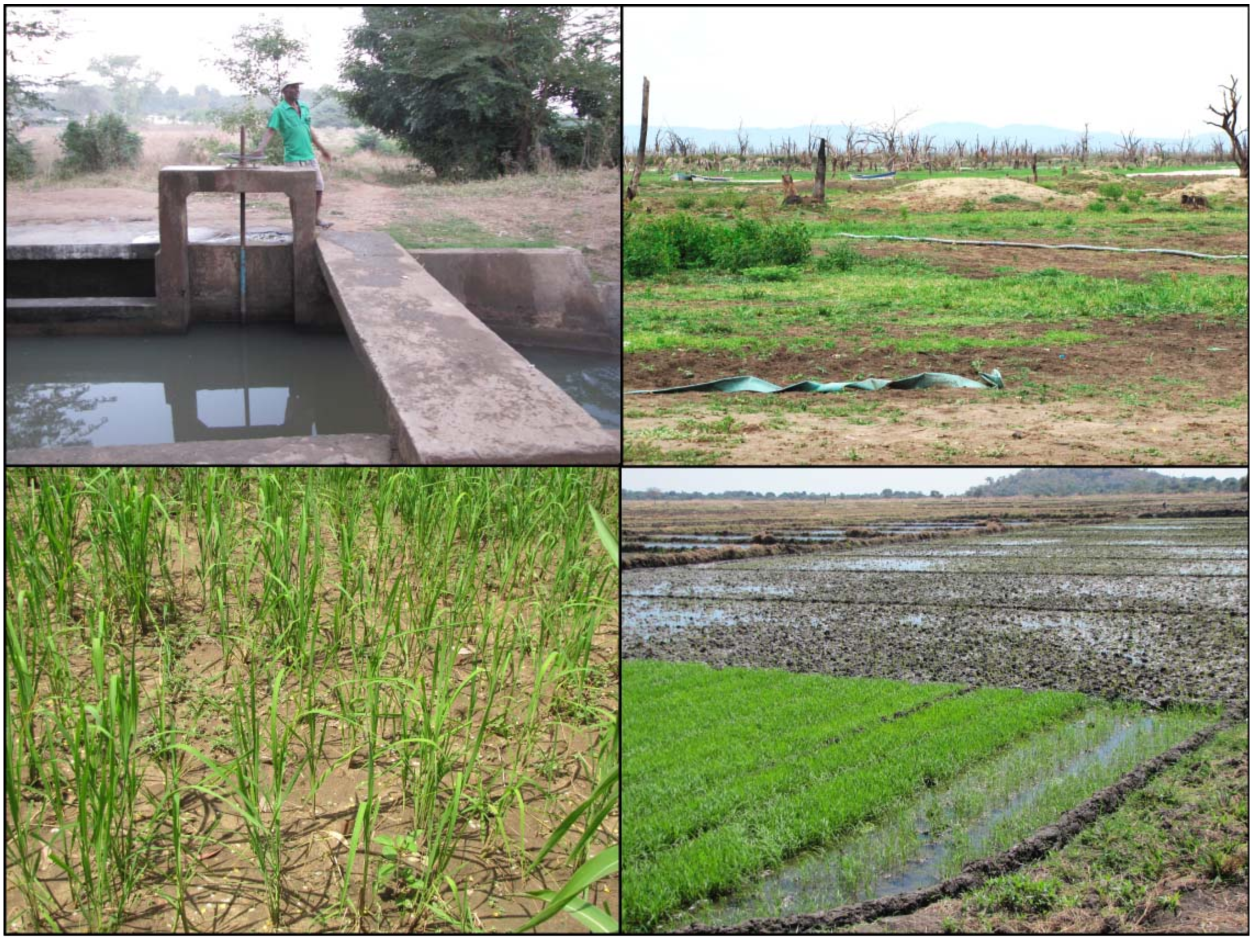
UNIVERSITY OF DAR ES SALAAM
INSTITUTE OF RESOURCE ASSESSMENT (IRA)

CROP AND WATER MANAGEMENT UNDER CLIMATE CHANGE SCENARIO ANALYSIS



A REPORT SUBMITTED TO USAID TANZANIA
JULY 2016

Table of Contents

List of Tables

List of Figures

Acknowledgements

The Project team at IRA wishes to thank partner researchers from Michigan State University (J.M. Olson, G. Alagarswamy, J. Andresen and N. Moore) and Agrible, Inc. (W. Northcott, P. Miller, C. Hawkins, D. Pike, C. Raj and P. Morse) for modeling, analysis and preparation of this report.

The project team also wishes to thank the collaborating institutions and key stakeholders for their contributions of expertise, information and data required for the development and calibration of the models that form the basis of the scenario analysis report. These institutions include, the Tanzania Meteorological Agency (TMA), the Rufiji Basin Water Board, the District offices of Kilosa and Kilombero, the Kilombero Agricultural Training and Research Institute (KATRIN), and the Ilonga Agricultural Research Institution. The project team also extends its heartfelt thanks to other stakeholders from Non Governmental Organisations (NGOs), academia and media for their invaluable time and inputs towards this process.

This report was made possible through support of the United States Agency for International Development-Tanzania under Fixed Amount Reimbursement Implementation Letter Number 2013-IL-SO13-01 under Strategic Objective Agreement No. 621-0013-05.. The opinions expressed herein are those of the author(s) and do not necessarily reflect the views of the U.S. Agency for International Development or the U.S. Government. The financial support and technical guidance by the USAID-Tanzania Mission has been of great value to realization of the project activities.

1. INTRODUCTION

This report provides results of extensive modeling in a Geographical Information System (GIS) framework and data analysis to examine the potential of various improved technologies to reduce the negative effects of climate change on rice and maize yields, and on water availability for irrigation in the Rufiji River Basin. A scenario approach was adopted to test the effectiveness of current, or baseline technologies against improved technologies under current and projected future climatic conditions.

This has been accomplished by calibrating rice, maize, climate and hydrological models to Rufiji River Basin conditions, running the models in an experimental framework under current and future climate conditions, and under various management options such as improved irrigation technologies or fertilizer applications.

The analysis was conducted using numerous datasets; four types of models (climate, crop, hydrological and land use) and statistical analysis. The methodology and datasets used are discussed in more detail in prior publications including by Olson *et al.* (2015); IRA (2015); Moore *et al.* (2012); Alagarswamy *et al*. (2015); and Andresen *et al.* (2014). Calibration of the models to local, observed or measured data was conducted as much as possible. However, the calibration and validation of the models was affected by the limited amount of observed data available (particularly observed crop yield, daily precipitation, stream flow across the Basin rivers and streams, water abstraction and irrigation technologies). Because of this, the results should be considered representative and the trends are indicative.

It should also be noted that simulations could not capture the entire reality faced by small-scale farmers in southern Tanzania. Crop models, for example, assume agricultural research station-like conditions with no yield loss due to weeds, pests, diseases, or early or late planting, so simulated yields are often higher than what farmers' experience.

Future climate modeling is extremely complex and results are uncertain. In this case, climate scientists prefer to provide results of several global climate models (GCMs) to illustrate the range of projected changes in temperature and precipitation. Although the GCMs for this analysis were chosen for their ability to simulate current trends in East Africa, of course it is not possible to judge their accuracy in projecting the future. Scientists have more certainty about the future trends in temperature than in precipitation. The future projections particularly of precipitation are thus not certain and please take the results as representative trends.

The purpose of the crop, climate, land use and hydrology modelling in this exercise is to isolate the impact of specific management practices on crop yield and water availability, holding other management and environmental variables constant, in order to obtain information on the potential benefits of improved technologies. For these purposes, model simulations are an ideal tool, permitting such questions to be examined without conducting numerous, multi-year field trials.

This report is divided into five chapters. Chapter 1 provides an introduction. Chapter 2 introduces the technology scenario approach. Chapter 3 presents findings comparing the effectiveness of the baseline and improved crop and irrigation technologies under current and future climate conditions while Chapter 4 provides a conclusion.

2. THE SCENARIO APPROACH

2.1. Baseline Scenarios

2.1.1. Introduction

The conditions for the baseline scenario adopted for this project were selected to reflect the current practices of many small-scale farmers, particularly those with few resources. In general, the selected practices require relatively low capital or financial inputs at the farm level, and require a low level infrastructure that would be provided by the government or other higher-level administrative authorities.

The crop yields and water availability from the baseline and improved adaptation technologies are examined under both current climate conditions and under future climate conditions. We can then compare the potential usefulness of the various technologies for climate change adaptation.

2.1.2. Baseline Crop Technologies

For the crops, the baseline scenario entailed the simulation of older varieties and low applications of external inputs (Alagarswamy et al. 2015; Andresen et al. 2014).

Older, open pollinated (not hybrid) crop varieties were selected. The seeds of these varieties would be readily available at no or little cost, and the farmers would not be required to purchase new seeds every growing season. These older varieties may have other benefits, such as taste, low nitrogen tolerance, and disease and/or pest resistance. Unfortunately their yield can be low, and the length of time to maturity can be long (which can reduce yield particularly under climate change conditions).

The maize variety that represents these conditions is Katumani Composite, a variety developed by the Kenya Agricultural Research Institute (KARI, now KALRO) in the 1970s for warm and drier conditions. It has been widely used in the lowlands of Tanzania, Uganda and Kenya. The crop model used, DSSAT CERES, had been earlier calibrated for Katumani Composite by KARI scientists, and the project team had access to these parameters. In the scenarios of improved technologies, the higher-yielding, hybrid maize H-614 variety was simulated. Some farmers already use a variety similar to this.

Two rice (Oryza spp.) varieties were selected for the baseline scenario. The first is the short duration Poussa 33 which is generally planted during the dry season, and the second is Kilombero, a long duration cultivar often grown in the rainy season. Kilombero has characteristics similar to the more commonly grown Supa, according to breeders at the Kilombero Agricultural Training and Research Institute (KATRI). So our results for that variety are labeled with either Kilombero or Supa. Supa is a popular variety among growers because of its nice aroma; indeed the price of Supa is higher than for other (including improved) varieties. The DSSAT rice model for these varieties, and for DST-85, an improved rice variety used in the improved technology scenarios, was calibrated using data and information from the literature and from KATRI.

The baseline scenario for the crops also includes low levels of external inputs. For both crops, this entailed low applications of fertilizer, of only 5kg nitrogen fertilizer per hectare, which is not unusual among small-scale farmers according to our surveys and focus group interviews. The baseline scenario also entailed the crops depending solely on rainfall, with no supplemental water supplied.

2.1.3. Baseline Irrigation Technology

The basis for developing the baseline scenario for the water availability simulations was two-fold. First, it entailed identifying the current flows and use of water in the Basin, including the amount of land currently under irrigation. This required a large scale effort to compile data and information on water abstraction by different types of users, stream flows, precipitation, land cover, population, soils, elevation and other variables to calibrate the hydrology model, and a widespread literature review of others' estimates and their methodology for these estimations (IRA 2014; Olson et al. 2015). Secondly, it involved replicating irrigation practices commonly used by small-scale farmers in the Basin, according to the focus group interviews, District officials and team member field visits.

The baseline and improved irrigation technologies that are simulated are summarized in Table 2. Basically, the baseline scenario assumes mostly unlined canals that are weeded and maintained by hand, little to no measurement or regulation of water abstraction, no return flow of water to the stream or canal of origin, limited (hand) leveling of fields, and flooding the field to water the plants (not using overhead sprinklers). The low water use efficiency, 15%, of this type of current system was obtained from earlier estimates (Ndomba et al. 2013).

2.1.4. Current Climate and Future Climate Scenarios

The crop yields from baseline and improved adaptation technologies are examined under both current climate conditions and under future climate conditions. We can then compare the potential usefulness of the various technologies in adapting to climate change. Results of the team's climate change research can be found in IRA 2015, Olson *et al.* 2015, Moore *et al.* 2012, and Andresen *et al*. 2014.

The datasets for current, or recent historical climate datasets used include:

a. Observed meteorological station data from the Tanzania Meteorological Agency
b. WorldClim (Hijmans *et al.,* 2005) which is a spatial (GIS) precipitation dataset with monthly means covering the period 1960 –1990

c. CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data, Funk et al. 2014) version 1.8.
d. NASA Power (NASA 2014) for minimum and maximum temperatures and solar radiation.

Global Climate Models (GCMs) provide future climate simulation results (Moore et al. 2012). Four AR5 IPCC models were selected for the Rufiji Basin region based on their ability to simulate observed spatial and temporal climate trends (Otieno and Anyah (2013), and to provide a level of comparison between GCMs:

a. CCSM4: Community Climate System Model, version 4 from the National Centres for Environmental Research, National Centre of Atmospheric Research, USA,
b. MPI-ESM-LR: Max Planck Institut für Meteorologie Earth System Model, Germany,
c. CanESM2: The Canadian Centre for Climate Modelling and Analysis Earth System Model, version 2,
d. MRI-CGCM3: Meteorological Research Institute, Japan.

The data were downscaled to 6 km and bias-corrected to daily time steps using a MATLAB program (http://globalclimatedata.org/) and modified to suit our needs. Historical data sources were based on CHIRPS v 1.8 for rainfall data and interpolated daily station data for historical temperature surfaces done for the hydrological modeling. Monthly perturbations were applied to daily time series for the years 2010-2060.

2.2. Improved Technology Scenarios

The improved technology scenarios test various crop and irrigation technologies to examine their effectiveness in improving yields and/or water availability under current and future climate conditions.

The improved technologies examined for the crops include newer, improved varieties, application of supplemental water, and improved nutrient management. These were examined individually and in combination. However, in the field the technologies are usually applied together. Improved crop varieties, for example, are usually not low nitrogen-tolerant (i.e., they perform poorly under low nitrogen conditions). However, they respond well to fertilizer applications (i.e., their yield improves greatly with fertilizer). Farmers who invest in improved variety seeds, therefore, usually also invest in fertilizer. Similarly, farmers who are able to invest in irrigation, which can be a very large financial investment, usually also invest in purchasing seeds and fertilizer in order to obtain a higher return to their investment.

Specifically, the improved crop technologies simulated are:

a. Varieties
    1. Rice: TXD-85, a higher-yielding and medium duration variety. This was selected based on a literature review and with input by rice breeders in Tanzania and the International Rice Research Institute (IRRI).
    2. Maize: H-614, a higher-yielding medium duration hybrid variety with characteristics of many improved varieties grown in the area. This was selected and model calibrated with input by breeders in East Africa and internationally.

b. Irrigation
    1. Rice: Rice being grown during the dry, winter season was simulated with supplemental irrigation provided as needed.
    2. Maize: Simulations were conducted of maize grown during the main growing season with supplemental irrigation as needed.

c. Nutrient management (nitrogen, the most limiting nutrient)
    1. Rice: Rice simulations compared yields grown under baseline (5kg/ha), 50 kg/ha and 100 kg/ha.
    2. Maize: maize simulations were conducted under baseline (5 kg/ha), 35 kg/ha and 85 kg/ha.

The surface water simulations used a series of gradually improved or more mechanized technologies including, critically, the return flow of unused water into the stream or canal. With each improvement, less water is lost to the agricultural system from infiltration, water logging and evaporation. Water efficiencies increase and thus more land could potentially be irrigated.

The technology scenarios were selected based on Tanzanian government and other Tanzanian institutions' plans and programs, and a wide literature review on irrigation systems in developing countries. In the Basin, versions of these scenarios are being used by different stakeholders. For example, Kilombero Plantations, Ltd. is using the improved technologies of the project's mechanized scenario. The government is implementing irrigation improvement projects. Many irrigation schemes are already managing, or restricting, water abstraction among their members.

Each level requires additional financial investment and water management at the farm and especially the village and higher levels. For example, one management change in improved technologies would be measurement of water levels and water abstraction, and managing or restricting abstraction accordingly. This is being done albeit without formal measurement in planned irrigation schemes. However, expanding this approach to address the wider issue of widespread water abstraction in the Basin could require major efforts at the Basin, district and village levels, since much abstraction for irrigation is currently "illegal" or conducted without a permit.

3. RESULTS

3.1. Rice: Comparison of Baseline and Improved Technology Scenarios

The baseline and improved technology scenario yields for rice varies across the Basin, depending on climate and soils. Rice is a tropical plant with particularly warm temperature requirements. Most varieties, including those grown in Rufiji Basin, thrive in warm temperatures (between 25°C and 30°C) and do not produce in cooler temperatures. Hot temperatures, however, suppress yields, and plants stop producing at temperatures over 35°C. Rice is also demanding of water, requiring substantially more than maize or other grain crops grown in Tanzania. Although it does not require continuously saturated soil, it grows poorly if water stressed particularly during transplanting and reproductive stages.

3.1.1. Fertilizer Response

A potentially important adaptation technology is improved nutrient management. The question being addressed is whether nitrogen fertilizer could reduce the variability of yield, and where in the Basin it would have the largest impact. To examine this, the effects of nitrogen fertilizer application on rice yield are examined under current and future climate conditions.

Two simulation approaches were used, point and spatial. At the point (particular site) level, sites were selected in key rice production areas, in sites that would provide a climatic contrast to current rice growing areas, and/or sites where the project's field work has been conducted. These simulations allow a detailed look at rice yield's response to fertilizer depending on temperature, precipitation and precipitation variability. Spatial (GIS) simulations were also conducted which provide a good visual comparison of yield response across the Basin.

The site locations cover different climates in the basin, from cool and wet zones in the highlands (e.g., Iringa Rural-2), and warm and wet locations in the Basin (e.g., Kilosa). Temperatures follow elevation closely and the highlands cool and usually wet, whereas the lower elevation zones are warm and can be either dry or wet. Typically inter- and intra-seasonal precipitation is more variable in drier zones, so these locations could be expected to have more yield variability.

Yields are optimal when TMax ranged from 28°C to 30°C and TMin ranged from 20°C to 23°C. Yields decline as one moves lower and temperatures warm, or as one moves higher and temperatures decline. Mean rice yields are highest in the moderate elevation site (Kilosa, elevation 531 m). With climate change, the zone of highest yield will thus move up the elevation gradient and the lowest zones can be expected to become too warm for optimal yields.

Simulations were conducted with three levels of nitrogen fertilizer (5, 50 and 100 Kg N/ha) using the Kilombero/ Supa variety (Table 1) (IRA 2015). Rice yields simulated with the baseline scenario of 5 Kg N, which is not an uncommon application, were very marginal yet similar to many farmers' yields (pers comm of Ephrem Mwelase, District Irrigation Officer, Kilosa, and Kisawasawa Village Extension Officer). However, simulated rice yields responded well to higher rates of N in all locations. Simulated yields using 50 kg N/ha were similar to or a bit higher than yields obtained by small-scale farmers applying fertilizer and using improved varieties (pers comm of David Kigosi, Ag. Extension Officer, Kilosa District and others). Simulated yields with an application of 100 kg N/ha reached 7 tonnes/ha, similar to the highest yields obtained by commercial rice growers in the region using intensive cultivation practices (pers comm General Manager, Kilombero Plantations Limited). Simulated yields were also in line with published results from neighboring areas (e.g., Kanyika *et al.,* 2007).

Site	**5 Kg N/ha**	**50 kg N/ha**	**100 kgN/ha**
Rufiji	334±96	2820±385	4947±558
Kilembero	63±57	2058±511	4637±336
Kilosa	675±170	3766±785	5724±868
Mbarali	77±64	2116±653	4709±819
Iringa	76±71	1365±521	3950±570
Kilolo	102±191	1056±522	3733±606
Mufindi	69±95	767±474	3029±734

Table 1: Simulated rice yield (mean ± SD) under 3 Nitrogen levels, current climate.

The results of Table 1 point to the critical importance of nutrient management for raising rice yields in the Basin. Baseline yields ranged from extremely low (under 100 kg/ha) in some sites with poor soils and less conducive weather, to almost 6,000 kg/ha with the higher fertilizer application in optimal weather and soil conditions. The highest returns to fertilizer were obtained in sites with moderately warm temperatures such as in Kilombero.

The potential of fertilizer to reduce the impact of climate variability on rice yield was also examined. Standard deviation (reflecting variability, shown following the ± symbol) are provided in Table 1, and variability is also illustrated in Figure 1 as graphs of annual yield and precipitation over 30 years using two historical climate datasets (CHIRPS and WorldClim), and for the two rice varieties (Poussa 33 and Kilombero/Supa) for the Rufiji site.

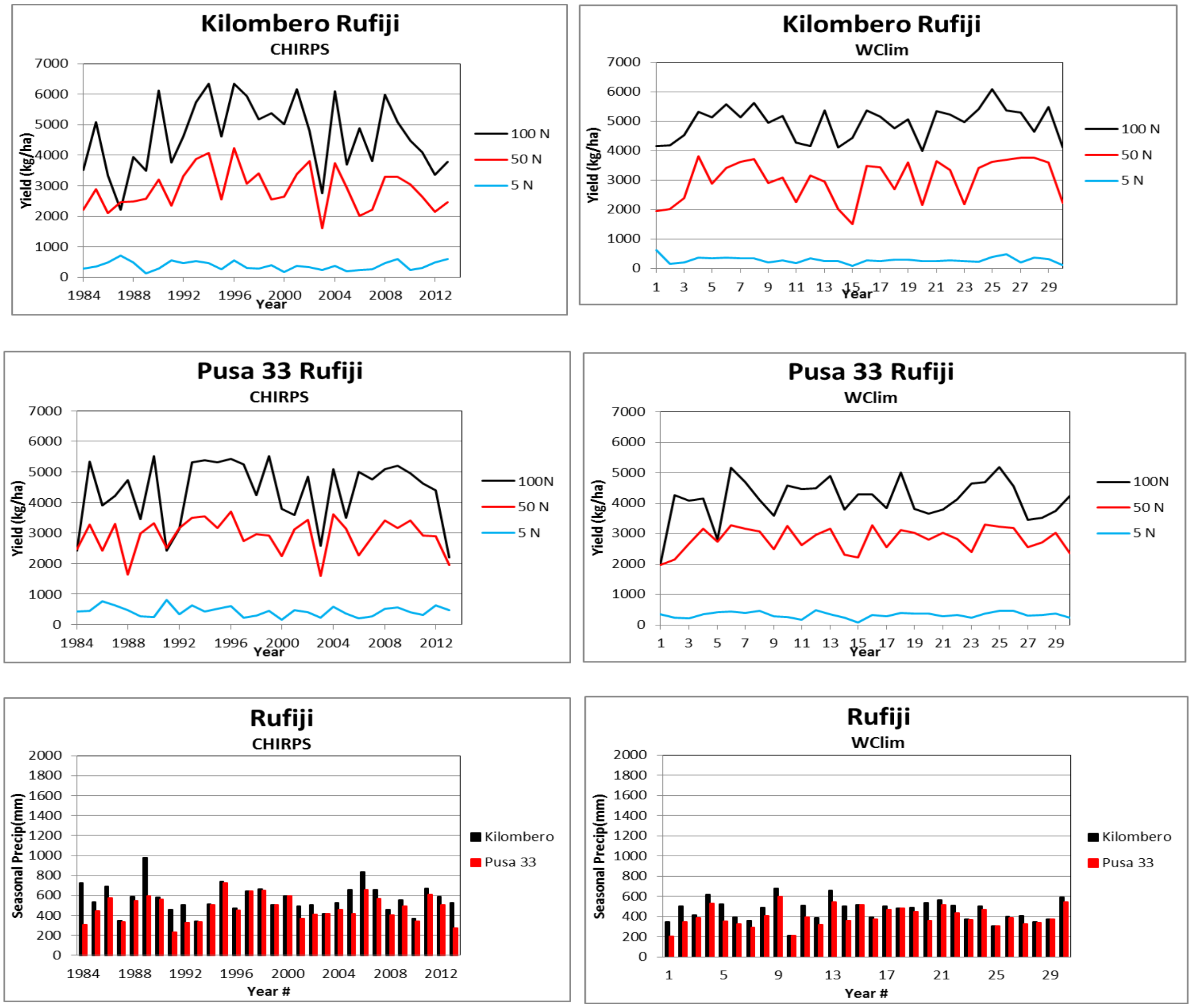


Figure 1: Inter-annual variation of simulated yield in Rufiji Station under three nitrogen fertilizer levels (5, 50, and 100 Kg N/ha) and two rice cultivars (Kilembero and Pusa 33) over 30 years.

As expected, the Rufiji project sites, which have relatively lower precipitation and the warmest temperatures, shows high inter-annual precipitation and yield variability. CHIRPS precipitation was somewhat more variable than WorldClim's. Fertilizer response is marked. Figure 1 illustrates the large difference in yield between the baseline 5 kg/ha (blue line) and the improved scenarios of 50 and 100 kg/ha (red and black lines respectively) across all years. However, in some years, the yield difference between fertilizer application amounts is much less; in those years, a break in precipitation affected rice yield despite high amounts of fertilizer application. This illustrates an important aspect of fertilizer use as an adaption technology. Fertilizer response is highest when weather conditions are good; in hot or drier conditions, including dry spells in the rainy season and shorter rainy seasons, yields are constrained and additional fertilizer provides only marginal benefits.

The difference in yield across different climate conditions can be seen in the spatial simulations of rice in the Basin in Figure 2. Production under two levels of nitrogen (N) fertilizer application (5 and 100 kg/ha) are presented using the improved variety, TXD-85, as an example. The rice had a high response to the N application. Indeed, yield with low N is mostly below 210 kg/ha, but the yield with the higher N application rose above 5,000 kg/ha in the highly productive zones with warm temperatures and sufficient precipitation. The *difference* map (left bottom) illustrates the gap in yield between the two technologies, or the additional amount of rice yield obtained with the higher fertilizer application—over 4,000 kg/ha across wide areas. As seen in the point modeling, the highest response to fertilizer is in the locations with optimal rice growing conditions. Where it is too cold in the Highlands or even a bit cooler and drier west of the Highlands, additional fertilizer provides lower benefits.

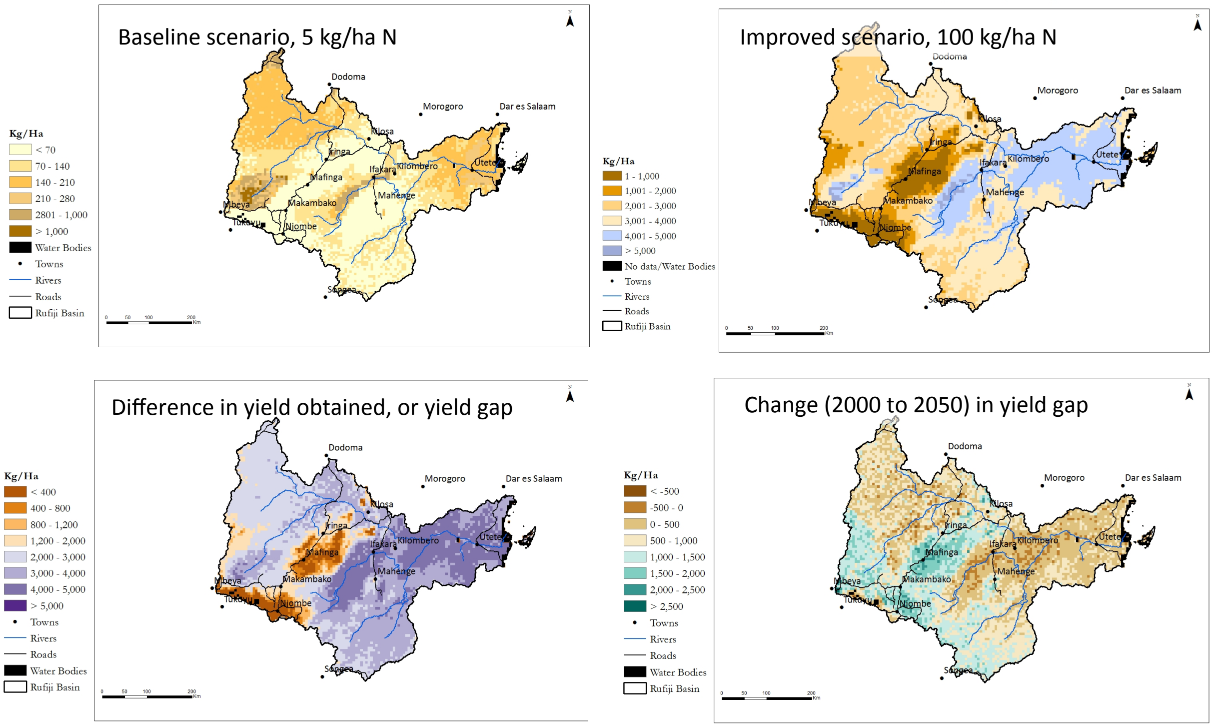


Figure 2: Current climate, rainfed: Simulated rice yield under baseline fertilizer scenario (5 kg/ha N), under improved technology scenario (100 kg/ha N), and the difference in yield between the two scenarios or the yield gap. WorldClim, TXD-85, December planting.

In the future as the climate warms and precipitation amounts and distribution within the year changes, rice yield response to fertilizer can be expected to change. As seen in previous milestone reports and in the Decision Support Tool, temperatures are projected to warm from 1.5 to 3.0 degrees C across the Basin, with the Highlands warming somewhat faster (IRA 2015; IRA 2016). Growing season precipitation is projected to decline somewhat in the Highlands but remain relatively high there, and either increase somewhat or stay the same depending on location and GCM. GCMs do not simulate changes in precipitation variability very well yet, but if current trends continue precipitation will become more variable with the onset of rainy seasons less reliable, and fewer wet days (i.e., more dry spells within the rainy season) (IRA 2014).

The effectiveness of fertilizer as an adaptation technology, then, can be expected to change depending on location and how the climate is expected to change there. Figure 3 provides a comparison, using the results from the MPI GCM.

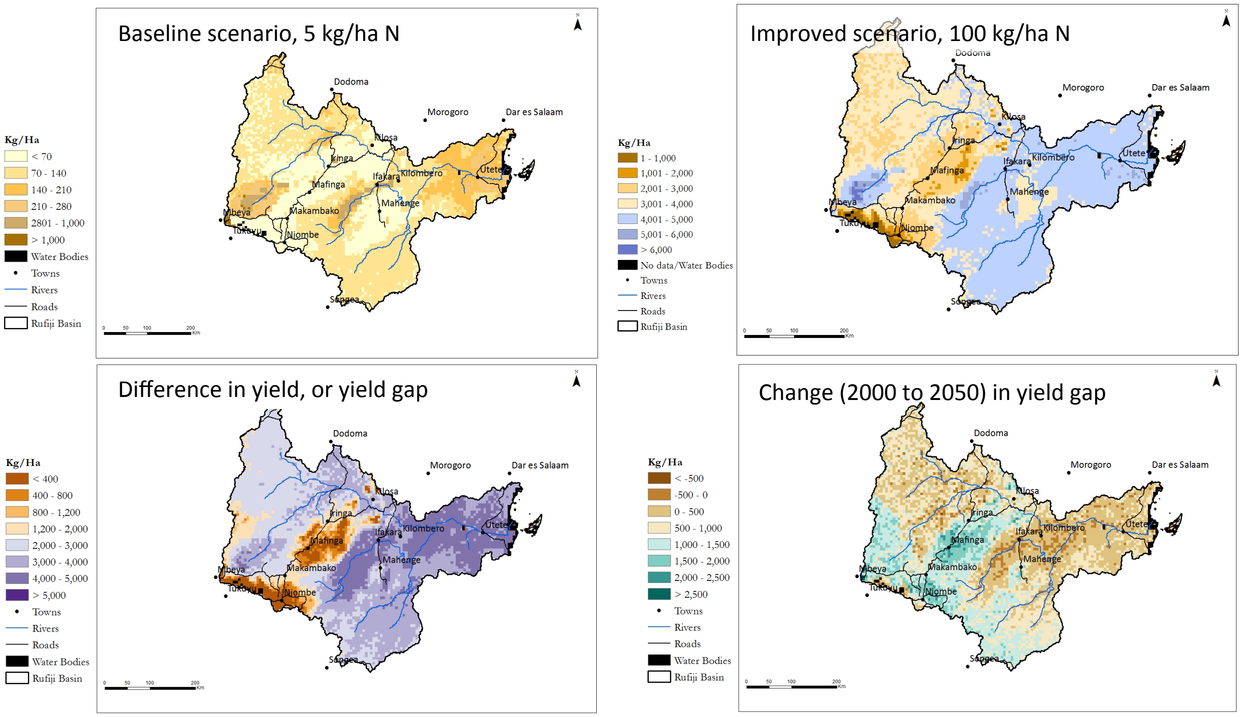


Figure 3: Future 2050 climate, rainfed: Simulated rice yield under baseline fertilizer scenario (5 kg/ha N), under an improved technology scenario (100 kg/ha N), and the difference in yield between the two fertilizer levels or the yield gap. Bottom right map: the change in the yield gap between 2000 and 2050. MPI GCM, TXD-85, December planting.

The large difference in yield between low and high fertilizer applications is even larger in the future. The difference or yield gap map illustrates the additional amount of rice yield obtained with the higher fertilizer application. Again, the additional yield is over 4,000 kg/ha across wide areas of the Basin where temperatures are conducive. The impact of climate change on rice production is important for both low and high N application levels. However, the negative impact of climate change is larger for higher applications of N and in wetter areas because the yield potential is larger there. In cooler or drier areas, such as west of the Highlands, the yield potential is lower and the impact of climate change on fertilizer response is less. Nevertheless, where temperatures are not too warm and water is sufficient, N applications can be expected to continue to provide large returns even if the returns aren't as large as they are currently. Nitrogen fertilizer is thus a good "no regrets" adaptation option.

3.1.2. Rice variety comparison

Another important possible adaptation to climate change effects is to plant newer varieties that may be more resilient to heat and shorter rainy seasons. A comparison is shown between the baseline technology variety, Supa (or Kilombero for the simulations), commonly grown and known for it good aroma, and an improved variety known as TXD-85 in Figure 4.

Under current climate conditions, the yield of TXD-85 compared to Supa is relatively large during the rainy season, particularly in higher-potential rice growing areas of Kilombero and east of the Highlands. The yield gap maps shows that where yields are constrained by cold in the Highlands, there is little benefit to the improved variety, and constrained by low precipitation such as west of the Highlands. Indeed, the improved variety provides an additional 2,000 or more kg/ha in yield in the high rice growing potential areas, but less than 100 kg/ha in the dry or cold zones.

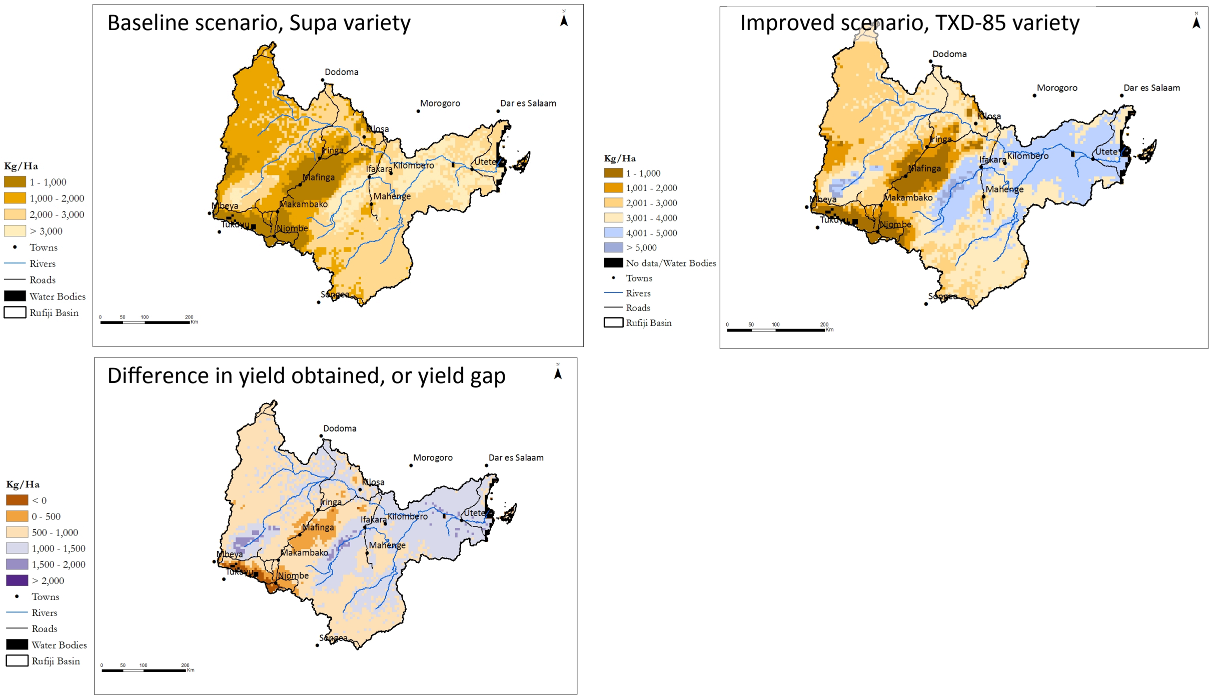


Figure 4: Current climate, rainfed: Simulated rice yield under baseline variety Supa and under improved technology scenario variety TXD-85, and the difference in yield between the two varieties or the yield gap. WorldClim, 100 kg/ha N, December planting.

The yield difference between the baseline and improved rice variety scenarios, however, is even greater during the dry, winter season when rice is irrigated. Irrigation removes the constraint of water stress on rice yield, so the improved variety performs very well. The potential of the improved variety is high when nutrient and water limitations are removed. This is illustrated in Figure 4 maps, which show rice yields of both varieties under an irrigated simulation. Comparing the yield gap maps in Figures 4 and 5 shows that a much larger area across the Basin has 2,000 or more kg/ha with the improved variety than under the baseline variety when both are under irrigation.

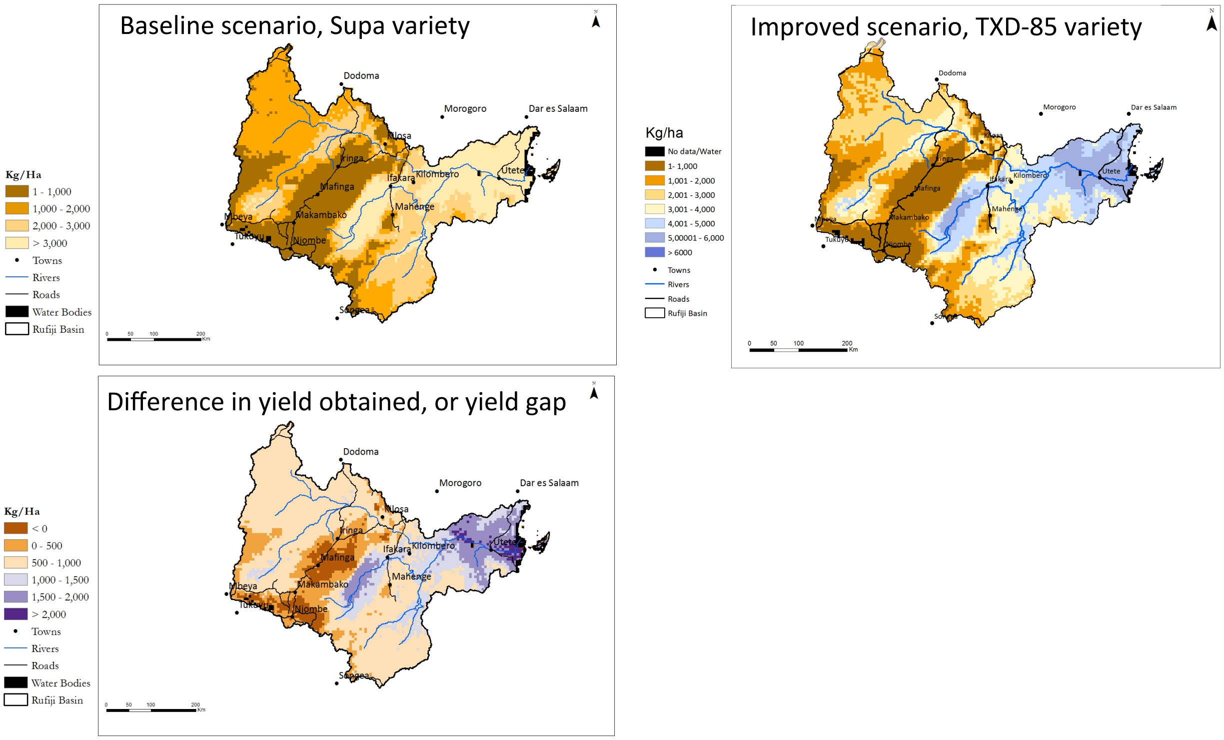


Figure 5: Current climate, irrigated: Simulated rice yield under baseline variety Supa and under improved technology scenario variety TXD-85, and the difference in yield between the two varieties or the yield gap. WorldClim, 100 kg/ha N, June planting.

However, it is important to test the relative effectiveness of the improved variety grown with irrigation during the winter, dry season under future climate conditions, as well. To do this, the same sets of simulations were conducted using several GCMs (see a larger set of maps in the Decision Support Tool). Figure 6 provides summary results: the variety yield gap for both time periods, and the change in variety yield gap map.

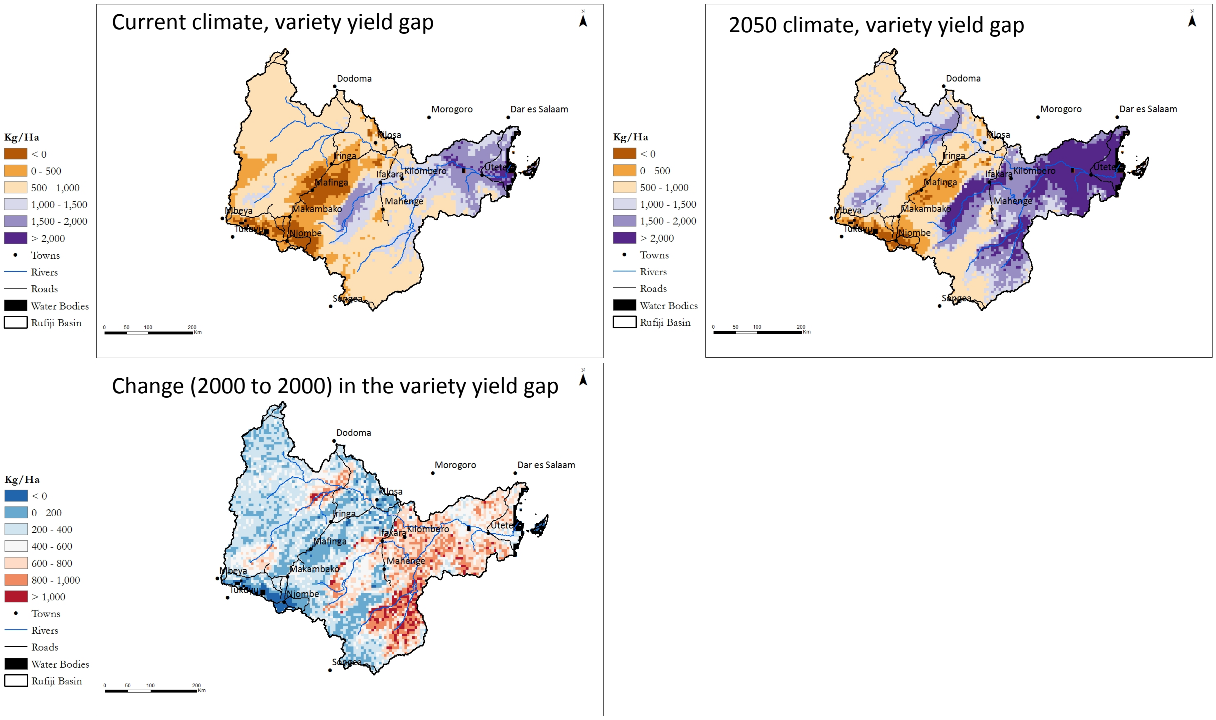


Figure 6: Irrigated conditions: The rice yield gap between the baseline variety Supa and improved technology variety TXD-85 in 2000 and in 2050, and the change in the yield gap between the two time periods. WorldClim (TXD-85-Supa), MPI (TXD-85-Supa), 100 kg/ha N, June planting.

The results of Figure 6 show a much larger yield gap between the two varieties under future climatic conditions than under current climate conditions. In other words, the difference between the high yields of the improved variety and the lower yields of the baseline variety is larger in the future. The difference is largest in the lowlands east of the Highlands, indicating that the improved variety may be more resistant than the baseline variety to the projected future hotter temperatures. Indeed, the bottom map of Figure 6, the change in the yield gap, confirms that the biggest difference between how the two varieties perform under climate change is in the warm east. In the cool Highlands and in the drier area west of the Highlands, there is less of an impact of climate change on the yield gap.

The baseline and improved variety scenarios, therefore, indicate that the improved variety out-performs the baseline variety now and in especially in the future, particularly under optimum climate, and nutrient and irrigation practice conditions. In areas that do not have an optimum climate for rice, where it is too cool or dry, for example, the yield benefits of the improved variety are smaller.

3.1.3. Irrigation of Rice

Irrigation is another critical climate change adaptation technology, because rice plants will require more water with the warmer temperatures and because precipitation appears to be shifting to be more variable and with fewer rainy days during the growing season. Simulated yields were compared, therefore, under current and projected future climatic conditions for both rainfed rice (grown during the rainy season) and irrigated rice (grown during the dry winter season) to identify the impact of climate change on irrigation benefits. The results are shown in Figure 7.

Under current climate conditions, rainfed rice yields vary greatly across the Basin, with the highest yields in the warmest, sub-humid zones east of the Highlands. These areas have very good conditions for rice with their warm temperatures and sufficient precipitation. Simulated yields in a few locations reach over 5,000 kg. Yields are lower in the western plains and especially the Highlands, where cool temperatures prevent plant growth and yield. Irrigated rice yields under current climatic conditions vary even more across the Basin. Yields are higher, over 6,000 kg/ha in the warmest areas, but the area yielding nothing is larger because it being during the colder winter months. In general, yields are lower than during the rainy season because of the cooler temperatures suppressing yields.

The simulated yields for 2050 have the same geographical distribution, with yields closely associated with elevation. However, the yields are generally higher during both seasons, with a larger area producing yields of 5,000 kg/ha or more, because rice prefers the warmer temperatures of the future. Rice may produce in the lower foothills of the Highlands where it is currently too cool.

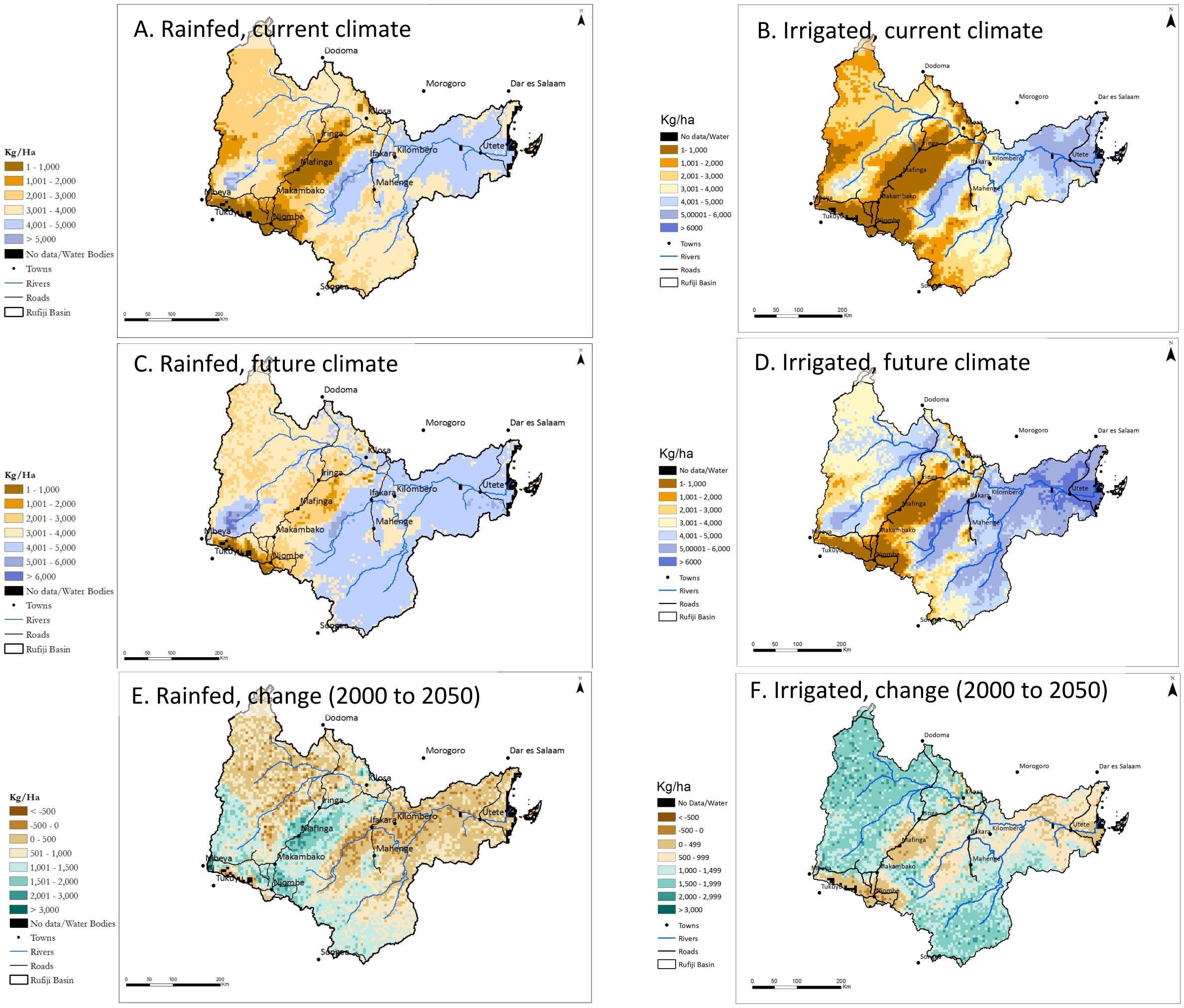


Figure 7: Simulated rice yields under rainfed (rainy season) and irrigated (winter dry season) conditions with current climate and future climate. WorldClim, MPI, TXD-85, 100 kg/ha N.

The two change maps, E and F of Figure 7 illustrate how climate change will affect rice differently in the two seasons and under different water management. In the summer, rainy season, water stress and warm temperatures are expected to become more of a limiting factor. Indeed, the hotter, drier locations and rice yield remain the same or decline in the future. However, where water stress is not important and temperatures are moderate such as in the higher elevation areas, yields generally stay the same or, in cooler areas, the yield improves.

In the dry, winter season when rice is grown under irrigation, water stress is not an issue and the warming temperatures generally lead to improving rising yields across the Basin. The positive impact of warming temperatures on rice is particularly striking in the western zone, where, with irrigation, rice will perform well in the future. The improvement in rice yield during the dry winter season occurs except 1) in the east where the heat reaches the point where it restricts plant growth and reproduction, and 2) in the Highlands where it remains too cold for rice.

3.1.4. Implications of Results for Rice

In summary, the improved technologies show much potential to improve rice yields under current and future climate conditions. Irrigation and other improved water management practices will become even more important for rice production in the future, when rising temperatures and changing precipitation patterns will lead to higher water deficits and declining yields without supplemental water. With sufficient water supplied through improved technology, rice can be expected to do well in the future except in some places in the east where hot temperatures will suppress yields, and of course in the Highlands where it will remain too cool.

The highly varied environmental conditions in the Basin thus affect the potential effectiveness of technologies:

1. The lowland areas east of the Highlands: Under current climate conditions, improved rice varieties have a higher yield potential compared to traditional, unimproved rice varieties. During the December growing season, nitrogen fertilizer application promotes higher yield when improved rice varieties are used (an increase of 3-4 tons per hectare). During winter dry season with irrigation, nitrogen fertilizer application and use of improved variety could also be a viable option. Applying nitrogen fertilizer and use of irrigation has a high potential for increasing rice yield in this region.
2. The lowland area west of the Highlands: Currently this region has a low yield potential even with improved rice varieties and use of nitrogen fertilizer. This situation can improve to some extent in future. Under fully irrigated conditions, fertilizer and newer rice varieties have tremendous potential to produce higher rice yields. In future this region along with lowland areas could augment rice production in the country.
3. Highland areas: Currently in this region rice could not be grown due to cooler temperature. But with future warming, some of the foothills or mid-elevation areas may support rice production.

3.2. Maize: Comparison of Baseline and Improved Technology Scenarios

Maize has been the focus of major research and development efforts to reduce its vulnerability to climate change through the development of improved technologies. Maize is particularly vulnerable to climate change and climate variability.

Water requirements for maize vary depending on variety, soil type and temperature, but generally it does best between 500 to 800 mm / growing season. However, yields are very sensitive to water deficits during the flowering period. Severe water deficits during silking and pollination may lead to little or no yield. There may already be an increase in the length and frequency of dry spells in the season in the Basin, and this would threaten yields. Other changes in precipitation, particularly in growing season onset and length, are also affecting successful planting, growth and yields.

Maize does best under moderate temperatures. It has a much higher ability to withstand cooler temperatures than rice, and so maize can grow in higher elevation zones than rice. In the lowlands, however, very warm minimum temperatures lead to higher respiration and less dry matter accumulation. Warmer minimum temperatures reduce maize yield while increasing its water demand. Indeed, extreme warm temperatures, over 35°C, are inhibitory at whatever stage of growth and yields fall off rapidly. Projected future temperature trends in the Rufiji Basin—more frequent hot days, warmer night time temperatures, and generally warmer temperatures—would thus negatively affect maize growth and reduce maize yields across the Basin except in the higher elevation zones. Warmer temperature also reduces the length of the growing season, or the number of days to maturity, and thus depresses grain development and yield.

The adaptation technologies to address these challenges often include using new, improved varieties, and improved water, soil and nutrient management. We will examine the potential impact of some of these improved technologies against baseline technologies on simulated maize yield under both current and future climatic conditions.

3.2.1. Fertilizer Response

An important limitation to maize yield in the Basin is plant nutrients, especially nitrogen and phosphorus. We examine the effectiveness of the application of nitrogen (N) fertilizer as an adaptation technology. The results of two N application levels are illustrated: a baseline technology of 5 kg/ha (very low but what many small scale farmers apply) and an improved technology scenario of a moderate level of 85 kg/ha N. Figure 8 illustrates the simulated yield of maize under both levels under the current climatic conditions. An older variety, Katumani composite is simulated.

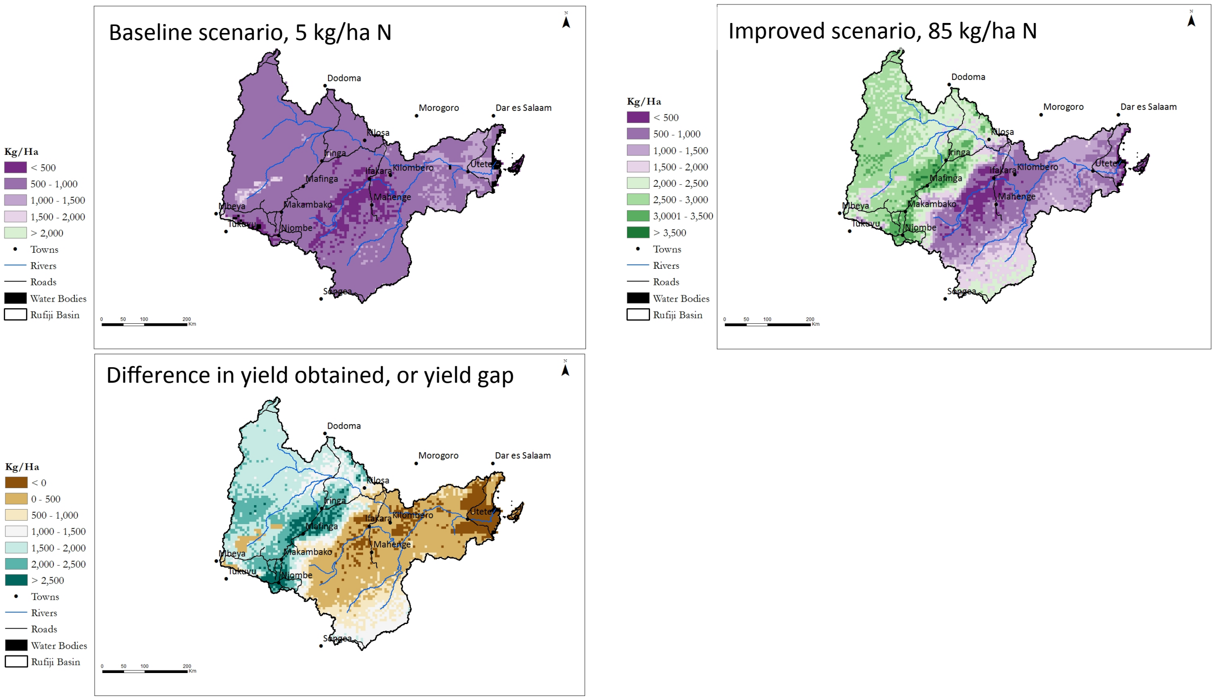


Figure 8: Current climate: Simulated maize yields under the baseline fertilizer scenario (5 kg/ha N), under the improved technology scenario (85 kg/ha N), and the difference in yield between the two fertilizer levels. WorldClim, Katumani composite, rainfed.

Yields with the baseline fertilizer level remains very low, fewer than 2,000 kg/ha, across the Basin, even in the Highlands. Yield is even lower in the warmest area where the heat restricts maize yields. In contrast, yields reach 3,000 kg/ha or higher in much of the Highlands and relatively cool area west of the Highlands with the higher fertilizer application.

The amount of additional yield obtained with the higher fertilizer application, or the yield gap, is illustrated in the bottom map. The area gaining the most is in cool, wet Highlands where growing conditions for maize are good. An additional 3,000 kg/ha is obtained with the improved scenario. Where temperatures are too warm, the fertilizer provides a much smaller benefit of less than 1,500 kg/ha.

The dramatic difference in yield between the two fertilizer levels is expected to remain in the future, as illustrated in Figure 9. Nevertheless, maize yield is expected to decline in the future under both levels of fertilizer application. The yield loss is smaller with the low fertilizer level, however, simply because plant growth is already severely constrained by nutrient deficits and so the warming doesn't have as much negative impact. With the higher fertilizer level, however, the plants are healthier, and the warming does affect growth. Yields are expected to decline from 200 to over 500 kg/ha across most of the east of the Basin.

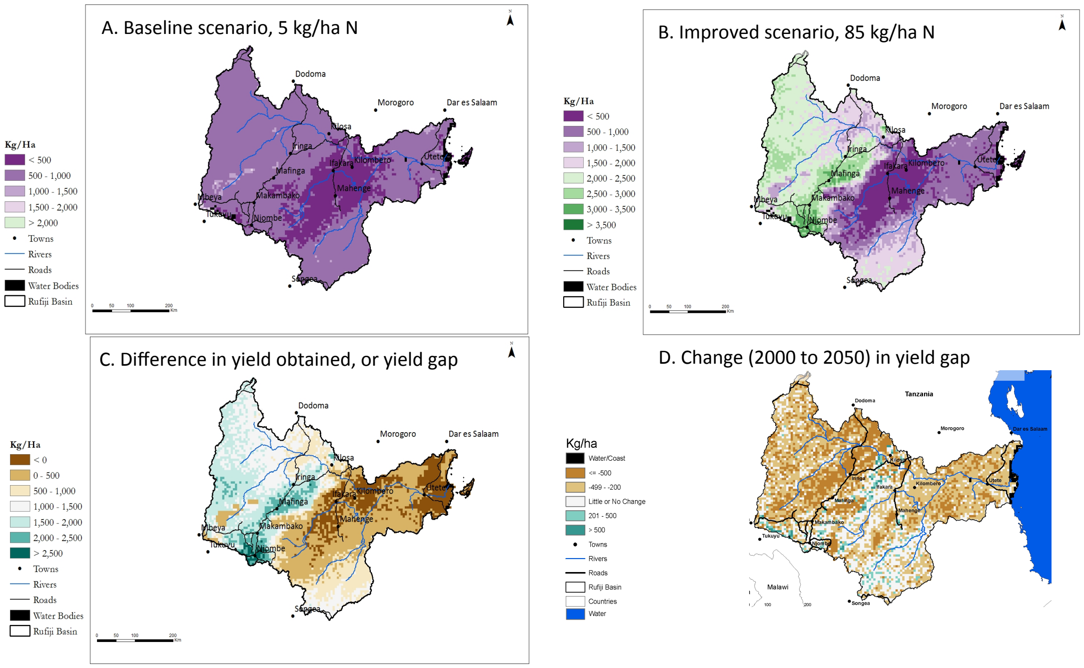


Figure 9:

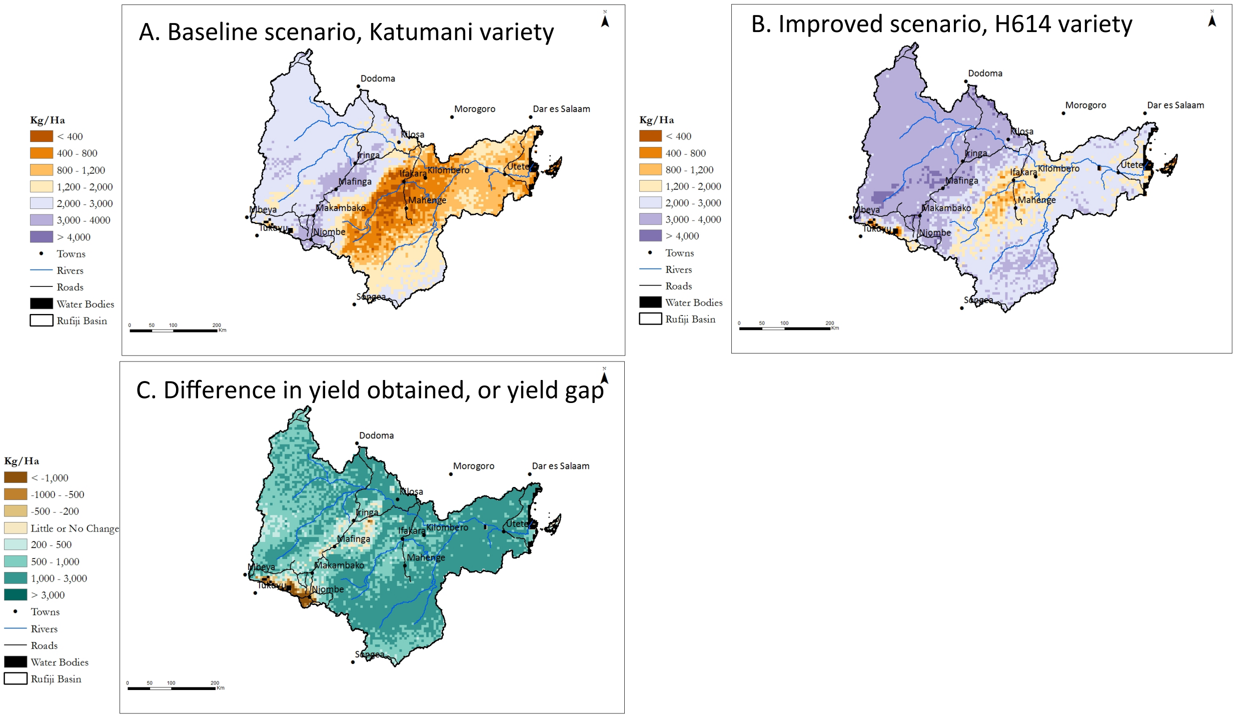
Figure 9. Future climate: Simulated maize yields under A. baseline fertilizer scenario (5 kg/ha N), B. improved technology scenario (85 kg/ha N), C. the yield gap or the difference in yield between the two fertilizer levels, and D. the change in the yield gap between 2000 and 2050. HadCM3, Katumani composite, rainfed.

Map C of Figure 9 shows the difference, or yield gap: the additional yield that would be produced with the higher fertilizer application. The same geographical distribution, of the cool areas experiencing a larger benefit from the fertilizer, remains in the future as under current climatic conditions. However, the amount of yield gained by the fertilizer is somewhat smaller in the future. The future's warmer temperatures restrict yield, even when nutrients are sufficient, because of their effect on plant growth and phenology. Map D illustrates this effect, comparing the yield gap between the current and future climatic situations. It shows that the yield benefits of fertilizer will shrink by around 500 kg/ha in the future (in brown) across most of the Basin. In the future, the benefits to fertilizer remain important, however, especially in the higher potential areas. In the hot and/or dry areas, fertilizer will have limited benefits. Improved nutrient management, therefore, would remain be a good "no regrets" option for adaptation for much of the Basin.

3.2.2. Maize Variety Comparison

Maize has been the focus of improved breeding for many years, with major advancements having been made. A climate change adaptation technology that has received much attention is improved varieties that can better tolerate drought and shorter rainy seasons. This section compares the effectiveness of an older variety, Katumani composite, with those of an improved, higher yielding hybrid, H614. Although H614 does not have the drought tolerant characteristics of some of the very new varieties, it provides revealing results.

Under current, rainfed climatic conditions and with sufficient nutrients, both Katumani and H614 varieties do best in the cooler areas, especially where rainfall is sufficient in the Highlands (Figure 10; please note the different legends in Map A and B). In the warm areas where rice does well, it is too warm for maize. In Map C, the turquoise color in the difference map reflects that, H614 performs better than Katumani of 2,000 or 3,000 kg/ha throughout the Basin. H614 does better particularly in the warm areas, such as east of the Highlands. There is less of a benefit to H614 in the slightly cooler zones.

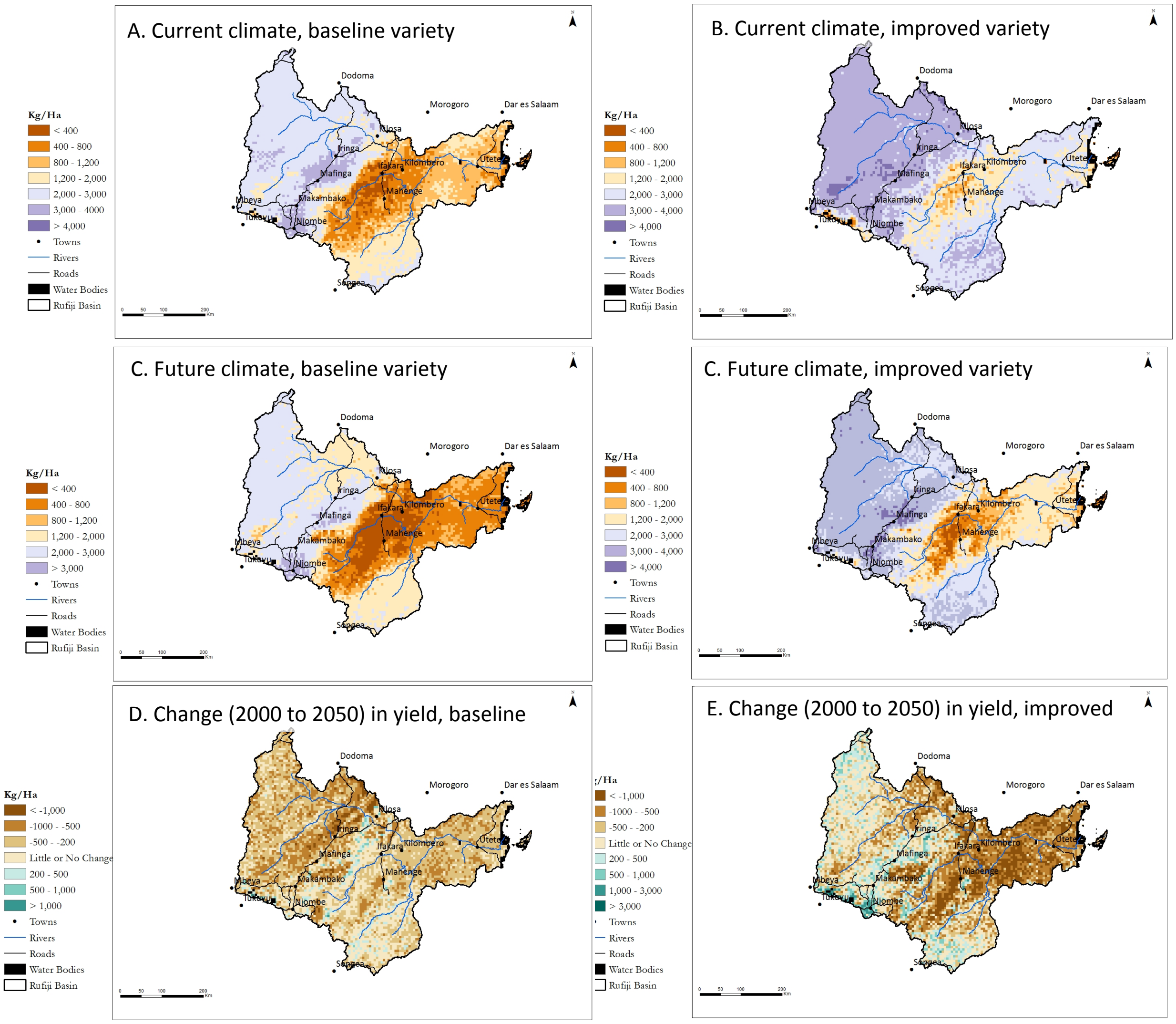

A. Baseline scenario, Katumani variety

B. Improved scenario, H614 variety

C. Difference in yield obtained, or yield gap

Figure 10: Current climate: Simulated yield under baseline variety Katumani and under improved technology scenario variety H614, and the difference in yield between the two varieties or the yield gap. WorldClim, 85 kg/ha N., rainfed.

In the future, the difference between the two varieties remains important, with H614 yielding higher than Katumani throughout the Basin (Figure 10). Under the warmer conditions, however, there is less of a benefit to H614 in the warmest zones east of the Highlands. Neither variety does well in these very warm conditions.


A. Current climate, baseline variety

B. Current climate, improved variety

C. Future climate, baseline variety

C. Future climate, improved variety

D. Change (2000 to 2050) in yield, baseline

E. Change (2000 to 2050) in yield, improved

Figure 11: Simulated maize yield of the baseline variety and improved variety under current and projected future climatic conditions, and the change in yield between 2000 and 2050. WorldClim, HadCM3, Katumani, H614, 85 kg/ha N, rainfed.

Figure 11 illustrates the impact of climate change on both varieties. The change maps, D and E, reveal the extent of the impact of climate change on declining maize yield (in brown) across most of the Basin for both varieties. The warming temperatures and little change in precipitation of the future would lead to higher water demand and cause higher water deficits and more heat stress. Only in the upper elevations of the Highlands is maize, of both varieties, expected to improve (in cyan) because the cold conditions there will moderate.

H614 would loose more yield than Katumani in the hot area east of the Highlands, but H614's yield would still remain higher there. It thus appears that even though H614 would loose over 1,000 kg/ha of yield because of the heat, it is more tolerant of heat than Katumani. Katumani's yield is more affected west of the Highlands, where H614 does well even under climate change. These results point out the importance of breeding heat-resistant as well as drought-resistant varieties for responding to climate change.

3.2.3. Irrigation Technology for Maize

Perhaps the most important maize yield-limiting factor in the Basin is water. Supplying supplemental water, or irrigation, is a potentially critical climate change adaptation technology because the rising temperatures will lead to an even higher demand for water, yet precipitation is not expected to rise. Although water requirements for maize vary greatly depending on variety, soil type and temperature, generally maize does best between 500 to 800 mm/growing season. However, yields are sensitive to water deficits during the flowering period. Severe water deficits during silking and pollination may lead to little or no yield. An increase in the length and frequency of dry spells in the season could thus threaten yields. Changes in rainy season onset and length would also affect planting, growth and yield.

The map on the left of Figure 12 is the maize yield under rainfed conditions only, whereas the map on the right is the maize yield with irrigation, or the "potential" yield. Please note the different legends required because of the wide differences in yield. Whereas the yield under rainfed conditions only reaches to a maximum of 4,000 kg/ha, the yield with irrigation reaches over 8,000 kg/ha across most of the moderate temperature and cooler zones. The yield of the irrigated maize is not quite as high, around 4, 00 kg/ha, in the east because of the negative effects of heat.

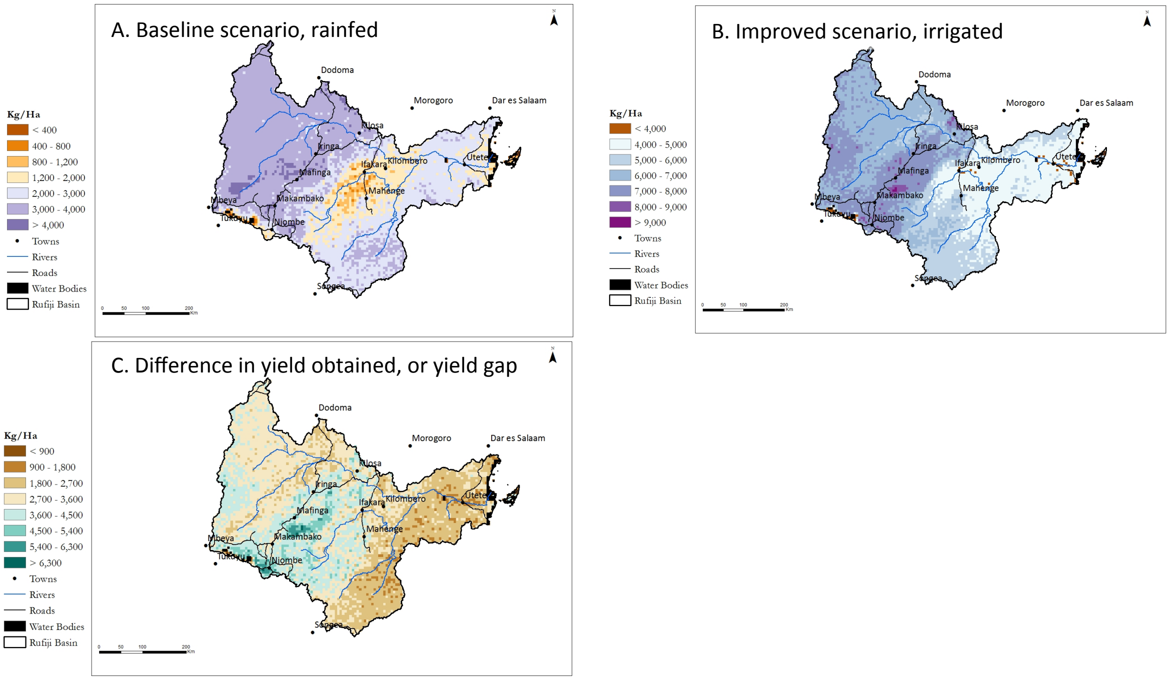


Figure 12: Current climate: simulated maize yield under A. rainfed and B. irrigated conditions, and C. the additional yield obtained with irrigation, or the yield gap. WorldClim, H614, 85 kg/ha N.

The difference or yield gap map C of Figure 12 provides information on how much additional yield is obtained with irrigation. The most benefit to irrigation is in the cooler areas of the Highlands, where over 4,500 kg/ha or more additional yield is obtained. The relatively cool but dry areas west of the Highlands also benefit from irrigation. However, in the warmer areas, only approximately 1,800 kg/ha or less additional yield is produced. With warming temperatures in the future, therefore, the effectiveness of irrigation may be less.

Figure 13 illustrates the results comparing current and future yields. The irrigated maize is still expected to produce a much higher yield than the maize grown under rainfed conditions (please note the different legends on the two maps). The irrigated maize yields almost double.

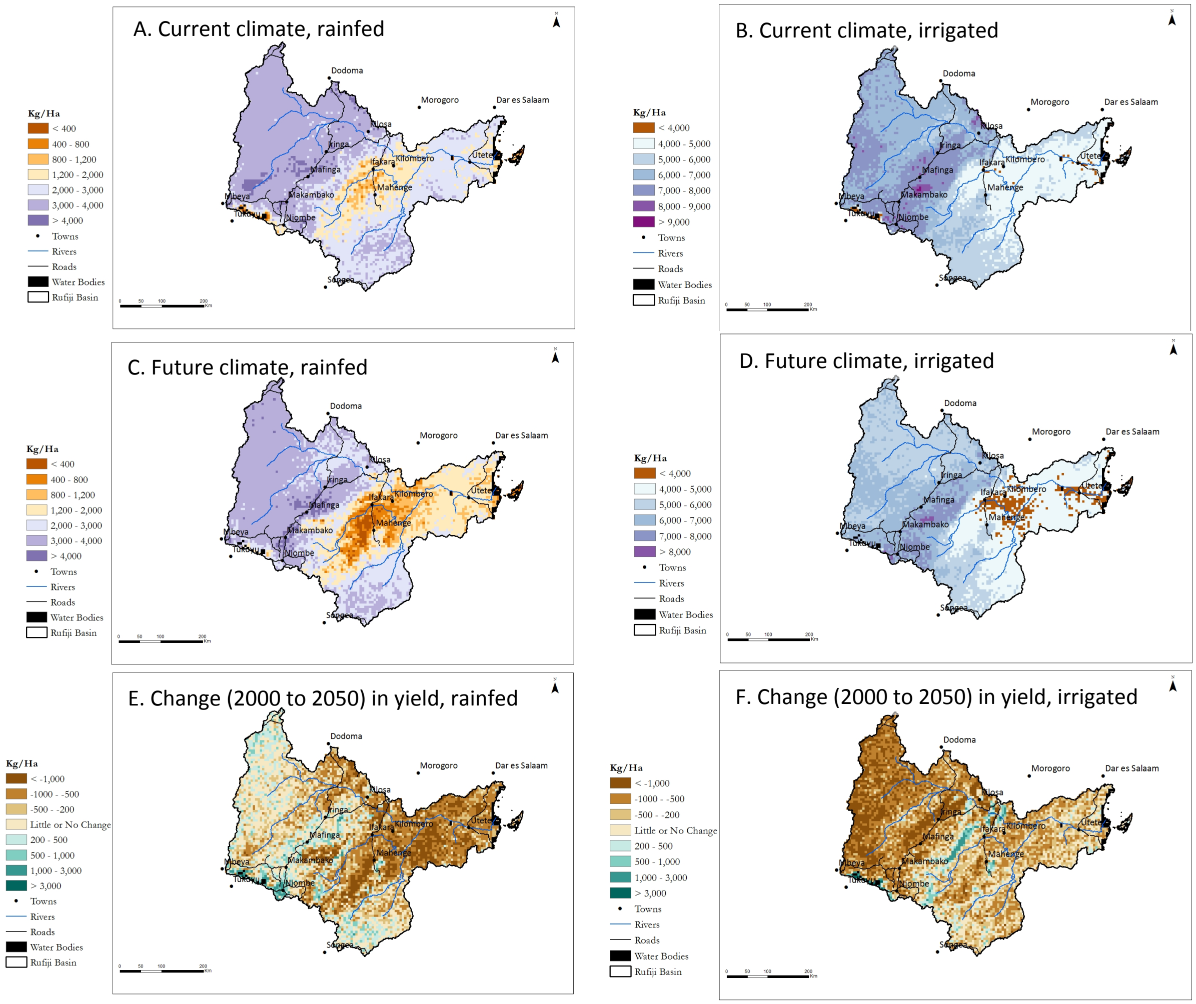


Figure 13: Simulated maize yields under current climate with A. rainfed and B. irrigated conditions, under future climate with C. rainfed and D. irrigated conditions, and the change in yield due to climate change of E. rainfed, and F. irrigated maize. WorldClim, HadCM3, H614, 85 kg/ha N.

However, the yields of both rainfed and irrigated maize have declined compared to under current climate condition. As the difference map reveals, the additional yield provided by irrigation is also less than under current climatic conditions. The warmer temperatures in the future repress maize yield, even when it is irrigated.

The change maps E and F of Figure 13 provide information on how much the yield is expected to decline in the future. Under rainfed conditions, the biggest yield loss is in the warmest area, where is declines by around 1,000 kg/ha, but elsewhere yield is not as impacted. However, the yield loss in the irrigated maize is largest west of the Highlands, where it is dry but temperatures had been earlier been conducive to maize. With the rising temperature, maize does not respond as much to the additional water.

In summary, irrigation is a potentially critical adaptation technology for maize to address the rising demand for water with warming temperatures, but the additional yield benefits of irrigation will decline in the future because crop growth and reproduction will be negatively affected by the heat. Nevertheless, large yield benefits to irrigation will remain.

3.2.4. Implications of Results for Maize

Recommendations for maize production based on the above results would vary across the Basin since the technologies will have different impacts depending on climatic conditions:

1. The lowland areas east of the Highlands: The yield potential with application of nitrogen fertilizer is moderate (2-3 t/ha). With warming expected in future, yield will be severely reduced due to an increase in water demand by the crop and also a reduction in growing duration. Unlike rice, fertilizer use as a management option may not be a viable option for maize in this region. Coping to future effect of climate for this region would be to grow a shorter duration maize variety that has more tolerance to heat.
2. The lowland areas west of highlands: Due to somewhat cooler temperature compared to lowlands east of Highlands, maize has higher yielding capacity under current climate conditions. Even with future warming this region could still be a higher maize yielding environment. Nitrogen fertilizer could probably a good management option to increase yields.
3. Highland areas: Currently due to cooler temperature maize can be grown profitably in the mid-elevation areas but not higher. But with future warming, more of this region could become suitable for maize cultivation.

The results point towards the following for improving maize and for rice yields:

1. Rice and maize yields greatly benefit from N applications, but the benefits are much smaller in the very warm and/or drier areas where expensive inputs may not provide much return. Input investments in these areas may not provide high returns.

2. During the cooler winter (June planting) season, if rice plants have sufficient irrigation and nutrients, yields will remain the same or even increase in the future in most areas.
3. Rice yields may improve in the foothills of the Highlands in the future permitting an expansion of rice to those areas, but the highest yields will remain in the lowlands.
4. However, both rainfed rice and maize yields are expected to decline in the future near the coast because of the impacts of hot temperatures on plant growth and, in some areas, worsening water deficits.
5. The beneficial effects of improved technologies of fertilizer, irrigation and high yielding varieties may decline in the future for both rice and maize where environmental effects (especially heat and water stress) severely affect plants. In many areas of the Basin, supplemental water provided during the rainy season will become increasingly important especially for maize.
6. This would call for focused breeding of heat tolerant (for both rice and maize) and drought-tolerant (for maize especially) varieties. Climate change can also be expected to alter the impact and distribution of plant pests and diseases, and breeding plans should also anticipate these changes.
7. A critically important adaptation in the basin to raise yield now and in the future is, however, is the use of efficient irrigation technologies and management.

3.3. Irrigation Technology Scenarios Compared

Adaptation strategies may include modifications to help smallholder farmers and other stakeholders improve water management for irrigation. At the Basin level, adoption of improved irrigation technologies would involve various levels of water management in order to provide sufficient water for consumption and sanitation for urban and rural populations, and to meet other water needs. For example, hydro-power generation is currently operating at approximately 20% of required demand due to an insufficient water level in hydro-generating power station dams. However, a major challenge is to meet the projected requirements for food and income. To accomplish this, irrigated areas within the Rufiji River Basin will need to expand and water use efficiency will need to improve significantly. Meanwhile the influence of climate change on power generation across the basin is an important consideration of current and future water requirements.

Basin-wide water resources demand is critically affected by the amount of irrigation. Information from multiple governmental and private project sources including water abstraction, population, irrigation water use efficiency and land use were incorporated into the hydrology model (MoW 2014; IRA 2015; Olson et al. 2015). Based on the results, it was concluded that water demand from consumptive use by people is a very small portion of the total water use. Irrigation is the primary water use requirement; other water resources are minimal compared to irrigation. Infrastructure changes are therefore required to increase irrigation efficiency to meet current water demands, to expand the area under irrigation, and to meet future water needs considering the potential impact of climate change.

The unexpected large amount of water being abstracted for irrigation can be illustrated by the process the team went through to calibrate the surface water model. After totaling all irrigated areas and combining with the amount of water required by irrigated rice, the low levels of irrigation efficiency, and the domestic consumptive water use, our calibrated watershed model was overestimating water availability based on hydrologic data from RWBO gauges in sub-basins with significant agricultural activity. In contrast, in headwater basins where these uses were minimal, our calibrated model of these basins was very accurate in reproducing outflow gauge data from the RWBO network including base flow amounts in the river network. In order to fully account for water use in the agriculturally-dominant basins, water withdrawals were increased to minimize the difference between model outflows and gauge data from RWBO. We suspect that the significant amount of water being used in these primary areas is comprised of low irrigation efficiencies, permitted uses, unregulated and un-permitted use, and diversions for use with no return flow. This point to the possibility that significant discrepancies may exist between published amounts of water use and actual amounts of water use.

3.3.1. Baseline Irrigation Technology Scenario

As it currently stands, traditional furrow and flood (paddy or ‘basin’) technique-based irrigation is in widespread use and this is being considered as the “baseline” irrigation technology. These methods have low levels of irrigation efficiencies and employ surface-based irrigation water distribution systems using canals (bunds) most often built of soil. Short canals built of heavier soils lead to higher irrigation efficiencies while longer canals built of light (sandy) soils leads to lower efficiencies. Efficiency ranges from 36%-54% for unlined, soil only, systems. Poorly maintained irrigation components - leaking or no irrigation gates, excessive flooding, and very little return flow, can contribute an additional loss of up to 50% of the values presented above. Some of the loss results from standing water percolating deep into the soil and other losses result from evaporation from the surface of the water. If weeds are permitted to grow in canals they not only impeded water flow but remove water from the system via transpiration. According to the Ministry of Water, as discussed by Ndomba et al. (2013), the existing irrigation infrastructure in Tanzania is both inefficient and improperly operated (including diversions with no return flow, improper flow control, and other problems). These problems lead to very low efficiencies in the range of 15-20%.

Little is known regarding efforts by landholders over the last decade to improve irrigation strategies across the Rufiji River Basin. While we know a few details regarding some of the water use permits across the basin, these sources do not indicate the types or methods of irrigation and water use that are permitted beyond a broad distinction of either irrigation or domestic water use.

3.3.2. Improved Irrigation Technology Scenarios

Various improved technologies can be adopted to improve water use efficiency and thus increase the area under irrigation, improve crop yields and thus raise crop production. These are often implemented as a series of technologies, depending on resources available and management structure. These are summarized in Table 2 as improved irrigation technologies, scenarios two through four.

One of the most important practices that can be adopted is to line primary and secondary canals with concrete. Lining surface water irrigation canals increases the efficiency of distribution of water by reducing the potential for siltation of channels and the opportunity for weeds to obstruct water flow. Lined channels have been shown to increase the efficiency from 54% to 59%, depending on length of run. However, lining canals has no effect on how efficiently the water is used when it reaches the fields. Other approaches must also be encouraged or implemented to improve irrigation efficiency in the field; these include the following:

Irrigation Technology Scenario	*Canals*	*Water use managed*	*Type of weeding*	*Water returned*	*Fields leveled*	*Flooded vs. pivot*	*% water use efficiency*
1. Baseline	Unlined	No	Hand	No	Poor	Flooded	15%
2. Improved surface	Cement lined, gates	Yes	Hand	No	Poor	Flooded	30%
3. Semi-mechanized	Cement lined, gates	Yes	Herbicide	Some	Moderate	Flooded	60%
4. Industrial	Central lines/ pipes, gates	Yes	Herbicide	Yes, pumped	Good	Pivot	85%

Table 2: Irrigation Technology Scenarios

1. Utilize metering devices and pay-per-use to discourage over-watering
2. Grade land slope for best soil wetting with minimal erosion and runoff
3. Channel excess water to return to source
4. Provide accurate weather forecasts to help improve irrigation timing and amounts
5. Encourage a randomized water allocation method for smallholders to reduce the risk of tail-end fields being allocated water ‘out-of-season’
6. Encourage the adoption of short season rice varieties to minimize seasonal water use
7. Eliminate ‘cascade’ flow (field to field) irrigation for non-rice crops
8. Demonstrate to growers proper furrow depth and width for optimal soil wetting
9. Size gates, spiles, siphon tubes or bund cuts to ensure proper soil wetting across field width for furrow irrigation systems
10. Install effective gates that provide proper ‘head’ for spiles or siphon tubes.

Where basin (flood) irrigation is used for rice, it is common for an excessive amount of water to be maintained over the field throughout the growing season, and where furrow irrigation is used upslope fields may be irrigated first then runoff water from that field is used to irrigate adjacent downslope fields (cascade flow). Both of these procedures are in use by smallholder growers and both accelerate water losses. Other reports indicate that smallholders owning fields at the tail-end of irrigation system may not get irrigation water early enough in the season to insure planting is done at optimal times. This means that tail-end fields may not get planted at all, or when planted late may require extra water to complete maturity during the dry season. Using a water allocation method that monitors the amount of water used and more equitably distributes water among fields near and far from the source should improve the efficiency of water use among growers.

In the Rufiji basin, sprinkler irrigation is used to a limited extent and primarily on sugarcane, and is usually used on non-rice crops. Compared to flood or furrow irrigation, sprinkler irrigation tends to require more of an initial investment, takes more fossil fuel energy to operate, and requires a more technical approach to maintenance. However, the furrow irrigation system, established it tends to be less labor intensive. A principal advantage of sprinkler irrigation methods is that it can be used over sloping or undulating topography. A disadvantage of sprinkler systems is that heavily silted water may plug spray nozzles, cause excessive pump wear, and coat the crop with sediment. Sprinkler irrigation systems include: center pivot, wheel line, stationary pipe, rain guns, and movable pipe or flex-line. Establishing or expanding sprinkler irrigation systems requires a relatively clean and reliable source of water and a system to supply fuel and maintenance for the diesel or gasoline powered pumps. Because of the investment required sprinkler systems are adopted initially by larger farms. However, it is feasible that smallholder co-ops might be able to employ sprinkler systems as well. Sprinkler irrigations system efficiencies are generally equal to or slightly better than a well operated surface irrigation scheme. However, their efficiencies will depend on wind, temperatures, and effective and timely operation of the equipment.

Although not mentioned in the improved technology scenarios, improvements in onsite water storage and harvesting from on-farm water tanks and groundwater systems (such as ponds and small dams) can be critical to help protect yields from climate variability during critical periods of grain fill and crop development. Storage of water in an elevated structure typically requires a significant expenditure of energy to pump water and to install pumping infrastructure; however, recent developments in solar-based pumping technology and advances in water storage approaches make these types of irrigation technologies more reasonable. Development of additional reservoirs for water resource management at the local or basin scale is also critical. While this is could be capital intensive for certain areas, these types of improvements can be completed by smallholder communities as part of their water management.

Although not irrigation, other agricultural technologies that conserve water can be used to improve the efficiency of water use. A number of these practices currently exist and others are being aggressively developed in countries around the world. These are discussed by Olson *et al.* (2015).

The bottom line is that existing irrigation systems in the Basin cannot simply be extended if baseline technologies or lower-level improved scenario technologies are used. Since water will be the limiting resource for the foreseeable future, it is imperative that existing water resources are used as efficiently as possible and that new sources of water are tapped to bring added irrigated land on line. The implementation of the improved technology scenarios with their associated management structures would greatly improve water use efficiency and thus allow more cultivated area to be irrigated. Indeed, it was determined that increased efficiency would double the amount of cropland that can be irrigated.

To simulate future conditions, the surface water model incorporated future projections of climate, land use and water abstraction amounts for non-agricultural uses. The future land use layers were based on projected rural and urban population growth (from census records and literature), recent rates of expansion of agriculture in the Basin (from land use change analyses), and agricultural expansion was constrained by the amount of arable land. It should be noted that the GCM used for the below results (MPI GCM) is a relatively wet model and considerably wetter than the current climate dataset (CHIRPS) used; the increase in amount of water available in the future that is illustrated should thus not be taken as the expected change in precipitation. Our other analyses and modeling indicates that the Basin is projected to experience warmer and somewhat drier conditions (Olson *et al.,* 2015).

Some the effects of the improved technology on water flow, and thus on the amount of land that could be irrigated now and in the future are presented in a summary form in Figure 13.

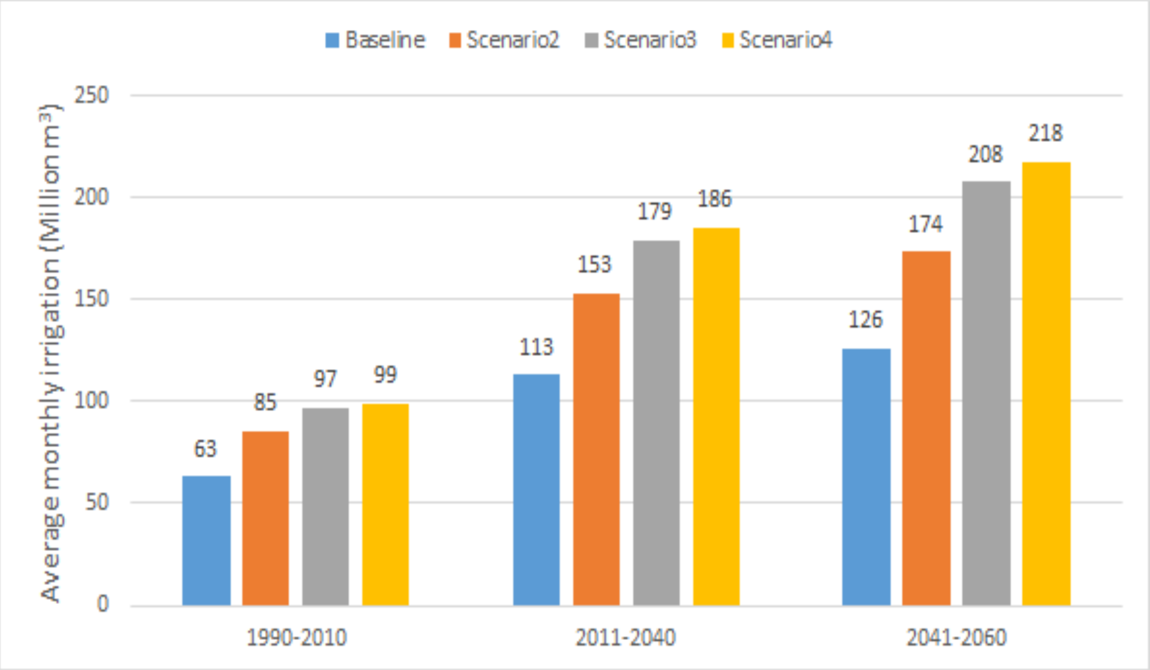


Figure 14: Simulated amount of water available for irrigation at the Basin level by different scenarios of irrigation technology under current, near future and far future climatic conditions. CHIRPS, MPI.

Figure 14 reflects the basic finding that the more efficient the irrigation, the more water is available. The graph represents the change in irrigation water volume under (1) technology improvement and (2) climate and land use change. The difference between bars within each time period indicates the effects of technology improvement. The area irrigated in one time period with four technology scenarios are similar, so the change in irrigated volume can be attributed to increased water availability in streams with better irrigation technology. The difference between three time periods could be attributed to increased irrigated area (from land use change), and climate change based increase in water demand (PET) and/or water availability (in streams).

In the Decision Support Tool, the user can do the same type of analysis for each sub-basin by selecting the technology scenario and amount of land under irrigation (IRA 2016). The tool provides results of the impact on water volume for that and downstream sub-basins.

A closer look at the impact of projected climate on water and thus on potential crop and water yield is found in Figure 15. It shows annual trends in precipitation, potential evapotranspiration (PET), actual evapotranspiration (ET) and water yield at the landscape level for the Rufiji Basin.

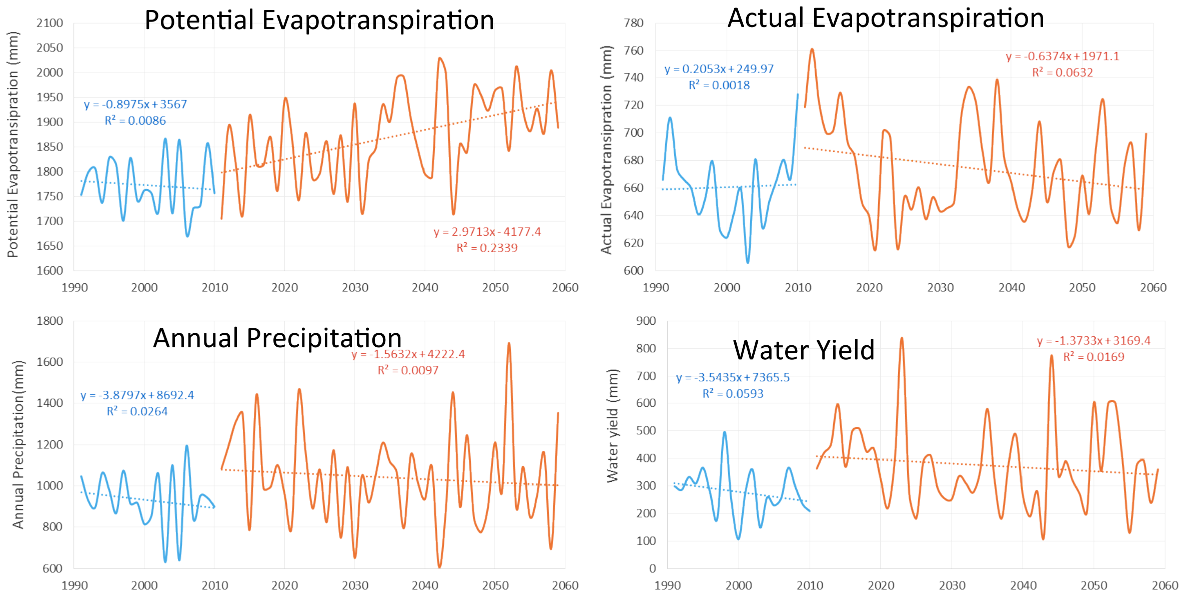


Figure 15: Climate projection effects on water yield variables from the surface water model. CHIRPS, MPI.

The annual trend indicates an increase in PET with climate change while the actual ET trend remained same during the simulation period. The comparison of PET and ET reveals that there will be rising water stress for rainfed crops; they will be receiving insufficient amounts of precipitation for their needs. The increase in PET is due to the warmer temperatures, but the change in precipitation is insufficient to offset the higher PET. The results also show a noticeable increase in inter-annual precipitation variability. The jump in the precipitation and water yield between the current climate (in blue, CHIRPS) and the future climate dataset (in orange, MPI) is an artifact due to differences in the datasets and do not reflect an expected sudden rise in precipitation. The trend in future precipitation and in water yield, according to MPI and most other GCMs, is a gradual decline. This projected declining trend in water yield should be considered in irrigation and other water use planning for the Basin.

A summary table (Table 3) of projected agricultural area under irrigation and non-irrigated land, with the projected MPI climate, population, land use, improved irrigation technologies and other factors incorporated, indicates that the land under irrigation may expand, but then the rate of expansion slows due to limited water availability. The land under cultivation, however, will continue to expand due to the demand of the increasing population for land and food. The result is that the percent of cultivated land under irrigation will not increase above its current low level.

	Irrigated area (km^2)	Non-Irrigated Agriculture area (km^2)	% agricultural area irrigated
1990-2010	5430	6435	0.46
2010-2040	10339	14188	0.42
2041-2060	11835	19010	0.38

Table 3: Projected change in land area of the Basin under irrigated and non-irrigated crops from the land use and surface water models. CHRIPS, MPI.

The location of the projected expansion of irrigation is limited to some sub-basins; however, depending on the availability of surface water, arable land, population growth and climate change (Figure 16). It should be noted that some of these are the same locations (e.g., sub-basins 1 and 20) where irrigated rice yields may rise in the future due to warming temperatures of climate change

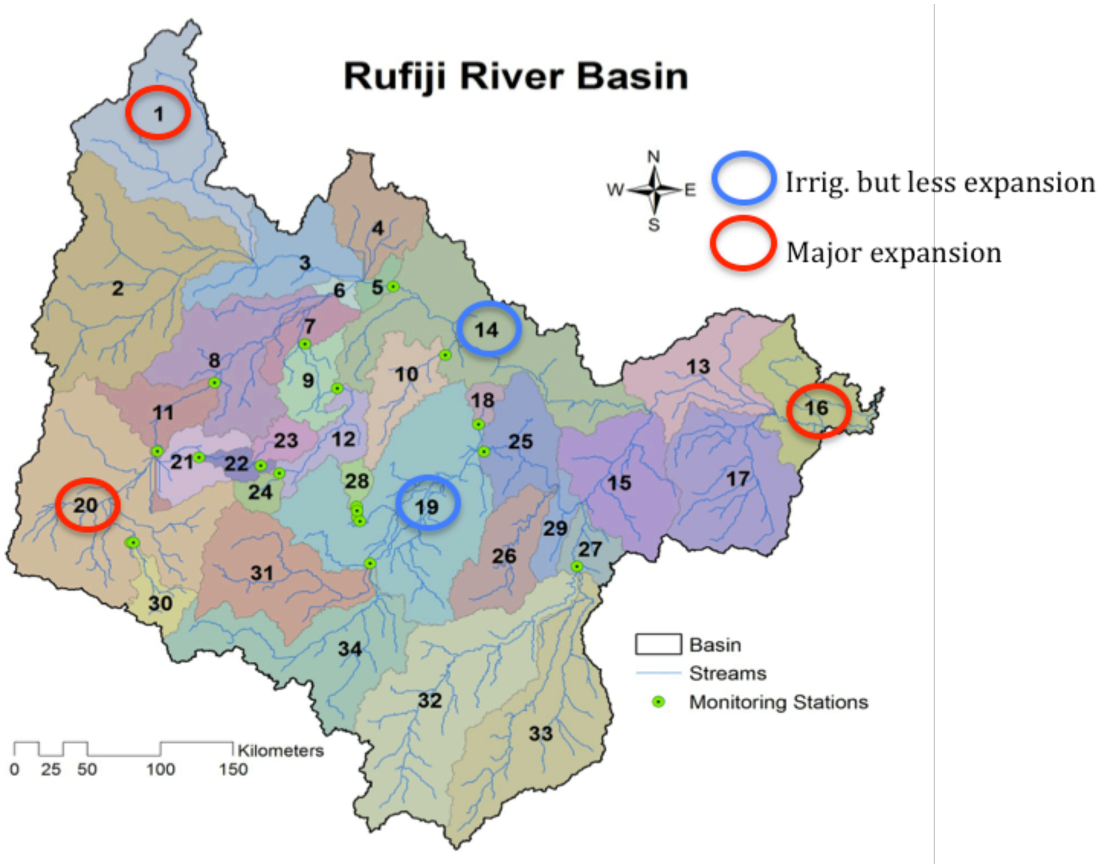


Figure 16: Sub-Basins with a High Potential of Irrigation Expansion to 2060.

3.3.3. Implications of results

The surface water simulation results and other sources point to the fact that almost all surface water in the agriculturally dominant areas of the Rufiji basin is already being used. While increases in rainfall may occur in some areas of Tanzania in the future, the experience of recent years shows that low rainfall years are prevalent and that rainfall may be gradually declining. The demand for irrigation water is currently very high and may be unmet. This is illustrated in that in wet years, agricultural production and irrigation amounts rise and consume twice the amount of water compared to dry years. Meanwhile, the increasing amount of land under rainfed and irrigated cultivation, including irrigation schemes, favors even more water usage across the Basin. This situation, combined with the high agricultural potential of much the Basin especially when irrigated (see Figures 7 and 12) point to the importance of raising water use efficiency with improved irrigation technologies.

4. CONCLUSION

The scenario approach was found to be useful. The particular effectiveness of baseline and selected improved agricultural technologies could be tested against the current and future climatic conditions to identify their relative advantage in improving production currently and in adapting to future climate change. The approach revealed that some technologies are particularly beneficial for raising current crop yields under current climatic conditions, but that their effectiveness may decline somewhat in the future.

The technology that provided the largest yield increase of any was the irrigation of maize during the main growing season, a technology that is currently not economically feasible. However the indications from recent and projected future climate trends indicate that crops will be demanding larger amounts of water due to the rising temperatures, yet precipitation will not increase to meet this demand and indeed may decline. The need for irrigation even during the rainy season therefore will become necessary in order to maintain current production. In contrast, the relatively low-cost technologies for the farmer, improved seed varieties and fertilizer applications, provide an immediate improvement in yields in locations where climatic conditions are favorable for the crop. However the rising temperatures and especially the higher water deficits in the future will cause the yield benefits from the technologies, especially fertilizer, to decline. Improved varieties were shown to continue to provide important benefits in the future especially if they are bred to be more heat resistant. Maize was shown to be more vulnerable to climate change than rice because of the impact of heat on maize reproduction and phenology, and its rising need for water. If provided sufficient water and nutrients, rice will produce well under future climate conditions across most of the current rice-producing areas of the Basin and indeed rice could expand in the future if irrigation water is available.

The analysis of irrigation technologies revealed the critical importance of improving water use efficiencies and management already, even without considering any expansion of irrigation. The current water abstraction levels in the main agricultural irrigated areas of the Basin appear to be already at their limit, and major changes to current irrigation practices would need to occur in order to meet an expansion of irrigation, hydro-power or other water use needs. Existing irrigation systems in the Basin cannot be extended if baseline or lower-level improved scenario technologies are used. Since water will be the limiting resource for the foreseeable future, existing water resources need to be used as efficiently as possible and new sources of water tapped to support additional irrigated land. The implementation of the improved technology scenarios with their associated management structures would greatly improve water use efficiency and thus allow more cultivated area to be irrigated. Indeed, it was determined that increased efficiency would double the amount of cropland that could be irrigated.

Important improvements in irrigation technology such as return flows and managing water abstraction would imply major management efforts at the District and Basin levels. Other technologies such as improved field leveling and canal improvements could be done at the village level. The investment in these technologies would provide substantial returns in terms of conserved water and ability to expand the area under irrigation. In contrast to most of the improved technologies for the crops, however, the investment for and management of irrigation technologies would need to be made at a higher administrative level.

The spatial modeling results revealed the large differences between areas of the Basin in how well technologies may benefit crop yields, and in how climate change will affect the crops and the yield benefits of the technologies. For example, fertilizer may provide a large boost in yield in one location but almost no increase in yield in another due to the differences in climate and soil. Because of this high spatial variability across the Basin, recommendations and programs need to be spatially differentiated to meet these particular effects.

A major gap in our understanding of the relative benefits of the technologies is their economic and administrative cost, and the potential economic returns to the technologies in different locations in the Basin. With this cost and benefit information, the implications from the crop and water yield results of the simulations could be better applied in policy and programs.

References

Andresen, JA, N.J. Moore, B. Lofgren, B. Pijanowski and D. Kim. 2014. Projected Land Cover Change Effects on East African Rainfall Under Climate Change. *International Journal of Climatology* 35(8):0973.

Alagarswamy, G., J. Olson, J. Andresen, J. Maitima, N. Moore, B. Mulenga, W. Otim-Nape, P. Thornton, P. Yanda. 2015. The Impact of Climate Change on Water and Nitrogen Deficits for Maize Production in East and Southern Africa. Poster presented at the conference, Transitioning Cereal Systems to Adapt to Climate Change, Nov. 13-14, Minneapolis, MN. http://www.aridcereals.org/posters/Alagarswamy_final.pdf

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Rowland, J., Romero, B., Husak, G., Michaelsen, J., and Verdin, A.P. 2014. *A quasi-global precipitation time series for drought monitoring*. U.S. Geological Survey Data Series 832, 4 p., http://dx.doi.org/10.3133/ds832.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, A. Jarvis. 2005. Very high-resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25, 1965–1978.

Maliondo, S.M.S., E.J. Mpeta and J.M. Olson. (2012). "Climate Change and Food Security in Tanzania: An Analysis of Current Knowledge and Research Gaps and Recommendations for a Research Agenda. iAGRI Reference Background Paper." October 2012. Ohio State University/ iAGRI/USAID. Available http://iagri.org/student-portal/choosing-your-research-topic/

Ministry of Water - URT. 2014: Integrated Water Resources Management and Development Plan for Lake Rukwa Basin, Final Interim Report II, Volume I: Water Demand Projections (2015 – 2035), developed by WREM International Inc., Atlanta, Georgia, USA, 96pp.

Moore, N., Alagarswamy, G., Pijanowski, B., Thornton, P., Lofgren, B., Olson, J., Andresen, J., Yanda, P. and Qi, J. 2012. East African food security as influenced by future climate change and land use change at local to regional scales. *Climatic Change*, 110, 3: 823-844

NASA (National Aeronautics and Space Administration). 2014. Prediction of Worldwide Energy Resource (POWER). Surface meteorology and Solar Energy. "These data were obtained from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program." Available from: http://power.larc.nasa.gov/index.php

Ndomba, P.M., V. Kongo, C. Richard, and F. J. Wambura. 2013. Enhancing Climate Change Adaptation in Agriculture and Water Resources. Report submitted by Bureau for Industrial Cooperation (BICO) College of Engineering and Technology University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania.

Olson, J., G. Alagarswamy, J. Andresen, N. Moore, W. Northcott, P. Miller, C. Hawkins, D. Pike and P. Morse. 2015. Analysis of the Impact of Climate Change on Crop and Water Availability, and Consideration of Potential Adaptation Practices for the Rufiji River Basin, Tanzania. Technical report submitted by Michigan State University to the University of Dar es Salaam for: "The Rice and Maize Resilience to Climate Change in the Rufiji Basin Project," October. 96 pp.

Otieno, V. O., & Anyah, R. O. 2013. CMIP5 simulated climate conditions of the Greater Horn of Africa (GHA). Part 1: Contemporary Climate. *Climate dynamics*, 41(7-8), 2081-2097.

University of Dar es Salaam Institute of Resource Assessment (IRA). 2015. Milestone 1.5: Technical Report on Climate Change Linkages and Impacts in the Medium Term. A Report Submitted to USAID Tanzania for "The Rice and Maize Resilience to Climate Change in the Rufiji Basin Project," February. 98 pp.

University of Dar es Salaam Institute of Resource Assessment (IRA). 2016. Milestone 3.1: Decision Support Tool. A Report Submitted to USAID Tanzania for "The Rice and Maize Resilience to Climate Change in the Rufiji Basin Project," June. 16 pp.