is to link the multiple-year household survey data sets that MSU has been involved in collecting in Kenya and Zambia, and MSU's coupled climate, crop, and land use models developed for East Africa, in order to improve understanding about how rural households are adapting to climate change (in terms of agricultural production practices and technologies, and other income-earning strategies), and to explore the impacts of anticipated future climate scenarios on farm household production, income, and food security, taking into account variation in local circumstances. This information will help refine the climate change models and estimates of future household technology adoption and investment decisions, with implications for country program and policy priorities.

Questions Addressed

The main questions addressed in the project were:

1. What have been the recent trends in rainfall and temperature, and how is the climate expected to change in the future? The historical (recent) trend analysis was conducted for Kenya and Zambia using a variety of datasets. For future climate trends, four Global Climate Models (GCMs) were used to simulate the 2000 and 2050 periods for the entire East Africa region (Kenya, Uganda, Tanzania), and for a region centering on Zambia.
2. How will climate change and variability affect crop productivity? The impact of variability on crop growth and productivity was examined for several sites in Kenya and Zambia using coupled crop-climate models and observed weather data. The impact of projected future climate change was examined for the East Africa and Zambia regions using GCM data. Four maize varieties, dry beans, sorghum and groundnuts were simulated.
3. What is the potential of agronomic practices to reduce the negative effects of climate change? Although not in the original proposal, the team felt this was important. The practices examined include nitrogen fertilizer (amount and timing of application), irrigation, different maize varieties, and minimum tillage.
4. What is the impact of climate change on households of different resource endowments, in different agro-ecosystems? Household models were constructed representing different resource endowments, and gender of head of household, for three agro-ecological zones in Zambia and two in Kenya. The impact of altered crop yields due to climate change on food (calorie) production and income was simulated.

5. How might these households adapt to the impacts of climate change? An important adaptation is switching to crop+technology regimes that perform better in a changed climate. Land use (the proportion of the farm under different crops and fallow) was allowed to change in the models as yields changed, to maximize food security or income given available resources. This simulated the decision process of farm households faced by changing crop productivity, and provides an indication of the success of this adaptation across different households and locations.

Highlights of Results

Warming temperatures and altered precipitation patterns are expected to affect the productivity of maize, beans and other crops, particularly in Africa where water and nutrient deficits already severely restrict harvests. This study examined the impact of climate change on crop productivity in East and Southern Africa, focusing on Kenya and Zambia, from the current period and 2050. It tested the potential of improved management practices and changes in crop choice or land use for climate change adaptation. The region ranges from near-deserts in northern Kenya to savannas and highlands in Western and Central Kenya, and extremely humid areas in Zambia. A combination of crop-climate and household models were used.

Coupled with climate models, the CERES Maize model embedded in DSSAT v. 4.0 was calibrated for the two countries, and point and spatial modeling were conducted using locally grown maize, dry bean and groundnut varieties. Historical climate datasets (observed, CHIRPS and WorldClim), and four GCMs (HadCM3, CSIRO, CCSM and ECHAM) downscaled to 6 km informed the crop modeling. Since maize is particularly sensitive to climate and nutrient deficit effects and is the staple food crop, it was chosen to examine the potential of management practices to aid in climate change adaptation.

Results include maps and graphs of yield changes due to projected climate change. The results show where water and nitrogen deficits are expected to change, and where yields may benefit from improved management practices.

Climate change is expected to generally reduce maize, bean and groundnut yields especially due to warmer temperatures leading to higher water demand. However, the study identified dry locations, particularly those with moderate temperatures such as in some medium-elevation areas, where lowering water deficits with supplemental water (e.g., by irrigation) would produce large maize yield benefits. The maize yield benefits from supplemental water, however, will shrink in the future because of other impacts of warmer temperatures suppressing yields, including more rapid maturity and hot temperatures inhibiting yield. Some highlands areas with sufficient precipitation will experience improved maize yield as cool temperatures warm, but at the expense of cool temperature crops such as tea and coffee. The physiology of beans is sensitive to warm and hot temperatures, and the crop simulations showed that climate change will lead to moderate declines in bean yield in East Africa. Zambian agriculture is less vulnerable to projected climate change because it is generally cooler and wetter than most of East Africa, and precipitation amounts are not projected to significantly change. However, precipitation variability, including dry spells in the growing season and irregular rainy seasons, will increasingly affect both Zambian and East African crops.

Across much of East and Southern Africa, nitrogen fertilizer would significantly raise yields. The yield benefits to nitrogen fertilizer are, however, also expected to decline in the future across large areas since fertilizer's ability to improve yields diminishes with higher water deficits. In wet zones such as in northern Zambia, on the other hand, the negative effect of climate change is related to more severe precipitation events leading to worsening nitrogen leaching. Multiple rather than single doses of nitrogen reduce yield variability and increase yield under these situations.

In sum, the impact of climate change and the potential of agronomic adaptation practices varies depending on location. Our results indicate that in most locations, however, nutrient management and irrigation will not be sufficient to compensate for yield losses due to climate change. Strategies such as improved land and water management, heat and drought tolerant crop varieties, and switching crops would be important to partially mitigate these impacts.

The study illustrates the benefits of high-resolution, process-based crop modeling to examine climate change impacts. The East Africa regional average change in maize yield is only -1%, but this hides localized impacts ranging from -3000 to +3000 kg/ha. The high variability in impacts of climate change and potential for improved management practices calls for locally specific adaptation recommendations.

To better examine the projected impacts of climate change and possible adaptations at the local and household levels, three locations were selected in Zambia and two in Kenya, to represent the variety of conditions. Household models were constructed to reproduce households of different resource endowments (smallholder, medium-scale, and female-headed).

Results of household modeling in Zambia show that climate change has differential impacts on yields as a function of crop and production practices used. In Eastern Province, for example, yields of most crops decline under both the dry Hadley and the wet CCSM GCM climate scenarios, but cotton yields actually rise (positive response to higher temperatures) and sunflower yields remain stable. In the household model, farmers select different crops (cotton, sunflower) and technologies (less fertilizer) under climate change. This permits them to maximize calorie production and reduce the expense of the now less-beneficial inputs. Calorie production per adult equivalent per day generally falls, but no household type in any site becomes calorie-deficient. Minimum tillage (MT) options were incorporated. MT activities require more labor for planting and weeding, but less than expected, hence labor shortages may not be a limiting constraint for MT adoption. MT activities were partially adopted in the model only when evaluated over a four-year time frame. When evaluated over a one-year period, benefits realized are not enough to offset MT investment costs.

The household modeling in Kenya was hampered by the nature of available data. The most complete model development and analysis was for Machakos County, where supplementary data on labor use were available. Even for the Machakos model, however, the results were less satisfactory than for the Zambia household models. Validation checks showed a less-than-desirable match between actual farm cropping patterns (as seen in the survey data), and optimal cropping patterns generated by the model. Nonetheless, results from this initial use of the Machakos model showed that even small-scale farms produced sufficient calories per adult under

current and future climate conditions. Both the medium- and small-scale farms responded in realistic fashion to the effects of climate change (CSIRO scenario) in terms of declining income and calorie production, moderated somewhat by changes in crops and land area cultivated.

Implications for Policy and Programs

Kenya versus Zambia

1. Impact of climate change: Kenya's agriculture is much more vulnerable than Zambia's. Climate change in Kenya is already affecting the low- and medium-potential zones, and threatens coffee and tea areas. Cooler and wetter Zambia will continue to be in a relatively good position compared to its neighbors. For example, key informants in Zambia suggested that Zambia's agro-ecological conditions were ideal for production of improved maize seed, such that Zambia could be the primary seed supplier for the surrounding region.
2. Vulnerable locations: In general, the drier and warmer regions of both Kenya and Zambia are likely to be hardest hit by climate change. Temperatures are reaching the point of inhibiting crop growth, and precipitation variability will be further increasing. The frequency of crop failures can be expected to rise. The possible exception, if GCM future projections are correct, is in northern Kenya where increasing precipitation may permit maize to be grown somewhat further north than it is currently.
3. Adaptations to climate change: The effectiveness of nutrient management on crop yield depends on sufficient moisture, so fertilizer use has large benefits in Zambia particularly compared to drier areas in Kenya and elsewhere. Irrigation has large potential benefits in Kenya, especially in drier, moderate temperature areas. With climate change, the yield benefits of both fertilizer and irrigation will shrink, but their importance in maintaining productivity will remain crucial.

Conclusions and implications (climate and crop modeling)

1. Climate trends and variability patterns are more complex in East Africa than Zambia. In both locations, there is more certainty about future temperature than rainfall trends and patterns.
2. In Zambia, farmer perceptions of climate change obtained from focus groups were compared to empirical climate records. In general farmer accounts were consistent with meteorological data on rising temperature, but diverged regarding rainfall trends. This divergence may occur because farmers track climate-related parameters that are salient in their lives but that are difficult to see in the meteorological data, or because farmers fail to differentiate yield impacts of weather from impacts of farming systems changes, soil degradation, or other factors affecting agricultural productivity.
3. The crop and climate modeling and analysis results project highly variable impacts of climate change on crop yields. Local topography, soils and initial climate conditions play an important role determining how climate change may affect crops. Climate change technical adaptation will require a combination of practices depending on location and household characteristics.

Implications for irrigation

1. Irrigation in moderate temperature areas of Kenya, Ethiopia and Uganda would generate very large benefits, over 6 metric tons/ha.

2. Hot areas, and of course wetter areas, would benefit much less from irrigation.
3. Benefits from irrigation will decline in the future due to hotter temperatures.

Implications for crop choice and crop breeding

1. Maize, bean and other crop varieties will need to be tolerant of warmer temperatures and extreme heat. Grains in particular will need to be resistant to the acceleration of plant maturity due to warmer temperatures.
2. Some (not all) areas should move towards shorter-duration varieties. The focus of adaptation programs on developing new short-duration varieties may not address the needs of the main maize-growing zones.
3. In areas of low and declining precipitation, varieties and crops resistant to within-growing season dry spells, especially during flowering, will produce more reliably.
4. Finding alternative crops or other income sources is critical to assist farmers in warmer and drier areas to diversify away from maize.

Implications for nutrient management

1. Low fertilizer levels significantly limit current yields. With climate change, the benefits of fertilizer will decline, since its ability to increase yields diminishes with water deficits. Fertilizer will remain a critical management practice, however, especially in medium and high potential areas.
2. In humid areas particularly, using small multiple doses rather than single doses of nitrogen fertilizer is as important as the amount applied.

Conclusions and implications (household modeling)

1. Model results showed that on-farm adaptation to climate change, through changes in crops and production technologies, is likely to mitigate but not necessarily offset the negative effects of climate change. This suggests that larger-scale adaptation measures are needed (e.g., heat-tolerant seed varieties, agricultural and water infrastructure investments and policies to reduce risk for farmers).
2. For most study sites in both Zambia and Kenya, household model results showed minimal negative effects of climate change on expected household welfare.
3. The fact that crops differ in their sensitivity to climate change has implications for agricultural policy related to promotion of particular crops. For example, maize production is promoted in both Kenya and Zambia (especially the latter), yet maize is more sensitive to climate change than cassava, another key food crop.
4. The impact of gender of the head of household did not make a significant difference in climate change adaptations or impacts in the household models. However, this may result from the fact that constraints faced by female-headed households other than limited land, labor and capital endowments could not be incorporated in the model.

Lessons Learned

Overall successes of the modeling approach

1. As noted above, the study illustrates the benefits of high-resolution, process-based spatial crop-climate modeling to identify climate change impacts on crops, especially in heterogeneous regions.
2. The system permits testing agricultural practices against climate change and variability. For example, one can test the resilience of one maize variety against another, or the benefits of different fertilizer rates, across the landscape.
3. The farm household models generated useful insights about key constraints and trade-offs faced by farmers, and about the rough magnitude of adjustments possible through alteration of on-farm production practices and crop/technology choices. The modeling results obtained were informative, but linking climate/crop and household models was more difficult than expected.
4. The availability of multi-year farm household survey data was valuable in both Zambia and Kenya, especially for providing empirical evidence of crop choice, production technology and practices, and household characteristics.

Data and methodological challenges

Data requirements.

To more fully realize the potential of crop models, more data is needed to calibrate and validate a wider range of crops and crop cultivars, as well as improved rainfall, temperature, and soils data. For farm household models to provide richer and more credible results, improved data is needed on area cultivated by crop and by field, and on labor requirements for production activities.

Climate – crop model linkages

GCMs were not designed to provide results for a specific region or for a particular decade, whereas dynamic crop models were designed to simulate the effect of daily weather on a single season's yield for a specific location. The limitations of GCMs for linking to the crop model were partially resolved in this project by downscaling GCM data to a higher spatial resolution of 6 km, obtaining simulated daily data from the monthly datasets using a weather generator program, and conducting crop modeling with observed, historical climate data where available to support statistical analysis of inter-annual and seasonal variability.

Despite the uncertainties and limitations of GCMs, they provide the best available projections of future climate change. GCMs dynamically incorporate the complex effects of enhanced greenhouse gases on the atmosphere. Also, GCM data are physically consistent; they take into account the spatial relationship in precipitation and other climatic processes between locations, hence they are the best available product.

Crop – household model linkages

Household models for Africa need information on climate change impacts for a much larger spectrum of crops and crop-technology combinations than crop models can currently provide for tropical regions. The spectrum of locally grown crop cultivars could be improved by increasing the amount of observed data available to calibrate the crop models. It may be harder to modify

the models to simulate the effect of some technologies or management practices, such as the application of phosphorus fertilizer.

In practice, crop models do not yet sufficiently incorporate the full range of current farmer practices and farm conditions (such as multi-cropping, degraded soil, weeds, pests and diseases). Simulated yields are much higher than those observed on-farm, which limits their utility in household models for estimating actual production.

For the household models, these limitations of crop models were partially offset by estimating statistical crop yield functions based on annual crop survey forecasts and other data (despite limitations of farmer-reported yield data). Future crop yields were then estimated based on the projected change in climate variables of two contrasting GCMs for those study areas, with these changes applied to the statistical crop yield functions.

Possible Next Steps

1. Use the crop-climate modeling framework to:
    a. Examine how new "climate resilient" maize cultivars respond to projected climate change and farmer management practices across a wide range of conditions. For example, where would the new maize cultivars perform better than, or worse than, existing cultivars? How are their yields affected by reduced fertilizer applications, compared to other cultivars?
    b. Compare the impact of climate change on different crops to identify, for example, the possible expansion or contraction of maize, cassava, and sorghum growing zones.
    c. Produce information on the impact of near-term and longer-term climate variability and climate change on national production of maize and other crops (taking into account spatial differences in agroecological and weather conditions), with implications for regional trade.
2. Link the new CHIRPS spatial historical precipitation dataset to the spatial crop model to examine recent climate variability in crop yield across space. Identify, for example, the impact of past El Niño and La Niña events on crop productivity across East and Southern Africa to provide insights into potential future El Niño impacts.
3. Collaborate with local scientists to build capacity for crop modeling linked to climate model data, in a GIS platform.
4. Encourage donor and national investment in better data and stronger local modeling / analytical capacity. For example, this could support enhancement of the farm household models to include livestock, perennial crop, and off-farm production or income-earning activities.

1. Introduction

This project originally spanned a three-year period from October 1, 2011, through September 30, 2014. It was granted a seven-month extension to April 30, 2015. The report presented here covers the entire project period. The amount of the award is $698,865. Project Co-Principal Investigators are Eric W. Crawford, Professor, Department of Agricultural, Food, and Resource Economics (AFRE), and Jennifer M. Olson, Associate Professor, Department of Media and Information. Other investigators include Jeffrey Andresen and Nathan Moore, Department of Geography, and Gopal Alagarswamy, Center for Global Change and Earth Observations. Other project personnel at MSU include Ayala Wineman, PhD research assistant (AFRE); Aaron Pollyea, Research Technologist (Geography); and Daniel Ddumba, PhD research assistant (Geography). Collaborating researchers in Kenya and Zambia are, respectively, Joseph Maitima, Director, and Martin Mworia, researcher, Ecodym Africa International, and Wellington Mulinge, Senior Research Officer, Agricultural Economics, Kenya Agricultural and Livestock Research Organization (KALRO, Kenya), and Brian Mulenga, Research Associate, Indaba Agricultural Policy Research Institute (IAPRI, Zambia).

2. Scope of the Report

This report is an overview and synthesis of material in the more detailed annual technical reports. Specifically, the report consists of (a) a brief summary of the purpose of the award and key project activities and results for the full project period (the initial three years plus the no-cost extension period from October 2014 through April 2015 extension period), and (b) overall implications and lessons learned from the project.

3. Purpose of Award

Briefly, the purpose of the activities supported under this Award is to link the multiple-year household survey data sets that MSU has been involved in collecting in Kenya and Zambia, and MSU's coupled climate, crop, and land use models developed for East Africa, in order to improve understanding about how rural households are adapting to climate change (in terms of agricultural production practices and technologies, and other income-earning strategies), and to explore the impacts of anticipated future climate scenarios on farm household production, income, and food security. This information will help refine the climate change models and estimates of future household technology adoption and investment decisions, with implications for country program and policy priorities. The complete Program Description and progress indicators for this award are contained in Annexes A and B.

3.1 Proposed project activities

The following activities were to be carried out during the original 3-year project period, beginning in Zambia in FY 2012 and in Kenya in FY 2013:

1. Historical analysis of rainfall patterns over space and time using weather station data and data from the African Rainfall Estimation Algorithm (RFE).

2. Analysis of impact of past climate variability and trend changes on maize yields, using climate-crop models, and on indicators of household well-being such as food security and income, using the multiple-year household data.
3. Projection of future climate scenarios and their impacts on maize yield and output.
4. Construction of farm household models, and incorporation into those models of projected future climate change and maize yield scenarios in order to identify impacts on future household production, farm and off-farm incomes, and food security.
5. Use of farmer and key informant focus groups to guide the design and interpretation of (1) and (2), and feedback groups to discuss the outcomes of (3) and (4).
6. Outreach to key stakeholders in the pilot countries and in the U.S.

3.2 Differences in implemented versus proposed project activities

Regarding activity (1)—Analysis of historical climate data to identify temporal and spatial trends. At the start of the project, the team knew of the limitations of observed weather data in Africa and hoped to analyze instead a new simulation dataset, RFE, from the University of California, Santa Barbara (UCSB). Since RFE was not yet ready, the team collaborated with UCSB to validate it using observed data that we had. Unfortunately RFE (now CHIRPS, Funk et al. 2014) was released too late for our team to link it to the crop model spatially for this project. However, we were able to obtain observed data from 10 meteorological stations across Zambia and did point analysis of CHIRPS data for 17 locations across in Kenya to examine trends in amounts and timing of precipitation from the 1980s to 2014.

Regarding activity (2)—Analysis of the impact of past (recent) climate change on maize yields and household well-being. The DSSAT crop model was prepared using local soil and climate datasets, and calibrated for four maize cultivars (two in East Africa and two in Zambia) and two groundnut cultivars (Zambia). Meteorological station and CHIRPS historical climate datasets described above informed the crop model to examine the impact of recent precipitation variability on yield, and the potential of fertilizer applications to reduce its impact.

Regarding activity (3)—Projections of future climate and maize yields. Four Global Climate Models (GCMs) were selected for the study, and data downloaded and downscaled for a 30-year period around 2000 and around 2050. The resultant projected climate change data was used as an input to the crop model to examine how future climate change would impact different maize varieties, under different fertilizer levels, and finally with and without irrigation. Groundnuts were also modeled for Zambia, and dry beans and sorghum for Kenya (using models calibrated by the team under previous projects).

Regarding activity (4)—Construction of farm household models. The original expectation was that the effects of climate change on crop yields could be simulated through use of DSSAT crop models and then incorporated into the household models. However, the production activities included in the model were specified in terms of characteristics (crop mix, seed and tillage type, and input use) that could not readily be incorporated in the DSSAT models. Therefore, crop yield functions (incorporating the effects of rainfall and temperature) were estimated from the survey data for each production activity, and used to predict the effects of future climate on crop yield.

Activities carried out but not originally planned included (among others) comparison of Zambian farmers' perceptions of climate change with observed weather data, econometric analysis of past

climate variability on household food security (considering quantity, quality, and stability dimensions (Wineman 2013, 2014: PowerPoint 13)), and a specific analysis of the impact of including minimum tillage production activities in the Zambian farm household models.

The main questions addressed in the project were:

1. What have been the recent trends in rainfall and temperature, and how is the climate expected to change in the future? The historical (recent) trend analysis was conducted for Kenya and Zambia using a variety of datasets. For future climate trends, four Global Climate Models (GCMs) were used to simulate the 2000 and 2050 periods for the entire East Africa region (Kenya, Uganda, Tanzania), and for a region centering on Zambia.
2. How will climate change and variability affect crop productivity? The impact of variability on crop growth and productivity was examined for several sites in Kenya and Zambia using coupled crop-climate models and observed weather data. The impact of projected future climate change was examined for the East Africa and Zambia regions using GCM data. Four maize varieties, dry beans, sorghum and groundnuts were simulated.
3. What is the potential of agronomic practices to reduce the negative effects of climate change? Although not in the original proposal, the team felt it was important. The practices examined include nitrogen fertilizer (amount and timing of application), irrigation, different maize varieties, and minimum tillage.
4. What is the impact of climate change on households of different resource endowments, in different agro-ecosystems? Household models were constructed representing different resource endowments, and gender of head of household, for three agro-ecological zones in Zambia and two in Kenya. The impact of altered crop yields due to climate change on food (calorie) production and income was simulated.
5. How might these households adapt to the impacts of climate change? An important adaptation is switching to crop+technology regimes that perform better in a changed climate. Land use (the proportion of the farm under different crops and fallow) was allowed to change in the models as yields changed, to maximize food security or income given available resources. This simulated the decision process of farm households faced by changing crop productivity, and provides an indication of the success of this adaptation across different households and locations.

Project reports and publications are listed in Annex C, PowerPoint Presentations in Annex D (a numbered list referenced in the body of the report), trips made under the project in Annex E, and selected figures in Annex F.

4. Summary of Activities and Results

4.1 Zambia

The impact of climate change on crop production was examined for Zambia in both the recent, historical period and using future climate projections. The results for the recent past, based on weather station data from the 1960s to present, cover specific sites across the country, whereas the projected future changes from 2000 to 2050 are shown in the form of country maps.

For a closer examination of the impact of climate change on households, three study sites were chosen (Annex F, Figure 1), each representing unique smallholder farming conditions: Northern province (relatively wet, 1,100 to 1,700 mm, representing agroecological zone (AEZ) III), Eastern province (somewhat drier, 800 to 1,000 mm, representing AEZ IIA), and Southern province (dry, 600-800 mm, representing AEZ I) (Siegel 2008). Project activities started in FY 2012. Basic results were completed in FY 2013, with continued work carried out in FY 2014 taking advantage of additional meteorological station rainfall data obtained with the assistance of USAID/Zambia, and addressing topics of interest (e.g., role of minimum tillage) expressed during outreach sessions with government officials, IAPRI researchers, and USAID and other donor representatives.

4.1.1 Climate and crop modeling and analysis

4.1.1.1. Methodology

The climate research for Zambia involved analysis of historical data to identify recent trends, and modeling and analysis of future climate projections. The datasets used included historical climate data (meteorological station data from the Zambia Meteorological Department, WorldClim and CHIRPS datasets) and future simulations from four Global Climate Models (GCMs).

The limited availability of observed weather data, particularly in Kenya, prompted the team to work with Chris Funk and colleagues at the University of Santa Barbara's Climate Hazards Group on the validation of CHIRPS, their new historical, spatial global precipitation dataset. The MSU team did extensive validation of earlier CHIRPS versions for Funk using observed meteorological station data from East Africa and Zambia. The released version of CHIRPS (Funk et al. 2014) was corrected too late for the MSU team to conduct spatial analysis of historical precipitation trends for this project. However, we did numerous point location analyses of precipitation, and used CHIRPS data in point crop simulations.

The available meteorological station data, for 10 stations located across Zambia, was analyzed to identify trends in annual and seasonal precipitation (and temperature where available) via a median of pairwise slopes regression. This is a regression that calculates the slopes between every possible pair of points in the data set. The slope is then calculated from the median of the paired point slopes. Finally, using this slope estimate, the intercept is calculated from the median of the residuals of the data points vs. the slope (Hoaglin et al. 1983) and a nine-year moving average is calculated.[3]

The GCMs were downscaled to a high resolution (6 km) using SRES scenario A1B (moderately aggressive growth). The models were chosen because they represent weather extremes (generally CCSM being very wet and HadCEM being very dry), and two widely used models that are in the middle (CSIRO and ECHAM5). The downscaling was conducted using thin plate smoothing splines via the ANUSPLIN V4.3 software (Hutchinson 2002). We created 30-year averages for each month for each GCM dataset. Two datasets were thus prepared per model, one centering on 2000 and one on 2050. The differences between them in temperature, precipitation and other

[3] This moving average is calculated for two reasons: (1) it is commonly used in graphs of precipitation to smooth out the year-to-year fluctuations yet still to reveal trends, and (2) few climate phases (such as ENSO) coincide with that nine-year period.

variables represent the perturbed climatology due to enhanced greenhouse gases. These results are illustrated in maps of projected changes in precipitation and temperature, and used as inputs to the crop model (Olson 2008; Moore et al. 2011; Thornton et al. 2009).

To estimate the impact of climate change on the growth, development and yield of crops, we used a deterministic, process-based simulation model, the Decision Support System for Agrotechnology Transfer (CERES Maize in DSSAT v4; Ritchie et al. 1998; ICASA 2007). Simulations were conducted at the point location and spatial levels. Various climate datasets were used as inputs in the crop models. These included historical climate data (meteorological station data from the Zambia Meteorological Department, WorldClim, NASA Power and CHIRPS datasets) and future simulations from four GCMs. DSSAT requires daily precipitation, maximum and minimum temperatures, and incident solar radiation data. Daily time series of these were generated from WorldClim and the GCM datasets with MARKSIM, a statistical weather generator (Jones and Thornton 2000). Temperature and solar radiation data from NASA Power (NASA 2015) were used in conjunction with the precipitation data from meteorological stations and CHIRPS. Soils data were derived from the Food and Agricultural Organization 1:5 million soils map of world (FAO 1995). We used representative soils profiles from the International Soils Reference and Information Center's World Inventory of Soil Emission Potential Data base (Batjes and Bridges 1994) as modified by Gijsman et al. (2007). Extensive calibration activities were conducted related to soil profile selection. They indicated a high sensitivity of maize yield to soil texture in Zambia, confirming the need to carefully select representative soil profiles.

We assumed current representative smallholder practices; planting was assumed to occur automatically once the soil profile received a thorough wetting at the start of the rainy seasons, and maize was planted at a typical density of 3.7 plants/m^2. Different input levels of nitrogen fertilizer were simulated for maize including, for the spatial analyses, a low (5 kg/ha) rate of application approximating what many small-scale farmers use, and two moderate rates (35 and 85 kg/ha). At the point level in 9 sites in Zambia, additional fertilizer application rates and timing simulations were conducted to examine the potential of fertilizer to reduce the effects of precipitation variability.

After initial modeling was conducted with parameters from a maize variety based on a South African cultivar, two other maize varieties were selected for Zambia: a shorter-season hybrid ("500 series") for medium- to low-potential zones, and a longer-season hybrid ("700 series") suited for mid- to high-potential zones. All subsequent maize simulations in Zambia were conducted with these two varieties. Groundnuts were also simulated. Calibration of the final two maize and two groundnut varieties was done with the assistance of Dr. Verma of the Zambia Seed Company.

DSSAT output variables include seasonal yield, length of growing season, and mean precipitation and temperatures; and daily water use, and water and nutrient stress. The crop model does not account for the effects of pests, diseases and natural calamities such as hail. Our results have the inherent inaccuracy of mono-cropping compared to the common practice of mixed cropping, and inaccuracies due to the limitations and uncertainties of the input data.

However, the results do provide spatially differentiated information on the sensitivity of crop varieties to climate change and nutrient stress.

4.1.1.2. Results of the climate and crop modeling and analysis

Recent Climate Trends. The analysis of recent climate trends in Zambia using meteorological station data showed that seasonal precipitation patterns are similar across the country (PowerPoint 2, 3). Nine of the ten stations showed a peak between December and January, with minimum precipitation or no precipitation found in June, July, and August. The exception was Livingstone with a peak in October. Average annual precipitation totals varied significantly, ranging from 630 mm (Livingstone) to 1288 mm (Kasama) with a south to north trend of increasing precipitation. As expected, variability (the standard deviation of precipitation) for a given month was highest during the wet months, with the dry months mostly dry with little variability.

Annual precipitation trends from 1961 to 2012 are generally negative, meaning decreasing precipitation (for examples, see Annex F, Figures 2 and 3). Of the ten stations analyzed, eight showed negative trends and two showed positive trends (Lusaka and Kasma). Amounts ranged from + 2.31 mm/year (Kasma) to -3.87 mm/year (Mbala) with an average of -1.29 mm/year change. Most change occurs in the September, October, and November (SON) period, followed by the December, January, and February (DJF) time period. The three most extreme changes are Livingstone (- 2.06 mm/year), Mbala (- 1.78 mm/year decline), and Kasemp (- 1.20 mm/year decline). The annual and seasonal trends did not show spatial correlation across the study area, nor was there a correlation between these trends and mean annual precipitation totals for the climate observation sites. Trends in the length of the rainy season paralleled the trend in amount of precipitation. Nine of the ten stations analyzed experienced a shortening of the season of around -0.3 days / year. The totals, however, do not reflect worsening precipitation variability, which is what farmers reported.

Temperature trends indicate a *steady warming across the country*. Daily minimum temperatures showed a rising trend every month, with 100 of the 108 station-month combinations showing statistical significance. Daily maximum temperatures also showed an increasing trend in temperature, with 88 of the 108 station-month combinations showing significance. The number of days over 35°C (critical for crops) is generally increasing in the warmer stations.

Despite the negative trends of declining precipitation and warming temperatures, *Zambia remains relatively humid and has moderate temperatures compared to most African countries, with a climate suitable for crop production*. An increase in precipitation variability, however, would negatively affect crops, as would any increase in the frequency of extremely warm days.

Projected Future Climate. Projected changes from 2000 and 2050 in annual precipitation for the four GCMs were produced (PowerPoint 3 and 8). The precipitation of the current (2000) time period was compared to a projected future time period (2050), and the change was mapped onto our best estimate of current climate (WorldClim). All four models showed *a rise in temperature across the country of between 1 and 3°C*, with the western part of the country projected to warm faster. However, there is not a "consensus" between GCMs on how precipitation may change. Two (CCSM and CSIRO) projected moderate increases in growing season precipitation of between 0 and 150 mm/growing season. HadCM5 and ECHam, however, projected moderate

declines of around the same magnitude. Generally, the northeast and northwest are projected to experience the modest declines in precipitation, and the south-central and southeast the modest increases.

The variations between the models highlights the uncertainty related to projecting future climate change, especially at the local to regional level. Although temperatures are expected to continue to rise at the same rate or faster than they have been during the past few decades, changes in precipitation are much more difficult to forecast with certainty. The impact of local-scale factors again complicates the effect of global climate change.

GCMs provide a general sense of trends in temperature, precipitation and other climatic factors. They do not yet, however, provide a good sense of how temporal variability in rainfall, for example drought frequency, may change. Our community workshops in Zambia indicated that the most important change in the weather that farmers perceive is in the timing of rainy seasons—the seasons seem to start later, and the start is unpredictable. They also notice a longer and more intense dry spell in January or February.

Impact of Climate Change and Nutrient Management on Crops. The results of the crop modeling are in the form of maps and graphs of yield and yield change over space and time (PowerPoint 3 and 8). In general, most of Zambia is conductive to maize production, with moderate temperatures and sufficient precipitation. However, the timing of precipitation (such as late or early onset and cessations of the rainy season) can have a major impact on plant growth and grain production. Dry or wet spells during the season are particularly damaging when they occur during germination, flowering, grain fill, or other sensitive times of plant growth. We therefore also examined how nutrient management could help reduce the impact of this precipitation variability.

To examine the effect of current climate variability and nutrient management on maize, maize simulations were conducted in nine sites across Zambia using meteorological station precipitation and NASA Power temperature and solar radiation data. The results indicated that across much of Zambia, yields benefit greatly from nitrogen fertilizer (PowerPoint 13, and Annex F, Figures 4 and 5). The exception is the drier and warmer areas in the extreme south of the country, where water deficits limit yield.

In the wetter locations, an unexpectedly large impact of rainfall on nitrogen leaching reduces the potential benefit of fertilizer. In these locations, multiple doses of fertilizer are required to produce the level of yields possible using that amount of fertilizer. Particularly in very wet years or in years with a high amount of rainfall in certain stages of growth, simulated yield is reduced by over 3,000 kg/ha if fertilizer is applied in a single dose compared to two doses. In these years with heavy rainfall during critical stages, all fertilizer from a dose applied at the start of the season can be leached and yields are as low as if no fertilizer had been applied. In some years in the wet location of Kasama, for example, a single dose of 85 kg/ha of nitrogen fertilizer applied at the start of the season produced 1,000 kg/ha, the same low yield as no fertilizer, but two doses summing to 85 kg/ha produced 6,600 kg/ha. With increasing intensity of precipitation events, leaching can be expected to worsen.

In drier locations, such as Chipata and Choma, multiple doses reduce yield variability, but yields are still variable due to high and precipitation variability and water deficits. The yield impact of nitrogen fertilizer appears to decline rapidly at around 450 mm/growing season, although this would depend on soils and variety.

The longer-duration maize variety produced higher yields in all locations in good years. However, in the driest locations, the shorter-duration variety had less reduction in yield and fewer crop failures.

The mapped crop simulation results show yield variations across Zambia under current climate conditions. Maize growing season rainfall averages around 650 mm in agroecological zone (AEZ) 1, which is characterized as a drought-prone and risky area for maize production. Simulated maize yield in AEZ 1 ranged from 1000 to 3000 kg/ha. AEZ 2 is characterized as a medium rainfall zone with a mean rainfall of 830 mm. Simulated maize yields ranged from 2000 to 5000 kg/ha depending on soils (sandy soils have lower yields) and precipitation. AEZ 3 has a mean rainfall of 1151 mm and clay soils, with simulated maize yields ranging from 4000 to 8000 kg/ha.

Crop modeling of groundnuts using observed historical weather showed that the yield was sensitive to high precipitation variability especially in the drier locations (e.g., Choma, Livingstone). Groundnuts are not, however, as sensitive as maize to problems of nitrogen leaching in very wet zones, though in Zambia the simulations reflect that groundnuts do better in zones that are warmer and not too humid.

The impact of future climate change on crops. The GCMs project warmer temperatures and moderate precipitation changes from 2000 to 2050. Under some soil and precipitation conditions, the maize modeling shows that higher rainfall would lead to moderate declining maize yields. The increase in rainfall particularly in sandy soils leads to leaching of soil nutrients, low pH, and eventual magnesium and aluminum toxicity. Without sufficient fertilizer and other soil management practices, the lack of nutrients becomes a significant limiting factor and cause yields to decline. This is the case in north-central and northeast Zambia under some of the GCMs. In the GCMs that project moderate declining precipitation, little maize yield change or even a modest increase in yield is projected in humid areas because water is still sufficient, leaching declines, and temperatures are more conductive (less cool). Note that GCMs, however, do not yet simulate precipitation variability well, although variability is expected to worsen, and this would reduce yields.

Groundnut yields are not expected to be affected significantly by climate change. The simulations indicate that as temperatures warm, groundnut yields may somewhat increase in zones that are currently cool and wet,. The crop modeling does not incorporate the potential increase in groundnut (or bean) yields due to CO_2 enrichment. However, the crop model does not reflect the impact of the warmer temperatures on plant diseases, which already restrict groundnut yield across Zambia. The warmer temperatures would probably intensify diseases and reduce yields.

In sum, the climate analysis and crop-climate simulations for Zambia indicate:

- Increasing precipitation variability, including dry spells in rainy season, may increasingly affect the drier zones. Reducing vulnerability to increased precipitation variability will require improved soil and water management. Maize will become increasingly risky.
- A significant soil nutrient deficit across the country. An application of relatively modest nitrogen fertilizer application of 85 kg/ha can triple yields in wetter areas (AEZ 2A & 3).
- Leaching significantly reduces yield especially in wet areas and sandy soils, but yields are very responsive to split nitrogen applications. Climate change is expected to lead to more intense rainfall events, worsening the problem of leaching.
- Assuming sufficient nutrients, water deficits become the main limiting factor across the South and West. Reducing vulnerability there will require improved soil and water management, and probably diversification away from maize.
- Climate change is expected to worsen water deficits in the South. Elsewhere, maize yields are expected to remain relatively the same. Application of fertilizer and high yielding varieties will remain the largest determinant of yield.
- Therefore, improved nutrient management will be an important intervention to reduce the impacts of climate change. However especially in the drier zones, improved water management will be necessary to maintain today's yields.
- In most places in Zambia, however, yields are expected to remain relatively the same. Despite the negative effects of projected climate change, Zambia is expected to remain a very productive country, and to be less affected by climate change than neighboring countries.

4.1.2 Focus groups

Focus group discussions were carried out in Eastern, Northern, and Southern Provinces in February and March, 2012, by project team members and representatives of the Ministry of Agriculture and IAPRI. Separate groups of men and women farmers were interviewed to determine perceptions of climate changes and typical adaptations used to adjust to their effects. Subsequent analysis was carried out to compare farmers' perceptions of changes in temperature and rainfall with trends shown in the actual met station data (see Mulenga and Wineman, 2014).

The farmers discussed their perceptions of how the climate has been changing. The most important change they noted was an increasing variability of rainfall. Respondents reported that the start of the rainy season was unpredictable, there are more frequent dry spells (2 to 3 weeks of no rain) in the middle of the season, and the rains can end early. The impact of these changes on their crops was considered to be substantial, particularly in the years with dry spells that occur in critical times for maize production. The most important impact on women was the greater amount of time they need to spend collecting water. Adaptations to these climate trends include crop and income diversification, staggered planting, and various conservation agriculture techniques. Overall, women tend to have fewer options for adjusting to climate change, especially off the farm. In Northern Province, for example, it was noted that fishing is not an option for women.

A comparison of farmer perceptions of climate change with actual meteorological data (Mulenga and Wineman, 2014, p. vii) showed that farmers offer remarkably consistent reports of a rainy season that is growing shorter and less predictable, with rising temperatures. Generally, farmers

perceive that the rainy season has grown shorter within the past 20 years, along with an increase in rainfall variability and extreme climate events. Most farmers report that temperatures have increased, and that these trends have diminished crop yield and food security. The focus group discussions reveal that farmers in Zambia perceive climate change as a problem and actively manage the associated risks. To address climate variability, farmers adopt new seed varieties, management practices, and livelihood portfolios, and in at least two locations, conservation agriculture seems to be a widely recognized toolbox of potential responses to climate change. However, the higher labor requirement of minimum tillage techniques presents a burden for poor households that cannot afford to hire in labor or purchase labor-saving technology.

In historical data from nearby meteorological stations, we find evidence of climate trends, including rising temperatures, which are consistent with some farmer reports. However, perceived rainfall trends are often not substantiated by the meteorological records. Mulenga and Wineman (2014) suggest that this latter discrepancy arises because not all aspects of climate that matter to farmers can be captured with standard (single-variable) analyses of meteorological data. Another factor could be that crop yields are responding to the combination of warming temperatures, which is drying them out due to higher evapotranspiration, and fewer but more intense rainfall events which leaves less water in the soil due to higher runoff. The annual or seasonal rainfall total therefore would underestimate the actual effect of warming temperatures and more variable rainfall on crop yields.

4.1.3 Household modeling

4.1.3.1 Methodology

Data used to design the household models for the three study areas[4] were drawn from a number of sources:

- Panel household supplemental survey data from 2001, 2004, 2008
- Rural agricultural livelihoods survey, 2012
- Crop forecast surveys for 2003 to 2012
- Farmer focus group discussions
- Zambia Meteorological Department rainfall and temperature data
- IPPC GCM climate predictions for 2050

These data were used (a) to identify the major crop production activities, in terms of crops grown, seed type (local versus improved), tillage method (hand versus ox), fertilizer use (yes/no), and time of tillage (early/late); (b) as a source of per-hectare labor and other input requirements, input costs, crop yields, and crop output prices; (c) as a source of information on the demographic composition of farm households and their endowments of land and other production assets; and (d) as the basis for estimating statistical crop yield functions, used to simulate the impact of future climate on crop yield.

Farm household linear program models were designed, based on adaptation of models developed for Eastern Province by Siegel and Alwang (2005), and extended to Northern and Southern

[4] Site 1 in Southern Province included Sinazongwe, Gwembe, and Siavonga districts; Site 2 in Eastern Province included Petauke, Katete, Chadiza, and Chipata; and Site 3 in Northern Province included Mpulungu, Mbala, and Mungwi.

Provinces. The basic structure of the model is shown in Annex F, Figure 6; for more details, see Wineman (2014c). Three household types were modeled: smallholder, emergent farmer, and female-headed household types.[5] Two alternative objective functions were specified for the models: maximization of household calorie production per adult equivalent, and maximization of profit. Minimum tillage activities were later added to the models to explicitly examine their feasibility and attractiveness.

For each of the three sites, the farm household models were used to determine the baseline optimal allocation of land to different crop production activities, taking into account land, labor and other resources available to the household, and yields prevailing under current climate conditions. Crop yields under future climate conditions (as of 2050) were then estimated using the statistical crop yield models and climate scenarios from two of the main models: Hadley (relatively "dry" in terms of predicting rainfall declines), and CCSM (relatively "wet," predicting rainfall increases). The models were run again incorporating these estimated future yields, in order to simulate the effects of climate change on the pattern of crop production and on various measures of household welfare (calories per adult equivalent (AE) per day,[6] net revenue, returns per AE per day, and returns to land). The impact of climate change on two alternative versions of a food security index was also analyzed (Wineman, 2013). A vulnerability analysis was carried out using Monte Carlo simulations to assess the probability for a given household type of falling below 3,000 calories per AE per day with the optimum farm plan, under both baseline and climate change scenarios. In a related exercise, we also examined the effect of climate variability on household food security in rural Zambia, measuring food security with a unique multidimensional index (Wineman 2013).

4.1.3.2 Results of the household modeling[7]

As would be expected, climate change has differential impacts on yields as a function of crop and production practices used.[8] As a result, farmers (in the household model) choose different crops (cotton, sunflower) and technologies (less fertilizer) under climate change. Calorie production per AE per day generally falls, but no household type in any site becomes calorie-deficient.

The adjustments in optimum cropping plan that the model generates under climate change (within the framework and conditions of the household model) permit a degree of on-farm adaptation that mitigates but does not necessarily offset the negative effects of climate change. (This may be partly because of the model's limited activity set, which does not include livestock, perennial crops, or off-farm activities.) For example, in the Eastern Province smallholder farm model and assuming the Hadley climate scenario, baseline calorie production is 4,938

[5] Characteristics of these farm household types were estimated from the survey data for each site. Rough average values across the three sites were: (a) smallholder: 1.9 ha of land, 2.75 working-age members, 250 ZMK cash available; (b) emergent: 7 ha, 3.25 working-age members, 1,500 ZMK cash available; and (c) female-headed: 1.5 ha, 2 working-age members, and 225 ZMK cash available. The set of crop regimes is the same for all household types.
[6] The calorie value of cotton was determined by converting its net revenue into a maize-meal equivalent by using the site-specific cost of maize meal, and then using the calorie value of maize.
[7] See PowerPoint 18.
[8] In Eastern Province, for example, yields of most crops decline under both the Hadley and CCSM climate scenarios, but cotton yields actually rise (positive response to higher temperatures) and sunflower yields remain stable.

cal/AE/day.[9] This falls to 4,584 cal/AE/day (a drop of 354), assuming yields with climate change but no change in cropping pattern. Allowing the model to adjust the cropping pattern raises outcomes to 4,829 cal/AE/day (a drop of only 109), meaning that on-farm adjustment has offset 69% ([354-109]/354) of the losses due to climate change. For emergent and female-headed households, these adjustment figures are 27% and 60%, respectively. In Northern Province, the adjustment effects are more modest: 26%, 1%, and 17%, for smallholder, emergent, and female-headed households, respectively. However, in Southern Province, because cotton is expected to respond positively to increasing temperatures, calorie production can actually improve, as indicated by adjustment percentages above 100%: adjustment effects are 326%, 117%, and 0% for smallholder, emergent, and female-headed households (whose cotton acreage does not change), respectively.

Two results emerged from analysis of impacts of adverse production conditions on household welfare:

1. Not surprisingly, smallholder farmers are most vulnerable to consumption shortfalls in a bad production year. Results of the Wineman (2013) food security index analysis indicate that poor households are vulnerable to both temperature and rainfall shocks, though these affect each dimension of food security (e.g., calorie availability, diet diversity) in a different way.
2. The vulnerability analysis showed that the probability of falling below 3,000 calories/AE/day will rise under both climate change scenarios. For example, in Northern Province, the probability of falling below this threshold is 8.6% under baseline conditions, but rises to 16.5% under the CCSM climate change scenario and to 21.6% under the drier Hadley scenario.

The main results of the modeling analysis of minimum tillage (MT) technologies are:

1. MT requires more labor for planting and weeding, but less than expected, hence labor shortages may not a limiting constraint for MT adoption.
2. Modeling the use of MT within a four-year time frame (to incorporate the lag between initial investment costs and longer-run benefits) shows partial adoption of MT. Modeling MT use within a one-year time frame (where long-run benefits are not fully incorporated) does not.

4.2 Kenya

To examine climate changes and their impact on crops, a similar approach was followed in Kenya as for Zambia. Historical data, where available, was analyzed and GCMs provided future climate projections that informed crop modeling.

The household modeling focused on three study sites: Machakos/Makueni in Eastern Province, representing smallholder farming in a medium-potential dry production zone; Meru/Embu in Eastern Province, representing smallholder farming in a high-potential high-rainfall zone, and Uasin Gishu/Eldoret in Rift Valley Province, representing emergent farming in a high-potential, high-altitude and high-rainfall zone. (See Annex F, Figure 7.)

[9] The models gave more credible results when farmers were assumed to maximize calories rather than profit.

4.2.1 Climate and crop modeling analysis

4.2.1.1. Methodology

To examine recent and projected climate trends, the team conducted statistical analyses of historical precipitation data, and conducted climate modeling to examine projected future climate trends. Obtaining observed weather data for Kenya, particularly the daily data required for analyzing changes in seasons or to use as inputs to the crop models, was very difficult. The meteorological station data that was obtained had too many missing values for statistically valid trend analysis. Therefore the team focused on validating CHIRPS data to use for that purpose. In Kenya, two stations—Eldoret in Uasin Gishu County, a humid and cool location, and Katumani in Machakos County, a warm and dry location—had sufficient observed data for comparing with CHIRPS (Funk et al. 2014). CHIRPS data spanned from 1981 to 2014, but comparisons were only made for the available times of the observed data (i.e., 1984 to 2008 for Eldoret and 1984 to 2011 for Katumani). Generally CHIRPS performed better at Eldoret than Katumani, but CHIRPS was considered sufficiently accurate for further analysis.

The team thus decided to conduct 1981 to 2014 precipitation trend analysis using the CHIRPS simulated daily data for 18 stations in Kenya, despite its known limitations. The variables examined were: annual and seasonal precipitation, number of wet days, and the start and end of the rainy season.

For simulated future climate and crop modeling, a similar methodology was followed in Kenya as for Zambia (see section 4.1.1.1). DSSAT v.4 was used to model maize and groundnuts. Climate datasets used included meteorological station data, WorldClim, NASA Power, and four GCMs downscaled to 6 km for time periods around 2000 and 2050. Soils data were derived from Food and Agricultural Organization 1:5 million soils map of world (FAO 1995) and soils profiles from the International Soils Reference and Information Center's World Inventory of Soil Emission Potential Data base (Batjes and Bridges 1994) as modified by Gijsman et al. (2007).

We assumed current representative smallholder practices; planting was assumed to occur automatically once the soil profile received a thorough wetting at the start of the rainy seasons. Different input levels of nitrogen fertilizer were simulated for maize including a low (5 kg/ha) rate of application approximating what many small-scale farmers use, and two moderate rates (35 and 85 kg/ha).

In Kenya, two maize varieties were modeled: Katumani maize, an older short-season variety developed by the Kenya Agricultural and Livestock Research Organisation (KALRO) for medium- to low- potential zones, and H614, a longer-season hybrid suited for mid- to high-potential zones. Calibration of the maize varieties was assisted by scientists from KALRO (Dr. Wafuma) and the Rockefeller Foundation/University of Reading (Dr. Githenyi). In addition, dry beans and sorghum were simulated.

4.2.1.2. Results of climate analysis

Recent climate trends. Due to the lack of sufficient meteorological station data, we conducted our analysis of recent precipitation trends using CHIRPS data. The results of the analysis of the Kenya CHIRPS historical simulated precipitation data showed that there were some spatial

patterns with both positive and negative temporal trends (PowerPoint 17). However, none of the trends were found to be significant at the 95% level or above using a simple linear trend fit.

Average annual total precipitation had a great range across the sites with the highest being 1392mm at Kisumu and the lowest being 255mm at Wajir, and the overall average being 797mm. Six stations showed an increasing trend in annual precipitation and 12 showed negative trends with the most extreme trends found at Eldoret (+8.4mm/year with a 45% significance) and Lamu (-14.7mm/year with a 57% significance). Seasonally, the overall pattern remained the same with most sites showing a decreasing trend in average seasonal precipitation but most trends had a 25% significance or below.

Overall, there was a tendency for increases in precipitation in the western part of Kenya (especially northwest). This was related to more wet days, an earlier start and later end of the rainy season, and more frequent 25mm or greater precipitation events. However, general decreases were found in central and eastern sections. Again, none of these changes in precipitation were statistically significant, which is likely linked with the relatively short period of record length.

The team's analysis of observed data in Uganda and Tanzania provide a regional view of historical trends. Generally, there have also been mean annual temperature increases across the region of approximately 0.2-0.4°C/decade since 1960. Mean annual precipitation rates across the region appears to have remained steady or declined during the past several decades. The largest decreases in the region were found in southern Tanzania and eastern Kenya. In Tanzania, annual rainfall has decreased at an average rate of approximately 3 mm/month or 3% per decade. Some of the decreases appear to be associated with a gradual compression or shortening of the rainy season(s). Long-term trends in portions of western Uganda suggest increasing long-season rainfall since 1960, although there have been decreases in that region during the most recent decade.

Future climate changes. Maps of projected climate change from 2000 to 2050 were prepared for each of the four GCMs for the East African region (PowerPoint 2). The GCM climate variables of the current (2000 to 2010) decade, the future decade (2050-2060), and the change between the two was mapped onto our best estimate of current climate (WorldClim).

The four GCMs project somewhat different trends in future annual precipitation, with CCSM, the wettest, projecting increases in particularly across Uganda and southern Sudan of over 200 mm/year. ECHam is the next wettest projection. It also shows moderate increases across the domain, particularly in Congo. Only the Indian Ocean coast and some highland areas are projected to receive declining precipitation. HadCM also projects some increases in precipitation, in central and northern Kenya, but much of the domain shows declining precipitation, especially along the Indian Ocean coast and, unlike any of the other four models, declines across the southern part of the domain. CSIRO is the driest of the models for East Africa. It does project moderate increases in precipitation in central and southern Tanzania, and central Kenya, but significant declines in precipitation elsewhere including Uganda, Congo, Rwanda, Burundi, and Western and Eastern Kenya. Thus there does not seem to be a

"consensus" on how precipitation may change. CCSM and ECHam do show similar geographical patterns of differences in the degree of projected increases in precipitation.

In general, the GCMs project a warmer and somewhat wetter region, especially in the northeastern part of the East Africa region. Note that neither the recent CHIRPS data nor meteorological station data display upward trends that tie in with this particular projected future increase in precipitation, perhaps because the GCMs do not incorporate the full effects of the rapidly warming Indian Ocean (Williams and Funk 2011). Across the rest of the region, the GCM projected future pattern of rapidly warming temperatures, and either moderate declines or little change in precipitation, is generally a continuation of current trends.

4.2.1.3. Results of the impact of climate change on crops

The results of the crop simulations reflect that under current climatic conditions, Northern Kenya has almost zero maize yield due to hot temperatures and very low precipitation, and parts of central and southern Kenya have low yields due to warm temperatures and low precipitation. In these warm and dry areas, inter-annual yield variability is high. In the Rift Valley and highlands of Kenya, however, maize yields are relatively high except where restricted by cool temperatures.

To examine the potential of fertilizer to reduce the negative effect of climate variability, we simulated maize production in a warm, dry (Katumani) and a cool, humid (Eldoret) location under 5 rates of nitrogen fertilizer using observed weather data (PowerPoint 17). Results indicate that split applications of nitrogen fertilizer even at moderate levels increase yield compared to single doses in both locations. However, the multiple doses of fertilizer are more beneficial in Eldoret than in Katumani; they even out and increase yields. The yield response to fertilizer, whether as single or multiple doses, in Katumani is small due to water deficits limiting yields.

Results indicate that projected future rising temperatures would have two major impacts on crops. One is increased evapotranspiration, which under limited water conditions causes water stress and reduces yield. The other is accelerated phenology in which the plant matures faster. Accelerated phenology reduces the time available for the plant to produce biomass and large kernels (for grain crops such as maize), and thus yields decline. In the maize simulations in East Africa, the warming effect and thus more rapid phenology reduces yield even where water is sufficient; this is particularly apparent in central Tanzania and throughout Uganda (Annex F, Figures 8, 9, and 10).

The yields of beans and many other legumes are similarly affected by heat, and the warming temperatures are projected to reduce dry bean yield across East Africa except in the highlands. Declining precipitation patterns will, however, affect beans less severely than it is expected to affect maize. The growing season for beans is shorter so they are less sensitive to the shortening of the rainy season. Also, most beans flower over a longer time period so the increasing frequency and intensity of dry spells during the rainy season would not reduce the bean harvest as dramatically as they do for grains that flower only once during the season. Nevertheless, the warming temperatures alone are expected to reduce bean yields. The crop modeling does not incorporate the potential increase in bean yields due to CO_2 enrichment, and this effect could help offset the impact of warmer temperatures where other limiting factors are not significant. Similarly, sorghum simulations indicate declining yields across the region related to warming

temperatures and higher water deficits; sorghum yields are, however, projected to decline less rapidly than maize yields in warmer climate zones.

In semi-arid northeastern and north-central Kenya where three of the four GCMs project increasing precipitation, maize yields would rise although in most areas not to the extent where maize becomes profitable. Less water-demanding crops such as sorghum may, however, become possible in areas currently too dry for crops.

The highlands in central and western Kenya are projected to have large increases in maize yield. The cold temperatures in the highlands are currently a limiting factor; with the projected warmer temperatures, maize in these zones with their good soils and sufficient precipitation would have higher production. Warmer temperatures, however, will be a negative factor for tea and coffee that require cool temperatures.

Finally, the coastal zone in Kenya would experience declining maize yields under the conditions of 3 of the 4 GCMs due to a decline in precipitation combined with warmer temperatures.

We tested the potential effectiveness of fertilizer as an adaptation strategy by comparing the change in yield between current and projected climates under different fertilizer rates. The results are that yields would decline more with moderate fertilizer than with low fertilizer rates. This is the case across much of the region, especially Uganda and Tanzania. This counter-intuitive finding comes from the fact that when nutrient levels are sufficient, then water deficits become the limiting factor. When nutrient levels are insufficient, the crop yields are low despite the amount of precipitation.

We also simulated the potential impact of supplemental water, or irrigation during the rainy season on maize productivity. Irrigation, not surprisingly, would increase yields dramatically (Annex F, Figures 11 and 12). The largest gains in yield are found where temperatures are conducive for maize, but where water deficits are high in rainfed conditions. This is the case across much of Kenya, especially in the mid-elevation zones (e.g., north of Mt. Kenya and in the Rift Valley). The increase in yield due to irrigation is small, however, where the temperature is too cold (e.g., the Aberdare mountains), or where the temperature may be conducive but there is already sufficient precipitation. Under future conditions, however, the yield benefits of irrigation would shrink because of the limiting effects of warmer temperatures on phenology and extreme hot temperatures inhibiting growth (Annex F, Figure 13). However, the land area where irrigation is necessary to produce a non-trivial yield will increase, since irrigation would counteract the effects of higher evapotranspiration due to warmer temperatures, and the effects of declining and more variable precipitation.

In summary, the crop and climate modeling and analysis results for Kenya indicate highly variable impacts of climate change on crop yields over Kenya and the East Africa region. Local topography, soils and initial climate conditions play an important role in determining how climate change may affect crops.

The impacts of future climate change to 2050 thus indicate:

1. Across most of East Africa, low fertilizer levels will continue to severely limit yields. Despite water deficits worsening in the future, low fertilizer applications will remain a limiting factor across much of the region.
2. In most maize-growing areas in Kenya, fertilized hybrid maize will continue to have higher yields than traditional drought-resistant varieties, except in years of significant drought.
3. In areas of low and declining precipitation, higher fertilizer levels will not compensate for the lack of water. Water deficits will overwhelm potential positive effects of fertilizer.
4. Worsening water deficits across most of the East Africa region will lower yields. Only the highlands will be spared because they will continue to have sufficient precipitation and maize will produce more there with the warmer temperatures.
5. The projected increase in yields in northern Kenya should not be interpreted as showing that maize will grow well there. The increase in precipitation in this area is uncertain, but if it occurs the area where maize can be grown may expand from the margins of current maize growing areas (e.g., in Central Kenya) into the semi-arid zones.

4.2.2 Focus Groups

Focus group interviews of men and women farmers were conducted by Ecodym Africa team members in the project's three main study sites for Kenya—Kateri in Meru County, representing a cool and wet high elevation site with intensive small scale agriculture, Ainabkoi in Uasin Gishu County representing another high elevation site but with large scale commercial maize and wheat production, and Mwala in Machakos County, which is drier with small-scale farming for domestic consumption and commercial production (Ecodym Africa Consultants 2014).

Farmers' perceptions of climate change focused on increased variability and declining rainfall. In the drier location, for example, droughts that had come once every 15 years are now coming approximately every 5 years. In the wetter locations, changes felt most keenly were unpredictability of the onset and cessation of the rainy seasons and less rain during the season. The cause of the declining yields was explained as a combination of soil degradation, poor rains, hotter temperatures, and worsening pests and diseases.

In highland Meru, farmers are shifting out of maize and into shorter season crops such as vegetables and Irish potatoes, and diversifying into dairy and off-farm employment. Responses to declining yields included investing in irrigation, improved seeds and fertilizer as well as switching crops. Since these adaptations require substantial investment, only the better-off households have been able to respond. Meanwhile, conflicts over irrigation water are rising.

In highland, commercial Uasin Gishu, farmers blame soil degradation and pests for causing declines in yields. Yields have declined, but not as steeply as in the other two sites. All crops including maize have been affected. Their response has been to switch to short-season crops such as cabbages and peas, and to rotate crops. Some who are able to are irrigating.

In dryland Machakos, farmers are attempting to reduce the risk of losing all because of the more frequent droughts and declining rainfall. The risk of poor crop yield and crop failure have significantly risen. Farmers say that the rains are now insufficient for an entire maize season. They thus intercrop maize with beans and other crops, and fewer farmers (around 25%) now

apply fertilizer to maize. They all, however, attempt to apply chemical pesticides because without it, they harvest nothing. Some have diversified into horticulture but that requires an investment (irrigation). Others are moving more into livestock because it is more resilient to variable rainfall. Today, women as well as men have no choice but to look for non-farm work.

4.2.3 Household modeling

The methods used in Kenya to design the farm household models are essentially the same as those used in Zambia, with some adjustments (explained below) resulting from differences in data availability. Data used to design the household models for the three study areas were drawn from the following sources:

- Panel household survey data collected by Tegemeo Institute for 1997, 2000, 2004, 2007, and 2010.
- Survey data for Machakos and Makueni collected under the joint KARI-McGill University Food Security Research Project and provided by Wellington Mulinge of KALRO.
- Kenya Farm Management Handbook Vol II (revised 2006) for Eastern and Rift Valley Provinces (Jaetzold et al., 2006a and 2006b).
- Focus group discussions between April and June 2014 regarding labor requirements and labor timelines for various crop production activities.
- Historical rainfall data from the National Weather Service Climate Prediction Center (CPC) as part of their Famine Early Warning System (FEWS) project.
- Historical temperature data from the NASA POWER data set.
- Future climate predictions from the IPCC for two general circulation models (GCMs). Specifically, the Hadley (HadCM3) model is selected as a relatively wet model, while CSIRO is a relatively dry model in Kenya.[10]

The data set does not include estimates of the area under each crop in fields containing multiple crops. This makes it difficult to calculate yields and crop budgets from the field-level data, because households in Kenya tend to plant a large number of crops and vegetables on a single field. In order to create yield estimates (kg per acre planted) for each crop, we first retained only the observations of field crops that are dominantly present in the study sites. We then classified each field according to the crops contained therein (e.g., maize only, maize and beans, etc.). For a field containing just one crop (after dropping the less significant crop observations), the area is assumed to be the area of the field. For a field containing more than one crop, the crop yield is specific to the crop mix (e.g., kg of maize produced per acre of a mixed maize-and-beans field). Data for fields containing too many crops, or a unique or rarely found crop mix, were not used.

Because a large majority of crop production takes place during the main rainy season, and the data set contains too few observations from the short rainy season, we only consider crop production from the main season. The main season refers to the January-March harvest in Eastern Province (Meru and Machakos) and the November-December harvest in the Rift Valley Province (Uasin Gishu). Unlike our work in Zambia, we do not create a separate model for

[10] Note that these models are predicted to be "wet" or "dry" considering total precipitation over the entire year. When focusing on only the main rainy season in each site, Hadley predicts a decrease in precipitation, while CSIRO usually predicts the opposite.

female-headed households. This is because, when estimating household characteristics using the 2010 panel wave, we do not have even 30 observations of such households in each site.

Crop activities were selected using much the same method as in Zambia. After classifying each field by the crop mix it contains, we pooled the observations across the six years captured in the panel data set, and evaluated the crop mix distribution by area and number of observations. We generally included crop mixes with at least 80 observations for a given site, and that constituted at least 5% of the area cultivated. Unfortunately, owing to lack of data on perennial crops, only seasonal crops are included.

Within each crop mix, we then selected specific management bundles (termed "crop regimes") to serve as crop activities for the representative farm. A "crop regime" is a mix of seed type (local or improved variety of seed/ planting material), fertilizer use (with or without chemical fertilizer), and method of land preparation (hand-hoe, oxen/tractor, or no land preparation, with the latter only considered for perennial crops). Because of insufficient data points, we did not account for level of management or for use of organic fertilizer. The most popular regimes are selected for each crop mix.

Expected crop yields were derived as an average (over the panel years) of yields for each crop regime (or each crop within a crop mix) in each site. Due to the low number of observations at a given study site, estimated yields were differentiated only by seed type and fertilizer use. The median yield values of these simplified categories were used in the model. Input requirements were derived from the Tegemeo panel data set. Prices of inputs and outputs were estimated as the average of the district median price in each panel year. Gross revenue (value of output) and net revenue (gross revenue minus variable costs) were calculated for each crop regime in each of the three sites.

Since the Tegemeo panel data did not report family labor use (except on the family's main maize field in one survey year), labor requirements and labor timelines used in the model were drawn from three other sources: farmer focus group discussions conducted by Joseph Maitima and Martin Mworia, survey data from the KARI-McGill University Food Security Research Project, and information in the two volumes of the Farm Management Handbook of Kenya cited above.[11] Labor requirements per acre were specified per two-week interval.

Two types of farm households were modeled: small-scale (less than 3 hectares) and medium-scale (between 3 and 20 hectares; not included for the Meru site). Characteristics of these households were estimated from the most recent wave of the Tegemeo panel data set (2012). Female-headed households were not modeled since at each site there were fewer than 30 observations on such households.

[11] In February 2015, data from a recent national survey carried out under the Agricultural Sector Development Support Programme (ASDSP) became available. This was a very large-sample survey that included detailed costs of production. Unfortunately, the survey did not include information on family labor use, so while analysis of this data could have helped to refine our crop budget estimates, it did not address our most pressing model design challenge, namely accurate specification of labor requirements.

Statistical crop yield functions similar to those developed for Zambia were used to estimate the impact of climate change on crop yield. Yields were specified to be a function of rainfall (amount and intra-season variability) and temperature (average across the growing season).

4.2.2.2 Limitations of the household modeling in Kenya

Several limitations of the household modeling need to be acknowledged. They result primarily from the nature of the data available. First, for intercropped fields (more common than mono-cropped fields), area by crop was not measured in the survey, which reduces the quality of estimated per-acre yields, inputs used, and net returns. Second, while perennial crops such as coffee, tea, and banana are important in our study zones, we were unable to obtain sufficient data on their production characteristics and costs and returns to support including these activities in the model. For lack of data as well, livestock production and off-farm activities were also not included. Third, the regime categories used in the models are rather coarse, with only partial consideration of crop management practices. Practices incorporated included fertilizer use, hoe vs. mechanized land preparation, and traditional vs. improved seed varieties, but not number of weeding operations. Fourth, our estimated labor timelines are also coarse, as they are derived from one round of focus group discussions rather than from survey data, and the various sources of data were often not consistent. Finally, we were not able to model production activities in the short rainy season. This would be desirable, since the GCMs make very different predictions about the level of rainfall in the short versus long rainy season. For example, while Hadley predicts a decrease in rainfall during the October-March season, it generally predicts an increase during the March-September season in locations with a bimodal rain pattern.

4.2.2.3 Results of the household modeling in Kenya

Ultimately, while the models for all three sites were run for test purposes, it was decided that data on labor requirements were not adequate for site 1 (Meru, eastern highlands) or for site 3 (Uasin Gishu, high-potential maize zone). Somewhat better information was available for site 2 (Machakos, eastern lowlands), thanks to our collaboration with Dr. Mulinge from KALRO and data he provided from the KARI-McGill University Food Security Research Project. Further development and testing was therefore carried out with the Machakos model, in order to generate provisional results at least for purposes of discussion.

Two household types were modeled for Machakos with the following characteristics based on median values from the survey data: (a) small-scale: 3.4 acres available, 4.3 working-age household members, and 9,600 KShs. in cash available; and (b) medium-scale: 12.5 acres, 4.0 working-age members, and 20,400 KShs. in cash. A calorie-maximization objective was used for the small-scale farm model and a profit-maximization objective for the medium-scale farm model.

Even for the Machakos model, however, the results were less satisfactory than for the Zambia household models. Validation checks showed a less-than-desirable match between actual farm cropping patterns (as seen in the survey data), and optimal cropping patterns generated by the model. For example, the small-scale farm results showed land allocated to beans (local variety, no fertilizer) and a maize-beans mixture (hybrid maize with local beans plus fertilizer, which fits observed cropping patterns. However, unrealistically, the medium-scale farm cultivated only local beans with no fertilizer, and both farm types left some of their land uncultivated (apparently due to labor constraints.

Other results from this initial use of the Machakos model were:[12]

- The medium-scale farm earned a net profit of 40,587 KShs. (approximately U.S. $450 to $470), and the small-scale farm generated 3,610 cal/AE/day.
- The result of climate change (CSIRO scenario) for the medium-scale farm is a switch in cropping pattern from beans to sweet potatoes. Net revenue falls, less land is cultivated, and farm production is still constrained by labor.
- For the small-scale farm, climate change results in a shift to sweet potato (CSIRO scenario) or beans (Hadley). More land is cultivated, the land constraint is now binding, and calorie production per AE per day either falls by 4% (Hadley) or increases by 23% (CSIRO).

5. Implications for Policy and Programs

5.1 Kenya versus Zambia

1. Impact of climate change: Kenya's agriculture is much more vulnerable than Zambia's. Climate change in Kenya is already affecting the low- and medium-potential zones, and threatens coffee and tea areas. Cooler and wetter Zambia will continue to be in a relatively good position compared to its neighbors. For example, key informants in Zambia suggested that Zambia's agro-ecological conditions were ideal for production of improved maize seed, such that Zambia could be the primary seed supplier for the surrounding region.
2. Vulnerable locations: In general, the drier and warmer regions of both Kenya and Zambia are likely to be hardest hit by climate change. Temperatures are reaching the point of inhibiting crop growth, and precipitation variability will be further increasing. The frequency of crop failures can be expected to rise. The possible exception, if GCM future projections are correct, is in northern Kenya where increasing precipitation may permit maize to be grown somewhat further north than it is currently.
3. Adaptations to climate change: The effectiveness of nutrient management on crop yield depends on sufficient moisture, so fertilizer use has large benefits in Zambia particularly compared to drier areas in Kenya. Irrigation has large potential benefits in Kenya, especially in drier, moderate temperature areas. With climate change, the yield benefits of both fertilizer and irrigation will shrink, but their importance in maintaining productivity will remain crucial.

5.2 Conclusions and implications (climate and crop modeling)

The crop and climate modeling and analysis results project highly variable impacts of climate change on crop yields. Local topography, soils and initial climate conditions play an important role determining how climate change may affect crops. Climate change technical adaptation will require a combination of practices depending on location.

[12] See PowerPoint 19.

5.2.1 Implications for irrigation

1. Very large benefits, over 6 metric tons/ha, to irrigation in moderate temperature areas of Kenya, Ethiopia and Uganda.
2. Hot areas, and of course wetter areas, would benefit much less from irrigation.
3. Benefits from irrigation will decline in the future due to hotter temperatures.

5.2.2 Implications for crop choice and crop breeding

1. Maize, bean and other crop varieties will need to be tolerant of warmer temperatures and extreme heat. Grains in particular will need to be resistant to the acceleration of plant maturity due to warmer temperatures.
2. Some (not all) areas should move towards shorter-duration varieties. The focus of adaptation programs on developing new short-duration varieties will not address the needs of the main maize-growing zones.
3. In areas of low and declining precipitation, varieties and crops resistant to within-growing season dry spells, especially during flowering, will produce more reliably.
4. Finding alternative crops or other income sources is critical to assist farmers in warmer and drier areas to diversify away from maize.

5.2.3 Implications for nutrient management

1. Low fertilizer levels limit current yields. With climate change, the benefits to fertilizer will decline, since its ability to increase yields diminishes when water is limiting. Fertilizer will remain a critical management practice, however, especially in wetter areas.
2. Effective fertilizer application, including using small multiple doses rather than single doses, is as important as the amount applied.

5.3 Conclusions and implications (household modeling)

1. Model results showed that on-farm adaptation to climate change, through changes in crops and production technologies, is likely to mitigate but not necessarily offset the negative effects of climate change. This suggests that larger-scale adaptation measures are needed (e.g., heat-tolerant seed varieties, agricultural and water infrastructure investments and policies to reduce risk for farmers).
2. For most study sites in both Zambia and Kenya, household model results showed minimal negative effects of climate change on expected household welfare.
3. The fact that crops differ in their sensitivity to climate change has implications for agricultural policy related to promotion of particular crops. For example, maize production is promoted in both Kenya and Zambia (especially the latter), yet maize is more sensitive to climate change than cassava, another key food crop.
4. The impact of gender of the head of household did not make a significant difference in climate change adaptations or impacts in the household models, However, this may result from the fact that constraints faced by female-headed households other than limited land, labor and capital endowments could not be incorporated in the model.

6. Lessons Learned About Methods

6.1 Overall successes of the modeling approach

1. This study illustrates the benefits of high-resolution, process-based spatial crop-climate modeling to identify climate change impacts on crops, especially in heterogeneous regions. For example, in the East Africa region, average expected change in maize yield is only -1%, but this hides localized impacts ranging from -3000 to +3000 kg/ha.
2. The system permits testing agricultural practices against climate change and variability. For example, one can test the resilience of one maize variety against another, or the benefits of different fertilizer rates, across the landscape.
3. The farm household models generated useful insights about key constraints and trade-offs faced by farmers, and about the rough magnitude of adjustments possible through alteration of on-farm production practices and crop/technology choices. The modeling results obtained were informative, but linking climate/crop and household models was more difficult than expected.
4. The availability of multi-year farm household survey data was valuable in both Zambia and Kenya, especially for providing empirical evidence of crop choice, production technology and practices, and household characteristics.

6.2 Methodological challenges

6.2.1 Data requirements.

To more fully realize the potential of crop models, more data is needed to calibrate and validate a wider range of crops and crop cultivars, as well as improved rainfall, temperature, and soils data. For farm household models to provide richer and more credible results, improved data is needed on area cultivated by crop and by field, and on labor requirements for production activities. However, estimation of the impacts of rainfall and temperature trends was hampered by the shortness of the panel periods, and by data gaps on crop-specific inputs and outputs per unit of land.

6.2.2 Linking climate, crop, and household models

6.2.2.1 Climate – crop model linkages

GCMs were not designed to provide results for a specific region or for a particular decade, whereas dynamic crop models were designed to simulate the effect of daily weather on a single season's yield for a specific location. Dynamic crop models thus require daily rainfall and temperature data, but GCM results are typically provided in a monthly time step. GCMs also do not reflect precipitation inter-annual to daily variability that highly impacts crops. Finally, the spatial resolution of GMCs is also very coarse, especially compared to the point or high resolution usually of interest to agriculturalists and planners.

The limitations of GCMs for linking to the crop model were partially resolved in this project by downscaling GCM data to a higher spatial resolution of 6 km (but uncertainty levels remain high), generating simulated daily data from the monthly datasets using weather generator software, and finally conducting crop modeling with observed, historical climate data where available to support statistical analysis of inter-annual and seasonal variability.

Despite the uncertainties and limitations of GCMs, they provide the best available projections of future climate change. GCMs dynamically incorporate the complex effects of enhanced greenhouse gases on the atmosphere. Also, GCM data are physically consistent; they take into account the spatial relationship in precipitation and other climatic processes between locations. This is why we prefer to use their data to drive crop models rather than a Monte Carlo approach or other simple perturbations added to a historical pattern. Other approaches to generate rainfall that are commonly used often result in unphysical temperature and rainfall data. While GCM projections have limitations, they are the best available, physically consistent product.

6.2.2.2 Crop – household model linkages

Household models for Africa need information on climate change impacts for a much larger spectrum of crops and crop-technology combinations than crop models can currently provide. The spectrum of crops could be improved by increasing the information available to calibrate crop models for cultivars commonly grown in the areas of interest. It may be harder to modify the models to simulate the effect of different technologies or management practices such as multi-cropping, conservation agriculture or sustainable rice intensification.

In practice, crop models do not simulate a sufficiently full range of current farmer practices and farm conditions (such as multi-cropping, degraded soil, weeds, pests and diseases). The result is that yields simulated by crop models are much higher than those observed on-farm. This makes it inappropriate to include crop yield estimates in the household models.

For the household models, these limitations of crop models were partially offset by estimating statistical crop yield functions based on annual crop survey forecasts and other data (despite limitations of farmer-reported yield data). Future crop yields were then estimated based on the projected change in climate variables of two differing GCMs for those study areas, with these changes applied to the statistical crop yield functions.

6.3 Possible next steps

1. Use the crop-climate modeling framework to:
    a. Examine how new "climate resilient" maize cultivars respond to projected climate change and farmer management practices. For example, where would the new maize cultivars perform better than, or worse than, existing cultivars? How are their yields affected by reduced fertilizer applications, compared to other cultivars?
    b. Compare the impact of climate change on different crops to identify, for example, the possible expansion or contraction of maize, cassava, and sorghum growing zones.
    c. Produce information on the impact of near-term and longer-term climate variability and climate change on national production of maize and other crops (taking into account spatial differences in agroecological and weather conditions), with implications for regional trade.
2. Link the new CHIRPS spatial historical climate dataset to the crop model to examine recent climate variability in crop yield across space. Identify, for example, the impact of past El Niño and La Niña events on crop productivity across East and Southern Africa to provide insights into potential future El Niño impacts.

3. Collaborate with local scientists to build capacity for crop modeling linked to climate model data, in a GIS platform.
4. Encourage donor and national investment in better data and stronger local modeling / analytical capacity. For example, this could support enhancement of the farm household models to include livestock, perennial crop, and off-farm production or income-earning activities.

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Annex A: Program Description[13]

Program Description

Introduction
The activities proposed for implementation under this associate award will contribute directly to the goals of the Feed the Future (FTF) initiative. FTF focuses on sustainable reductions in hunger and poverty, with two key objectives: "accelerating inclusive agriculture sector growth and improving nutritional status" (FTF 2010, v). Climate change is recognized as a cross-cutting issue to be considered in designing programs to address FTF goals. The FTF Guide recommends that assessment of climate risk should be incorporated into food security efforts, stating: "Ensuring a sustainable and resilient agricultural development strategy requires countries to understand the potential implications of current and anticipated climate risks and vulnerabilities on the strategic objectives of their food security programs" (FTF 2010, 30-31).

Relatedly, the FTF Global Food Security Research Strategy notes that "advances in modeling of climates, production systems and actual or potential threats (e.g. pathogens, drought) can help guide research investments." (FTF 2011, 38). In addition, Zambia and Kenya include significant areas that fall into two of the Research Strategy's priority production systems, namely maize-based production systems in Southern and Eastern Africa and the East Africa highland system in which maize is also important. Regarding the former system, the Research Strategy notes that "maize is the defining crop for millions of food-insecure smallholders," and that "sustainable intensification equates with improving resilience in the face of frequent drought through improving soil moisture holding capacity and diversification for both fertility and income growth" (FTF 2011, 31)

Background
An increasingly important limiting factor for increased food production in Africa and Asia is climate, particularly low or erratic precipitation. Efforts to increase food production need to consider expected changes in climate as they affect agricultural productivity. These changes will affect high productivity zones, availability and access to food in neighboring deficit zones, as well as regional trade patterns. Efforts to develop agricultural responses resilient to climatic changes are limited by a lack of information on current and future environmental limitations, particularly at the sub-national level, and on their likely impacts on household food security.

Coupled climate, crop, land use and surface water simulation models can allow realistic analyses of the direct and interactive impacts of climate, soils and technological factors on crop production at a small fraction of the staff, financial and time requirements associated with standard field-level research. Nationally representative farm household survey data can provide the basis for modeling household production and income-earning activities in major agroecological zones, and for evaluating the impact of climate and weather factors on household food security outcomes.

Michigan State University has two groups of faculty members and researchers whose work relates to the above topics. First, a group of geographers and agro-climatologists has a regional

[13] As set forth in the technical proposal for the award.

climate-land modeling framework calibrated for East Africa that explores current and future effects of climate and management factors on crop production. Second, the MSU Food Security Group, consisting of nearly 20 faculty members based on campus and in the field, carries out a number of projects related to food security, of which the most significant is the Food Security III Cooperative Agreement. FSG projects in eastern and southern Africa have included support for multiple years of nationally representative farm household surveys, collected by the Central Statistical Office in Zambia and by the Tegemeo Institute and the Central Bureau of statistics in Kenya. These surveys include panels of the same households covering three different years in Zambia (with a fourth panel wave planned in 2012) and five different years in Kenya. Years and sample sizes are shown in Table 1. A map of the survey coverage in Zambia is in Annex F.

Table 1. National Farm Household Panel Surveys in Zambia and Kenya

Zambia		Kenya	
Year	**Sample Size**	**Year**	**Sample Size**
2001	6,922	1997	1,535
2004	5,421	2000	1,512
2008	8,094	2004	1,397
2012	(coming mid-2012)	2007	1,342
		2010	1,309

The East Africa regional modeling framework generates mapped results at the 18 x 18 kilometer scale, and site-level, higher-resolution results at the 6 kilometer scale. Climate data coupled to a process-based crop model can identify the effects of climate, climate variability and management practices such as fertilizer use, crop variety and planting dates on yields of rice, maize and other crops. The climate model coupled to a surface water model can provide information on the impact of climate change on water availability for human consumption, irrigation, or electricity generation. The model results can inform decisions on what crop varieties and management practices would be the most productive under current and projected future climate change. It can also provide information on the impact of climate change and variability on the amount of production available for household food security and trade. This type of modeling analysis can therefore directly support the value chain development objectives addressed by USAID.

In addition to modeling future crop productivity and water availability, analysis of historical data (remote sensing and meteorological station data) can provide information on climate trends from the 1960s to present, and their impact on maize and rice productivity. Critical questions being asked by governments, such as how rainy seasons are changing in length, start date, and reliability, or whether droughts are becoming more frequency and severe, can be examined.

There are several different potential approaches to defining the onset and cessation of the rainy season. For onset there are two potential approaches we are likely to use:

(1) Onset = first four rainfall events of 10 mm or more with no 7-day dry spell between any two such rainfalls. The reverse would be the cessation of the rainy season. Or,

(2) From Liebmann et al. (2007), using a formula for accumulated rainfall: Where the rainy season is the longest period for which anomalous accumulation remains greater than the annual

mean accumulation. This would also define the cessation point. For reliability, each station has data for a reliability function based on rainfall probability as outlined in Tshecko (2004).

The research and the policy-making process is being informed by engagement with rural communities to learn of their strategies for responding to current and expected climate change. Ecodym will be engaging with rural communities in Kenya through focus group discussions. MSU will hire local consultants to conduct focus group discussions in Zambia. Such information can inform the experimental design and the interpretations of modeling results, and results in more realistic and effective adaptation mechanisms.

MSU's Food Security Research Project (FSRP) in Zambia, funded for 2010-2015 by USAID and SIDA, will include nationally representative household data collection and food policy analysis that supports the goals of FTF and the Comprehensive African Agriculture Programme (CAADP). Climate change research by University of Zambia faculty and collaborators will be supported under the FSRP competitive grants program, and will focus on identifying farm household coping and adaptation strategies in response to climate change. The household-level economic modeling proposed for this Award will provide information on the impact of potential FTF project interventions and of climate variability on different household wealth categories, and support economic, nutrition and food security impact analysis of project interventions and climate change.

Purpose of Award

The purpose of the activities supported under this Award is to link the multiple-year household survey data sets available to MSU, and MSU's coupled climate, crop, land use, and water availability models, in order to improve understanding about how rural households are adapting to climate change (in terms of agricultural production practices and technologies, and perhaps other income-earning strategies), and about the impacts of anticipated future climate scenarios on farm household production, income, and food security. This information will help refine the climate change models and estimates of future household technology adoption and investment decisions, with implications for country program and policy priorities.

Proposed Activities

Briefly summarized, the proposed activities are as follows. The work will be carried out in two pilot countries, Zambia and Kenya, with Zambia activities beginning in Year 1 and Kenya activities beginning in Year 2.

1. Historical analysis of rainfall patterns over space and time using weather station data and a new promising Africa-wide data source, African Rainfall Estimation Algorithm (RFE).RFE and the Rainfall Estimation Algorithm refer to the same thing. RFE is the acronym for the operational product (daily precip. estimates across the African continent at 0.1 deg. spatial resolution), which is based on version 2.0 of the algorithm implemented in 2001. Data are currently available back to 2001 but efforts are underway to extend the data series back to 1982. Data are available via ftp at ftp.cpc.ncep.noaa.gov/fews/newalgo_est/ Nick Novella (Nicholas.Novella@noaa.gov) is the primary NOAA contact for this program.

2. Analysis of impact of past climate variability and trend changes on maize yields, using climate-crop models, and on indicators of household well-being such as food security and income, using the multiple-year household data. As a comprehensive, dynamic crop model, DSSAT simulates crop growth and productivity on a daily or more frequent basis and directly links the effects of water supply on plant growth and development. Maize, for example, is very sensitive to a short dry period during its flowering stage. DSSAT should better reflect the overall impact of precipitation amounts and timing during the growing season than the Water Resource Satisfaction Index (WRSI) model, which is based on the mass water balance approach. Dynamic crop growth during the season is not explicitly accounted for in WRSI.

3. Projection of future climate scenarios and their impacts on maize yield and output. The results of downscaled GCMs and linked crop modeling will be geo-referenced. The output will be in the form of maps and data (e.g., maps of change in temperature, precipitation during growing season, change in maize yields, etc.). The scale of analysis is flexible; we have been using 6 km for the high-resolution, localized analyses.

4. Construction of farm household models, and incorporation into those models of projected future climate change and maize yield scenarios in order to identify impacts on future household production, farm and off-farm incomes, and food security. The result will be a prototype model that would provide household-to national-level information on impacts of recent and future climate change and variability (see Table 2).

5. Use of focus groups to guide the design and interpretation of (1) and (2), and feedback groups to discuss the outcomes of (3) and (4).

6. Outreach to key stakeholders in the pilot countries and in the U.S.

Annex B: Performance Indicators and Targets, FY 2012 to 2014

Indicator	Target FY 2012	Target FY 2013	Target FY 2014
4.8.2-6 Person hours of training completed in climate change supported by USG assistance	a/		
4.8.2-14 Number of institutions with improved capacity to address climate change issues as a result of USG assistance	3 b/	8 c/	10 d/
4.8.2-26 Number of stakeholders with increased capacity to adapt to the impacts of climate variability and change as a result of USG assistance	4 e/	65 f/	105 g/
4.8.2-27 Number of days of USG funded technical assistance in climate change provided to counterparts or stakeholders	40 h/	36 i/	18 j/
Custom Indicator: Number of climate mitigation and/or adaptation tools, technologies and methodologies developed, tested and/or adopted as a result of USG assistance	3 k/	7 l/	9 m/

a/ No training explicitly included in proposal or budget.

b/ IAPRI (Indaba Agriculture Policy Research Institute, Zambia); UNZA (University of Zambia); GART/ZARI Research Station, Zambia.

c/ (b) plus 3 farmer groups (Zambia) and Ecodym plus Ministry of Agriculture (Kenya)

d/ (c) plus 2 farmer groups (Kenya)

e/ IAPRI (1 researcher); UNZA (3 researchers)

f/ (e) plus 3 farmer groups x 20 participants (Zambia) plus Ecodym (1 researcher)

g/ (f) plus 2 farmer groups x 20 participants (Kenya)

h/ 20 days (Zambia) plus 20 days (Kenya)

i/ 18 days (Zambia) plus 18 days (Kenya)

j/ 6 days (Zambia) plus 12 days (Kenya)

k/ Methods for identifying climate trends; crop model calibrated for Zambia; draft farm household model for Zambia.

l/ (k) plus crop model calibrated for Kenya and draft farm household model (Kenya) plus two adaptation technologies identified for Zambia

m/ (l) plus two adaptation technologies identified for Kenya.

Annex C: Project Reports and Publications

Project Reports

Implementation Plans

1. Implementation Plan for Year 1 (FY 2012), February 12, 2012.
2. Implementation Plan for Year 2 (FY 2013)—FINAL April 26, 2013
3. Implementation Plan for Year 3 (FY 2014), December 11, 2013
4. Implementation Plan for Year 4 (FY 2015), September 12, 2014

Annual Progress Reports

1. Technical Progress Report for Year 1: October 1, 2011 to September 30, 2012, by Eric Crawford, Jennifer Olson, and Gopal Alagarswamy, October 17, 2013.
2. Technical Progress Report for Year 2: October 1, 2012 to September 30, 2013, by Eric Crawford, Jennifer Olson, and Ayala Wineman, March 10, 2014.
3. Technical Progress Report for Year 3: October 1, 2013 to September 30, 2014, by Eric Crawford, Jennifer Olson, and Ayala Wineman, March 10, 2015.

Other Project Reports

FY 2012

Olson, Jennifer, and Eric Crawford, "Report on Trip to Zambia: Climate Change and Household Modeling Project," November 7-14, 2011.

FY 2013

Crawford, Eric, and Jennifer Olson, "Report on Trip to Kenya and Zambia Under the Project "Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty," July 7-21, 2013.

FY 2014

Crawford, Eric, and Jennifer Olson. 2014. Report on Trip to Zambia Under the Project "Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty." August 16-24, 2014.

Ecodym Africa Consultants. 2014. Report on Focus Group discussions in Meru, Machakos and Uasin Gishu Counties Addressing the Impact of Climate Change on Agricultural Systems in Kenya. April 28, 2014.

Mulenga, Brian, and Ayala Wineman. 2014. Climate Trends and Farmers' Perceptions of Climate Change in Zambia. Working Paper 86. Indaba Agricultural Policy Research Institute (IAPRI), Lusaka, Zambia.

Mulenga, B.P., H. Ngoma, and S.T. Tembo. 2015. Climate Change and Natural Resources in Zambia: Opportunities, Threats and Challenges. In: The State of Zambian Agriculture in 2014-15 IAPRI (Ed.), Lusaka: IAPRI.

Mulenga, B.P., A.Wineman, and N.J.Sitko. 2015. Climate Trends and Farmers' Perceptions of Climate Change in Zambia. Journal article manuscript in preparation.

Wineman, Ayala, and Brian Mulenga. 2014. Sensitivity of field crops to climate shocks in Zambia. Draft. August 18.

Wineman, Ayala, and Eric Crawford. 2014a. Climate change and crop choice in Zambia: A mathematical programming approach. Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2014 AAEA Annual Meeting, Minneapolis, MN, July 27-29.

Wineman, Ayala, Eric Crawford, and Wellington Mulinge. 2015. Climate change and crop choice in Kenya. Draft, March.

Wineman, Ayala. 2014a. Maize production in the future. March 31.

Wineman, Ayala. 2014b. Modeling minimum tillage among smallholders in Eastern Zambia. Draft. July 22, 2014.

Wineman, Ayala. 2014c. Climate change and crop choice in Zambia; A mathematical programming approach (with detailed appendix). Draft. March 10.

FY 2015

Olson, Jennifer, Gopal Alagarswamy, and Nathan Moore. 2015. Crop and Climate-related Modeling Datasets That Were Used or Generated during the Project, "Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty." May 12.

Academic Publications and Presentations

Alagarswamy, G., Jeffrey Andresen, Jennifer Olson, Philip Thornton, Nathan Moore. 2013. Climate Change Impacts on Maize Production in East Africa. In proceeding of: *The Association of American Geographers Annual Meeting*. April 11, 2013. http://meridian.aag.org/callforpapers/program/AbstractDetail.cfm?AbstractID=52606

Alagarswamy, Gopal, Jennifer Olson, Jeff Andresen, Nathan Moore, Philip Thornton, Pius Yanda, Joseph Maitima, Jenni Gronseth, David Campbell. 2015. The Highly Variable Response of Maize Yield to Climate Change across East Africa. Poster presented at the: 5th AgMIP Global Workshop, Gainesville FL, February 25, 2015. http://www.agmip.org/wp-content/uploads/2015/03/Alagarswamy-Gopal.pdf

Alagarswamy, Gopal, Jennifer Olson, Jeff Andresen, Joseph Maitima, Brian Mulenga, Nathan Moore, William Otim-Nape, Phillip Thornton, Pius Yanda. 2015. The Impact of Climate Change on Water and Nitrogen Deficits for Maize Production in East and Southern Africa. Poster to be presented at the conference: Transitioning Cereal Systems to Adapt to Climate Change (http://www.aridcereals.org/). Nov. 13-14, 2015. Minneapolis, MN

Moore, N., Alagarswamy, G., Pijanowski, B., Thornton, P., Lofgren, B., Olson, J., Andresen, J., Yanda, P. and Qi, J. 2012. East African food security as influenced by future climate change and land use change at local to regional scales. *Climatic Change* February 2012, Volume 110, Issue 3, pp 823-844. http://link.springer.com/article/10.1007%2Fs10584-011-0116-7

Moore, N., J. Andresen, G. Alagarswamy and J. Olson. 2013. *Variations in downscaled projections for East African climate to 2050.* In proceeding of: *The Association of American Geographers Annual Meeting*. April 11, 2013. http://meridian.aag.org/callforpapers/program/AbstractDetail.cfm?AbstractID=51063

Moore, N., G Alagarswamy, J Andresen, J Olson, P Thornton 2013. Use of a crop climate modeling system to evaluate climate change adaptation practices: maize yield in East Africa. AGU Fall Meeting Abstracts pg 1086. http://abstractsearch.agu.org/meetings/2013/FM/GC33A-1086.html

Moore N, Andresen, J., Lofgren, B., Pijanowski, B., & Kim, D. Y. 2015. Projected land-cover change effects on East African rainfall under climate change. International Journal of Climatology. 35, 8: 1772–1783. http://onlinelibrary.wiley.com/doi/10.1002/joc.4117/abstract

Mulenga, Brian, and Ayala Wineman. 2014. Climate Trends and Farmers' Perceptions of Climate Change in Zambia. Working Paper 86. Indaba Agricultural Policy Research Institute (IAPRI), Lusaka, Zambia.

Olson, J.M., G. Alagarswamy, J. Andresen, J. Maitima, A. Majule, N. Moore and P. Yanda. 2013 Identifying the Impact of Climate Change on Agriculture in Heterogeneous East Africa: Results of Mixed Methods and a Coupled Climate-Crop Modeling System. Paper presented at the conference, Climate Change, Sustainable Intensification and Food Security in Sub-Saharan Africa at Sokoine University of Agriculture. November 2013. https://drive.google.com/file/d/0Bz1agTfIh5DPc3VTVWNqcmpxVEE/edit ; http://iagri.org/events/climate-change-conferences/international-conference-on-climate-change-2013/

Olson, Jennifer, Dan Weiner, Tom Smucker. 2014. "Top-Down vs. Bottom-Up, or Vulnerability vs. Resilience." Resilience 2014: Resilience and Development, Mobilizing for Transformation. Montpellier, France. May 2014. http://resilience2014.sciencesconf.org/25421,

Olson, Jennifer. 2013. "Farmers Adapt to Climate Change While Policy Makers and Scientists Attempt to Communicate. In proceeding of: The Association of American Geographers Annual Meeting. April 11, 2013. http://meridian.aag.org/callforpapers/program/AbstractDetail.cfm?AbstractID=53057

Wineman, Ayala. 2013. The Multidimensional Nature of Household Food Insecurity in Rural Zambia: A Panel Analysis. Master's Thesis.

Multi-Media Outputs

1. "On the Edge of Climate Change" video (to be broadcast on WKAR TV in Fall 2015): https://www.youtube.com/watch?v=XPsh9lLzIQg

2. The Food Fix Podcast "Jennifer Olson: Climate Change and Farmers", March 16, 2015. http://foodfixpodcast.podomatic.com/entry/2015-03-16T09_20_49-07_00

3. The Food Fix Podcast "Victoria Breeze: Climate Modeler Helps Real People", March 22 2015. https://msufoodfix.wordpress.com/2015/03/20/climate-modeler-works-on-real-problems-to-help-real-people/

4. Radio interview of Olson on our climate change research for a segment on the "Greening of the Great Lakes" on WJR (760 AM); aired August 23 & 24, 2014 and featured on "Michigan Environmental Issues" online news site mlive.com.

Annex D: Project PowerPoint Presentations

Presentations available on project website, http://fsg.afre.msu.edu/climate_change/index.htm

FY 2012 (October 1, 2011, to September 30, 2012)

1. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Michigan State University. Eric Crawford, Jennifer Olson, Jeffrey Andresen, Joseph Maitima (Ecodym, Kenya). Presentation at USAID/East Africa, February 6, 2012.
2. Progress Report Year 1. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford and Jennifer Olson. USAID, Washington, D.C. September 19, 2012.

FY 2013 (October 1, 2012, to September 30, 2013)

3. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford and Jennifer Olson, Michigan State University. Presentation at USAID, Lusaka, Zambia, July 17, 2013.
4. Methodologies to Examine the Impact of Climate Change on Crop Productivity in East Africa. Climate Change, Sustainable Intensification and Food Security in Sub-Saharan Africa. Jennifer Olson, Gopal Alagarswamy, Jeffrey Andresen, Joseph Maitima, Amos Majule, Nathan Moore, and Pius Yanda. Presentation at Sokoine University of Agriculture, Morogoro, Tanzania, Nov. 13, 2012.
5. Supplementary Materials. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford and Jennifer Olson, Michigan State University. Presentation at USAID, Lusaka, Zambia, July 17, 2013.
6. USAID Briefing and Planning Meeting. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford and Jennifer Olson, Michigan State University. Presentation at USAID/Kenya and USAID/East Africa, Nairobi, Kenya, July 8, 2013.
7. Year 2 Progress Report. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford and Jennifer Olson. USAID, Washington, D.C. October 28, 2013.

FY 2014 (October 1, 2013, to September 30, 2014)

8. Climate Trends and Impacts on Agriculture in Kenya. Jennifer Olson, Gopal Alagarswamy, Jeff Andresen, Joseph Maitima, Nathan Moore, Martin Mworia. Presented at the Kenya Agricultural and Livestock Research Organisation, Katumani, Kenya, Dec. 15, 2014.

9. Climate Change Impacts on Agriculture and Household Decisions, and Implications for Adaptation. Jennifer Olson, Eric Crawford, Ayala Wineman, Brian Mulenga, Lydia Chabala, and Elias Kuntashula. PowerPoint presentation given at Chrismar Hotel, Lusaka, Zambia, Afternoon April 10, 2014.

10. Latest results on Climate Change and Variability Impacts on Crop Productivity in Zambia. Jennifer Olson, Gopal Alagarswamy, Jeff Andresen, and Nathan Moore. Presented at IAPRI, Lusaka, Zambia, August 19, 2014.

11. Modeling Climate Change Impacts on Farm Households in Zambia. Ayala Wineman, Eric Crawford, and Brian Mulenga. Presented at Chrismar Hotel, Lusaka, Zambia, Afternoon April 10, 2014.

12. Modeling Climate Change Impacts on Farm Households in Zambia. Ayala Wineman, Eric Crawford, and Brian Mulenga. Presented at IAPRI, Lusaka, Zambia, August 19, 2014.

13. Multidimensional household food security measurement in rural Zambia. Ayala Wineman. Selected presentation at the Agricultural and Applied Economics Association Annual Meeting, July 27-29, 2014, Minneapolis, MN.

14. Overview and current results of studies by IAPRI, MSU, and UNZA on climate change trends and impacts in Zambia. Jennifer Olson, Eric Crawford, Ayala Wineman, Lydia Chabala, and Elias Kuntashula. Presented at IAPRI, Lusaka, Zambia, April 8, 2014.

15. Year 2.5 Progress Report. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford and Jennifer Olson. USAID/Kenya, March 5, 2014.

<u>FY 2015</u> (October 1, 2014, to April 30, 2015 = Project end date)

16. Climate change and crop choice in Zambia: A math programming approach. Ayala Wineman. Presentation at Graduate Student Research Symposium, Dept. of Agricultural, Food, and Resource Economics, Michigan State University. March 2015. Best Presentation, Work in Progress category.

17. Climate Change and Variability Effects on Crop Growth, and Technology Options for Kenya. Jennifer Olson, Gopal Alagarswamy, Jeff Andresen, Joseph Maitima, Nathan Moore, Michigan State University & Ecodym Africa. Presentation at USAID-Kenya, Nairobi, April 9, 2015.

18. End-of-Project Report. Eric Crawford, Jennifer Olson, and Ayala Wineman, Michigan State University. Presentation at USAID, Washington, D.C., April 23, 2015.

19. Modeling Climate Change Impacts on Farm Households in Kenya. Eric Crawford and Ayala Wineman, Michigan State University. Presentation at USAID/Bureau for Food Security, Nairobi, Kenya, April 9, 2015.

20. Modeling Climate Change Impacts on Farm Households in Zambia and Kenya. Ayala Wineman and Eric Crawford, Michigan State University. Presentation at USAID/Bureau for Food Security, Washington, D.C., November 17, 2014.

21. Multidimensional household food security measurement in rural Zambia. 2015. Ayala Wineman. Selected presentation at the Future of Food and Nutrition Graduate Research Conference, April 11, Boston, MA.

22. Year 3 Latest Results. Improved Modeling of Household Food Security Decision Making and Investments Given Climate Change Uncertainty. Eric Crawford, Jennifer Olson and Ayala Wineman, Gopal Alagarswamy, Jeff Andresen, Joseph Maitima, Nathan Moore and Brian Mulenga. Presentation at USAID, Washington, D.C., November 17, 2014.

Annex E: Project-related Trips

FY 2012

1. November 5-15, 2011: Co-PIs Crawford and Olson traveled to Zambia to meet and discuss joint research activities with individuals involved in climate change and agricultural development research at the University of Zambia (UNZA), agricultural research institutions, ministries and the Food Security Research Project and Indaba Agricultural Policy Research Institute (FSRP/IAPRI) team.
2. February, 2012: Crawford and Olson, with MSU climatologist Jeffrey Andresen, traveled to Kenya (Feb. 5 to 8) and to Zambia (Feb. 8 to 16).
3. September 18-21, 2012: Crawford and Olson traveled to Washington, D.C., to present a progress report on Year 1 at USAID (presentation on September 19, 2012).

FY 2013

1. July 2013: Eric Crawford and Jennifer Olson traveled to Kenya on July 7 to 13, and to Zambia on July 13 to 20.

FY 2014

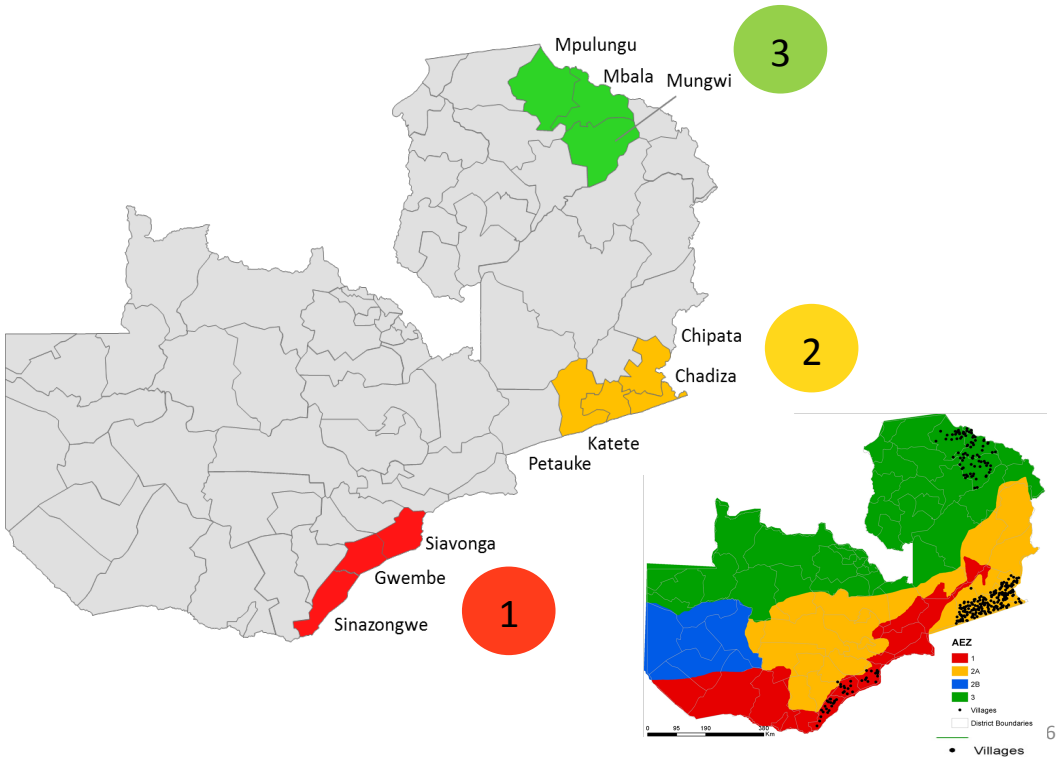
1. October 27-28, 2013: Crawford and Olson traveled to Washington, D.C., to present a progress report on Year 2 at USAID (presentation on October 28, 2013).
2. March 2014: Eric Crawford and Jennifer Olson traveled to Kenya from March 1 to 12 to launch focus group discussions and to meet with staff from the Tegemeo Institute regarding collection additional data for the farm household models.
3. April 2014: Eric Crawford, Jennifer Olson, and Ayala Wineman traveled to Zambia from April 5 to 12 to make presentations as part of an IAPRI-organized policy conference held on April 10.
4. August 2014: Eric Crawford and Jennifer Olson traveled to Zambia from August 16 to 24 to make end-of-project presentations to IAPRI, USAID, and other stakeholders.
5. September 2014: Eric Crawford and Jennifer Olson traveled to Kenya from September 26 to October 1 to follow-up on in-country focus group discussions and secondary data collection activities.

FY 2015

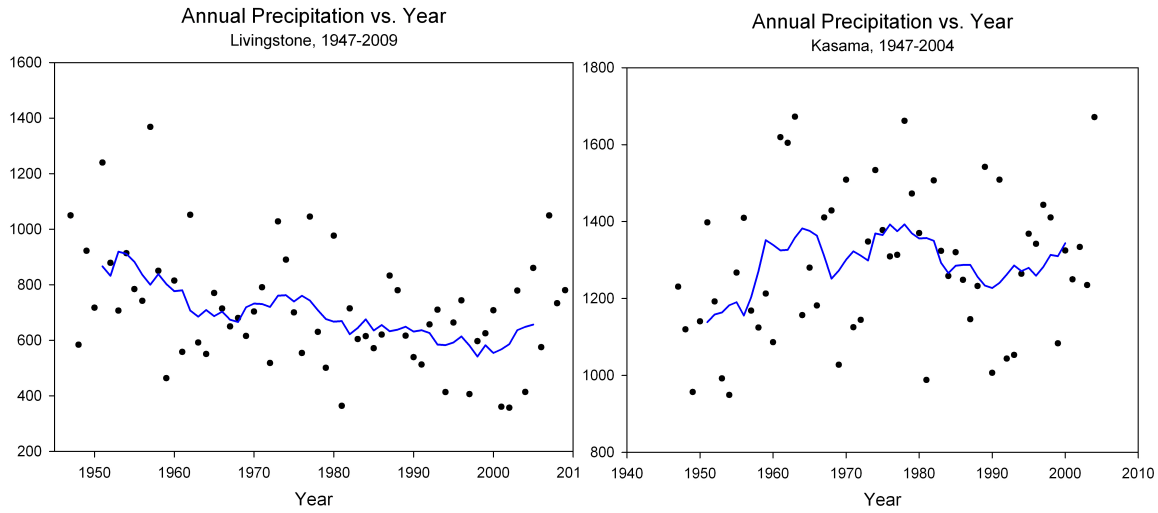
1. October 2014: Ayala Wineman traveled from Tanzania to Kenya to participate in a policy conference (funded under another grant), and to consult researchers at the Tegemeo Institute and KARI regarding additional data sources for the farm household modeling.
2. November 2014: Eric Crawford, Ayala Wineman, and Jennifer Olson traveled to Washington, D.C., from November 16 to 17, to present a progress report on Year 3 at USAID (presentation on November 17).
3. April 2015: Eric Crawford and Jennifer Olson traveled to Kenya from April 7 to 11 to make an end-of-project presentation to USAID/Kenya (presentation on April 10).
4. April 2015: Eric Crawford, Ayala Wineman, and Jennifer Olson traveled to Washington, D.C., from April 23 to 23 to make an end-of-project presentation to USAID and to hold related meetings (presentation and meetings on April 23).

Annex F: Figures

Figure 1. Study Sites in Zambia



Figures 2 and 3: Nine-year moving average trend line in annual precipitation in Livingstone and Kasama, Zambia.



Data source: Zambia Meteorological Department.

Figures 4 and 5: Simulated maize yield in Zambia in 2050 with low (5 kg/ha, on left) and moderate (85 kg/ha, on right) nitrogen fertilizer application. Maize cultivar: 700 series. GCM: HadCM3.

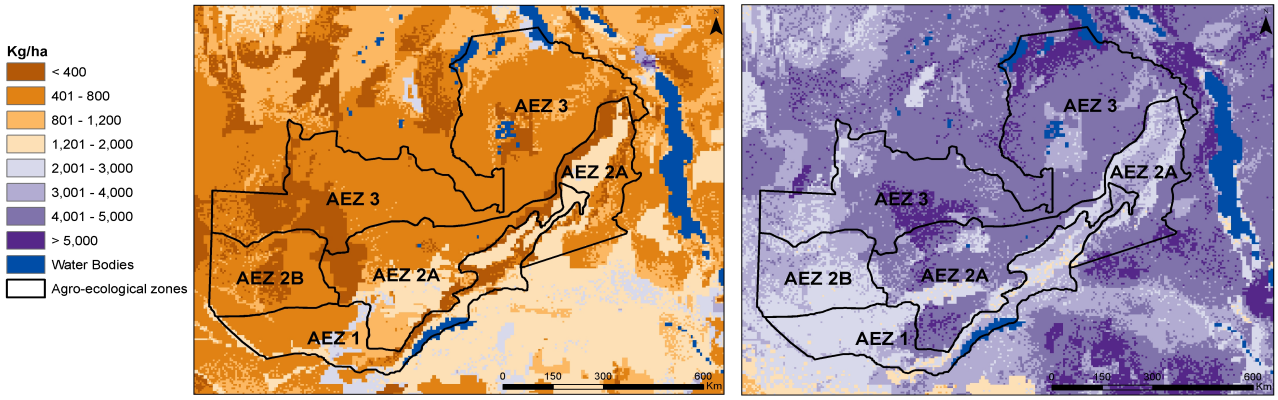
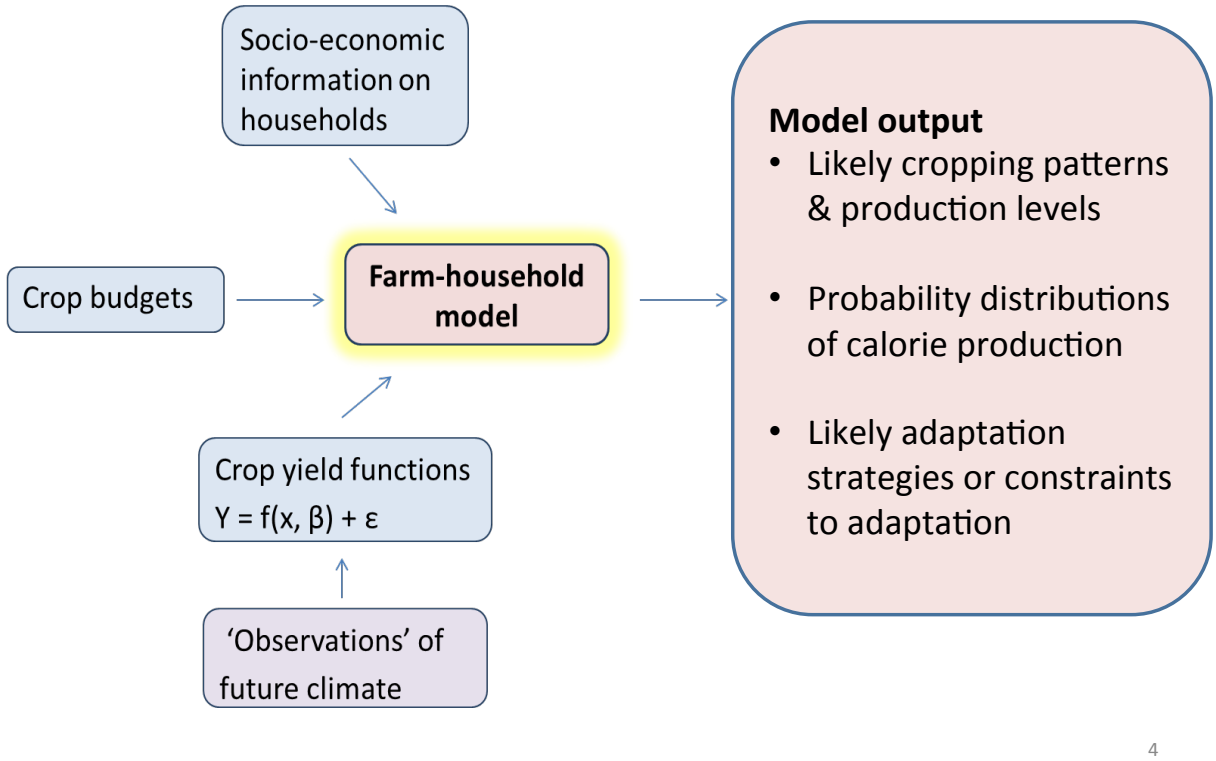
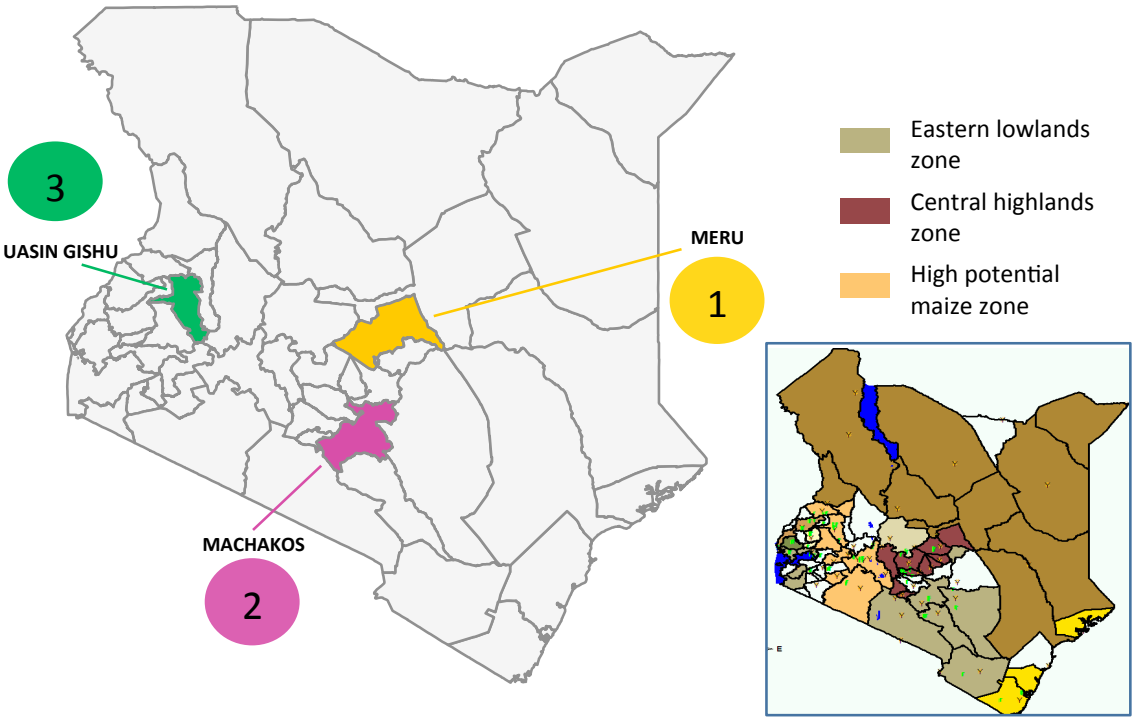


Figure 6. Basic Structure of the Farm Household Model



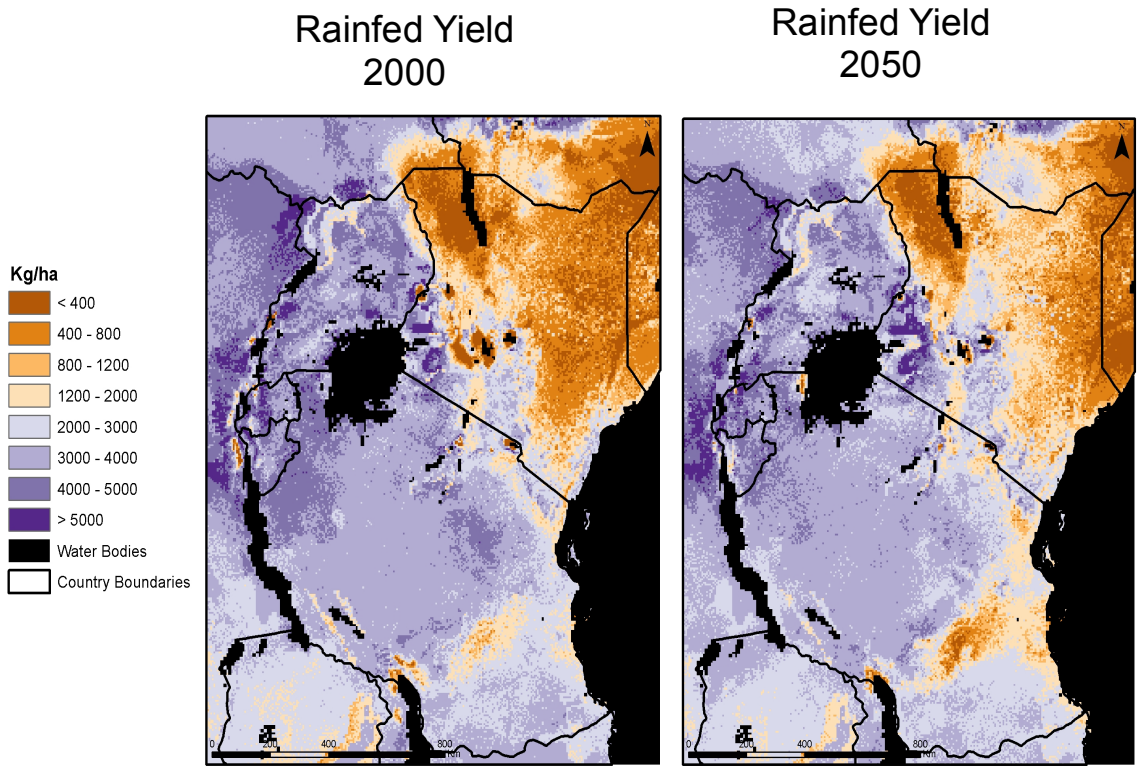
2000 2050

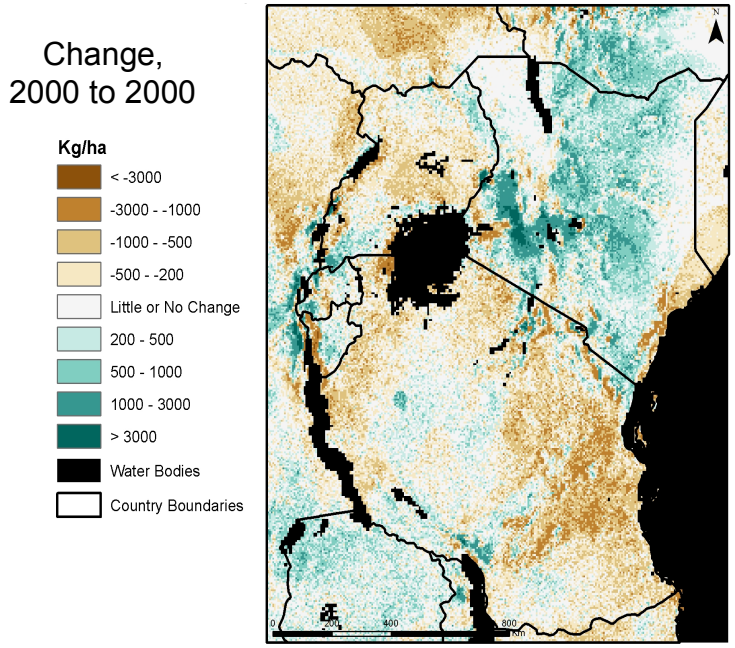
Figure 7. Study Sites in Kenya



8

Figures 8, 9 and 10. Simulated maize yield in East Africa in 2000 and 2050, and change in yield between 2000 and 2050. Maize cultivar H614, 85 kg/ha N, GCM HadCM3.





Figures 11 and 12. Simulated potential maize yield in East Africa in 2000 and 2050, with supplemental irrigation (maize cultivar H614, 85 kg/ha N, GCM HadCM3).

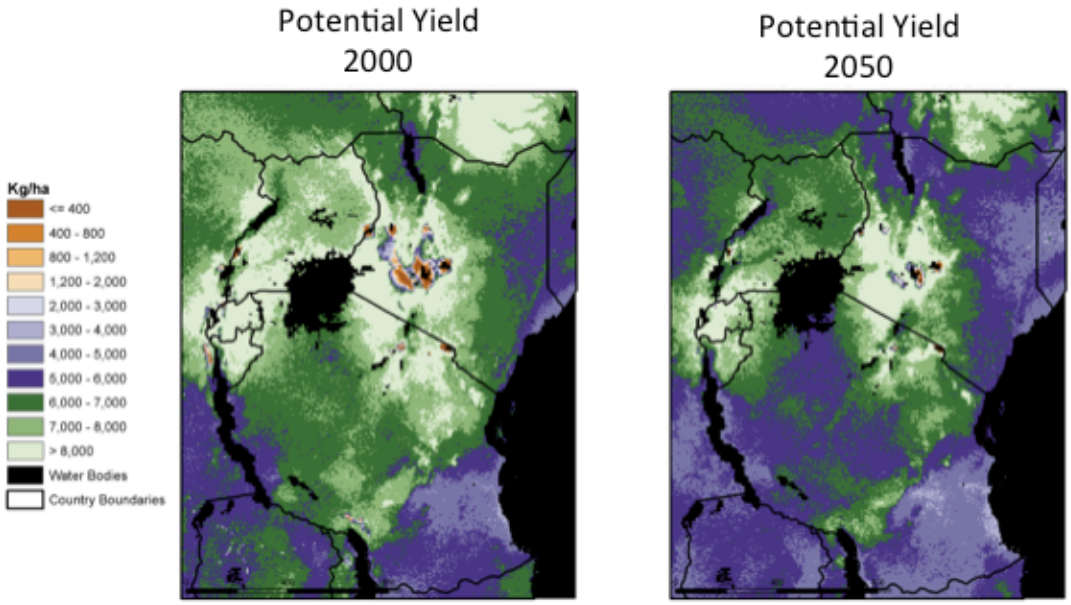
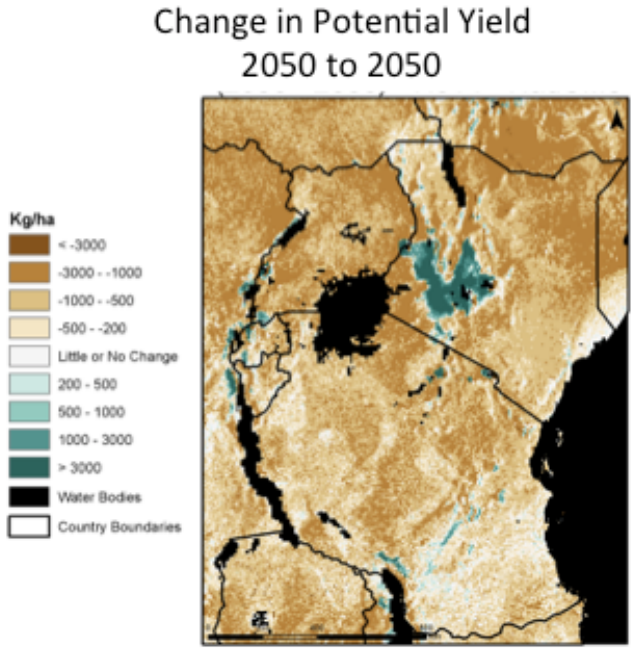



Figure 13. The change in simulated potential maize yield between 2000 and 2050, reflecting the impact of climate change on irrigated maize yield (maize cultivar H614, 85 kg/ha N, GCM HadCM3). Brown indicates declining yield, cyan increasing yield.