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Impacts of Climate Change on Rice and Maize, and Opportunities to Increase Productivity and Resilience in Malawi

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Acronyms

ANUSPLIN	Software developed by the Australian National University for transparent analysis and interpolation of noisy multi-variate data using thin plate smoothing splines
AR5	Fifth Assessment Report
CCSM	Community Climate System Model
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CSIRO	Commonwealth Scientific and Industrial Research Organization
DSSAT	Decision Support System for Agrotechnology Transfer
ECHAM	Global Climate Model developed by the Max Planck Institute for Meteorology
ET	Evaportranspiration
FAO	Food and Agriculture Organisation
FAOSTAT	Online database provided by FAO
GCFSI	Global Center for Food Systems Innovation
GCMs	Global Climate Models
GIS	Geographical Information System
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institute Pierre Simon Laplace Global Climate Model
IQR	Interquartile Range
LUANAR	Lilongwe University of Agriculture and Natural Resources
MADD	Malawi Agricultural Development Division
MPI	Max Planck Institut für Meteorologie Earth System Model (NOTE: both ECHAM and MPI are from Max Planck, but are different global climate models.
MSU	Michigan State University
NASA	National Aeronautics and Space Administration
NSO	National Statistical Office
RCMs	Regional Climate Models
SRES	Special Report Emissions Scenarios (of the IPCC)

Acknowledgments

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Executive Summary

The goal of the Malawian Innovation Activity project, "Improving Food Security and Resilience to Climate Change," is to provide new information for the Malawian government, researchers, and communities to improve Malawian crop productivity, and enhance the resilience of the country to climate change and climate variability. The Malawian Innovation Activity is an undertaking of the Michigan State University (MSU) Global Center for Food Systems Innovation (GCFSI). GCFSI is one of eight development labs funded by the US Global Development Lab at the United States Agency for International Development (USAID). The GCFSI Malawian innovation activity's focus is on how multipurpose legumes may be scaled for sustainable intensification of maize systems, and what the potential impacts would be across the food system in Malawi. Other GCFSI researchers examined issues related to multipurpose legumes, so this team was asked to examine maize, which is the main crop usually grown with multipurpose legumes and rice, which is another major food crop in Malawi.

Among the questions addressed is, what are the geographic patterns of maize and rice productivity currently, and how would climate change alter that productivity pattern? The results show where scaling may be most productive now and in the future. Also addressed is what potential agronomic practices would promote climate resilience in the maize/legume and rice systems, and where those practices would provide the best effect. To answer these questions, we first analyzed recent climate trends in Malawi, and identified how rice and maize are sensitive to climate changes. We then linked climate data to the DSSAT crop model to examine how climate affects crop growth and productivity. The climate data used included historical data from the Malawian meteorological agency and other historical climate data, and projected future climate data from four downscaled global climate models (GCMs). These modeling results cover the entire country, so findings are in the form of maps. The crop model was calibrated to Malawian environmental conditions and crop varieties. This allowed us simulate the impact of recent and future climate changes on crop productivity across Malawi. We then conducted scenario analyses with the crop-climate modeling framework to test the effectiveness of agronomic practices (especially nutrient and water management) to increase current yields, and to reduce the negative impact of projected future climate change. Finally, we conducted a literature review and key informant interviews regarding climate change impacts and adaptations at the community level, and prepared a summary of Malawian governmental climate change and agriculture policy (Zulu 2017). The MSU team is composed of Jennifer Olson, Gopal Alagarswamy, Jenni Gronseth, Nathan Moore and Leo Zulu. They worked with Lilongwe University of Agriculture and Natural Resources (LUANAR) researchers Alexander R. Phiri and Josephine Zimba. Olson and Zulu traveled to Malawi in July and August 2014 to meet with the LUANAR researchers; and with Zimba, they visited key governmental agencies, such as the Department of Climate Change and Meteorological Services, the Ministry of Agriculture, and the Lifuwu Rice Research Station. They also met with farmer organizations and irrigation schemes in southern and central Malawi.

Maize, rice and legumes are sensitive to climate change and variability. Indeed, Malawi is among the world's dozen most vulnerable countries to the adverse effects of climate change, and among those with the least resources to adapt. This threatens food security and the livelihoods of 85% of Malawi's predominantly rural population, most of whom are dependent on low-input, rain-fed agriculture.

The analyses concluded that the climatology of Malawi is fairly supportive of agricultural production. Much of the country does not suffer from extreme temperatures and receives adequate precipitation for one harvest per year. Precipitation varies across the country, however, with the highlands, lakeshore, and south receiving adequate precipitation to support rice and other high value commodities, and much of the rest, particularly the central region, receiving only modest amounts. Similarly, temperatures vary from cool/cold temperatures in the highlands to warm/hot temperatures, especially in the lowland zones in the south.

In the already warm south, temperatures are steadily rising, and the frequency of hot days is increasing. This is critical because rice and maize are sensitive to hot temperatures over 35°C (95°F), especially during the flowering stage, since even a day of extreme heat can cause sterility. In the south, the number of days with hot temperatures is probably already reducing yield. In the southern and central regions, total seasonal precipitation is highly variable and there is no clear trend in changes season amounts. However, it is reported that a dry spell in mid- January to mid-February appears to becoming more intense, and the rainy season onset is often delayed and rainy season may be shortening. These would cause poor establishment of crops and low production, especially if the dry spell is during the flowering stage. In the north, our data shows declines in precipitation, particularly in March and April. The total amount of precipitation is still relatively high, however. There are, however, fewer cloudy days and more hot, sunny days.

In the future, Malawi is expected to become significantly warmer, with an increase between 1.5°C and over 3.5°C by 2050. Projected changes in precipitation are not consistent between GCMs, but the projected changes in total rainy season precipitation are not large. The projected changes are smaller than current inter-annual variability in some locations. Indeed, what GCM mapped results do not reflect is the increase in precipitation extremes and variability that is expected due to climate change.

The crop-climate simulations provide information on several management aspects related to the impact of climate change. They include the following:

1. In locations of sufficient rainfall and moderate temperatures, such as in the northern and central region stations examined, rice and maize yields can attain high levels and response rates to fertilizer are high. Leaching of nitrogen during high rainfall years reduces yields, especially under lower nitrogen applications. This would call for recommendations of multiple doses of fertilizer throughout the season. Fertilizer and other soil improvement practices would, therefore, be a critical, no-regrets option for adaptation to climate change.

2. By addressing low nutrient levels, maize yields in the future may be expected to remain at the 4,000 kg/ha level and higher across the highlands and plateau regions. In the south, however, the expected future warming added to current warm temperatures will negatively affect maize production, and yields are expected to decline. Returns to fertilizer in these hot conditions would be low.

3. In locations of lower rainfall and warm temperatures, water deficits constrain yield, and yield variability is high. Under these conditions, fertilizer response rates are much lower. The yield in Kasinthula, the station with warmest temperatures and lowest rainfall, is suppressed because of both water stress and the direct effects of hot temperatures on the plants. Under these conditions, irrigation during the rainy season would improve yields and fertilizer response rates, but the warm temperatures could still constrain yields.

4. The simulations illustrate a critical climate change effect on rice and maize, that of hot temperatures directly lowering yield. A large impact on rice was apparent after 2005 in the southern stations. Simulated yields in one station were halved due to the impact of extreme temperatures. Frequencies of hot days is already increasing in all regions, and will continue to become more frequent. There are few management factors that would reduce the direct impact of hot temperatures, other than selecting varieties that may be less sensitive.

5. Our results showed that winter rice production depends almost entirely on irrigation water, and that the plants are susceptible to breaks in water availability particularly during seedling establishment and flowing stages. With warming temperatures, water demands will rise. There is already increasing competition for available irrigation water, and climate change will exasperate the problem.

In summary, climate change is already impacting crop productivity and farmers in Malawi, and the effects of climate change are expected to intensify in the future. Although adaptation strategies are being promoted and some farmers, particularly those with more resources, are adopting them, the future warmer temperatures and worsening water deficits will restrict their ability to maintain current yield. The impact of current and projected future climate change on crops varies across the country, and these results inform potential scaling. The region that will be most affected, and that is already suffering the effects of warming temperatures, is the south.

Central Malawi will be increasingly affected but not at the same level. The agriculture in northern Malawi, since its initial climate is wetter and cooler, will not be as severely impacted.

1. Introduction

The goal of the Malawian innovation activity, "Improving Food Security and Resilience to Climate Change," is to provide new information for the Malawian government, researchers, and communities to improve Malawian crop productivity, and enhance the resilience of the country to climate change and climate variability. Malawi is prone to climate variability and extremes that put its food security situation at risk. Strengthening its agricultural system while taking into account current and future climatic risks is critical. This technical report provides results of our research on the impact of climate change and variability on rice and maize, two major crops in the country, and then identifies the potential impact of improved agronomic management practices, including fertilizer and irrigation, on crop yield using a coupled climate- and crop- modeling framework.

Although small, Malawi has a varied agro-ecology ranging from hot, lowland zones to cool and temperate highlands. The long coastline of Lake Malawi provides an important resource for irrigation. Climate change is expected to affect regions of the country differently. The identification of the potential effectiveness of improved agricultural practices would, therefore, need to consider the varied geography—soils, climate, water availability and elevation—in its analysis to provide location-specific recommendations and activities.

To do this, we built on MSU expertise, databases, and calibrated models, and collaborated with Malawian scientists and researchers. A collaborative process led to an experimental design that tested Malawian crop cultivar characteristics and crop management practices under current and future climate conditions. The results can inform agronomic research to develop cultivars and practices to improve current yields and reduce the negative effects of climate change. It also provides critical information for agricultural extension services, and national level policy and planning.

This report begins by providing background information on rice and maize in Malawi, and how the two crops are vulnerable to climate change. It then describes the methodology and datasets used in this study. The next section presents data describing the climatology, and recent and projected future climate trends, in Malawi. Results are then provided on the impact of recent climate change and variability, and projected future climate change, on rice and maize productivity. Implications of using fertilizer or other management practices to reduce the negative effect of climate change are discussed.

2. Background on Rice and Maize in Malawi

Rice and maize are major food and cash crops in Malawi, and are central to smallholder farming systems. Maize is the main food staple and is grown throughout the country; indeed, Malawi is often considered too dependent on this crop for its food and nutrition. Rice production, on the other hand, is concentrated in smaller locations of the country. It is a crop that is, however, growing rapidly in importance, especially in urban markets. Farmers in many parts of the country are rapidly expanding their cultivation of rice.

This section provides a background to the production of rice and maize in Malawi, and summarizes their sensitivity to climate change and variability.

2.1 Rice Production in Malawi and Sensitivity to Climate Change

Rice (Oryza spp.) is a tropical plant that thrives in hot and warm climates. Rice grows best in warm daytime temperatures, but extreme heat events over 35°C for even a few hours can damage plant processes and lead to lower yields and sterility (Jagadish et al. 2007) (Figure 2.1). Rice is also sensitive to cold temperatures, which can slow growth and damage the plant causing smaller or failed harvests. Warmer minimum (nighttime) temperatures also reduce yields; it is estimated that yields decline 10% for every 1°C rise in minimum temperatures (Laborte et al. 2012; Welsh et al. 2010).
With climate change, temperatures are steadily warming in the Malawi. Hot temperatures over 35°C are becoming more frequent, and minimum temperatures are rising faster than maximum temperatures. Therefore, rice may be increasingly susceptible to warmer and extreme temperatures. On the other hand, higher elevation zones are warming rapidly and they may become more favorable for rain-fed rice production.

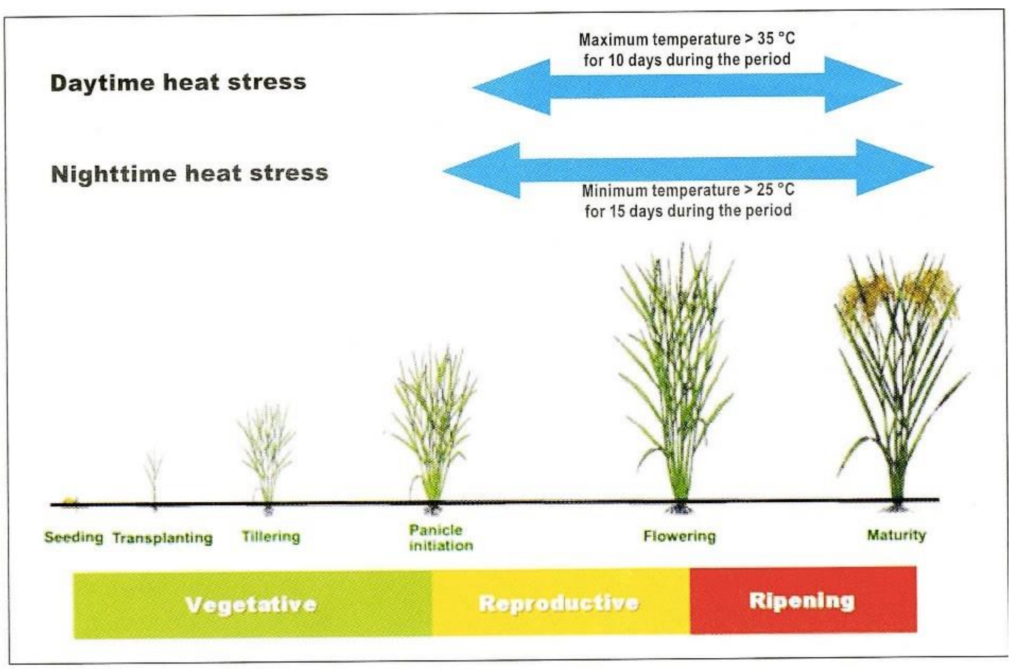

Figure 2.1. Heat stress thresholds at critical growth stages of rice. Source: Laborte et al. 2012.

Rice is also demanding of water, requiring substantially more than maize or other grain crops grown in Malawi. Depending on the variety (especially the duration of its growing cycle), it can require between 450 and 700 mm during its growing season, or between 900 and 2,250 mm/day (FAO 1985). Although it does not require continuously saturated soil, it grows very poorly if it is water stressed, particularly during its transplanting and reproductive stages.

In Malawi, much of the rice is grown during the rainy season under rain-fed conditions with minimal irrigation, so precipitation amounts and timing are critical. Increasingly, however, farmers are cropping two seasons of rice per year by growing an irrigated crop during the winter, the dry season. Rice production and yield are highest in the districts with higher rainfall and warm temperatures, i.e., along the lakeshore and in the lowlands of the Shire Valley especially near surface water sources for irrigation (Figures 2.2 and 2.3). Indeed, much of the rest of Malawi is either too dry or cool for rice production.

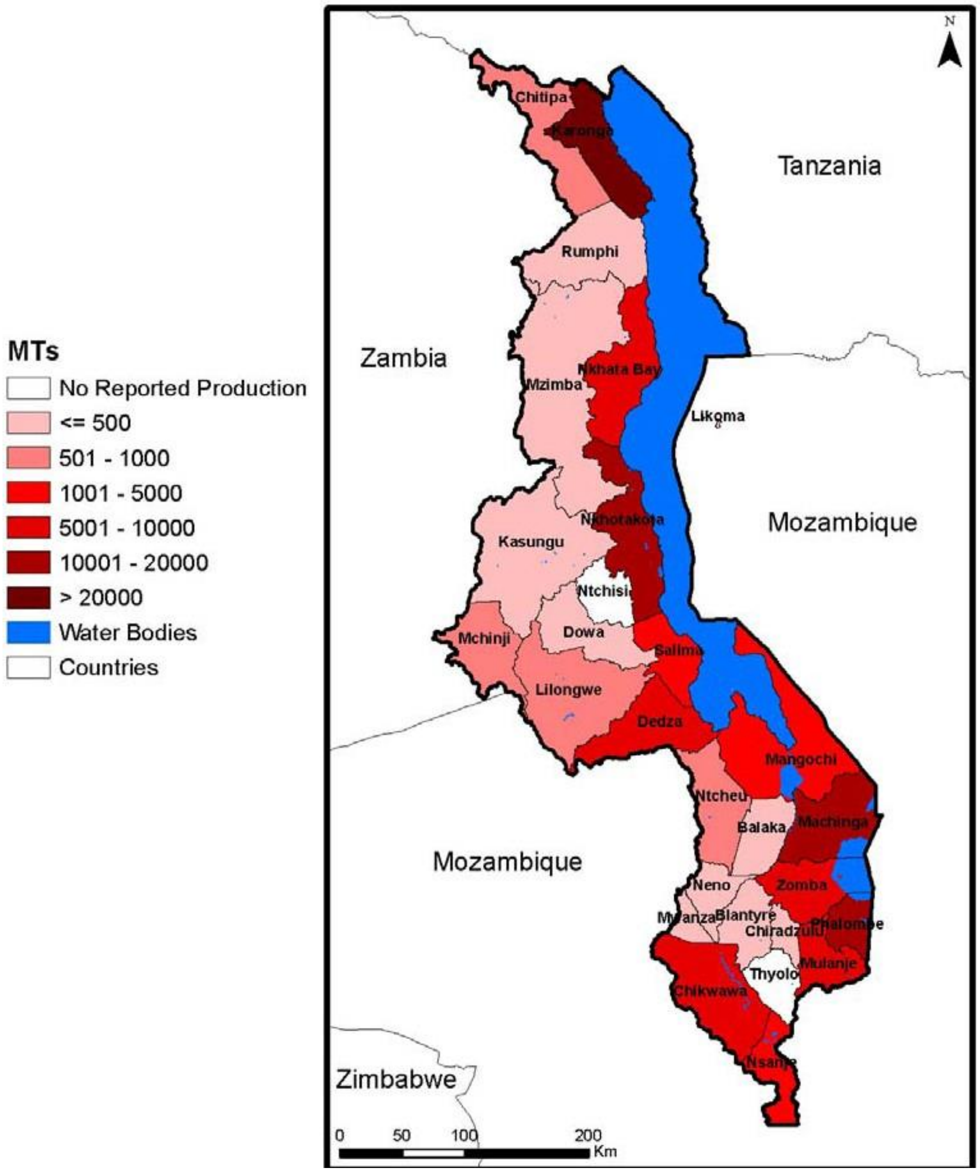

Figure 2.2. Map of rice production in 2012/13 by district. Data source: NSO 2014.

The increase in winter cultivation is leading to a rapid increase in the amount of rice produced nationally while the area harvested has risen at a slower rate (Figure 2.4). When rice production statistics are examined by the Agricultural Development Division, it appears that some divisions, particularly MADD in the southern lakeshore and Karonga in the north, are leading this rapid expansion in land cultivated and in production (Figures 2.5 and 2.6).[2]

2 See locations of Agricultural Development Divisions regions in Annex.

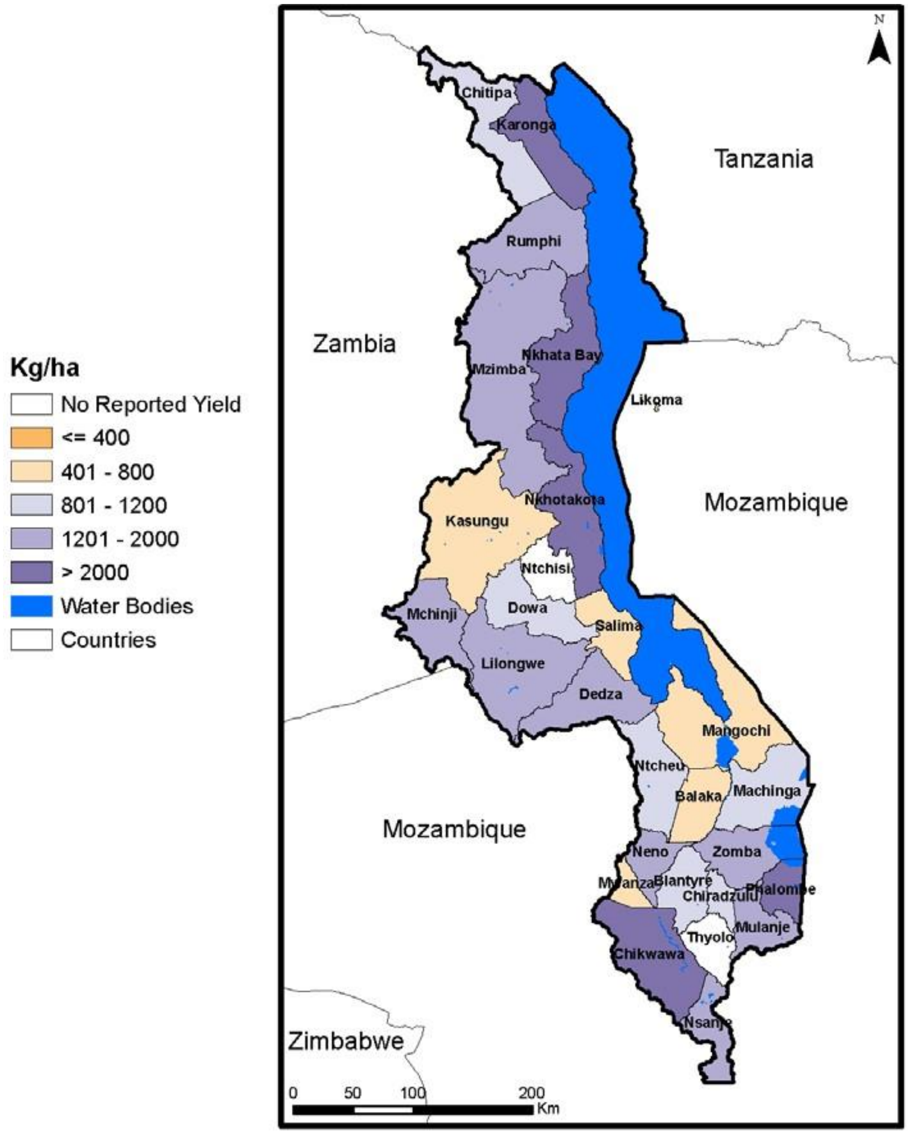

Figure 2.3. Map of rice yield in 2012/13 by district. Data source: NSO 2014.

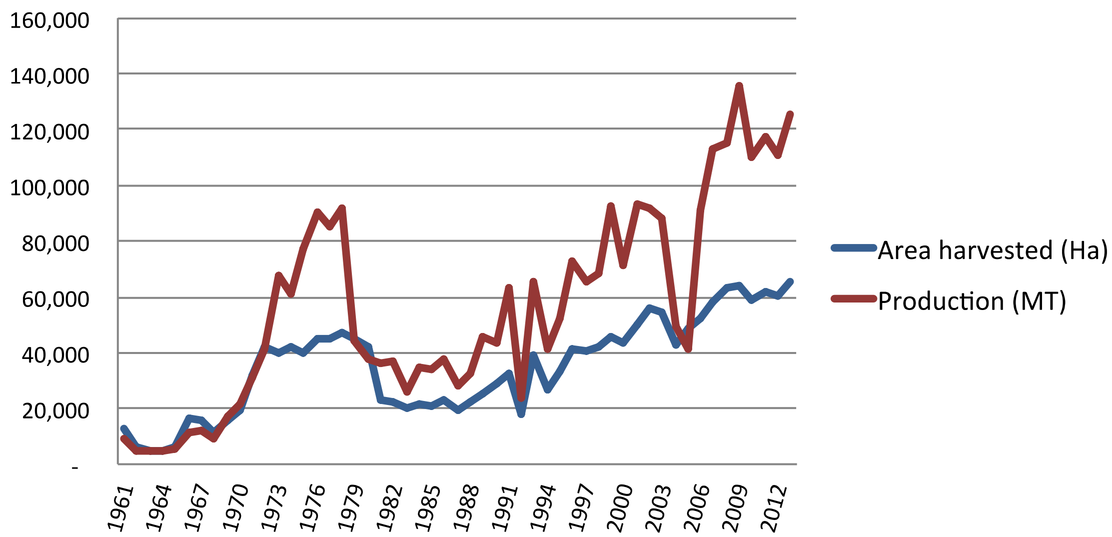

Figure 2.4. Malawi rice area harvested and rice production, 1961-2013. Data source: FAOSTAT 2014.

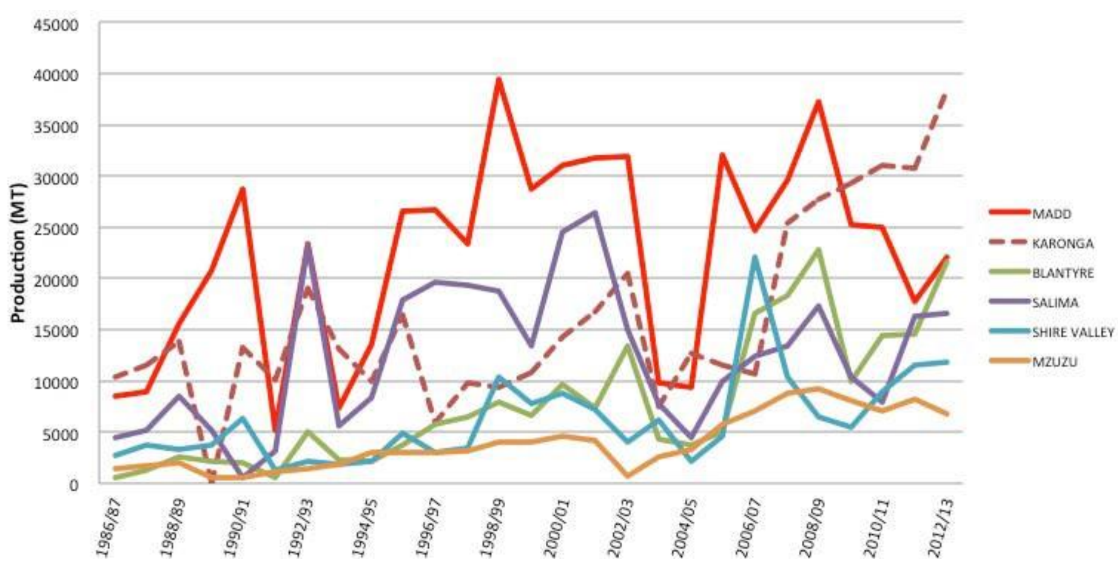

Figure 2.5. Rice production (MT) by agricultural development division, 1986-2013. Data Source: NSO 2014.

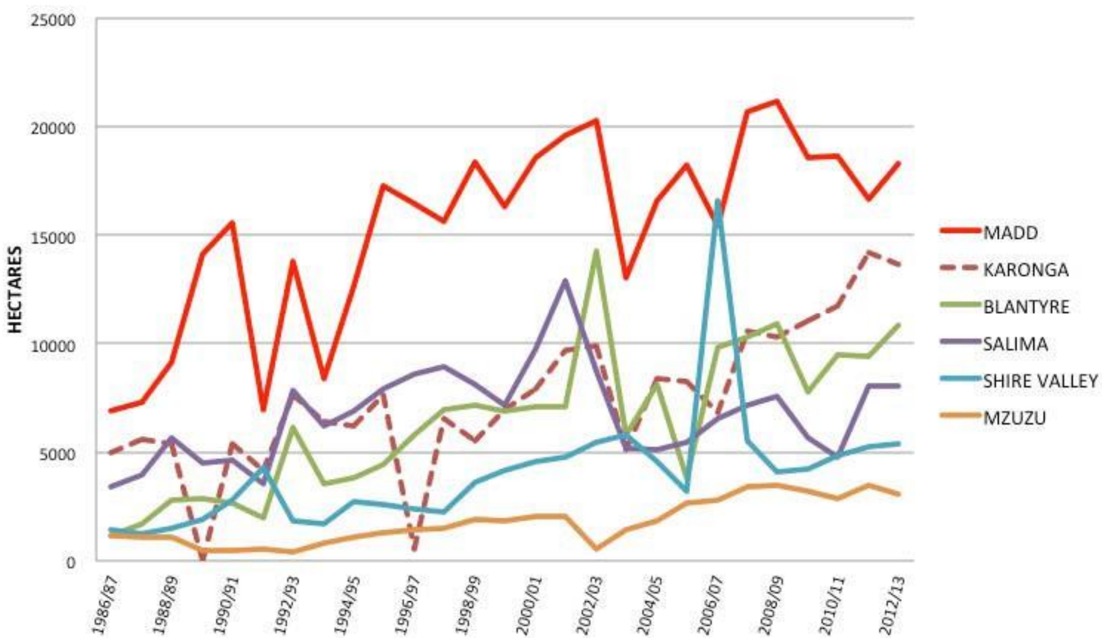

Figure 2.6. Land (ha) under rice cultivation by Malawi agricultural development division, 1986-2013. Data source: NSO 2014.

Rice yield statistics differ between FAOSTAT and the National Statistical Office (NSO), unlike the statistics for production and area harvested (Figure 2.7 and 2.8). According to FAOSTAT, rice yield increased dramatically between 1961 and 1975, and has been increasing at a slower rate since to current levels of around 2,000 kg/ha. NSO, on the other hand, shows little change in yield until around 2002, when yield statistics increased dramatically up to 8,000 kg/ha. The difference could be due to how double cropping (during the rainy season and the winter) is counted, and the increase in yield in the NSO statistics may be reflecting a rise in winter rice production.

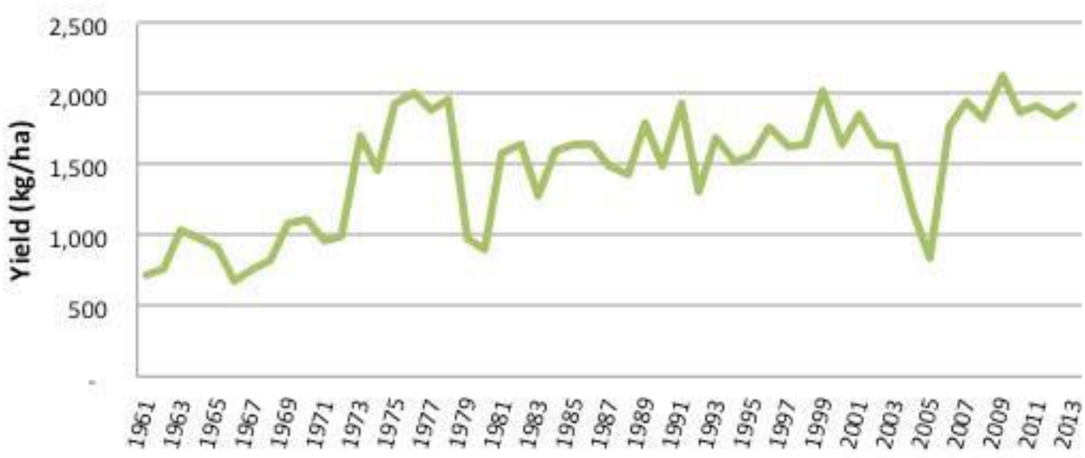

Figure 2.7. Rice yield (kg/ha) in Malawi, 1961-2013. Data source: FAOSTAT 2014.

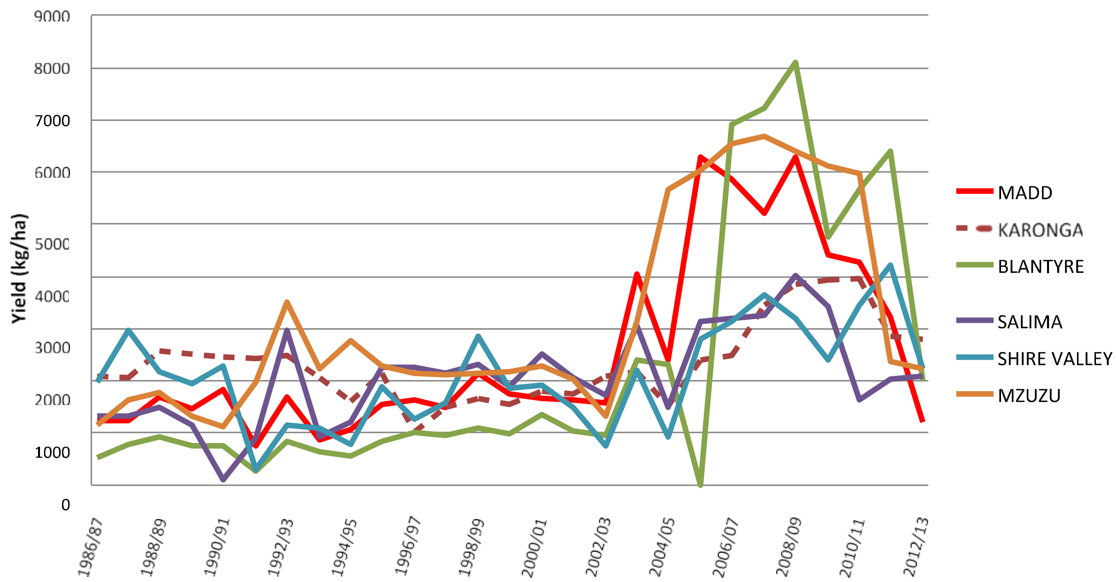

Figure 2.8. Rice yield (kg/ha) by agricultural development division, 1986-2013. Data source: NSO 2014.

The increased amount of land put into irrigated rice cultivation during the winter reflects the growing market demand for rice. However, it also reflects growing dependence on surface and shallow well water for irrigation. Farmers are reporting that there is increasing competition for this water between upstream and downstream users, and that climate change has reduced water availability. Growers in one rice scheme (Domasi in the Southern Region) reported that they have been forced to reduce their winter production from 75% to only 25% of their scheme's land due to the lack of irrigation water.

Growers in Domasi, Nkhate and other rice schemes reported that the main climate-related issue in rice production is a change in the rainy season. It starts later and ends earlier; this is causing a decline in production. The April, June and July rains brought by the *Chiperoni* winds that come from Mozambique have decreased and there is much less residual moisture in the soil for winter crops. In 2014, the rains ended early in May. They fear that this shift in the rainy season may threaten future rainy season and winter rice production.

2.2. Maize Production in Malawi and Sensitivity to Climate Change

Maize (*Zea mays*) is a tropical grass, yet is vulnerable to climate change. Its temperature range is greater than for rice, especially its ability to withstand cooler temperatures. However, its growth and yields are also affected by hot temperatures over 35°C; temperatures above 35°C are considered inhibitory at whatever stage of growth. Generally, the warmer the temperature, the faster the plant completes its life cycle (phenology). In warm temperatures like Malawi's, rapid plant growth can lead to lower yields because the plant (stem and leaves) mature before grains completely filled. Like rice, warmer nighttime temperatures reduce its yield while increasing its water demand (FAO 2013). Recent temperature trends in Malawi—more frequent hot days, warmer nighttime temperatures, and generally warmer temperatures—would thus negatively affect maize growth and reduce maize yields.

Water requirements for maize vary greatly depending on variety, soil and temperature, but generally it does best between 500 and 800 mm/growing season. However, yields are very sensitive to water deficits during the flowering period. Severe water deficits during that period, particularly at the time of silking and pollination, may lead to little or no yield, or to a reduction in the number of grains per cob (FAO 2013).

Maize is thus particularly vulnerable to breaks, or dry spells, in the rainy season that occur during silking. As mentioned above, the Malawian Department of Climate Change and Meteorology and farmers in Malawi have noticed an increase in the length and frequency of dry spells in mid-season, and this could threaten maize yields, especially when the dry spell coincides with the flowering stage. Other changes in precipitation, particularly in rainy season amounts and length, would also affect maize growth and yield in the country since the drier zones depend on rain-fed maize for their food security. Rising temperatures contribute to more rapid growth and thus evapotranspiration and water requirements. These factors, combined with declining precipitation, could significantly affect maize yields.

Despite these climatic considerations, maize production in Malawi is also highly tied to fertilizer application. The soils of Malawi are typically nutrient poor. When a government program supplying subsidized fertilizer and improved seed began in 2005/2006, yields and production increased dramatically despite the benefits being less than widespread (Pawl and Thurlow 2014; Figure 2.9). Yields went from a national average of around one ton per hectare to 3.5 tons per hectare (FAO 2014). Unlike rice, the increase in maize production in Malawi has been primarily due to increases in yield rather than to increases in the amount of land farmed.

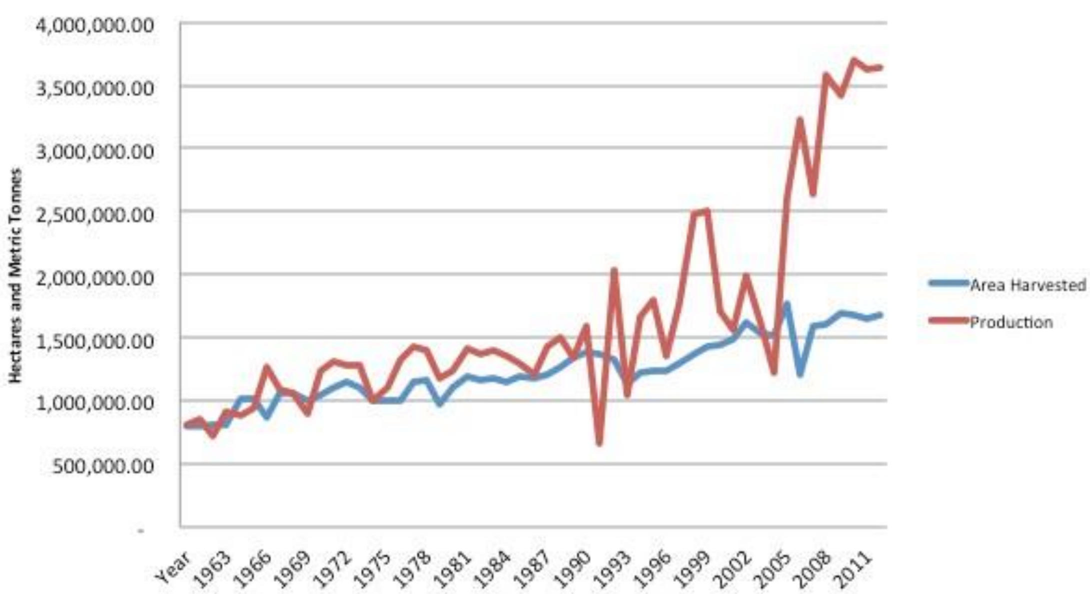

Figure 2.9. Maize area harvested (ha) and production (MT) in Malawi, 1961-2013. Data source: FAOSTAT 2014.

In summary, both rice and maize are vulnerable to aspects of climate change occurring in Malawi: more frequent hot days, warming temperatures (especially minimum temperatures), mid-season dry spells, and the shortening of the rainy season. For rice, these changes may particularly affect the winter growing season due to declining residual soil moisture and availability of irrigation water, but may increasingly affect the rainy season rice production as well. Maize is particularly vulnerable to mid-season dry spells and to any shortening of the rainy season. Warming temperatures with related higher evapotranspiration rates are expected to exasperate these changes in precipitation. The potential impact of future climate change will be examined below.

3. Methodology

For the requirements of this analysis, a suite of datasets and models have been used to analyze the impact of climate change and variability on rice and maize in Malawi. The approach of coupling climate and crop models for this type of research was developed by the team earlier for East Africa (Olson et al. 2009; Moore et al. 2012).

This section provides an overview of the methodology used. In summary, this has involved preparing and analyzing climate datasets for Malawi, preparing crop models for Malawi, and linking climate datasets to the crop models.

3.1. Historical Climate

Global climate models (GCMs) and associated regional climate models (RCMs) provide a general sense of trends in temperature, precipitation, and other climatic factors. They do not yet provide a good indication of how rainfall variability over time changes overall seasonal precipitation. The team therefore conducted an analysis of meteorological station data from the Malawi Meteorological and Climate Change Service to identify whether any recent changes in rainfall and temperature patterns are significant (but we were limited in the quality and availability of data; long-term data with few breaks is required to conduct statistical analysis of trends).

Due to the requirements of the crop model for daily, continuous weather data, we needed additional historical data in addition to meteorological station data. To meet this requirement, we used a method to generate continuous data based on observed data. The new dataset was based on meteorological station data (mostly from 1961 and 2004). Monthly means were calculated and then 30 years of daily weather generated using MarkSim. The result was a 30-year daily precipitation dataset. The results represent that time period, but do not represent particular, individual years. This dataset is referred to as "1960s to 2000s" in Figure 5.1.

A new spatial precipitation dataset for Africa, known as "CHIRPS" (Funk et al. 2014) that covers 1982 to 2013 was also used; data was extracted from CHIRPS to obtain daily data for each rice station's location. CHIRPS is a daily spatial precipitation dataset developed with 0.05° resolution satellite imagery and meteorological observed station data. It is a new dataset that is still being refined; however, the project team has tested earlier versions of it in collaboration with Funk, and feels that it is comparable if not superior to similar datasets. CHIRPS data was extracted for the locations of the rice research stations. Historical temperature data was obtained from NASA (2014). CHIRPS precipitation is higher in some stations (e.g., Domasi) and lower in other stations (e.g., Kasinthula) than the 1960s-2000s supplemented observed dataset. Finally, a daily spatial weather dataset representing the current period was prepared using the monthly means data from "WorldClim" (Hijmans 2005).

Note that all the precipitation and temperatures datasets used are generated data to some degree, and thus would not be as accurate as observed data. The results are not meant to replicate reality, but to provide insights into the potential impact of climate variability and change on plants.

3.2. Projected Future Climate

To provide information on expected future climate conditions and potential impact on rice and maize, four general circulation models (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 HadCM3 being very dry), and two widely used models that are in the middle (CSIRO and ECHAM5). The downscaling was conducting using thin plate smoothing splines via the ANUSPLIN V4.3 software (Hutchinson 2002). These data were splined using latitude and longitude as independent variables for rainfall, and latitude, longitude, and elevation for temperature. Data were downscaled to the 6km surface using a second-order spline. Because splines do not fit all data points, the interpolated surfaces become significantly smoothed when compared to individual station data. We splined 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 difference between them in temperature, precipitation, and other variables represent the perturbed climatology due to enhanced greenhouse gases; these results are illustrated in the following maps of projected changes in precipitation and temperature.

The higher resolution downscaling better represents the high degree of spatial variation in climate due to the high relief and the large lakes of the region, and the impact of this climate variability on agricultural systems. A key finding from previous analyses conducted by this team using a regional climate model is the high degree of spatial heterogeneity of the impact on climate change on crops in East Africa, with, for example, climate change affecting highlands very differently from adjacent lowlands (Moore et al. 2011; Thornton et al. 2009). The higher resolution analysis would produce better understanding of this spatial heterogeneity, especially important for planning and program purposes.

In addition to the above GCMs whose data was linked to the crop models, precipitation change results for four GCMs from the new Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) scenarios are presented in Annex 1. They were selected for having the lowest systematic bias and interquartile range (IQR) error during their realizations of the 1981-2010 historical period for eastern Africa (Stocker et al. 2013; Otieno and Anyah 2013). The selected models are CCSM (USA), IPSL (France), MPI (Germany), and MRI (Japan). Results from the high or runaway (RCP8.5, right side) representative concentration pathways (RCPs) or levels of greenhouse emissions are provided. Illustrated are projected results of changes in precipitation from current to mid-century periods during the March-April-May and the October-November-December periods.

3.3. Crop Modeling

Crop models simulate the growth of crops, such as rice and maize, under various conditions. They can replicate the impact of individual or a combination of changes in temperature, water, nutrients or other management factors on crop growth and production. Dynamic crop growth models in particular, which simulate the daily growth patterns responding to daily changes in the plant's environment, are useful in identifying the impact of dry spells, extreme temperature events, or other within-seasonal events.

For this project, we selected two dynamic crop growth models: the CERES Maize and the CERES rice model embedded in the Decision Support System for Agrotechnology Transfer (DSSAT) crop modeling framework (Hoogenboom et al. 2010). DSSAT version 4.5 was used. The DSSAT crop models have been extensively tested in many parts of the world. Jones et al. (2003) refer to 15 studies in Africa that involved detailed crop model calibration and validation, several of which involved the testing of CERES-Maize in Eastern and Southern Africa (Muchena and Iglesias, 1995; Thornton et al., 1995, 2009; Wafula, 1995; Schulze, 2000).

A challenge with crop models is calibrating the model to best replicate local conditions and observed plant growth and yield. This process is generally difficult in Africa and many other places due to limitations of available environmental data (soil characteristics and daily climate), detailed cultivar information, and measured plant growth and yield statistics. Our approach was to obtain as much data as available for Malawi or for similar locations, use globally available datasets as appropriate, and communicate with modeling and agronomic experts. In Malawi, results from rice research trials for six locations was available (Kanyika et al. 2007), so the rice model was prepared and validated with this data and other information provided by researchers at Lufuwu Rice Research Station. These are thus the six rice research stations represented in this study.

We conducted two types of analyses: the impact of historical climate variability on yield, and the impact of projected future climate change on yield. For the historical analysis, six meteorological stations were selected as nearest to the rice research stations (Table 3.1). Statistical analysis of meteorological station data from Karanga, Salima and Mimosa are presented in the Section 4.

The input climate data used in the historical crop modeling was from four sources, as described above. For precipitation, they include a point-level meteorological station-derived dataset, point-level extractions from CHIRPS version 1.8, and spatial datasets WorldClim and GCMs. For the crop modeling, the two point-level precipitation datasets were combined with daily temperature and solar radiation data from NASA's Prediction of Worldwide Energy Resource for the modeling (POWER) (NASA 2014). For the spatial crop modeling, the climate data came from WorldClim, which represents current climatic conditions (covering the period 1960–1990). To obtain daily data for the 30-year period, we used the weather generator MarkSim (Jones and Thornton2000). The projected future climate data was from the four downscaled AR4 GCMs, as described above.

Table 3.1. Rice research and associated meteorological stations.

Rice Station	Elev (m)	Associated Met Station
Lufilya	1110	Chitipa
Hara	619	Karanaga
Lifuwu	629	Salima
Mkondezi	503	Nkhtabay
Domasi	713	Mimosa
Kasinthula	145	Thyolo

The soil property data for the historical point-based modeling was obtained from a fairly new soils dataset for Africa with a 1 km resolution. It was created by ISRIC World Soil Information based on soil profile and other existing data (ISRIC 2013). For the spatial analysis, we used representative soil profiles from the International Soils Reference and Information Centre's World Inventory of Soil Emission Potentials (WISE) database (Batjes and Bridges, 1994), as modified and reformatted by Gijsman et al. (2007).

The rice model was calibrated to two cultivars grown in the region, the short-duration (120-140 day) Poussa 33, which is generally planted during the dry, winter season (July-November), and Kilombero, a long-duration (135-150 day) cultivar grown in the rainy season (November-April). The rice simulation was done during both seasons.

During the rainy season, it was grown as a rain-fed crop. During the off season (July- Nov), it was grown as a fully irrigated crop, since very little precipitation is received. Both rain-fed and irrigated crops were transplanted as 30-day-old seedlings. The rainy season crop was transplanted on December 25, and the off season crop was transplanted on July 20.

For the point simulations of the rain-fed main season rice crop, we used fertilizer urea at 25, 50 and 100 kg N/ha. The recommended amount is closer to 100 kg/ha, but many farmers apply 25 or 50 kg/ha due to resource constraints. In the modeling, half of fertilizer was applied at transplanting and the other half was applied 30 days after transplanting. For the fully irrigated crop, we used 100 kg N/ha as two equal doses with timing as per the rain-fed crop.

Since very small amounts of precipitation are received during the months between July and November, we used the automatic irrigation option of the modeling software. When moisture in top 30 cm of the soil falls below 50% of available soil moisture, the crop was irrigated to bring soil moisture back to field capacity. This prevents any water deficit during crop growth. On average during the 1983-2012 crop, it was irrigated with 484± 53.8 mm (mean ± SD) of water.

For the maize modeling, we used the CERES-Maize model (Ritchie et al., 1998) embedded in Decision Support System for Agrotechnology Transfer (DSSAT) v 4.5 (Hoogenboom et al. 2012). The DSSAT CERES maize model was calibrated for a maize cultivar type grown in the region, a long-duration, 700-series hybrid maize variety. It is a higher-yielding cultivar that requires more water and responds more to nutrients than shorter-duration or local varieties, and is thus more sensitive to climate changes. This report provides results of rain-fed maize, simulated under different nutrient (nitrogen) applications. We assumed current representative smallholder cultural practices for maize cultivation; planting was assumed to occur automatically once the soil profile received a thorough wetting at the start of the rainy seasons, and the crop was planted at a density of 4 plants/m2. A low input level of fertilizer (5 kg/ha) at planting approximates what a resource-poor small-scale farmer would use, and an 85 kg/ha of mineral nitrogen fertilizer applied at planting time and 45 days after planting was used to represent a medium-scale farmer and to illustrate the potential benefit of fertilizer. Following methods described by Thornton et al. (2009) and using a proxy medium- to late-maturing maize variety, we simulated spatial variation of maize yield in Malawi at a subnational level (resolution of 6 km).

The crop models are designed to replicate conditions similar to agricultural research stations with excellent management and with no pest or disease problems. The effect of climate or other specific conditions are therefore clearer to identify. There are, therefore, differences in yields between those of crop models and research stations, and those of farmers' fields. This station vs. farmer field yield gap can be attributed to the following:

1. Tillage.
2. Spacing. Farmers may plant fewer seeds, and plant randomly.
3. Weeding can be a big problem.
4. Inadequate fertilizer application and soil management
5. Pests and diseases.
6. Soil degradation and erosion.

The combination of these and other factors, along with climate change, thus affects yields and food security. This report focuses on the impact of climate change and variability on maize and rice production, and examines the application of nutrients as a possible adaptation.

4. Climatology and Climate Trends

The climatology of Malawi is fairly supportive of agricultural production. It does not suffer from extreme temperatures, and much of the country receives adequate precipitation for one harvest per year. This generalization, however, masks the geographical variability in the country affecting the distribution and productivity of crops. Climate change and variability also has a major influence on agricultural production.

This section examines the climatology and climate trends in Malawi, and focuses particularly on the main rice producing areas.

4.1. Introduction to the Climate of Malawi

Temperatures in the country vary little between seasons. In most locations, the diunal variation between nighttime and midday is larger than the seasonal variation (Figure 4.1). Temperatures are closely related to altitude, with higher areas experiencing cooler temperatures than the lowlands (Figure 4.2). The lakeshore and large areas in the Shire Valley in the Southern Region benefit from both warm temperatures and high precipitation levels (Figure 4.3). Not surprisingly, these are the main rice production zones. Rain-fed rice is grown there during the rainy season with little to no irrigation. In areas of lower precipitation, maize and other crops dominate.

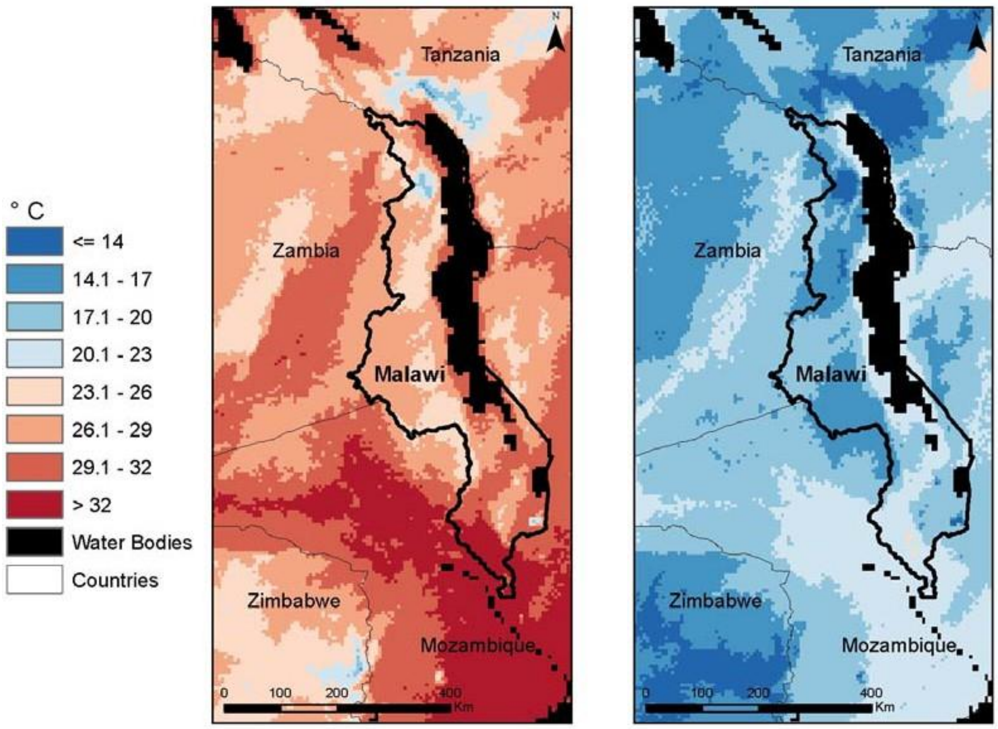

Figure 4.1. Maps of growing season average daily rainy season maximum (left) and minimum (right) temperatures (°C) ~2000. Data source: WorldClim (Hijmans et al. 2005).

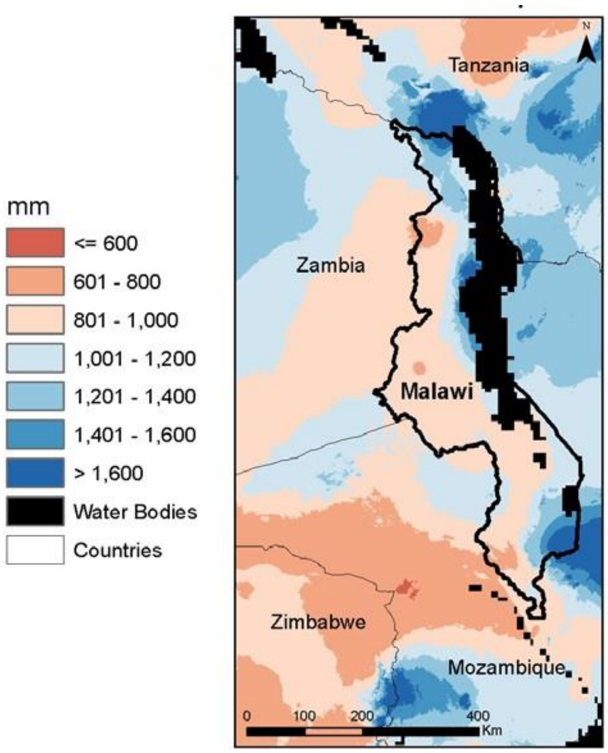

Figure 4.2. Map of total annual precipitation (mm) ~2000. Data source: WorldClim (Hijmans et al. 2005).

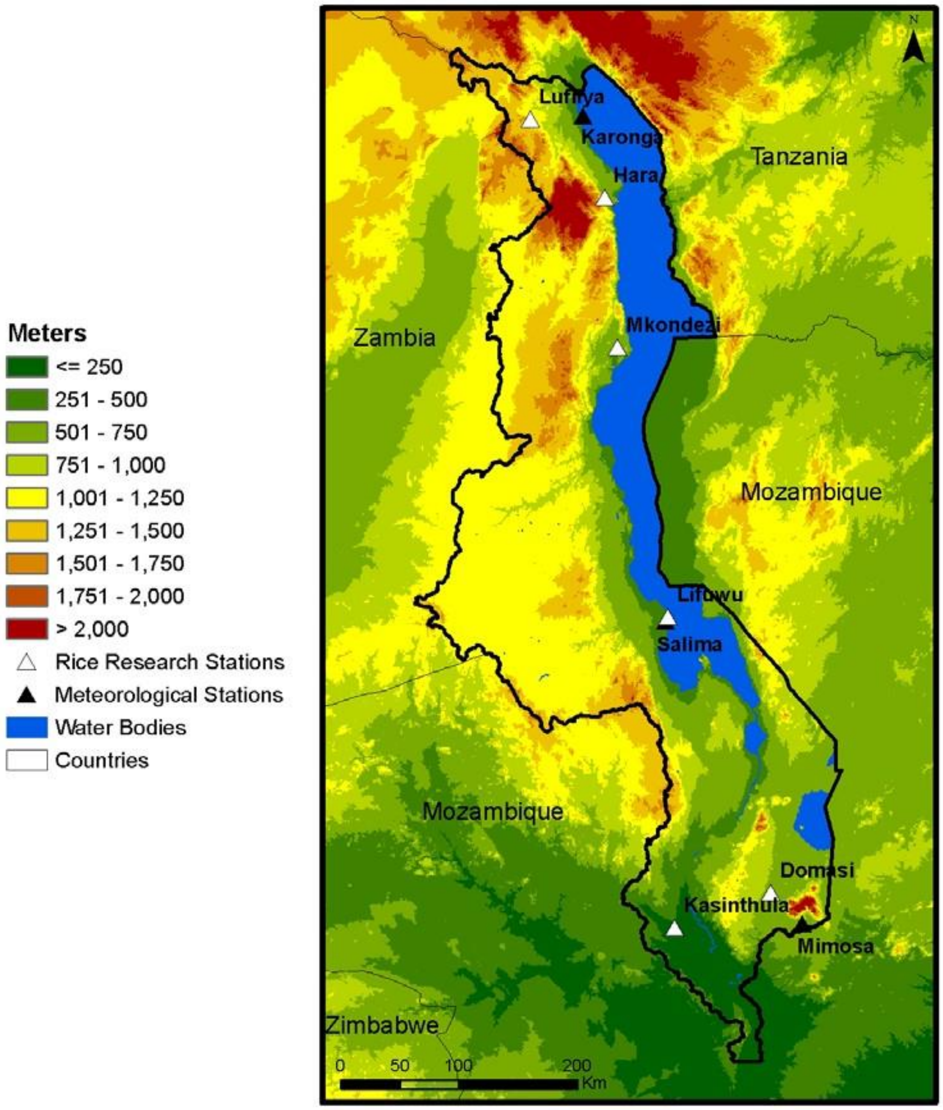

Figure 4.3. Map of elevation, and rice research and meteorological stations.

The rest of the section examines in more detail the climatology of three important rice production areas: the northern zone near the lakeshore using data from the Karonga meteorological station; the central zone also near the lakeshore using data from the Salima meteorological station; and finally the southern region using data from the Mimosa meteorological station (Figure 4.3). Although nearly on the same longitude, their latitude ranges from -9.95 degrees to -16.08 degrees. As illustrated below, this difference is sufficient to affect the seasonal timing of the rains and thus the agricultural calendar, and how climate change is affecting them.

4.2. Southern Region

The southern region of Malawi is a major rice producer, with its warm and wet climate, and lakes, rivers and streams available for irrigation. The Mimosa meteorological station is our selected station to examine for this report. It is the closest station to the Domasi rice scheme in the Shire Valley.

Mimosa, at 650 metres altitude, is in a wet zone receiving an average of more than 1,600 mm annual precipitation. The precipitation pattern is unimodal with the rains starting in October, peaking in January, and ending in May (Figure 4.4). Most of the annual precipitation falls during this growing period (averaging 1305 mm), but a moderate amount (averaging 342 mm) continues to fall during the winter (Figure 4.5). Even with inter-annual variability, the growing season precipitation was more than sufficient (in the 1961-2003 period for which we have observations) to support rice with the exception of one year.

During the winter season, precipitation rates decline rapidly, but it usually continues to fall if at a reduced level. This small amount of precipitation and residual soil moisture provides some moisture for planting sweet potatoes, beans or another crop. The available precipitation in the winter, however, is insufficient for rain-fed rice or most other crops without supplemental irrigation.

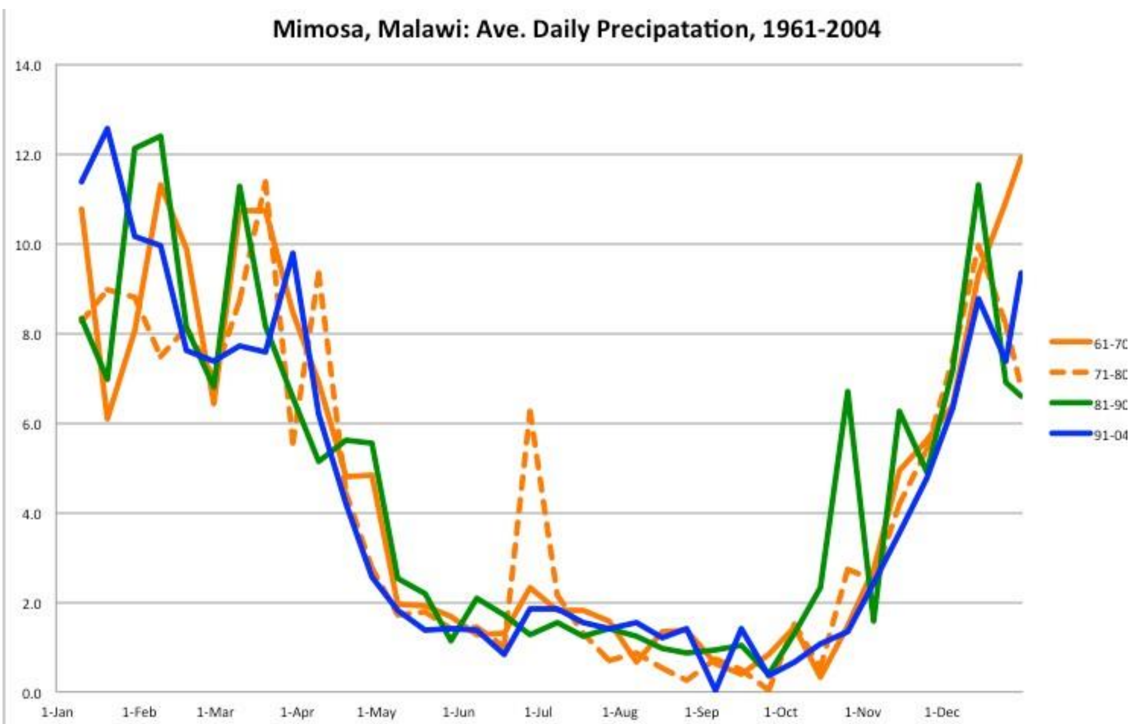

Figure 4.4. Precipitation (mm) in Mimosa during the year, 1961-2004; presented by decade. Data source: Malawi Meteorological Services.

There does not appear to be a change in the amount of growing season or winter precipitation during the time period for which we have meteorological station observations (1959 to 2003). Farmers' perceptions of declining precipitation and especially irrigation water in the winter may be related to 1) steadily warming temperatures leading to higher evapotranspiration and plant water requirements, 2) possible changes in the onset or duration of the rainy season, or increases in the duration or frequency of dry spells in the rainy season, and 3) increased water extraction upstream for irrigation.

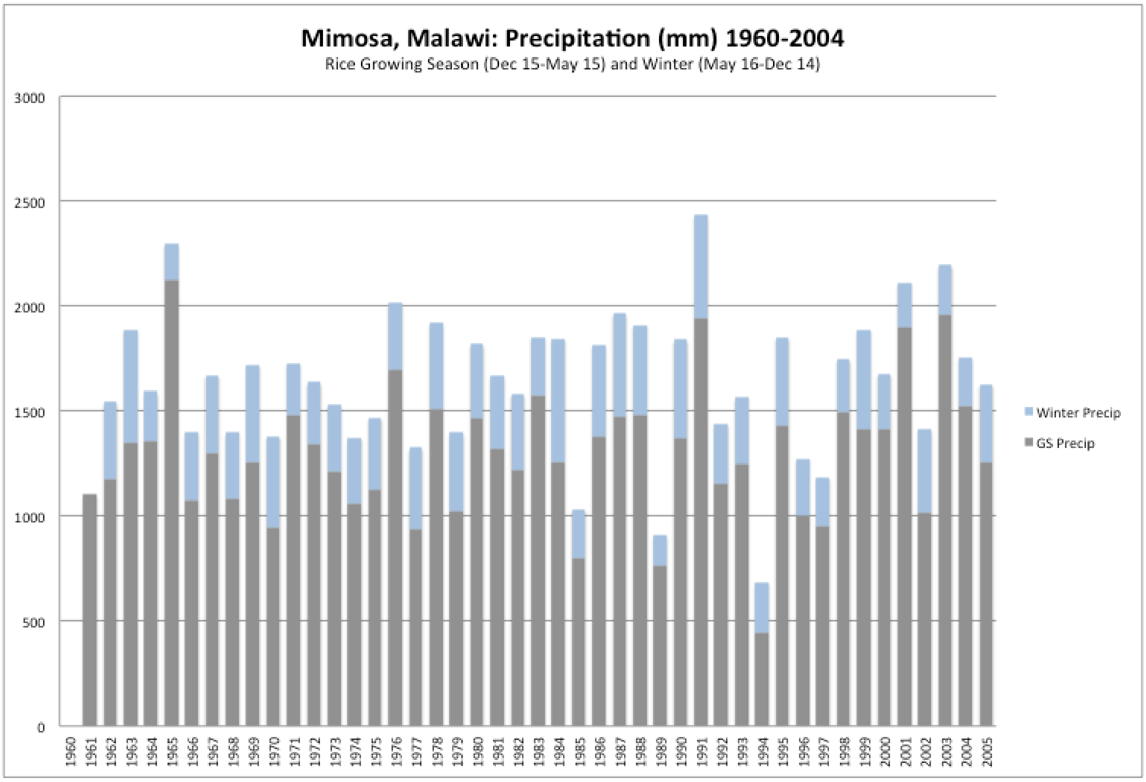

Figure 4.5. Growing season and winter precipitation in Mimosa, 1960-2004. Data source: Malawi Meteorological Services.

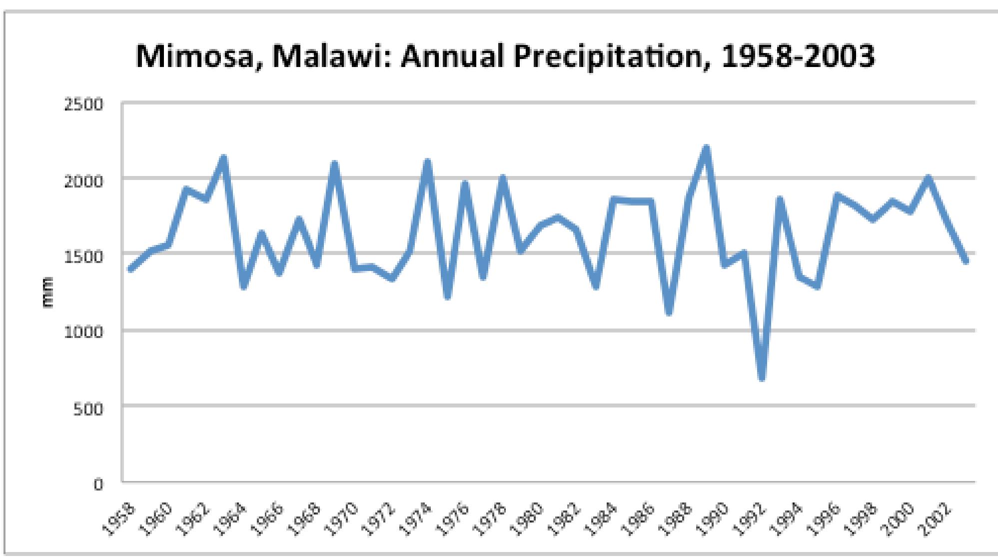

Figure 4.6. Annual precipitation in Mimosa, 1958-2003. Data source: Malawi Meteorological Services.

Indeed, the Malawi Meteorological Department noted that a dry spell in mid-January to mid-February is becoming more intense and covering more of the country.[3] At times the dry spell is

3 Personal communication, Adams Chavula, principal agricultural meteorologist, Department of Climate Change and Meteorological Services (July 18, 2014).

combined with the delayed onset of the rainy season to December or even January, causing very poor establishment of crops and low production. This appears to be most frequent in the South, especially in El Nino years. El Nino tends to lead to declines in precipitation in the South and increases in the North, but the effects are very irregular. The meteorological service also noted that the rainy season appears to be starting later and ending earlier. The government is promoting early maturing hybrid maize cultivars because of this shift, although the problem is not throughout Malawi.

Temperatures in this area are warm or hot, but have a large diurnal variation (Figure 4.7). The average annual maximum temperature (TMax, the midday temperature) is 28°C and minimum temperature (TMin, nighttime temperature) is 16°C. The TMax temperatures do not vary much between seasons (Figure 4.6). However, the TMin changes from an average of 18°C in the growing season to only 14°C in the winter. Projected climate change is for warming temperatures, especially during nighttime and winters. This warming during the cool Malawi winters may actually benefit winter rice production.

Temperatures in southern Malawi are steadily warming. This is showing up even in the limited period for which we have observations. Maximum temperatures are warming somewhat faster than minimum temperatures, especially in the winter.

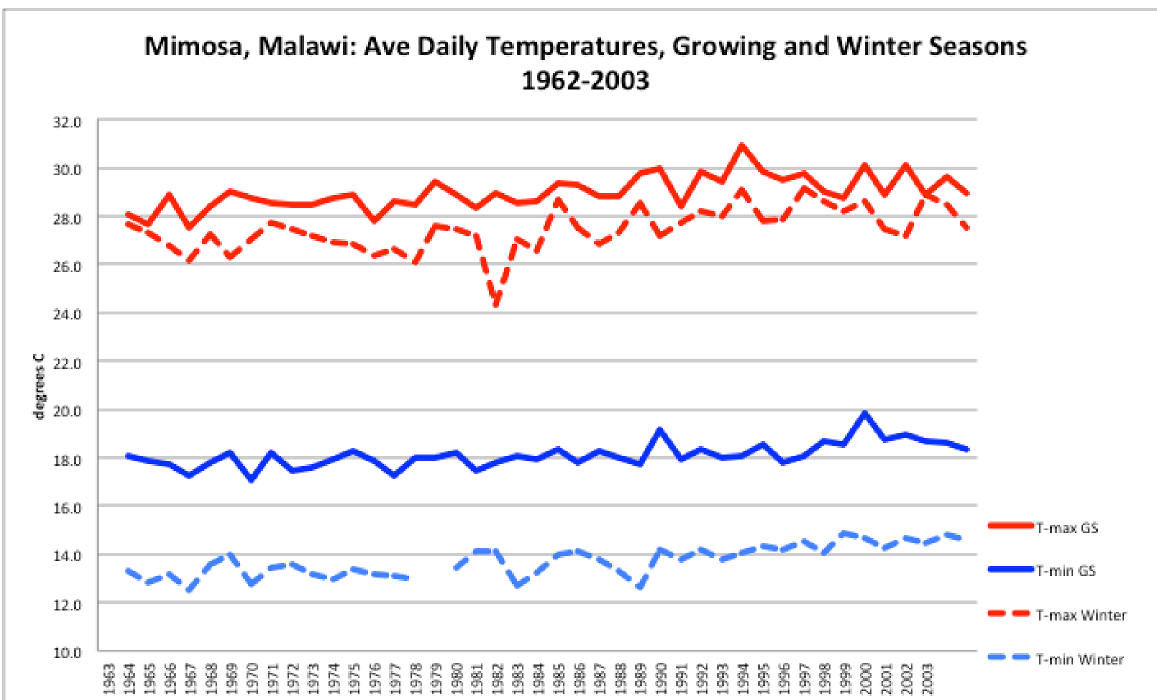

Figure 4.7. Growing season and winter maximum and minimum temperatures in Mimosa. Data source: Malawi Meteorological Services.

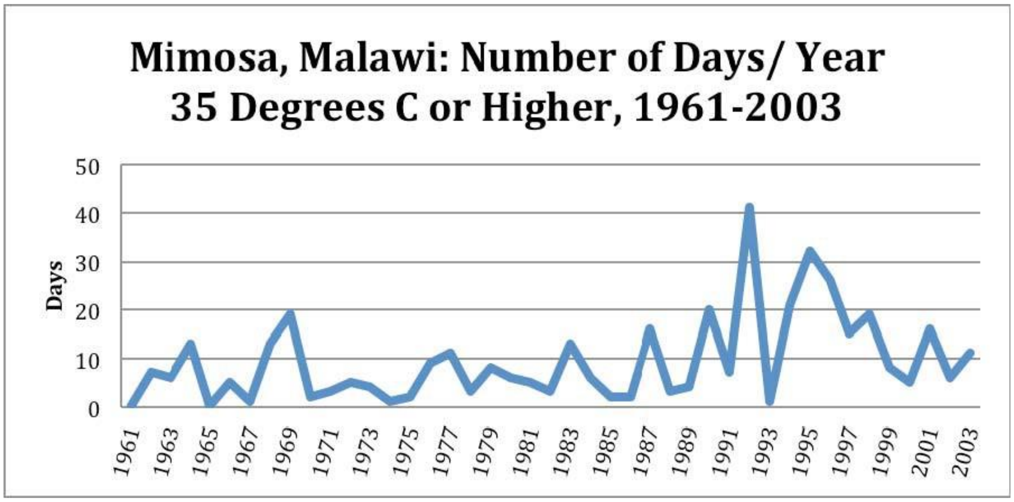

Figure 4.8. Number of hot days >35°C per year in Mimosa. Data source: Malawi Meteorological Services.

Rice and maize are sensitive to hot temperatures over 35°C, especially during the flowering stage. Hot temperatures reduce rice and maize yields. Not only is the average maximum temperature rising, but also the number of years with a substantial number of hot days appears to becoming more frequent (Figure 4.8). In Mimosa, the warmest of the stations examined, the large number of days with hot temperatures can be expected to be negatively affecting rice production already. Projected climate change is for warmer temperatures, and more frequent extreme temperatures and precipitation. The Shire Valley would be expected to be particularly affected by the warming temperatures and more frequent hot temperature extremes.

In summary, although total precipitation amounts may not be changing, the impact of climate change (particularly warming temperatures and increasing precipitation variability) may already be affecting crop productivity and livelihoods.

4.3. Central Region

The central region of Malawi is another large rice producing area. Rice is grown both as rain-fed during the rainy season, and is irrigated along the lakeshore during the winter. Malawi's main rice research institute, Lifuwu, is in Central Malawi in the Southern Lakeshore zone, near the Salima meteorological station. The Salima station, which is at 509 meters altitude, provides the illustration of climatology for this lakeshore area.

Similar to the Southern Region, this area is relatively wet and receives an annual average of 1251 mm of precipitation. Of this annual amount, almost all falls during the growing season, 1213 mm, whereas only an average 38 mm falls during the winter (Figure 4.9). The rains start rapidly in November and end abruptly in May. The peak is in January/February. The lack of precipitation during the winter reduces the ability to grow rice or other crops without full irrigation.

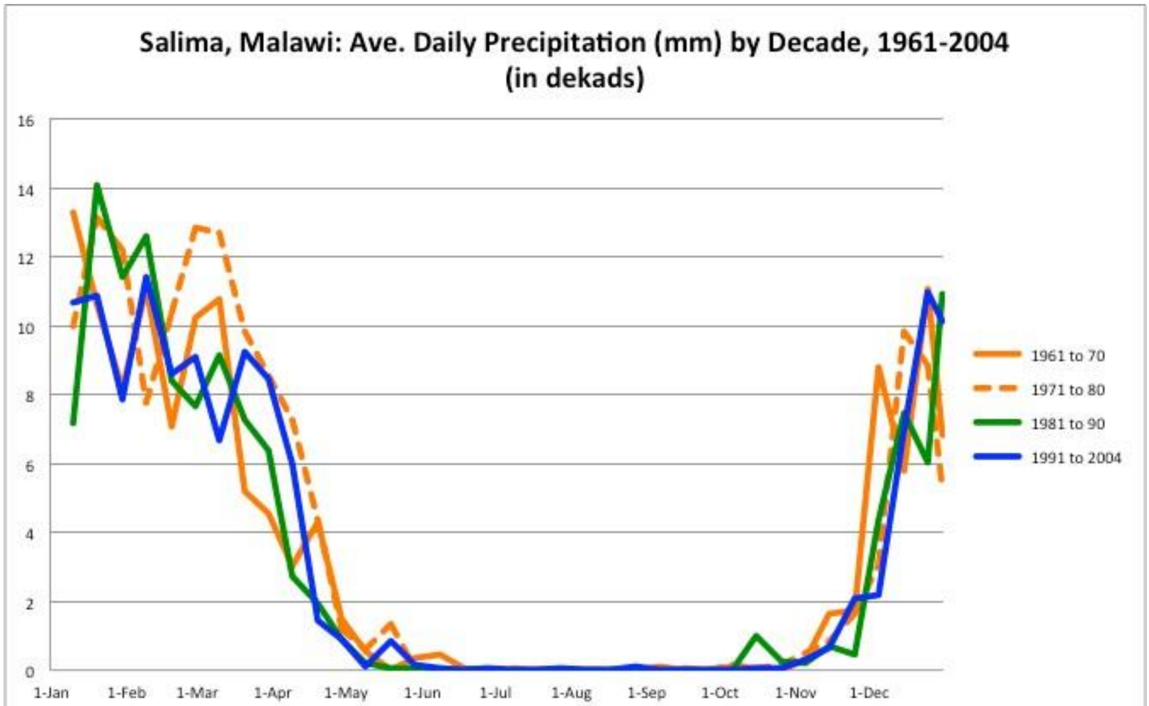

Figure 4.9. Precipitation in Salima during the year, 1961-2004, by decade. Data source: Malawi Meteorological Services.

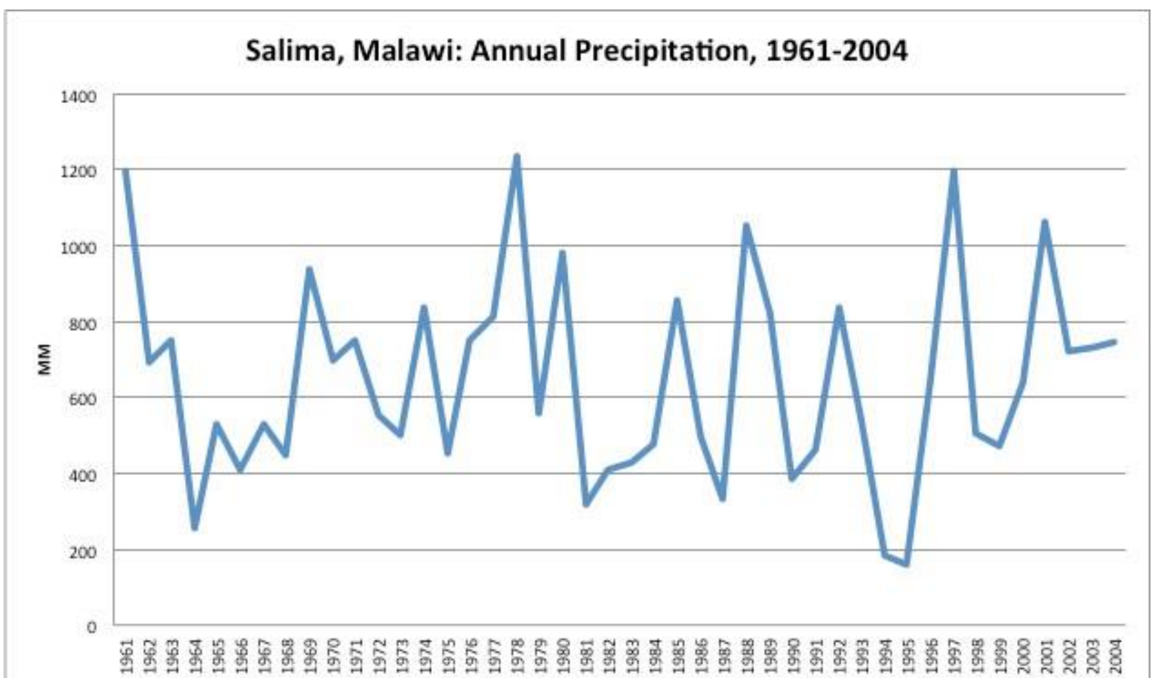

Figure 4.10. Annual precipitation in Salima, 1961-2004. Data source: Malawi Meteorological Services.

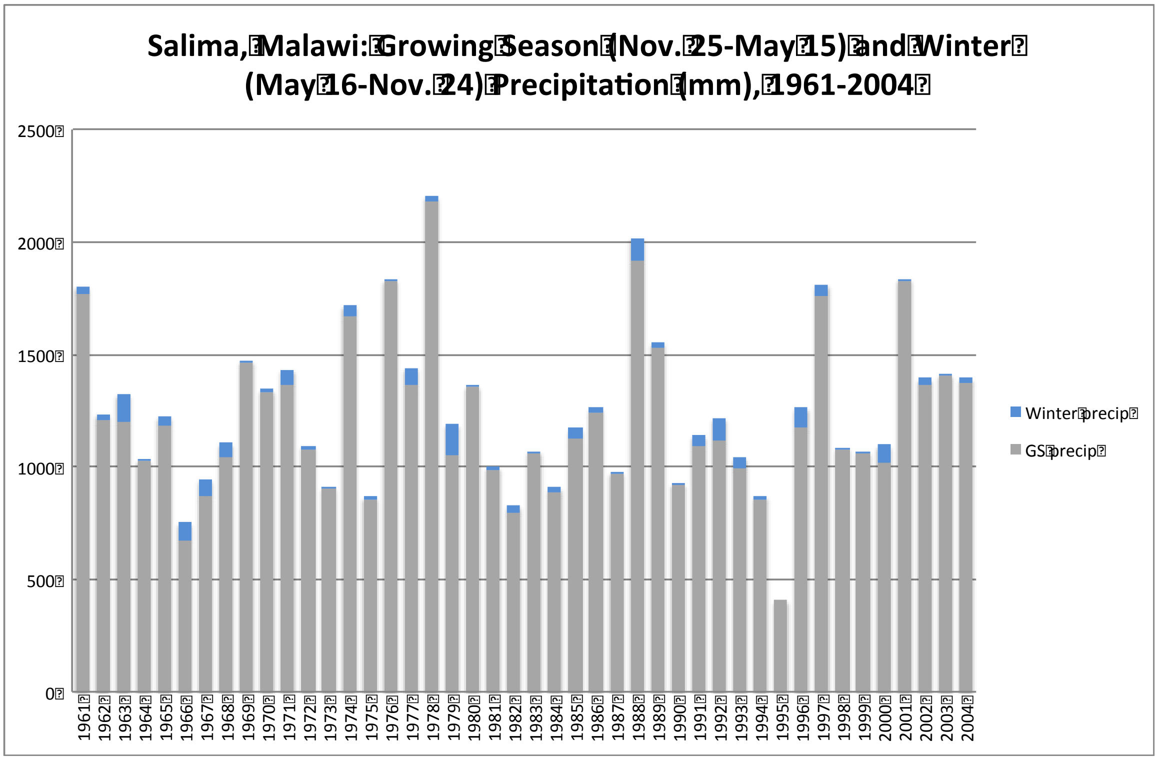

Figure 4.11. Growing season and winter precipitation in Salima, 1961-2004. Data source: Malawi Meteorological Services.

The inter-annual and intra-seasonal precipitation variability is higher than in the South (Figure 4.10). Growing season precipitation during the 1961-2004 period ranged from 2179 mm in the 1977/78 growing season to 409 mm in the 1994/95 growing season. The impact of this wide variability on rice production is tested in the sections below with results of rice modeling using historical climate data. There is no apparent change in the annual amount or seasonal pattern of precipitation during the 1961-2004 period.

Temperatures in Salima are somewhat warmer than in Mimosa. The annual average maximum temperature is 29°C, which doesn't change much over the course of the year. The annual average minimum temperature is 16°C, which rises to 18°C in the growing season and declines to 14°C in the winter.

During the period examined, there was little change in these average temperatures. The frequency of hot days over 35°C, however, did increase significantly, although highly variable (Figure 4.11). This rise in frequency of extremes is what is expected in climate change, and so extreme temperature events affecting crops can be expected to become increasingly common, and seriously affect crop production.

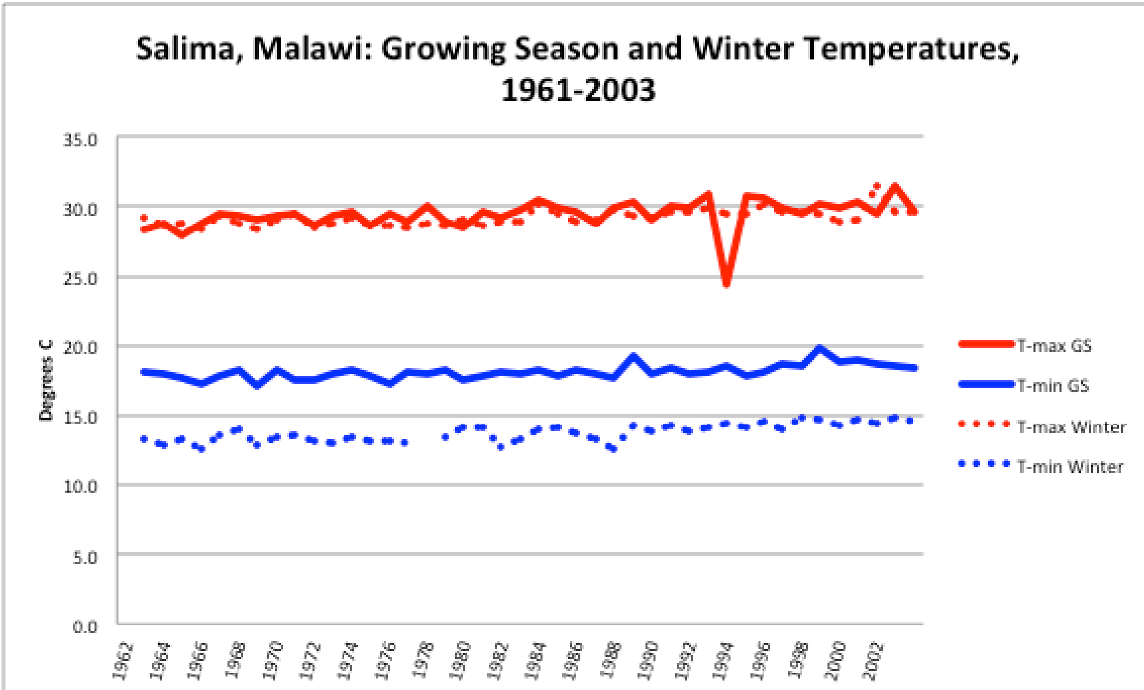

Figure 4.12. Growing season and winter maximum and minimum temperatures in Salima, 1961-2003. Data source: Malawi Meteorological Services.

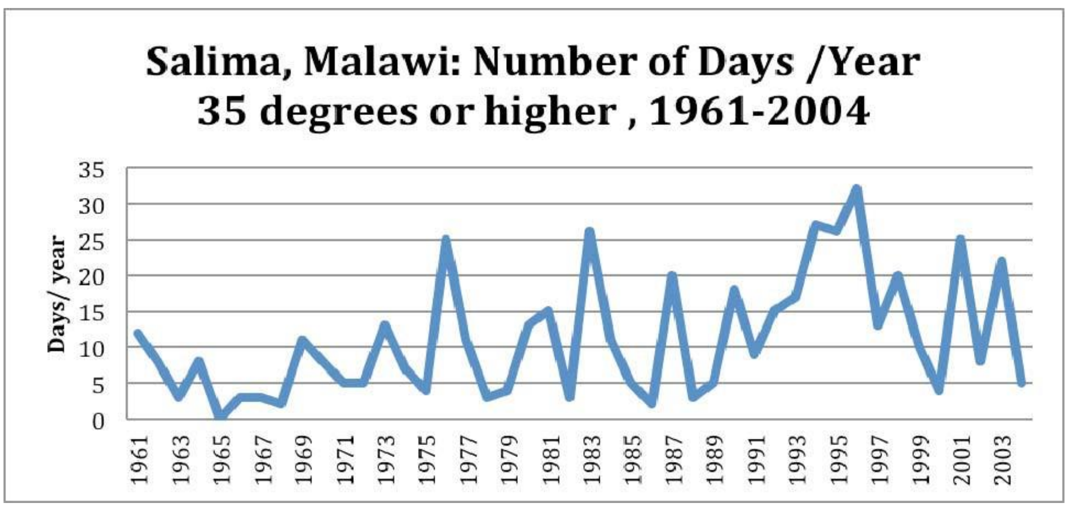

Figure 4.13. Number of hot days over 35°C per year in Salima, 1961-2004. Data source: Malawi Meteorological Services.

4.4. Northern Region

The Northern Region also produces rice, especially in the Northern Lakeshore zone, and some rain-fed rice in higher elevations inland. To examine the climatology of this region, we selected the Karonga metrological station, at 478 meters elevation, which has a climate similar to the Hara rice station.

Similar to Mimosa and Salima, Karonga is generally wet and warm. It receives an annual average of 1120 mm of precipitation, almost all (995 mm) during the November-to-May growing season (Figure 4.13). The rainy season is later in the year than in the South and Central Regions, however. It starts in November or December, peaks in April, and ends in June. Indeed, there is a bimodal tendency, with a dip in February and then the main rains from March to May.

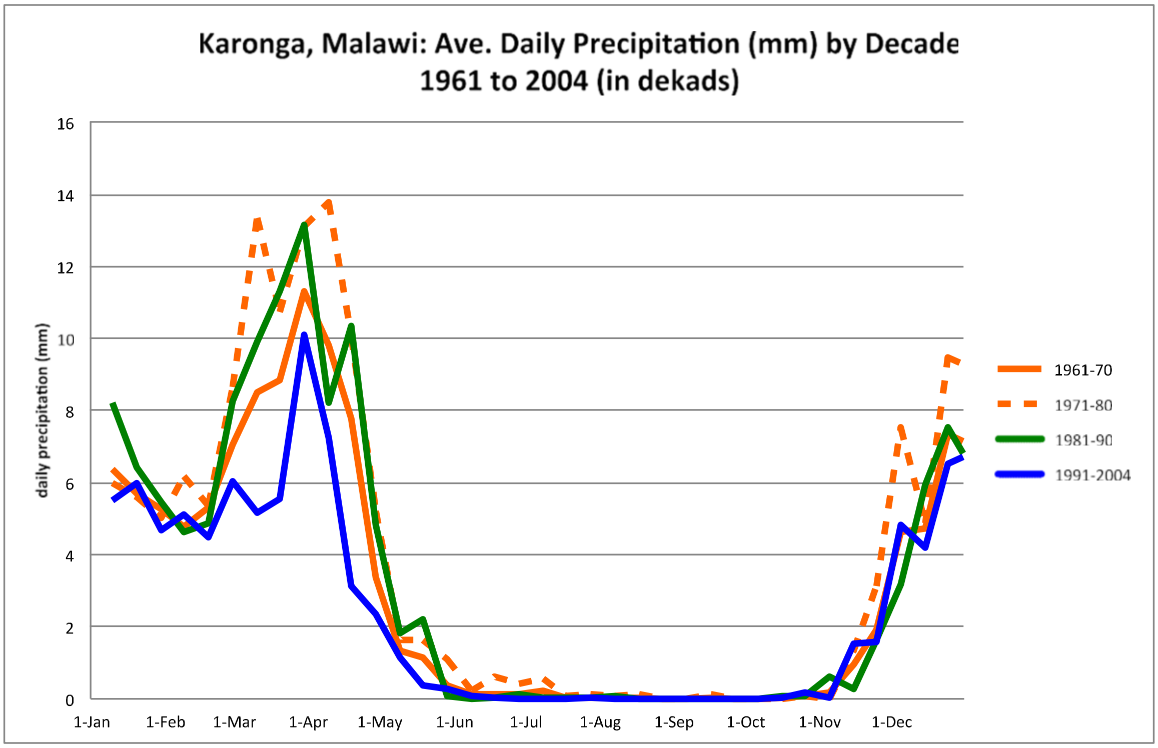

Figure 4.14. Precipitation in Karonga during the year, 1961-2004, by decade. Data source: Malawi Meteorological Services.

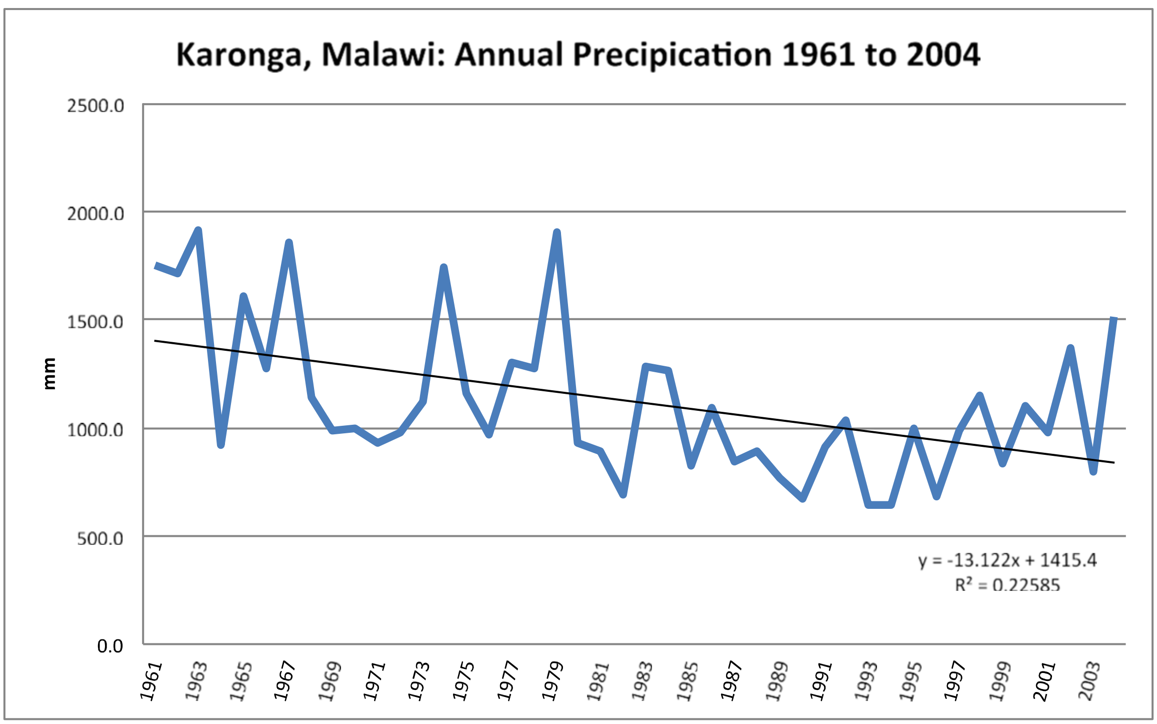

Figure 4.15. Annual precipitation in Karonga, 1961 to 2004. Data source: Malawi Meteorological Services.

The trend in changing precipitation amounts is also more similar to southern Tanzania than to southern Malawi. Annual precipitation declined during the 1961 to 2004 period for which we have meteorological station observations (Figure 4.15). It appears from Figure 4.14—which compares precipitation by decade—that the decline occurred predominately in March and April. The data shows that there was an uptick in precipitation during the end of the period examined. We intend to examine more complete datasets in the future to identify whether the uptick or downward trend continued.

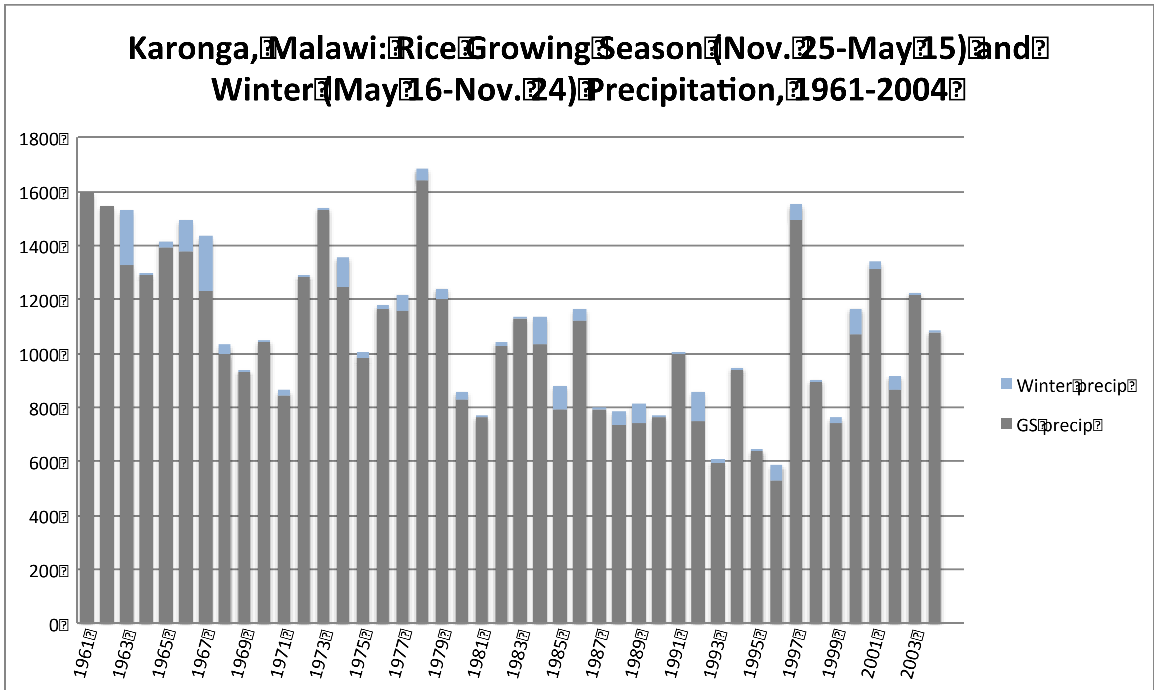

Figure 4.16. Growing season and winter precipitation in Karonga, 1961-2004. Data source: Malawi Meteorological Services.

Temperatures in Karonga are somewhat warmer than in Mimosa and Salima. Average annual maximum temperatures are 30°C, and this changes little during the year (Figure 4.17). The average annual minimum temperature is 16°C, varying from 14°C in the winter and 18°C in the growing season. During the period examined (1961-2003), there was only a slight trend upwards of temperatures.

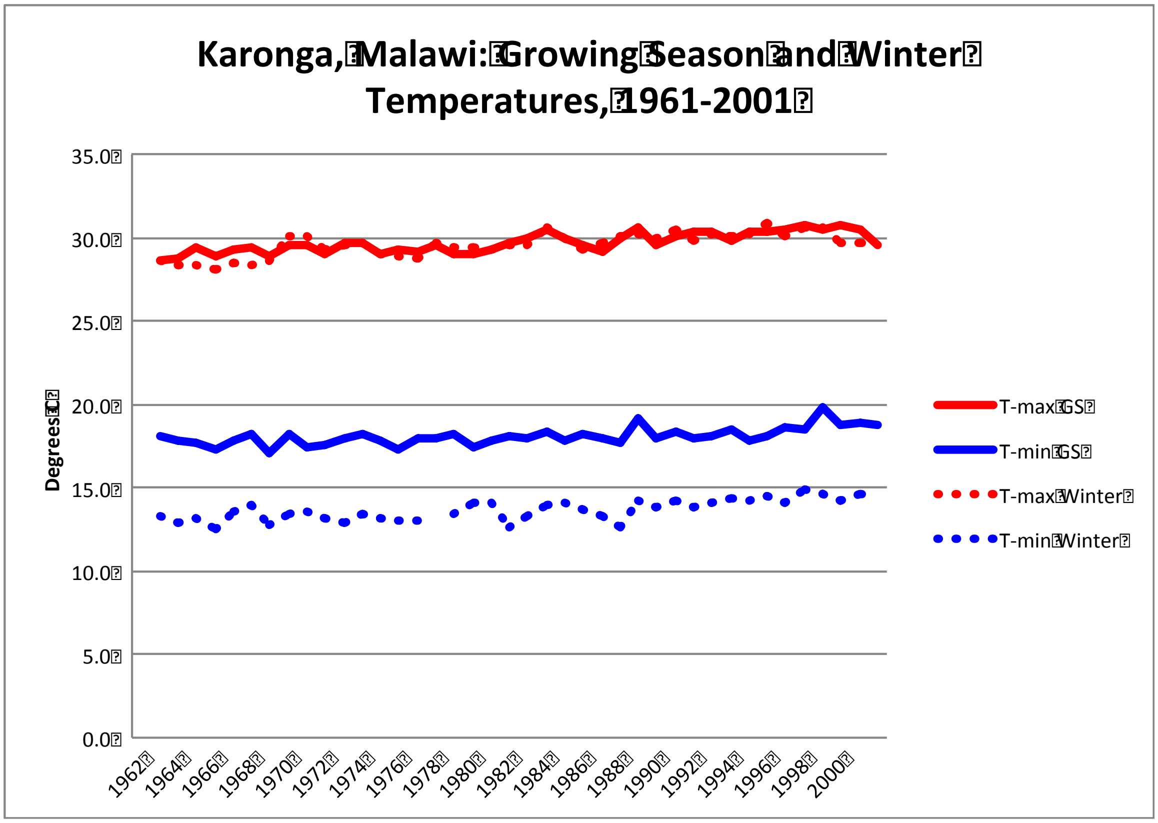

Figure 4.17. Growing season and winter maximum and minimum temperatures in Karonga, 1961-2001. Data source: Malawi Meteorological Services.

However, the number of hot days 35°C and higher has been increasing rapidly (Figure 4.18). At the start of the period examined, there were no hot days, but they have become increasingly common. This trend of more hot days would fit with the trend of declining precipitation. There are fewer cloudy days and more hot, sunny days.

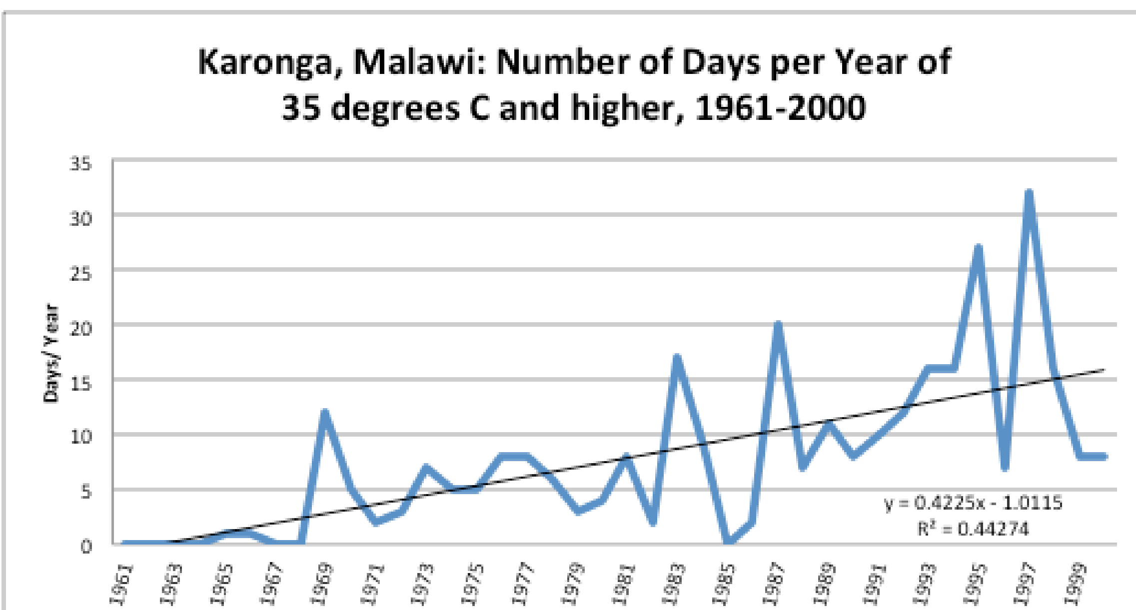

Figure 4.18. Number of hot days >35°C per year in Karonga, 1961-2000. Data source: Malawi Meteorological Services.

In summary, this brief analysis of historical climate data indicates the following:

1. Temperatures are generally slowly warming, particularly minimum temperatures.
2. However, the frequency of hot days over 35°C is already large and increasing rapidly, particularly in the north. This may be affecting rice and maize.
3. Precipitation trends are not clear in the south and central region, where inter-annual variability is larger than any short-term trend visible in the limited period for which we have data.
4. Particularly in the south, a dry spell in mid-January to mid-February appears to be becoming more intense. Reports are that the rainy seasons are getting shorter.
5. Precipitation in the north is declining steadily, particularly in March and April. There are fewer cloudy days and more hot, sunny days.

4.5. Future Climate Projections

Data from four global climate models (GCMs) that represent the current and mid-century periods were downscaled and analyzed (see methodology section for details) (Moore et al. 2012). Presented here is a summary of what the models indicate for projected changes in temperatures and precipitation during the growing (rainy) season in Malawi. These GCM datasets were used as inputs to the rice and maize crop models to examine the impact of projected climate change on crop yield (results presented in subsequent sections).

Temperatures are expected to rise substantially in Malawi. The projections of all four GMCs indicate much warmer conditions, with an increase between 1.5°C and over 3.5°C between the 2000 and 2050 period temperatures (Figure 4.19). Both minimum and maximum temperatures are expected to increase, leading to more frequent hot days and warmer nights. The models differ somewhat in degree of warming, partly related to differences in cloudiness. However, the warming trends is clear, and is similar to global patterns.

The models are not, however, consistent with their projections of changes in precipitation (Figure 4.20). Two of the four models (ECHAM and HadCM3) indicate that precipitation during the rainy season will decline somewhat, by around 150 mm in the growing season by 2050. The declines are somewhat larger near the lakeshore. The other two models (CCSM and CSIRO) indicate that precipitation will increase by a similar amount.

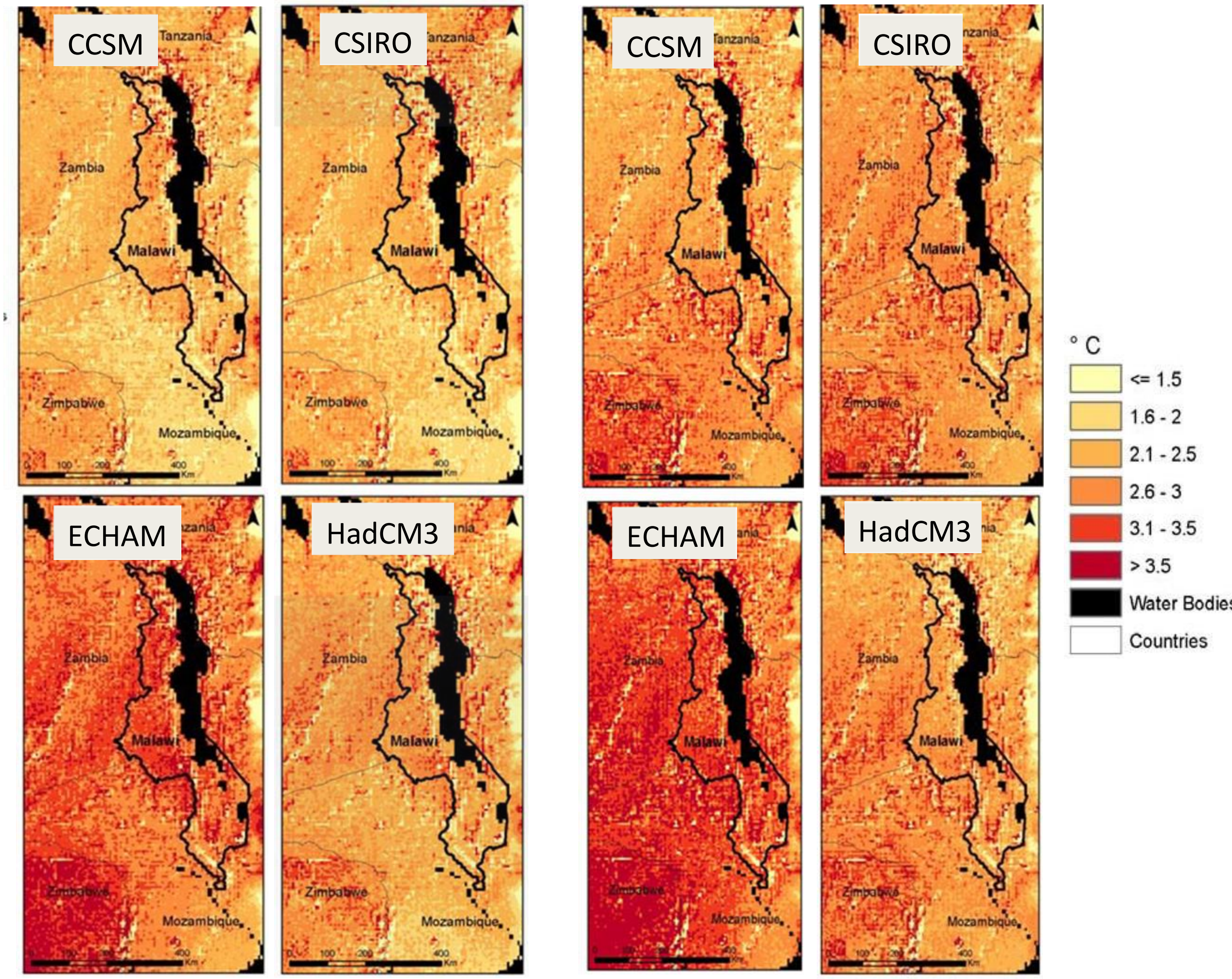

Figure 4.19. Maps of projected change in minimum (left four panels) and maximum (right four panels) temperatures between ~2000 and ~2050 under 4 downscaled GCMs.

Again, however, they project some declines, especially along the northern lakeshore. In either case, the projected changes in total rainy season precipitation are not large—they are smaller than inter-annual variability in some locations. Indeed, what GCMs and these maps do not reflect is the increase in precipitation extremes and variability that is expected globally due to climate change.

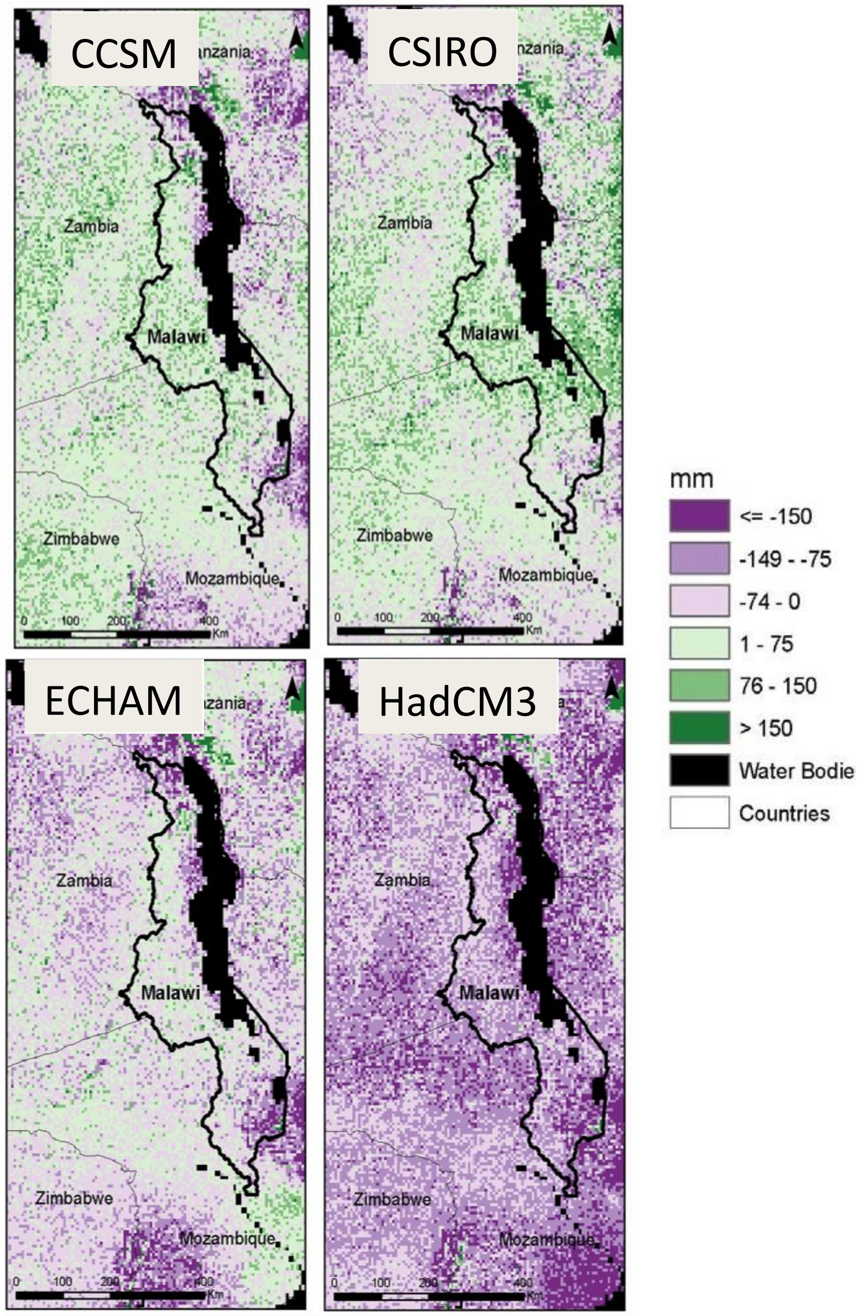

Figure 4.20. Maps of projected change in growing season precipitation (mm) between 2000 and 2050 in Malawi under 4 downscaled GCMs.

The next generation of GCMs, IPCC's Assessment Report 5 models, also project widespread warming in Malawi. Their projections of changes in precipitation indicate little change or a moderate decline during the October-November-December period (see Annex). During the January-February-March period, however, the models are not consistent. Three of the four project either little change or a moderate increase in precipitation, but one projects declining precipitation particularly on the lakeshore and in parts of Shire Valley.

In summary, climate changes projected for Malawi:

1. Widespread warming temperatures, of both minimum and maximum temperatures.
2. Precipitation projections are not consistent between models, but generally the models indicate only moderate changes (either increase or decrease) or little change in total rainy season precipitation.
3. Not shown in the maps, however, is the expected increase in temperature and precipitation extremes, and more intra-seasonal and inter-annual precipitation variability.

5. Impacts of Recent Climate Variability on Rice and Maize

This section examines the growth and yield of rice and maize under historical (recent) climate conditions in Malawi. The results provide information on the effect of climate variability and change on yield, and provide baseline data for measuring the impact of future climate. We simulated the potential of fertilizer to assist in increasing yields generally, and in reducing the effect of climate variability on yields.

The section starts by presenting results regarding rice, including the results from two historical point-level precipitation datasets and from spatial modeling. It then provides results for spatial modeling of maize under two fertilizer application levels.

5.1. Rice

The research question we are asking is, what is the effect of precipitation variability and warming temperatures on rain-fed rice production, and do fertilizer applications assist in reducing yield variability? To answer this, we simulated two rice varieties commonly grown in Malawi. The first is a long-duration (130-150 day) rice variety grown during the rainy season, Kilombero. The model simulated that 20-day-old seedlings were transplanted in the field on December 20, provided some initial irrigation water, and afterwards the plants had only precipitation and no additional irrigation. It thus represented rain-fed conditions, which characterize the main rice production system in the country. The second variety, Poussa 33, is a short-duration (100-130) variety usually grown in the dry season, the winter, with residual soil moisture and irrigation. For the winter season, the model was set to simulate transplanting the 20-day-old seedlings on July 20. Irrigation water was provided as needed.

Six rice research stations—from northern to southern Malawi—were selected as the locations for point-level simulations (see their locations on Figure 4.3). Measured yield data for these stations was available (Kanyika et al. 2007), and so the model was prepared and validated with this data and other information provided by researchers at Lufuwu Rice Research Station. At each station, three nitrogen fertilizer application levels were simulated: 25, 50 and 100 kg N/ha. Three historical precipitation datasets were used as inputs to the crop model (CHIRPS, supplemented observations and WorldClim). The precipitation and temperatures datasets used are generated data to some degree, and thus would not be as accurate as observed data. The results are not meant to replicate reality, but to provide insights into the potential impact of climate variability and change on plants.

First, graphs are presented of change in rain-fed rice yield over time during the rainy season, using CHIRPS precipitation and NASA temperature datasets. This provides information on the variability of rice yield due especially to precipitation variability. Next will be graphs of yield change over time during the winter season of irrigated rice, again using CHIRPS precipitation and NASA temperatures. This provides information on the effect of temperature changes on rice yield and evapotranspiration rates.

5.2.1. Rainy Season Rice

The following results are from simulations conducted with 1982 to 2013 CHIRPS and NASA weather data using the Kilombero rice variety. The four rice research stations illustrated start from the northern-most station, Lifuya, to the southern-most station, Kasinthula (graphs of two other stations are not included since they resemble the results of other sites, but their results are in Table 6.1). All the stations are in major rice growing areas of Malawi usually receiving 600 mm of precipitation or more during the growing season. A yield gap analysis was conducted to identify years and locations where soil constraints (e.g., nitrogen) or climate (water stress, temperatures) limit production, and to identify the potential of fertilizer to bridge the yield gap.

Figures 5.1 and 5.2 provide the results of 12 simulations conducted under rain-fed conditions.[4] Each station has findings for 3 nitrogen fertilizer levels (25 kg/ha, the blue lines; 50 kg/ha, the red lines; and 100 kg/ha, the black lines). At 100 kg/ha, the rice plants experience little nutrient stress and this level is similar to recommendations. Farmers, however, often apply only 25 or 50 kg/ha depending on resources available.

The results indicate that the maximum yield is around 9,000 kg/ha with a 100 kg/ha nitrogen application, and that this level is frequently attained in the northern (site 1) and central (site 2) regional zones. In these two sites, there is more than sufficient precipitation to prevent water stress, and response rates to nitrogen fertilizer are relatively high. Temperatures are also moderate, with maximum temperatures averaging around 25°C.

The two southern sites, however, show the effects of both more variable and less precipitation, and warm temperatures. The yield in Domasi, site 3, is on average 7,000 kg/ha and the yield is highly variable. Some years attain the maximum of around 9,000 kg/ha, but yield often falls below 6,000 kg/ha especially when seasonal evapotranspiration (ET) is near to season precipitation (PRECIP) amounts, reflecting water stress (e.g., 1987, 1994, 1995 and 2005), or when the distribution of precipitation during the season is poor. Poorly distributed precipitation during the season also leads to irregular and low return rates to fertilizer, because in those years, water stress—not nutrient stress—becomes the critical limiting factor suppressing yield.

[4] For Figures 5.1 to 5.4. Top graph: yield under three nitrogen (N) fertilizer applications. Second graph: growing season precipitation (PRECIP) and evapotranspiration (ET). Third graph: growing season average maximum (mid-day, TMAX) and minimum (night-time, TMIN) temperatures.

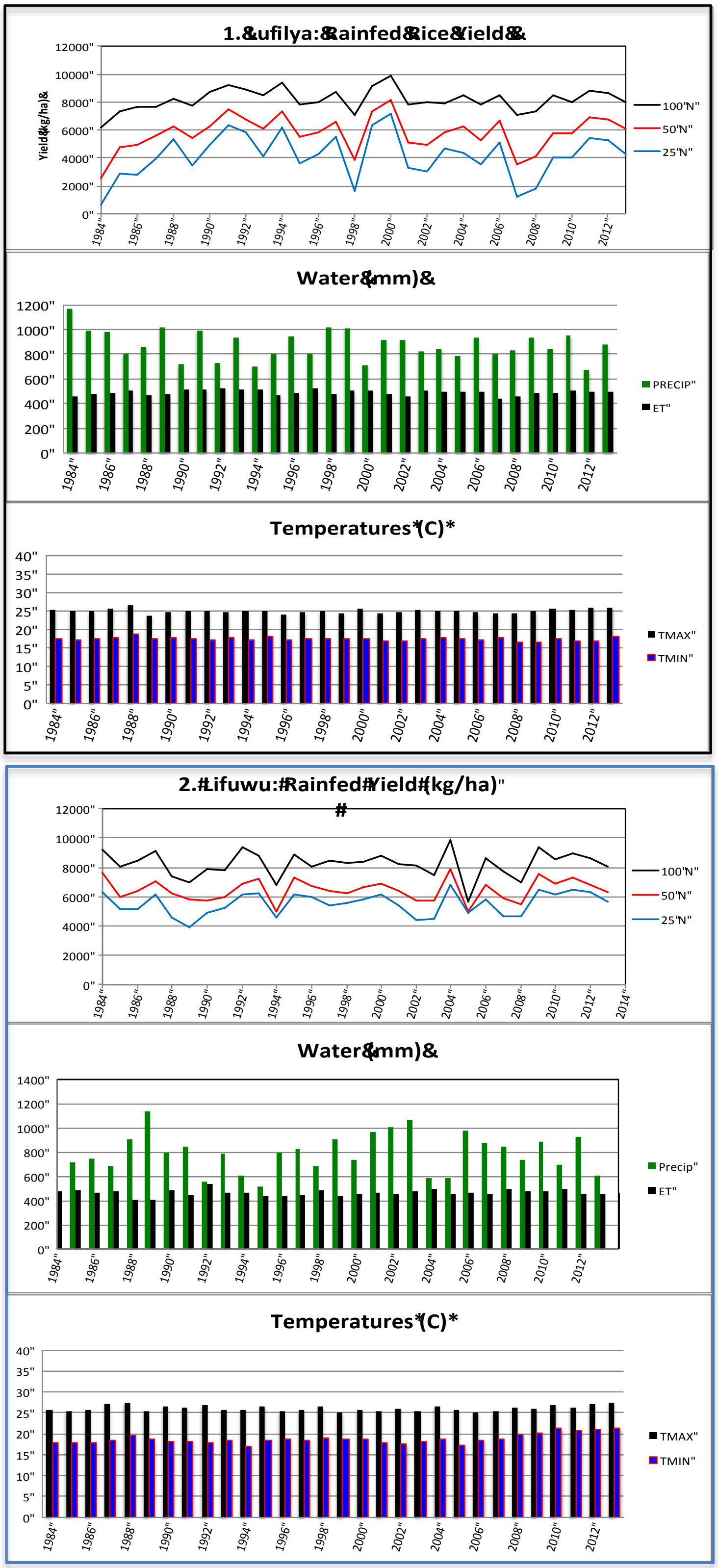

Figure 5.1. Graphs of simulated rain-fed rice yield, 1982-2013, for Lifuya and Lifuwu. Kilombero variety grown with CHIRPS and NASA weather datasets.

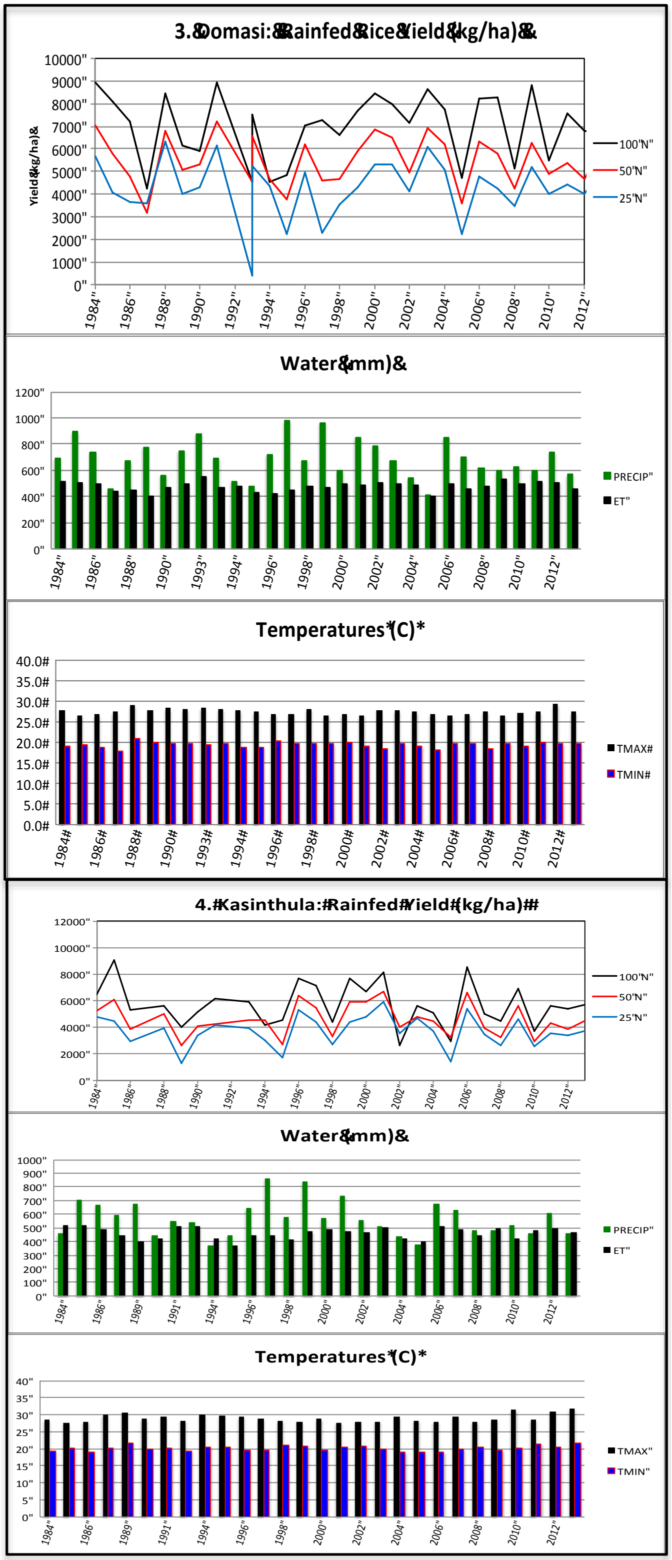

Figure 5.2. Graphs of simulated rain-fed rice yield, 1982-2013, for Domasi and Kasinthula. Kilombero variety grown with CHIRPS and NASA weather datasets.

In site 4, Kasinthula, the yields at an average of 5,500 kg/ha are the lowest of the stations, and yield variability is highest. The low yields are due to less precipitation and warmer temperatures; ET is frequently similar to precipitation. In years of unusually high precipitation, leaching of nutrients reduces yields (e.g., 1997 and 1999). However, nitrogen response rates are generally low due to water limitations. The warm average maximum temperatures of around 32°C would also affect the plants, particularly on hot days over 34°C which can cause sterility. In other words, without additional irrigation during the rainy season, yields in Kasinthula will be low, but hot temperatures may also be suppressing yields.

In summary, the rainy season simulations provide information on several aspects of the impact of current climate conditions on rice productivity. They include following:

1. In locations of sufficient rainfall and moderate temperatures, such as in the northern and central region stations examined, rice yields can attain high levels without irrigation and the response rates to fertilizer are high. Leaching of nitrogen during high rainfall years reduces yields, especially under lower nitrogen applications. This would call for recommendations of multiple doses of fertilizer throughout the season.

2. In locations of lower rainfall, particularly growing season precipitation under 500 mm combined with warm temperatures, water stress constrains yield and yield variability are high. Under these conditions, fertilizer response rates are much lower. The yield in Kasinthula, the station with warmest temperatures and lowest rainfall, is suppressed because of both water stress and the direct effects of hot temperatures on the plants. Under these conditions, irrigation during the rainy season would improve yields and fertilizer response rates, but the warm temperatures could still constrain yields.

5.2.2. Irrigated Winter Rice

A similar set of simulations was conducted to examine rice productivity during the winter season, when a short-duration variety was simulated under automatic irrigation. The variety Poussa 33 was simulated using 1982 to 2013 CHIRPS and NASA weather datasets. The results would illustrate the impact of climate, particularly temperatures, on the ET and yield of rice. Since water stress is not a constraint under automatic irrigation, fertilizer response rates would not vary much, so results from only the higher level of 100 kg/ha nitrogen fertilizer are illustrated here.

Figures 5.3 and 5.4 present the results. As expected under irrigated conditions, the impact of precipitation variability is not important and yields are relatively constant.

Indeed, in sites 1 and 2 in the northern and central regions, yields reach 9,000 kg/ha almost every year as the plants experience no water or nutrient limitations, and the moderate temperatures are conducive. Winter, dry season, precipitation is minimal and irrigation supplies almost all of the water requirements—an average of around 500 mm. Starting around 2005, maximum temperatures begin to increase from an average of 26-27°C to around 31-32°C. These higher temperatures do not, however, suppress yields.

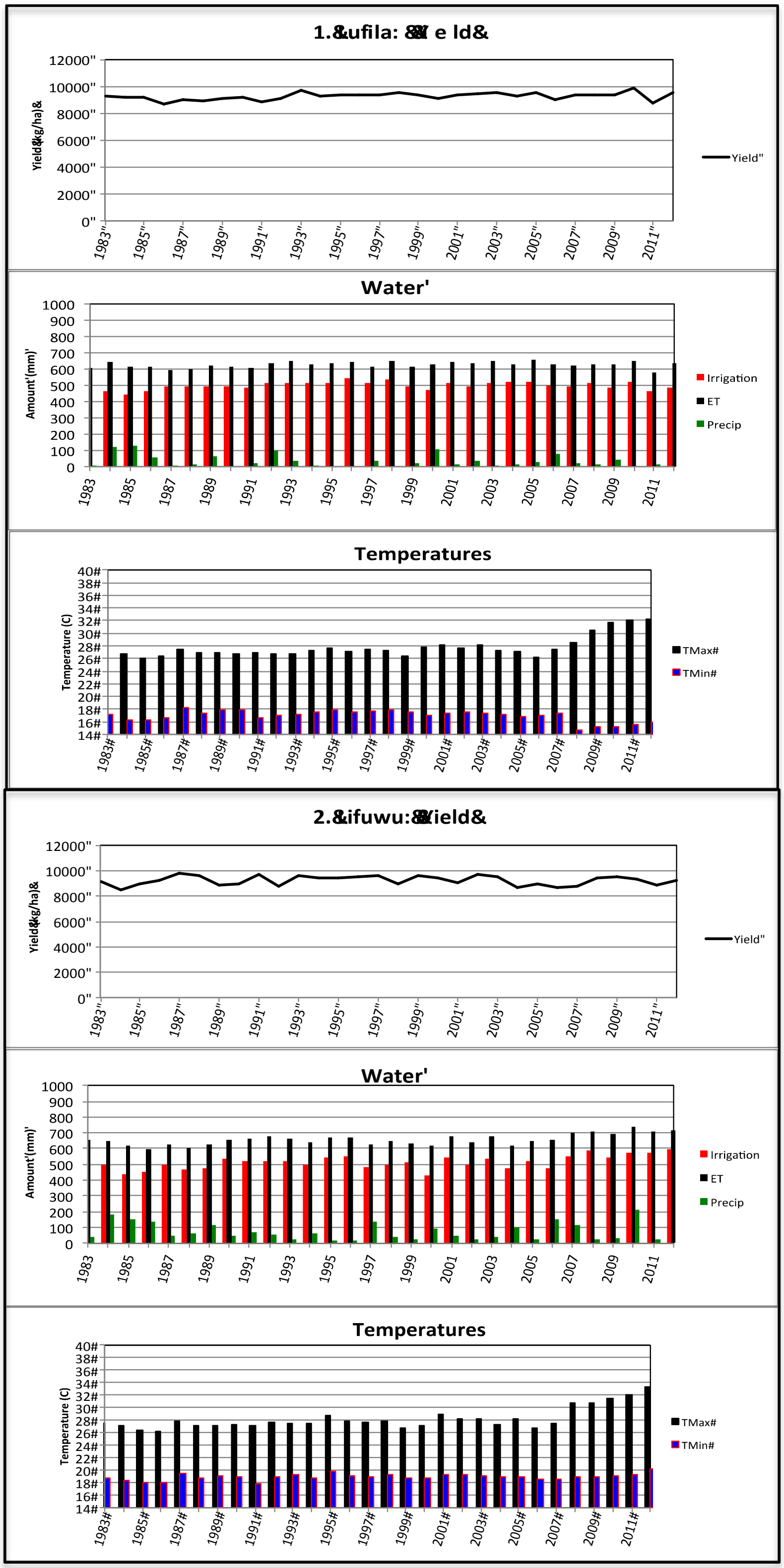

Figure 5.3. Graphs of irrigated winter rice simulation results, 1982-2013, for Lifuya and Lifuwu. Poussa 33 variety grown with CHIRPS and NASA weather datasets.

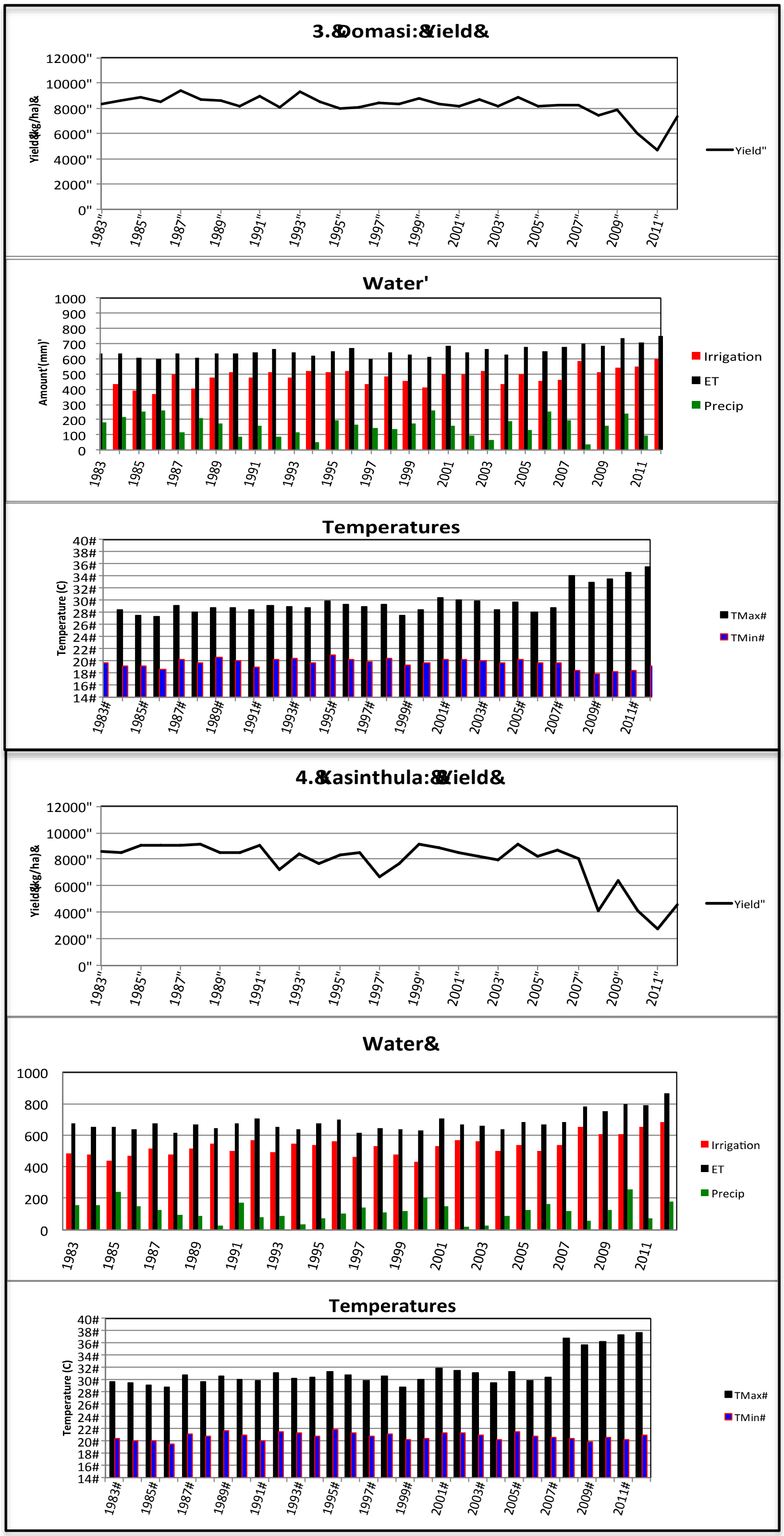

Figure 5.4. Graphs of irrigated winter rice simulation results, 1982-2013, for Domasi and Kasinthula. Poussa 33 variety grown with CHIRPS and NASA weather datasets.

In the two southern stations, however, yields decline from around 9,000 kg/ha to under 5,000 kg/ha starting in 2005 when temperatures warmed. In site 3, Domasi, the average maximum temperature increased from around 32°C to around 34-36°C. Once the average reached around 34°C, yields started to be affected. Similarly, in site 4, Kasinthula, the average maximum temperatures increased from around 32°C to 34-36°C. Evapotranspiration increased somewhat and irrigation rose to around 640 mm per growing season with these higher temperatures to, but water stress is not a factor under the automatic irrigation assumption. The large yield declines, from around 8,000 kg/ha to 2,000-4,000 kg/ha, are a direct result of the hot temperatures.

In summary, the irrigated winter rice simulations illustrate another critical climate change effect on rice, that of hot temperatures directly lowering yield. The impact was apparent after 2005 in the southern stations. Even short periods of hot temperatures during the reproductive stage of rice cause sterility. There are few management factors that would reduce the direct impact of hot temperatures, other than selecting varieties that may be less sensitive.

5.3. Maize

Our maize modeling in Malawi was conducted to examine the impact of climate change on maize, and to test the potential effect of applying nitrogen fertilizer. This section focuses on current maize growth conditions in the country.

In Figure 5.5, the left map shows simulated maize yield under low fertilizer application, and the middle map yield under a moderate fertilizer application (the legend is the same for both maps). With low fertilizer levels, simulated yields do not rise above 2,000 kg/ha. However, with a moderate fertilizer application, simulated yields increase to 4,000 kg/ha and higher. The right map illustrates the gains in yield provided by the additional fertilizer, which are in the range of 1,500 to over 4,200 kg/ha. Where environmental conditions are supportive, yields increase substantially. In hot or cold areas, in sandy soils, or where rainfall limits production, however, the yield benefit to fertilizer can be low.

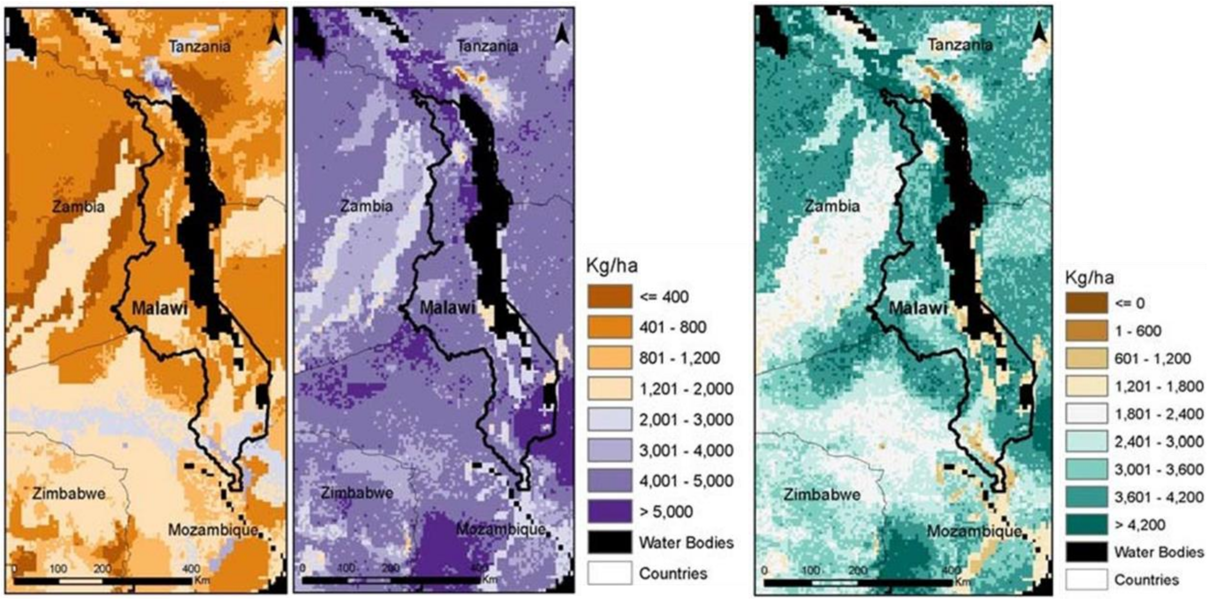

Figure 5.5. Maps of simulated maize yield in 2000: Left map: yield with *low* nitrogen (5 kg N/ha). Middle map: yield with *moderate* (85 N kg/ha). Right map: difference in yield between low and moderate fertilizer applications (i.e., the yield benefit to adding fertilizer).

Malawi therefore has important constraints to rice and maize yield due to several factors. The first is that Malawi has generally nutrient-poor soils. For both rice and maize, therefore, there are substantial gains in yield with even moderate amounts of fertilizer. The benefits to fertilizer vary across the country, however, with higher potential zones having a much higher benefit than lower potential zones. In addition, nitrogen fertilizer can reduce some of the variability in yields associated with precipitation variability, particularly when the fertilizer is applied in multiple doses to reduce the effects of leaching. A second constraint that Malawian rice and maize production is beginning to experience, and that will worsen with time, is the impact of hot temperatures during the plants' reproductive stages. Even a few days of hot temperatures can reduce yields by a substantial amount, as seen in our results from the Kasinthula station. Some varieties are somewhat more resistant to these hot temperatures, but the hot temperature impacts can be expected to increase. Thirdly, rice production in Malawi is increasingly grown during the winter season which our results show relies almost entirely on irrigation water, depending on location. Although yields can be high during this season, plants are vulnerable to breaks in the water supply especially during seedling establishment and reproductive stages. The effects of climate trends, of warming temperatures increasing demand for water, and in some locations declining precipitation and/or reduced water availability, can threaten winter rice production.

6. Impacts of Projected Future Climate Change on Rice and Maize

In this section, results will be presented from linking GCM data to the rice and maize crop models in order to estimate the impact of future climate change on rice and maize productivity. The impact of four different GCMs were simulated—those that are presented in Section 4 on future climate change. They are in rough order from the GCM projecting somewhat drier conditions (HadCM3) to the GCM projecting somewhat wetter conditions (CCSM), though none of them project large changes in precipitation for Malawi.

6.1. Rice

For the rice study, two approaches were followed. First presented are the results of detailed modeling and analyses that were conducted at the point level at the six rice research stations. This was done to provide more detailed information not only on projected changes in yield, but also changes in associated variables. To do this, 30 years of current climate (from CHIRPS and the supplemented-observed dataset termed 1960s-2000s) and 30 years of future climate (from the GCMs) were used as inputs to the rice model. The second approach was to conduct spatial modeling of the rice model linked to five climate datasets—one representing current climate (WorldClim) and four representing future climate (four GCMs).

The results from the first approach are rice yield and related variables for each of the six rice research stations. Table 6.1 has the results presented in order from the northern-most station to the southern-most station (see Figure 4.3 for station locations).[5]

The results reflect simulations conducted of Kilombero rice variety with 100 kg/ha nitrogen fertilizer application, so with little nutrient stress. The results would thus better illustrate climate effects on plants grown. As described in more detail in Section 3, the rice was grown during the rainy season under rain-fed conditions. Thirty or more year means and standard deviations, and climate variables are included.

The first key result is that the main climate change influence on crops expected in the future is due to warming temperatures. In all locations, temperatures are expected to increase by between two to four degrees centigrade by 2050. Both maximum and minimum temperatures increase, with maximum temperatures rising somewhat faster. Although all locations are expected to experience this rise, the impact in the places already warm will be the most severe due to those locations already having maximum temperatures near the high temperature threshold for rice and maize.

The second key result is that the relatively small projected changes in seasonal total precipitation amounts are not expected to affect rice yields significantly. In some locations, total precipitation is expected to increase somewhat and in others decrease somewhat, depending on the GCM.

However, the combination of warming temperatures and little or no change in precipitation will in most cases lead to plants increasing uptake of water. Where precipitation is sufficient and temperatures remain below the heat threshold, as in the northern stations, ET may increase but yield is maintained or even increases. Yields may decline in locations where precipitation may not be sufficient or where temperatures rise, as in Domasi.

The spatial analysis of rice yield under current and projected future climate conditions are presented below. Again, the simulations were conducted of Kilombero rice variety under rain-fed conditions, and with a 100 kg/ha nitrogen fertilizer application.

[5] Table ** columns: A=rice yield (kg/ha); B=standard deviation of yield; C=average daily maximum temperature; D=average daily minimum temperature; E=growing season precipitation (mm); F=standard deviation of precipitation; G=growing season evapotranspiration (mm). Rows: weather datasets.

Table 6.1. Rain-fed rice modeling results under two historic and four projected climate datasets (Kilombero variety with 100 kg/ha nitrogen fertilizer).

	A. Yield (kg/ha)	B. SD of yield	C. TMAX C	C. TMIN C	E. PRCP mm	F. SD of prcp	G. ET mm
Lufilya							
1960s-2000s	6894	821.4	25	17	1005	241.2	376
1982-2013 CHIRPS	8165	780.1	25	17	878	115.7	490
2050 HadCM3	7343	577.6	28	20	865	195.6	369
2050 ECHAM	7043	413.8	29	21	849	163.8	340
2050 CSIRO	7210	539.2	29	20	890	212.4	350
2050 CCSM	7418	609.8	28	20	933	164.5	379
Hara							
1960s-2000s	7076	739.3	26	18	938	216.2	370
1982-2013 CHIRPS	8177	508.3	26	18	743	116.3	471
2050 HadCM3	6968	965.5	27	18	942	239.7	365
2050 ECHAM	6844	811.5	27	19	1056	243.9	366
2050 CSIRO	6911	696.9	27	18	1051	210.1	368
2050 CCSM	6620	838.3	27	18	1086	202.8	363
Mkondozi							
1960s-2000s	7152	526.2	29	20	940	158.6	324
1982-2013 CHIRPS	9047	636.6	26	19	839	157.7	467
2050 HadCM3	6724	629.0	31	23	774	112.2	324
2050 ECHAM	6486	630.5	32	23	859	137.5	323
2050 CSIRO	6605	519.0	31	23	982	158.9	336
2050 CCSM	6662	628.6	31	22	983	196.5	334
Lifuwu							
1960s-2000s	6448	1619.6	28	20	854	351.6	370
1982-2013 CHIRPS	8237	892.9	26	19	786	160.9	465
2050 HadCM3	6557	759.4	31	23	796	253.8	357
2050 ECHAM	5512	1016.6	32	23	787	219.6	343
2050 CSIRO	6567	784.2	31	23	976	265.0	354
2050 CCSM	6859	756.1	31	23	964	241.9	365
Domasi							
1960s-2000s	7264	886.1	27	18	986	233.7	442
1982-2013 CHIRPS	6994	1465.0	27	19	687	145.3	478
2050 HadCM3	6674	1166.4	29	20	886	260.7	413
2050 ECHAM	7545	710.7	30	21	919	178.5	388
2050 CSIRO	7536	622.6	30	21	944	163.3	386
2050 CCSM	7568	1397.5	29	20	994	262.9	448
Kasinthula							
1960s-2000s	5566	3095.7	31	20	602	143.9	478
1982-2013 CHIRPS	5506	1756.0	29	20	580	129.7	465
2050 HadCM3	5826	1700.3	32	22	638	168.4	500
2050 ECHAM	5516	2192.2	33	23	620	167.0	500
2050 CSIRO	6139	1483.2	33	22	634	155.1	492
2050 CCSM	6359	1148.5	33	22	695	222.3	507

Figure 6.2 illustrates simulated rice yield across Malawi under current climate conditions (left map) and two 2050 climate conditions. The drier GCM, HadCM3, and the wetter GCM, CCSM are provided here for illustration. The maps show large variability of rice yields when grown under rain-

fed conditions across Malawi, from no or very low yield in the cold highlands (green), to low yields across most of the country due to low precipitation (browns), and to relatively high yields along the lakeshore and in the Southern Region (purples). This general pattern is not expected to change in the future. Indeed, other than improving conditions and rising yields in the highlands due to warming temperatures, little change is easily discerned.

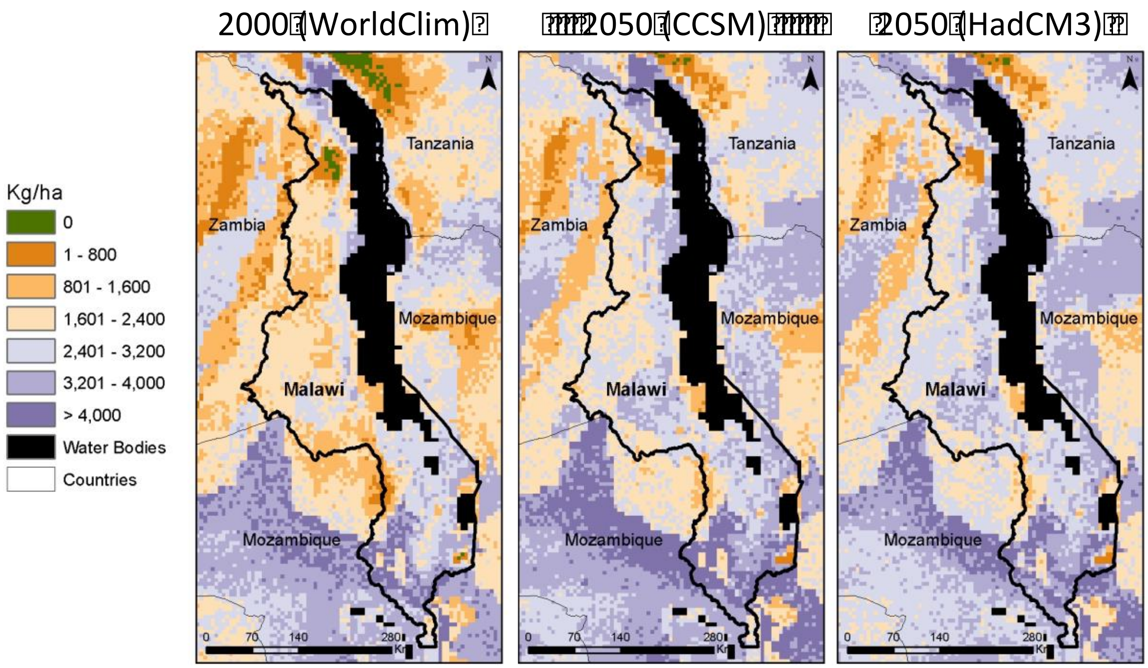

Figure 6.2. Maps of simulated rice yields in 2000 and 2050 (CCSM and HadCM3). (Kilombero rice rain-fed with 100 kg/ha nitrogen application).

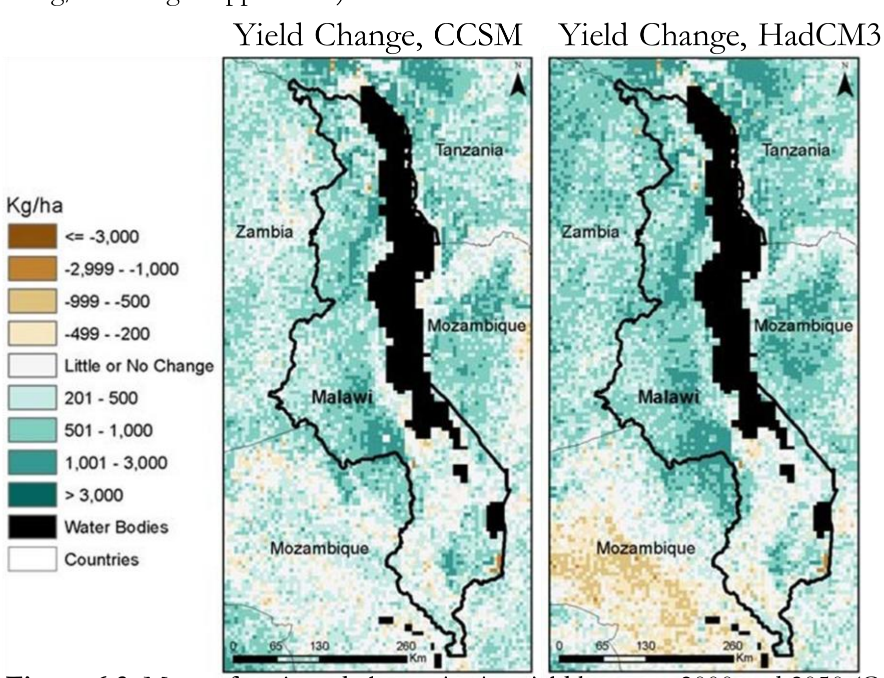

Figure 6.3. Maps of projected change in rice yield between 2000 and 2050 (CCSM and HadCM3) (Kilombero rice rain-fed with 100 kg/ha nitrogen application).

Figure 6.3 illustrates the projected change in yield between 2000 and 2050, or the difference in yield between the left map and the two right maps of the prior figure. Unexpectedly, the projected change in rice yield is mostly positive for Malawi in the north and central regions, due to only small projected changes in precipitation and warmer conditions. In the highlands and plateau, the projected increases in temperature would be expected to have a beneficial impact on rice because temperatures.

Temperatures there are changing from a relatively cool 26-29°C maximum and under 14°C minimum to around 2°C higher, which would favor higher yield. Even with those projected small increases in yield, however, the North and Central regions will still have low rice yields except for along the lakeshore and highlands. In contrast to the rest of Malawi, the projected increases in temperature in the south will not be beneficial because temperatures there are already sufficiently warm and indeed are reaching the heat threshold for rice. The projected increase in temperature, with small changes in precipitation, would thus not lead to major changes in yield in the south.

The small changes or increases in projected future rice yield are not what would be expected when compared to the findings presented earlier based on recent trends and farmer experiences. The difference between our findings on recent trends and what is projected for the future points out the difference in findings between detailed analyses using local, observed data and doing analyses with GCM data for a geographic area such as Malawi. Important climatic changes occurring in Malawi and elsewhere near the equator include changes in precipitation seasonality (e.g., onset and length of rainy seasons) and variability (inter-annual and intra-seasonal including distribution, frequency and intensity of rain events, and extremes). These temporally and spatially detailed changes in precipitation, especially those occurring near the climatically complex equator zone are often not well captured by GCMs. The impact of those shifts in and variability of precipitation, however, have major impacts on crop production and are requiring farmers to change their agricultural practices to adapt.

6.2. Maize

This section provides results of the impact of projected future climate change on simulated maize growth and productivity in Malawi. In addition, the authors conducted sensitivity experiments to examine how maize growth and production would be affected by management practices under current and projected climate conditions. Three of the most important adaptation practices being considered currently in Africa are 1) short-season or drought-resistant maize varieties so that maize is less vulnerable to highly variably rainy seasons and to water stress due to the higher temperatures, 2) better management practices, including fertilizer application, to reduce the plant's susceptibility (the so-called no regrets option), and 3) irrigation. To best illustrate the effect of climate change and management factors on yield, we selected a relatively high performance, long-duration maize variety modeled (700 series) because it would tend to be sensitive to nutrient and water limitations. The basic question being examined is, is fertilizer an effective adaptive strategy for coping with climate change?

The following figures provide results to help answer this question. Figure 6.4 illustrates the results of eight simulations: two fertilizer levels (the top four maps show results for low, and the bottom four maps for moderate, fertilizer), and for each fertilizer level using the climate of four GCMs. The results are similar to the results under current climate conditions (see Section 5). The yield response to nitrogen is quite dramatic across Malawi (the top compared to the bottom maps). Yields increase from less than 800 kg/ha to over 4,000 kg/ha across much of the country. In higher potential zones including the highlands and well-watered lowlands, temperatures and precipitation are conducive for maize and it responds with large increases in yield. Yield response is much lower in drier areas or areas of sandy soils. An unexpected finding is that despite the difference in projected precipitation between models (see Section 4: CCSM and CSIRO project moderate increases and ECHAM and HadCM3 project moderate declines), the projected yield appears to be fairly similar across the GCMs.

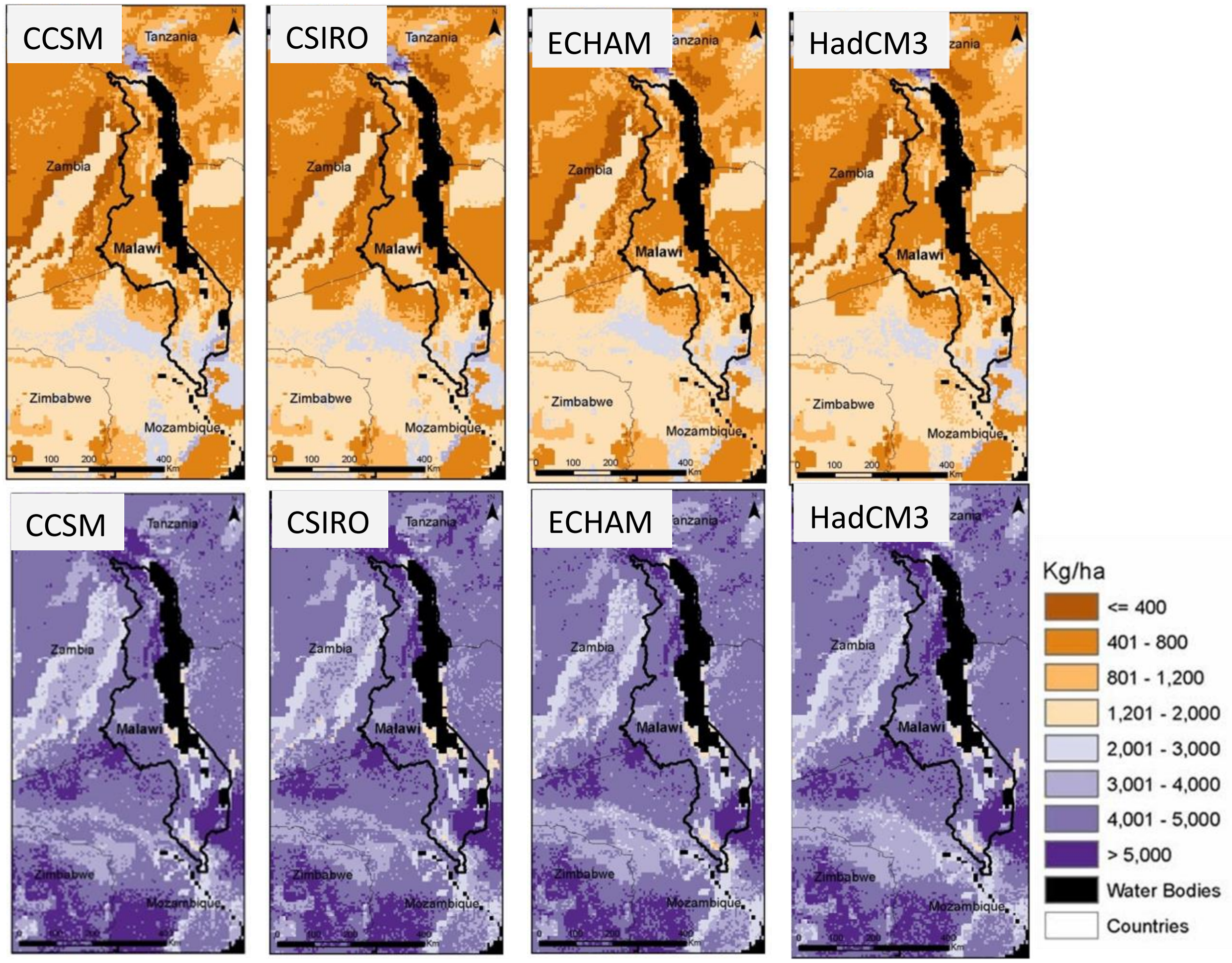

Figure 6.4. Simulated maize yield (kg/ha) in 2050: top four maps: with *low* nitrogen (5 kg/ha N) fertilizer under 4 GCMs. Bottom four maps: with *moderate* nitrogen (85 kg/ha N) fertilizer under 4 GCMs.

To better understand the impact of climate change on maize, we then compared the yield under current and future climate conditions. Figure 6.5 presents these results, which are the expected *change* in yield between 2000 and 2005. Browns represent yield declines and teals represent yield increases. Again, the top maps are the results with low fertilizer and the bottom maps are the results with moderate fertilizer application.

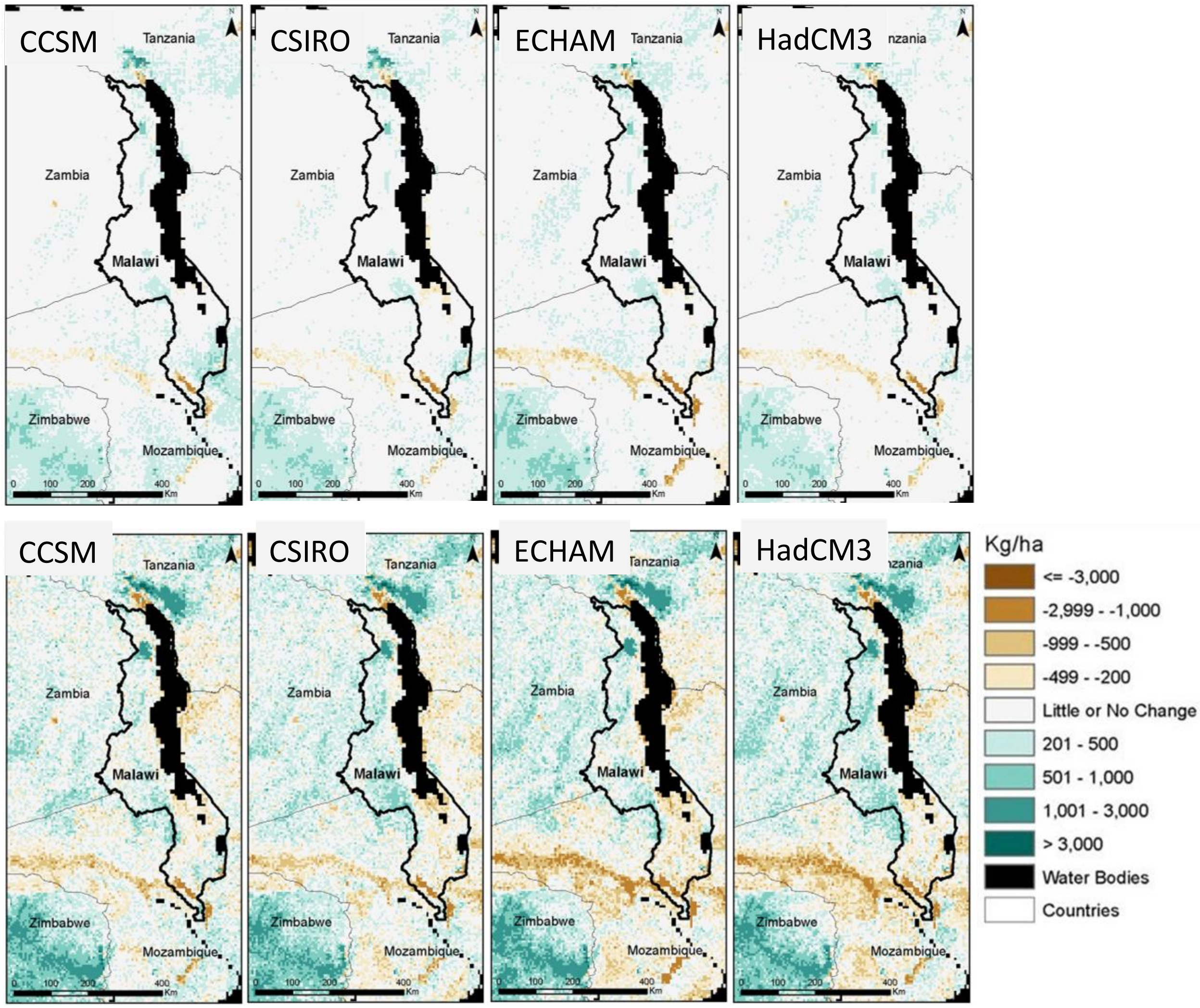

Figure 6.5. Maize yield *changes* between 2000 and 2050: Top four maps: change in simulated yield (kg/ha) with *low* nitrogen (5 kg/ha N) fertilizer under 4 GCMs. Bottom four maps: change in simulated yield (kg/ha) with *moderate* nitrogen (85 kg/ha N) fertilizer under 4 GCMs.

The Figure 6.5 results better show the impact of climate change on yield. Indeed, in the maps of low fertilizer application, the impact of climate change is not expected to be large. Under these nutrient stress conditions, yields are severely constrained, and the plant growth and yield is limited by nutrient stress. The warmer temperatures and moderate changes in precipitation do not affect yields much due to this overriding nutrient stress. However, under moderate fertilizer application, there is less nutrient stress and the plant growth and yield increase, and its growth then reflects any impact of warmer temperatures and changes in precipitation.

The results show that yield is expected to increase across highlands in particular, and to a smaller degree across the western plateau of the country. On the other hand, yields are expected to decline in the southern region. The pattern holds across all four GCMs. It appears that in the higher and medium elevations, the plant is responding to the beneficial aspects of warming temperatures, which are allowing it to grow better. In the south where temperatures are already very warm, the additional warming is causing yield declines because of a more rapid phenology, higher evapotranspiration and additional water stress.

The last set of maize maps (Figure 6.6) illustrates the yield benefit of adding fertilizer (the yield gap). They were made by subtracting the yield under low from the yield under moderate fertilizer levels for future climate conditions. The yield benefits remain large in the future, between 3,000 and 4,000 kg/ha across much of Malawi. The higher potential areas, with conducive temperatures and precipitation, gain the most. The very warm or dry areas, or areas with sandy soil which would lead to high nitrogen leaching, have a much lower nitrogen response.

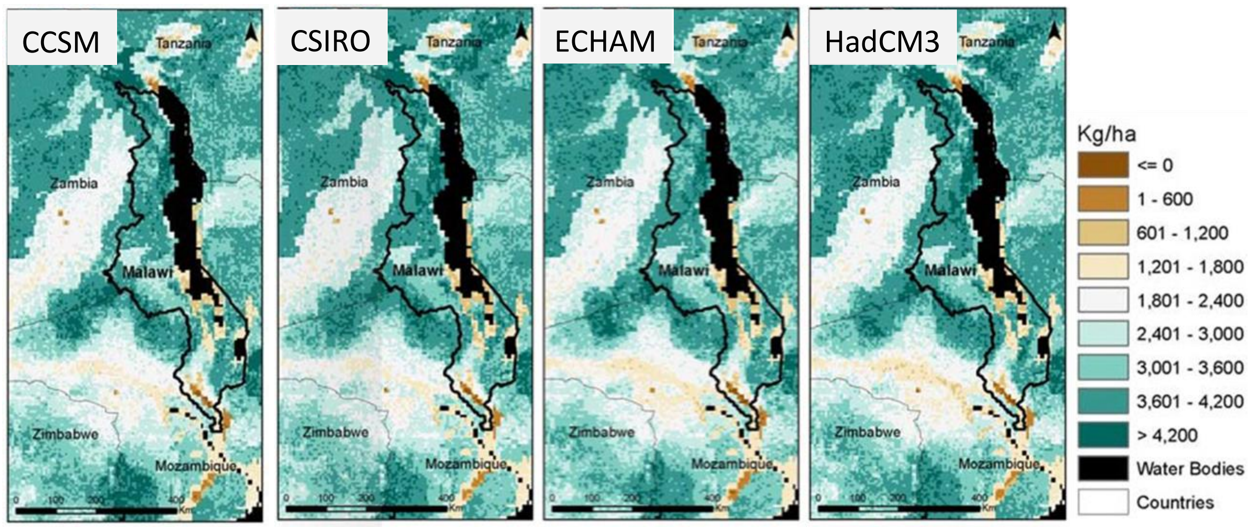

Figure 6.6. Benefits of fertilizer application on maize yield: difference in yield between low (5 kg N/ha) and moderate (85 kg N/ha) fertilizer applications in 2050 under 4 GCMs.

The conclusion is that climate change is expected to affect maize production in Malawi, but that improved management factors can mitigate this impact for much, but not all, of the country. In the future, addressing nutrient limitations will remain crucial to producing maize. Maize yields are low and will remain low in the future due to nutrient limitations. By addressing low nutrient levels, maize yields may be expected to remain at the 4,000 kg/ha level and higher across the highlands and plateau regions. In the south, however, the expected future warming added to current warm temperatures will negatively affect maize production and yields are expected to decline. Returns to fertilizer in these hot conditions would be low.

In summary:

1. Under the current and future climates, additional application of N fertilizer even at moderate levels dramatically increases maize yield.
2. Future climate impacts on maize grown with moderate fertilizer levels varies across the Basin:
    a. Higher elevation areas showed a positive response of higher yield due to warming temperatures and the Highlands becoming more suitable for maize.
    b. Most of the south would experience yield declines even with fertilizer because heat and water stress becomes more of a limiting factor
3. Therefore, application of fertilizer and adoption of short duration, drought resistant maize varieties by themselves are unlikely to be a sufficient adaptation strategy in the South.

Water can be expected to increasingly become a critical limiting factor affecting maize production.

7. Conclusion and Implications

This report examined the impact of historical and projected future climate change and variability on maize and rice productivity in Malawi. Its results have implications for agricultural planning and research, and for climate change and agriculture research. This section will first address the guiding questions posed by the GCGSI Malawian innovation activity. It will therefore describe the results related to how climate change is expected to impact agricultural productivity across Malawi, and implications for scaling maize and other crop production. It will then discuss implications for agronomic practices to promote climate resilience in the maize/legume and rice systems, and where those practices would provide the largest effect. We then reflect on the contribution of this research to GCFSI, LUANAR and the Global Development Lab, and mention possible next steps.

7.1. Scaling Implications

By conducting analysis of recent climate trends in different metrological stations across Malawi, and by conducting spatial (GIS) crop-climate modeling of the whole of Malawi, we obtained an understanding of how climate change is affecting agriculture in different parts of the country, and where the scaling of a maize-legume system would be most affected by climate change. We found that there are at least three distinct regional variations in agricultural potential, and how those regions will be affected. They are termed the north, central and south for ease of discussion, but the maps in the above sections reveal more nuanced geographical variations.

In the already warm south, temperatures are steadily warming and the frequency of hot days is increasing. This is critical because grain, legume and other crops are sensitive to hot temperatures over 35° C (95° F), especially during the flowering stage. For rice, even a day of extreme heat can cause sterility. The number of days with hot temperatures is probably already reducing yield in the south. The warmer temperatures also lead to higher crop evapotranspiration and larger water needs, but precipitation is not expected to increase. It is reported that a dry spell in mid-January to mid-February appears to becoming more intense, and the rainy season onset is often delayed and rainy season may be shortening. These would cause poor establishment of crops and, especially if the dry spell is during the flowering stage, low production. Therefore although much of the south has good current conditions for producing crops, climate change is impacting the future of the region in two ways: temperatures are very warm and are expected to increasingly impact crop production, and rainfall is highly variable and this variability will increase. Because of the variability and increased water demand by crops with the warmer temperatures, harvests may become more volatile and decline. A plan to expand (scale) a cropping system in this region would thus need to consider the warm temperatures and precipitation variability.

In the Central Region, total seasonal precipitation is also relatively high, but very variable. The frequency and intensity of a dry spell in January and February may also be worsening here. The temperatures in the Central Region are not as warm as in the south, but temperatures will increase in the future and impact production. The central region, therefore, may be a good location to scale a cropping system that is not sensitive to dry spells in the rainy season or other precipitation variability effects.

In the north, our data shows significant declines in precipitation amounts, particularly in March and April. The total amount of precipitation in the north is still relatively high, although there are fewer cloudy days and more hot, sunny days. The north is cooler that the other regions, but here, as in the south, the frequency of hot days is rapidly increasing. This region would thus support the scaling up of a different type of cropping system than in the south and center.

7.2. Implications for Climate Resilience

The first key result of the research is that the most important climate change influence on crops in the future is due to warming temperatures. In all locations, temperatures are expected to increase by between two to four degrees centigrade by 2050. Both maximum and minimum temperatures increase, with maximum temperatures rising somewhat faster. Although all locations are expected to experience this rise, the impact in the places already warm will be the most severe due to those locations already having maximum temperatures near the high temperature threshold for rice and maize.

The second key result is that the relatively small projected changes in seasonal total precipitation amounts are not expected to affect crop yields significantly. In some locations, total precipitation is expected to increase somewhat and in others decrease somewhat, depending on the GCM. However, precipitation variability is expected to continue to increase, leading to more frequent and intense dry and wet spells in the rainy season, more variability in amounts between seasons, and changes in the length of the rainy seasons. The combination of warming temperatures and little or no change in precipitation will in most cases lead to plants increasing their demand for water. Where precipitation is sufficient and temperatures remain below the heat threshold, as in the northern stations, evapotranspiration may increase but yield is maintained or even increases. Where precipitation is may not be sufficient or temperatures rise to the heat threshold, as in Domasi in Central Malawi, yields may decline.

To counteract these climate change impacts, the crop-climate simulation results provide information on some management options. The nitrogen fertilizer implications are especially relevant for maize, rice and other crops but not for legumes. The implications include the following:

1. In locations of sufficient rainfall and moderate temperatures, such as in the northern and central region stations examined, crop yields can attain high levels and response rates to fertilizer are high. Leaching of nitrogen during high rainfall years reduces yields, especially under lower nitrogen applications. This would call for recommendations of multiple doses of fertilizer throughout the season. Fertilizer and other soil improvement practices would, therefore, be a critical, no regrets option for adaptation to climate change. By addressing low nutrient levels, maize yields in the future may be expected to remain at the 4,000 kg/ha level and higher across the highlands and plateau regions. In the south, however, the expected future warming and increased precipitation variability, added to current warm temperatures, will negatively affect maize production and yields are expected to decline. Returns to fertilizer in these hot conditions would be low.

2. In locations of lower rainfall and warm temperatures, water deficits constrain yield and yield variability is high. The yield in Kasinthula, the station with warmest temperatures and

lowest rainfall, is suppressed because of both water stress and the direct effects of hot temperatures on the plants. Under these conditions, irrigation during the rainy season would improve yields and fertilizer response rates, but the warm temperatures could still constrain yields.

3. The simulations illustrate a critical climate change effect on crops, that of hot temperatures directly lowering yield. A large impact on rice was apparent after 2005 in the southern stations. Simulated rice yields in one station were halved due to the impact of extreme temperatures. Frequencies of hot days is already increasing in all regions, and will continue to become more frequent. There are few management factors that would reduce the direct impact of hot temperatures, other than selecting crops or varieties that may be less sensitive, or providing shade.

4. Our results showed that winter rice production depends almost entirely on irrigation water, and that the plants are susceptible to breaks in water availability particularly during seedling establishment and flowing stages. With warming temperatures, water demands will rise. There is already increasing competition for available irrigation water and climate change will exasperate the problem.

7.3. Contributions of the Research and Next Steps

The research results provide new information for Malawi on the current and future impacts of climate change on crops across the country. We sincerely thank the Malawian researchers for providing information and guidance permitting the analyses to occur. The approach will hopefully provide platform for LUANAR students to further and better analyze current climate trends and their impact on agriculture. Capacity building activities such as in crop modeling, agro-climatology and climate modeling could greatly assist LUANAR and the country.

The results themselves, and perhaps more importantly the development of the spatially-explicit crop-climate modeling framework, are important contributions to GCFSI and the Global Development Lab. The modeling framework can be applied to different crops and in different locations across Africa or elsewhere to ask questions regarding the impact of climate change and variability, and the potential for adaptation practices such as irrigation, fertilizer management and new varieties to increase resilience.

Next steps would be to indeed expand the crops examined to include legumes, for example, or new climate-resistant maize varieties. Additional potential adaptation practices could be included in the analysis.

In Malawi, follow-up research to examine the impact of climate change and variability on crops and livestock, and on households, would be important. The impact of warming temperatures on pests and diseases, for example, is an unanswered question. How households are being affected, and what affects their interest in and ability to adopt adaptation practices, are additional critical issues.

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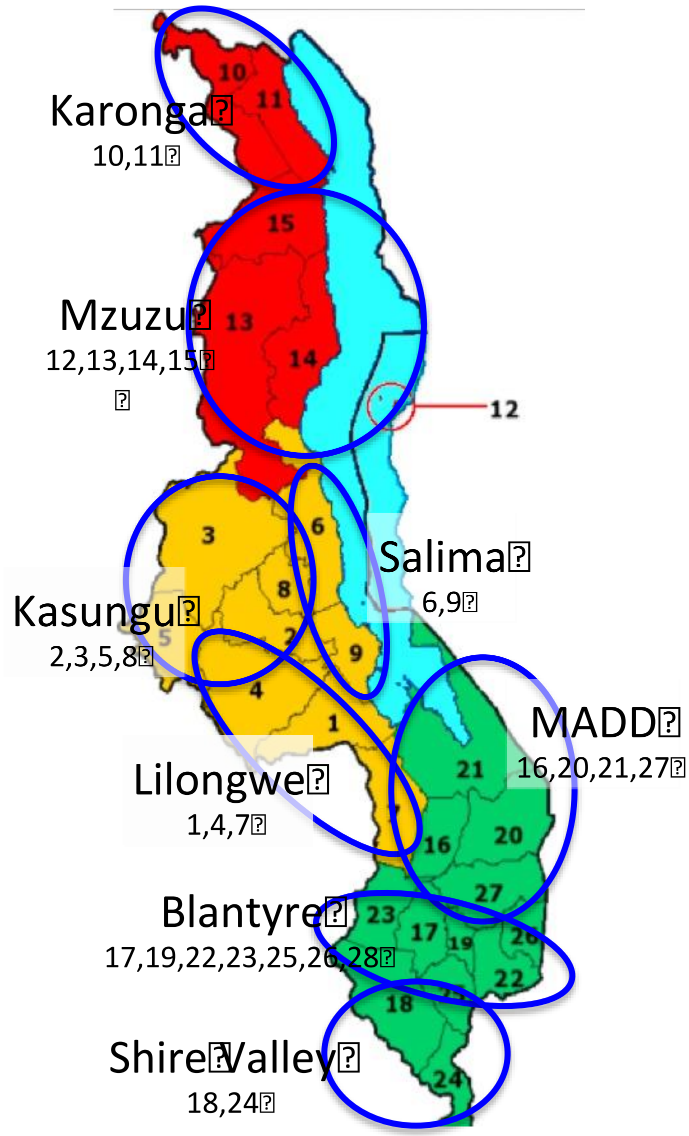
Annex

Annex 1. Location of Malawi agricultural sones. Source of base map: Districts of Malawi, Wikipedia. http://en.wikipedia.org/wiki/Districts_of_Malawi



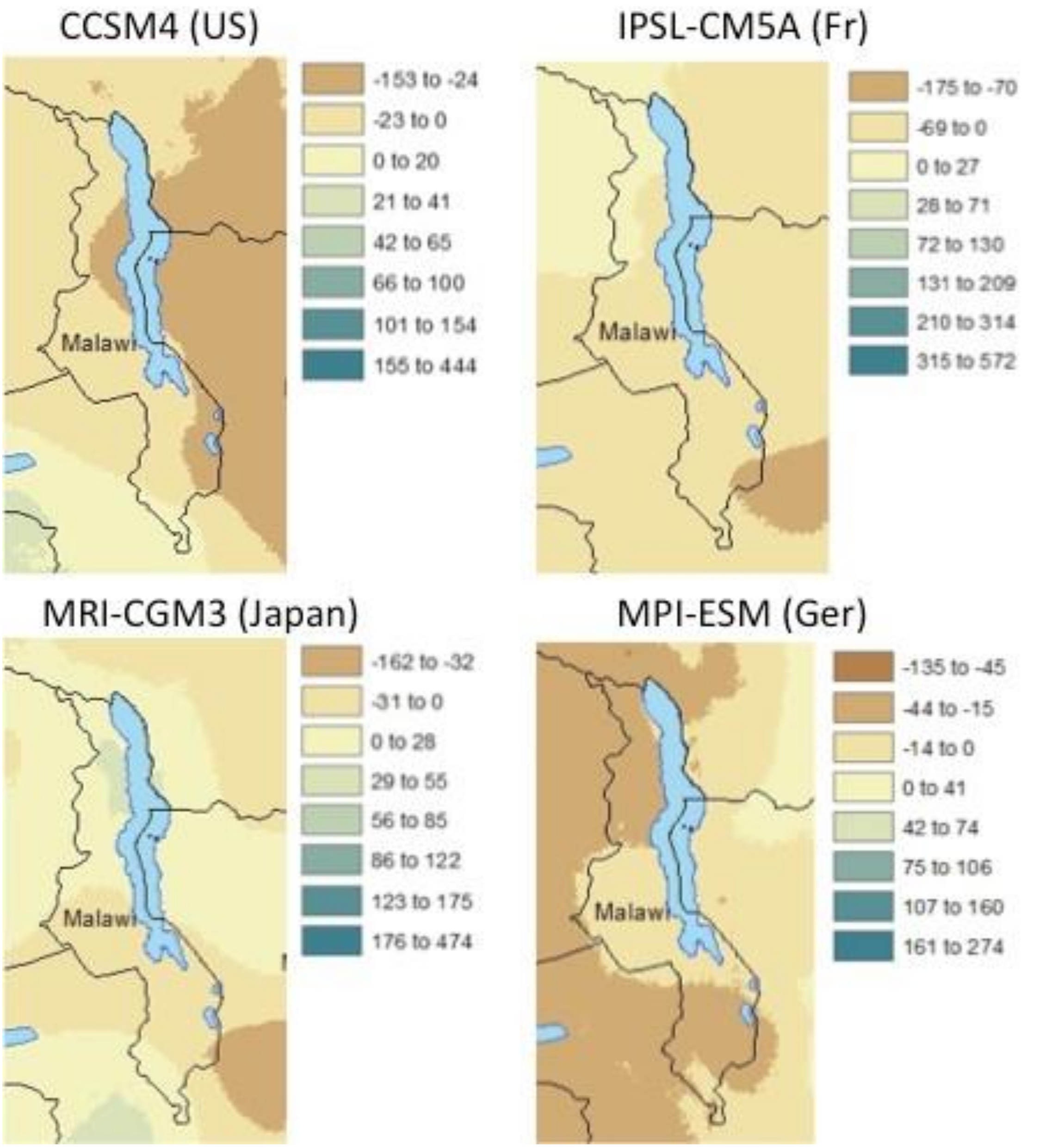
Central Region
1 - Dedza
2 - Dowa
3 - Kasungu
4 - Lilongwe
5 - Mchinji
6 - Nkhotakota
7 - Ntcheu
8 - Ntchisi
9 - Salima

Northern Region
10 - Chitipa
11 - Karonga
12 - Likoma
13 - Mzimba
14 - Nkhata Bay
15 - Rumphi

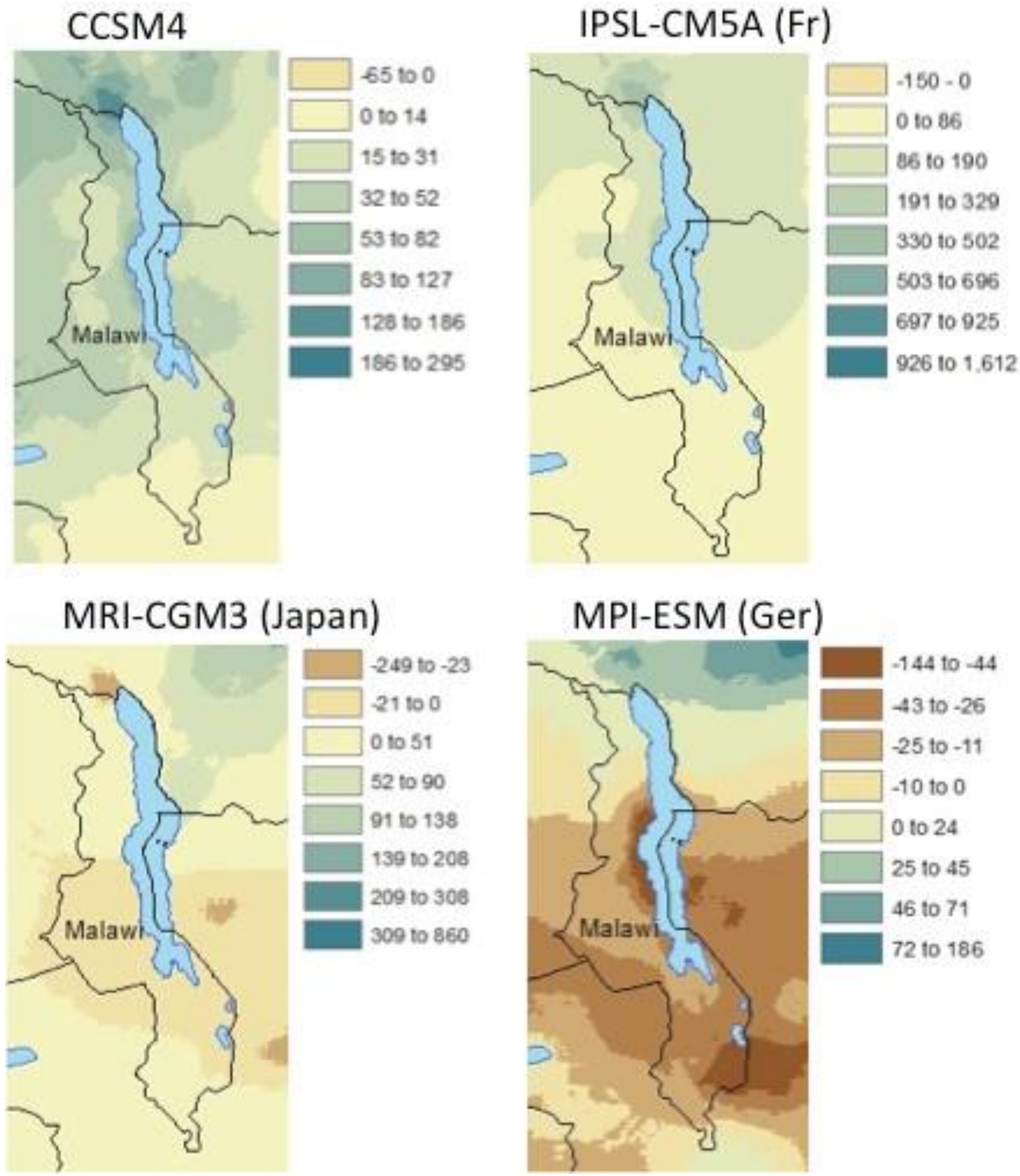
Southern Region
16 - Balaka
17 - Blantyre
18 - Chikwawa
19 - Chiradzulu
20 - Machinga
21 - Mangochi
22 - Mulanje
23 - Mwanza
24 - Nsanje
25 - Thyolo
26 - Phalombe
27 - Zomba
28 - Neno

Annex 2. Change in precipitation, 2000 to 2050, of AR5 GCMs for Malawi; RCP 8.5 (rapid growth) scenario. Note that legend scales vary.

A. October-November-December Months



A. **March-April-May Months**



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