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Climate Change, Agriculture, and Food Security in Tanzania

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Abstract

The consequences of climate change for agriculture and food security in developing countries are of serious concern. Due to their reliance on rain-fed agriculture both as a source of income and consumption, many low-income countries are generally considered to be most vulnerable to climate change. Here, we estimate the impact of climate change on food security in Tanzania. Representative climate projections are used in calibrated crop models to predict crop yield changes for 110 districts in Tanzania. These results are in turn imposed on a highly-disaggregated, dynamic economy-wide model of Tanzania. We find that, relative to a no climate change baseline and considering domestic agricultural production as the principal channel of impact, food security in Tanzania appears likely to deteriorate as a consequence of climate change. The analysis points to a high degree of diversity of outcomes (including some favourable outcomes) across climate scenarios, sectors, and regions. The economic modelling indicates that markets have the potential to smooth outcomes on households across regions and income groups, though noteworthy differences in impacts across households persist both by region and by income category.

Keywords: climate change, agriculture, food security, crop model, CGE model, Tanzania

JEL classification: Q1, Q54

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Tables and figures appear at the end of the paper.

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1 Introduction

The consequences of climate change for agriculture and food security in developing countries are of serious concern, not least because food supplies are already inadequate and poverty severe in many low-income countries, particularly in Africa. Moreover, many low-income countries are considered to be most vulnerable to climate change, mainly due to their reliance on rain-fed agriculture. Previous studies linking climate change to food security have typically used agricultural crop models (see, for example, Parry et al. 2004). Their predictions range from precipitous declines in yields for major African food crops (Schlenker and Lobell 2010) to more modest reductions (Lobell et al. 2008; Nelson et al. 2010), and even to improvements (Butt et al. 2005).

Previous studies have, however, suffered from at least one of four limitations. First, they often provide global or regional assessments. Yet, climate change is expected to vary widely within continents and even countries, and so adaptation policies require higher-resolution information, possibly even at sub-national levels (Lobell et al. 2008). Second, despite considerable uncertainty surrounding future climate change, some studies rely on only a few climate projections (see, for example, Butt et al. 2005). Third, many calibrated agronomic crop models exclude 'autonomous adaptation' that may offset at least some climate change damages. Finally, previous studies typically measure direct or partial equilibrium production changes, but may exclude indirect and general equilibrium effects, including price and household income changes and inter-sectoral linkages. Since food security depends on both food availability and accessibility, it is inadequate to measure production changes without considering, for example, the impacts of climate change for households' incomes (Parry et al. 2004; Ahmed et al. 2009).

In this paper, we estimate the impact of climate change on agricultural production in Tanzania using detailed sub-national crop models. Four projections are drawn from available general circulation models (GCM) to reflect a range of possible temperature and precipitation changes by mid-century. These climate projections are then used in calibrated crop models to predict crop yield changes, which are in turn imposed on a highly-disaggregated, dynamic economy-wide model of Tanzania. This model captures indirect effects and permits (some) autonomous adaptation. The economic model allows us to evaluate the availability (production) *and* accessibility (income) dimensions of food security. In the next section, we describe the selected climate scenarios and the crop modelling framework used to translate climate conditions into crop yields. We then describe the economy-wide model and present the results from our simulated baseline and climate change scenarios. We conclude by summarizing our results and identifying areas for further research.

2 Climate change and agricultural crop yields

2.1 Selecting climate change scenarios

General circulation models (GCM) produce a wide range of future climate change scenarios, especially when examined at the country-level (see Solomon et al. 2007). Apart from differences in the science of modelling global climate systems, there is also uncertainty in other key variables such as how the global economy will evolve in coming decades. To account for this, GCMs typically employ different ‘emission scenarios’ based on assumptions about future populations, technological advances, and global agreements to reduce carbon emissions.

To capture a range of possible climate change realizations, we select four projections with different temperature and precipitation outcomes averaged over all land areas of the country. The scenarios employed are presented in Table 1. In addition, to temperature and precipitation deviations, the table presents the climate moisture index (CMI) (Willmott and Feddema 1992), which is an indicator of a region’s aridity, at the national level. The CMI depends on average annual precipitation (P) and potential evapotranspiration (PET). A climate is classified as semi-arid (semi-humid) and then arid (humid) as PET increases (decreases) relative to precipitation. The CMI is defined as:

$$CMI = -1 + P/PET \quad \text{when } PET > P$$

$$CMI = 0 \quad \text{when } PET = P$$

$$CMI = 1-(PET/P) \quad \text{when } PET < P$$

A CMI of -1 is very arid and a CMI of +1 is very humid. The CMI is dimensionless since it is a ratio of two depth measurements.

The scenarios are labelled WET, DRY, COOL, and HOT. The COOL scenario is relative to the other scenarios, and projects a mean average temperature increase of 1.1 degrees Celsius by 2041–50 compared to 1.9 degrees Celsius in the HOT scenario. Three of the four scenarios project an increase in precipitation reflecting an analysis of climate futures for Tanzania conducted by the Tyndall Center (2010). While precipitation rises in three scenarios, the climate moisture index remains fairly constant in two of the three because rising temperatures increase PET. It is of some interest to note that the WET scenario for Tanzania is the same scenario identified by the World Bank as the driest scenario globally out of all 56 possible scenarios considered for analysis (World Bank 2010). This is a reminder that local conditions can differ drastically from broader averages. Overall, the GCMs suggest that Tanzania’s climate will become warmer and precipitation more uncertain as a result of climate change.

To develop a baseline ‘no climate change’ scenario, we use historical daily climate data for 1997–2006 (i.e. mean, minimum, and maximum surface temperatures and precipitation) retrieved from the NASA POWER database (Stackhouse 2010). A random 50-year baseline climate sequence was drawn from this historical series. Our baseline scenario therefore assumes that future weather patterns will retain the characteristics of historical climate variability. It should be noted that the purpose of the baseline scenario is not to predict future weather patterns, but to provide a counter-factual for the climate change scenarios. Therefore, taking the baseline scenario, we overlay a ten-year moving average of the daily deviations in temperature and precipitation predicted by the GCMs. This procedure produces the four ‘synthetic’ climate projections mentioned above. This method applies historical climate variability (i.e. the historical baseline, which remains constant across all scenarios) and overlays future climate changes. With these climate scenarios in hand, we turn to assessing the implications of climate change for crop production.

2.2 Crop and water balance models

We use a generic crop model called CLICROP to simulate the impact of the baseline and climate change scenarios on rain-fed and irrigated crop yields and on irrigation water demand. CLICROP was specifically designed to capture climate change impacts since it models water stress from both insufficient and excess water supply (measured daily). Yield reduction due to retarded root growth resulting from excess water is known as ‘water-logging’. Water-logging reduces yields via oxygen loss and root growth hindrance (see Sieben 1964). The inclusion of water-logging and crop-specific parameters is an extension over simpler models, such as the FAO’s CROPWAT. Moreover, CLICROP’s daily time scale allows it to capture the shorter but higher intensity rainfall expected in Eastern Africa (Solomon et al. 2007).

The effects of the atmosphere (i.e. temperature and precipitation) are modelled indirectly in CLCROP via evapotranspiration (Allen et al. 1998) and infiltration to the soil layers (based on soil properties). Soil composition is considered at each site and is used to calculate soil moisture in each soil layer, including the moisture allowed to percolate into deep soil layers. Water balances and the upward flow of soil water are then measured. As rain falls on the given soil, certain amounts are allowed to run off, infiltrate and percolate through deep layers (in addition to the demands of evapotranspiration). Crops are then allowed to draw water from the soil layers. Crop yields are estimated using the approach proposed by Allen et al. (1998) with the additional possibility that yields are reduced when excess water results in submersion.

For this examination, the effects of CO_2 fertilization are not considered in our analysis. As a result, we may overestimate yield losses caused by climate change. Recent free-air carbon enrichment (FACE) studies contradict the results of earlier closed laboratory experiments that suggested the presence of strong positive productivity effects for major crops due to higher CO_2 concentration levels (Long et al. 2006). At the same time, the validity of FACE results has been questioned (Tubiello et al. 2007); and the debate appears to be unresolved at present.

CLICROP was run at a 1°×1° resolution (i.e. 111 square kilometre grids in a country measuring 945,000 square kilometres). Separate models were developed for the nine major crops of Tanzania (i.e. root crops, groundnuts, maize, millet, potatoes, sorghum, soybeans, sweet potatoes, and wheat). Predicted yields for each sub-national region are calculated as the sum of overlaid gridded results weighted by geographic area. CLICROP was calibrated to information on soil parameters from the FAO Soils Database (e.g. field capacity, wilting point and saturated hydraulic conductivity) (FAO-UNESCO 2005). Regional information on crop growing seasons and planting dates from provided by Sacks et al. (2010). Finally, crop locations were based on You et al. (2006) for the year 2000, and crop parameters were drawn from Allen et al. (1998) and Doorenbos and Kassam (1979).

2.3 Crop modelling results

Although CLICROP analysis was conducted for nine crops, we focus on the results for maize for purposes of exposition. Maize is the principal food crop in Tanzania, representing 35 and 45 per cent of calories consumed by poor urban and rural households, respectively (Pauw and Thurlow 2010). Tanzanian farmers allocate about one-third of their crop land to growing maize, mainly without the use of irrigation (see Table A1 in Appendix A). Deviations in dry-land maize yields therefore provide a first-cut indicator of food availability in Tanzania (Thornton et al. 2009). In addition, the implications of climate outcomes for maize are likely to be similar for sorghum and millet, making the coverage of caloric sources and land use, particularly for more vulnerable populations, even broader.

Table 2 summarizes the deviations in mean maize yields from a 'no climate change' baseline scenario for the 10-year period 2041–50. The administrative regions are grouped into similar agro-climatic zones based on Fan et al. (2005). There is a high degree of variation both across the four climate scenarios considered and across sub-national regions. For example, maize yields in the northern zone are projected to increase substantially in the WET scenario, but decrease by similar amounts in the HOT and DRY scenarios. Varied impacts also occur across regions but within the same scenario. For example, average maize yields in the WET scenario are projected to increase by 15 per cent in Manyara in the northern zone, but decline by 12 per cent in Tabora in the central zone. Nevertheless, a few regularities emerge. Maize yields are generally more favourable under the COOL and WET scenarios than under the HOT and DRY scenarios. In addition, yield declines are much more prevalent across regions and scenarios than are yield increases. In particular, under the HOT and DRY scenarios, yields rise in only a few regions and these increases are in all instances small. Finally, the coastal islands remain virtually unaffected in all climate scenarios.

Figures 1 and 2 provide insights into the geographic correlation of results. They show maize yields for each scenario for 110 districts in Tanzania. The darker lines show the boundaries of the larger administrative regions presented in Table 2. Once again, there is substantial regional variation in our results. For example, the COOL scenario shows significant yield increases in the northern zone (i.e. in the districts surrounding Mount Kilimanjaro), while yields decline slightly in the southern coast and southern highlands. By contrast, yields are damaged though-out the country in the HOT scenario, with particularly strong negative impacts in the northern and Lake Victoria regions. The WET and DRY scenarios contrast similarly. The WET scenario shows mean yield increasing around Kilimanjaro and its southern slope while they dramatically decrease in the western regions around Lake Tanganyika.

In summary, there are strongly heterogeneous impacts across the four climate scenarios. However, as expected, there is some regional correlation in results. Climate outcomes favourable (unfavourable) to maize farmers in a particular region are also likely to favour (harm) maize farmers in neighbouring regions. At the same time, geographical impacts can vary dramatically across scenarios, with some scenarios producing favourable outcomes while others resulting in pronounced negative impacts. Obviously, from a national food availability perspective, the impacts on yields in the major producing regions are more important. Maize is not equally important in all parts of the country and for all household groups (e.g. poor/non-poor and farm/non-farm). Since our objective is to evaluate the economic implications of climate change for agriculture as a whole and for broadly-defined food security, we employ, in the next section, an economy-wide model of Tanzania in order to sort through these impacts.

3 Economy-wide impacts and food security

3.1 Economy-wide model

The crop modelling results discussed in the previous section are passed down to a recursive dynamic computable general equilibrium (DCGE) model of mainland Tanzania, which estimates the economic impact of the baseline and climate change scenarios, including indirect or economy-wide linkages between the agricultural and non-agricultural sectors. Our model belongs to the structural neo-classical class of CGE models (see Dervis et al. 1982). DCGE models are well-suited to analysing climate change. First, they simulate the functioning of a market economy, including markets for labour, capital and commodities, and therefore can evaluate how changing economic conditions are mediated via prices and markets. Secondly, DCGE models ensure that all economy-wide constraints are respected, which is crucial for long-run climate change projections. Finally, CGE models contain detailed sector breakdowns and provide a 'simulation laboratory' for quantitatively examining how the individual impact channels of climate change influence the performance and structure of the whole economy (see Lofgren et al. 2002 for a detailed exposition of the base modelling framework adapted for this analysis).

Economic decision-making in the DCGE model is the outcome of decentralized optimization by producers and consumers within a coherent economy-wide framework. A variety of substitution mechanisms occur in response to variations in relative prices, including substitution between factors, between imports and domestic goods, and between exports and domestic sales. Production and trade function elasticities were drawn from Dimaranan (2006). The Tanzania model contains 28 activities or sectors, including 12 agricultural subsectors (see Pauw and Thurlow 2010). Six factors of production are identified: three types of labour (unskilled, semi-skilled, and skilled), agricultural land, livestock, and capital. Agricultural activities and land are distributed across the 20 administrative regions of mainland Tanzania. This sectoral and regional detail captures Tanzania's economic structure and influences model results. Table A2 in Appendix A outlines the disaggregation and regional characteristics of the model. A detailed description of the agro-climatic zones of Tanzania can be in the National Adaptation Programme of Action for Tanzania (United Republic of Tanzania 2007).

Climate change affects agricultural production, economic growth, and household incomes in the DCGE model via predicted annual yield deviations for rain-fed crops estimated by CLICROP. The DCGE then determines how much resources should be devoted to each crop given their profitability relative to other activities. This reallocation of resources permits some autonomous adaptation by farmers and non-agricultural producers. For example, representative farmers in each region within the DCGE model allocate their land and capital between crops based on long-run rates of technical change and climate change. However, farmers are unable to anticipate weather conditions for a particular season, and so once planted, land cannot be reallocated, even if weather patterns are not as expected. The representative producer in our model therefore corresponds to a 'typical farmer' (see Füssel and Klein 2006), who does not assume that historical weather patterns will persist indefinitely, but neither do they have perfect foresight of future climate change. Rather they adapt their behaviour based on the gradual realization of climate change.

The long timeframe over which climate change will unfold implies that dynamic processes are important (Arndt et al. 2011a). The recursive dynamic specification of our CGE model allows it to capture annual changes in the rate of physical and human capital accumulation and technical change. So, for example, if climate change reduces agricultural production in a given year, it also reduces income and hence savings. This reduction in savings displaces investment and lowers production potential and economic growth. Given our long-run focus, our macroeconomic 'closure' assumes that changes in aggregate absorption are proportionally distributed across nominal private and public consumption and investment via distribution neutral changes in savings rates. Government savings are flexible, tax rates are fixed, and the real exchange rate adjusts to maintain an exogenously determined current account balance. In summary, our DCGE model is well-suited to capture path dependent effects within a consistent macroeconomic framework.

3.2 Baseline scenario

In order to estimate the economic impact of climate change for Tanzania, we first specify a baseline scenario that reflects development trends, policies, and priorities in the absence of climate change. The baseline provides a reasonable trajectory for growth and structural change of the economy from 2007 to 2050 that can be used as a basis for comparison.

Economic growth in the DCGE model is determined by rates of factor accumulation and technical change. For population and labour supply, we assume that Tanzania's population will continue to grow, but at a decelerating rate (i.e. 2.0 per cent today falling to 0.3 per cent by 2050). We assume that the expansion of cultivated crop land will slow such that growth in agricultural production becomes increasingly dependent on the adoption of improved technologies rather than land expansion. As described earlier, the crop models use historical climate data to define year-on-year yield fluctuations in the baseline for each crop and region. Exogenous long-term agricultural productivity growth is set at 0.8 per cent per year in agriculture and 1.2 per cent in non-agriculture. Improvements in the education levels of Tanzania's workforce are assumed to continue, with supply and productivity rising faster for skilled and semi-skilled workers than for unskilled workers (i.e. at 2.0 and 1.5 per cent per year, respectively, compared to 0.5 per cent). Under the above assumptions, Tanzania's economy gradually develops, with agriculture's contribution to gross domestic product (GDP) falling from 27.8 to 14.1 per cent during 2007–50. Overall, per capita GDP grows at an average 2.2 per cent per year in the baseline, leading to significant improvements in average household welfare.

3.3 Economy-wide modelling results

The DCGE model uses the crop yield results from Section 2 to estimate the economy-wide impacts of climate change. We first discuss the macroeconomic results from the model, which are summarized in Table 3. We focus on changes in 'absorption', which is the broadest measure of national welfare. Absorption tracks an economy's use of goods for household consumption (C), investment (I), and government expenditure (G). Absorption is closely related to GDP growth. Formally, absorption (A) is defined as

A=C+I+G. Recalling that GDP=C+I+G+X-M, where X is exports and M is imports, we can write that A=GDP+M-X. In other words, absorption is the volume of goods produced by the economy plus the goods that foreigners supply to the economy (imports) less the goods sent out to foreigners (exports). One advantage of measuring outcomes based on aggregate absorption is that it is less sensitive to our choice of 'closure rules', which influence the relative sizes of absorption's C, I, and G components.

Table 3 reports average annual growth rates of real per capita absorption over the entire 2007–50 simulation period. Changes in annual growth rates are small, with discernable reductions for only the HOT and DRY scenarios. However, even small reductions in growth rates accumulate over time. For example, by the end of the 2040s, national absorption is 0.77 and 1.7 per cent below the baseline in the HOT and DRY scenarios, respectively. This is consistent with the larger and more widespread reductions in crop yields experienced under these two scenarios (see Table 2).

We measure the total economic damages caused by climate change via the agricultural sector as the cumulative loss or deviation in national absorption from the baseline using a five per cent annual discount rate. The largest damages occur in the DRY scenario, where the total discounted loss throughout the 2007–50 period amounts to US$13 billion (measured in 2007 prices). This amount is two-thirds of Tanzania's GDP in 2007. By contrast, total discounted absorption rises in the WET scenario by US$3 billion suggesting possible gains from climate change for Tanzania.[1]

Table 3 also decomposes economic damages across time periods. Despite the escalating biophysical effects of climate change on agricultural yields towards the end of our simulation period, applying a five per cent discount rate means that a significant share of the economic costs or benefits of climate change will accrue over the next two decades. This is because crop yield reductions are often temporary during a bad year and can immediately rebound in the subsequent year if the season's climate improves. In other words, crop yield losses in a given year are usually temporary, unlike damages to assets which may have lasting effects, such as roads damaged by flooding. This partly explains why agricultural damages are more evenly distributed across time periods. However, if we did not discount effects further into the future, then the costs or benefits of climate change would be larger and more heavily weighted towards the middle of the century. Moreover, it should be noted that most GCMs predict a pronounced aggravation of climate change impacts during the second half of the century. Were the time horizon of our analysis extended beyond 2050, then later periods would begin to exhibit progressively stronger impacts.

One of the advantages of CGE models is their ability to decompose national impacts to the sector and regional levels. Table 4 reports deviations in real GDP from the baseline in 2046–50 for different sectors. Since agriculture is our only impact channel through which climate effects economic growth, it is not surprising that this sector exhibits the largest changes in our four scenarios. However, agriculture provides important inputs into downstream sectors, such as agro-processing. For example, agricultural GDP is

1 Other impacts, such as increased frequency and intensity of flooding events, were not modelled for the case of Tanzania. The impacts of these events are potentially large (Arndt et al., 2011b) and could easily overwhelm the benefits of enhanced moisture to crops.

11.5 per cent below the baseline in the DRY scenario by the end of the 2040s. This reduces the supply of raw inputs (e.g. grain) to downstream agro-processing sectors (e.g. milling), causing their GDP to contract by 7.8 per cent. However, not all sectors are adversely affected, even in the DRY scenario. For example, food imports increase in order to offset declining domestic production in the DRY scenario (see Table 3). Accordingly, some traders in the service sector benefit from higher demand for their services. Despite the expansion of services, forestry and fishery, which are only indirectly affected by climate change in our analysis, the net effect of climate change is a significant reduction in national GDP in the HOT and DRY scenarios and a slight decrease/increase in the COOL and WET scenarios, respectively.

Table 5 presents deviations in real agricultural GDP from the baseline for the different regions in the model. It should be noted that the DCGE model is for mainland Tanzania only, and so does not reflect changes on the coastal islands (i.e. Pemba and Zanzibar). Almost all regions are adversely affected in the HOT and DRY scenarios, with particularly large reductions in agricultural GDP in the northern and central zones and around Lake Victoria. These regions represent a large share of Tanzania's agricultural sector, and so a drop in their production has national level implications. Similarly, while overall agricultural production rises in the WET scenario, it hides significant regional variation. While production increases in the northern zone and northern coast, it falls in most other regions, including around Lake Victoria. There are also differences in regional outcomes even within agro-climatic zones, such as within southern coast. Such pronounced regional variation underscores the need for sub-national assessments, especially for designing policy responses to climate change.

Households in the DCGE model are affected by climate change via changes in both agricultural incomes and consumer prices. Households can adapt to these changes by reallocating their resources (e.g. land, labour and capital) towards less-affected sectors or occupations (e.g. non-farm activities). However, if agricultural production falls as a result of climate change then consumer prices for agricultural products will likely increase. Producers may then allocate more of their resources towards climate change affected sectors in order to take advantage of higher prices. This will certainly be the case for farmers in regions that are less adversely affected by climate change. Households' adaptation decisions therefore involve production and demand considerations, both of which are captured in a general equilibrium model.

Table 6 reports deviations in households' real food consumption expenditure from baseline by 2046–50. Changes in food consumption in each scenario are less pronounced than changes in agricultural GDP. Two factors drive this result. First, Tanzania is able to import food to replace falling domestic supplies. For example, the 11.5 per cent decline in national agricultural production in the DRY scenario (see Table 4) is partially offset by a 37.1 per cent increase in net food imports (see Table 3), leaving national food consumption to fall by 8.0 per cent (see Table 6). Second, the model assumes that transport systems are sufficiently developed in Tanzania by 2050 that food is effectively traded in national markets. This means that falling production and excess demand in certain regions can be supplied by producers in other regions. In this way, market forces will distribute changes in national food consumption across regions and household groups.

The impact of climate change on incomes and food security therefore depends on three household characteristics. First, climate change has region-specific implications, with some regions benefitting from improved conditions while others are adversely affected. Second, climate change will affect crops differently, and so changes in households' agricultural incomes will depend on their cropping patterns and their ability to reallocate farm resources between farm activities. Finally, agriculture generates only part of households' incomes and food comprises only part of their consumption basket. Climate change will therefore affect households differently based on their income and consumption patterns.

In sum, despite endogenous market-based adaptation, there are still significant differences in outcomes across household groups and regions. For example, lower-income households experience larger declines in per capita food consumption than higher-income households in the COOL and DRY scenarios. This is because poorer households are typically more reliant on agriculture for their livelihoods, and because they spend a larger share of their incomes on food. Likewise, while all regions around Lake Victoria experience similar reductions in agricultural GDP (see Table 5), household food consumption declines by 10.5 per cent in Kagera and by only 6.7 per cent in Shinyanga. This is because households in the Shinyanga region are less dependent on agricultural incomes, and are more heavily engaged in non-farm activities than are households in Kagera. Finally, food consumption amongst non-farm households also declines in the DRY scenario, due to rising food prices and falling real incomes (i.e. due to falling demand for non-agricultural products).

4 Conclusions

Relative to a no climate change baseline and considering domestic agricultural production as the principal channel of impact, food security in Tanzania appears likely to deteriorate as a consequence of climate change. This relative decline comes about through reductions in agricultural production, principally food production, due to increases in temperature and changes in rainfall patterns. In the DRY scenario, agricultural production levels are more than 10 per cent below the levels of a hypothetical no climate change scenario by mid-century. This reduced productive capacity also limits growth in exports and growth in household incomes hence reducing the overall capacity of the economy to obtain and distribute food from international markets. It is important to point out that the results do not point to an absolute decline in the levels of food security indicators, such as total agricultural production and household purchasing power. Rather, the rate of improvement in these indicators in three out of four scenarios is reduced. In addition, in one scenario, projected changes in climate are favourable to agricultural production and food security. Overall, the analysis points to a high degree of diversity of outcomes across climate scenarios, sectors, and regions. The economic modelling indicates that markets have the potential to smooth outcomes on households across regions and income groups, though noteworthy differences in impacts across households persist both by region and by income category.

The methodology applied is well-suited to considering the implications of climate change for growth, development, and ultimately food security. However, while the economic modelling framework is comprehensive, the treatment of climate change within the modelling framework is not. Climate change could impact food security through numerous additional channels beyond reductions in potential yields. These additional channels merit particular attention in future research. We will briefly discuss three. First, the increase in intensity of rainfall due to climate change has the potential to increase the frequency and intensity of flooding events (Arndt et al. 2011b). As recent events in Pakistan illustrate, flooding can be highly destructive. Not only does flooding cause a spike in food insecurity in the short-run, it frequently wipes out economic infrastructure, such as transport networks, with potentially long-term implications for production and growth (Chinowsky 2011). Second, the results presented reiterate the importance of long-run accumulation (Arndt et al. 2011a). If rates of growth decline even slightly over long periods of time, this decline eventually leads to significant economic impacts. In this context, it is important to recall that the (assumed) underlying rate of agricultural productivity growth is the same across all climate scenarios. It is certainly conceivable that climate change could reduce the expected rate of underlying agricultural productivity growth for any given level of effort devoted to new technology generation and adoption. Finally, all world prices are assumed to be constant. If the climate outcomes in the DRY scenario also resulted in reduced (increased) production globally, then the impacts of the reduction in agricultural production would be magnified (mitigated) by increased (decreased) prices for food commodities on world markets.

Overall, while significant progress has been registered, we remain at nascent stages in understanding the implications of climate change, across the multiplicity of possible dimensions, for food security in vulnerable low income countries such as Tanzania.

Appendix A

Table A1: Disaggregation of the Tanzania DCGE model

Agricultural sectors	Maize, Sorghum, Millet, Rice, wheat & barley, Cassava, Root crops, Pulses, Oilseeds, Horticulture, Export crops, Livestock, Other agriculture.
Non-agricultural sectors	Mining, Meat processing, Maize milling, Rice milling, Other milling, Other food processing, Export crop processing, Chemicals, Machinery, Other manufacturing, Electricity, Water distribution, Construction, Trade and transport, Other private services, Public services.
Sub-national regions (for agricultural sectors only)	Arusha, Coast, Dodoma, Dar es Salaam, Iringa, Kagera, Kigoma, Kilimanjaro, Lindi, Mara, Mbeya, Morogoro, Mtwara, Mwanza, Manyara, Rukwa, Ruvuma, Shinyanga, Singida, Tabora, Tanga.
Factors	Primary school and uneducated labour, Secondary school educated labour, Tertiary educated labour, Agricultural capital, Mining capital, Non-agricultural capital, Agricultural crop land (by region), Livestock capital (by region).
Households	Farm households (by region and national per capita consumption expenditure quintile), Rural non-farm households (by national per capita consumption expenditure quintile), Urban non-farm households (by national per capita consumption expenditure quintile).

Table A2: Land and population distribution across regions and farm households

	All households	Non-farm households			Farm households							
		All	Urban	Rural	All	North zone	South highlands	North coast	South coast	Lake Victoria	Western zone	Central zone
Population (1000)	31,683	5,890	3,590	2,301	25,793	2,517	3,963	3,657	1,690	7,889	1,972	4,105
Number of households	6,393	1,360	878	482	5,033	480	938	698	431	1,273	355	859
Household size	5.0	4.3	4.1	4.8	5.1	5.2	4.2	5.2	3.9	6.2	5.6	4.8
Per capita exp. (US$)	329	558	687	356	277	339	288	372	355	214	324	209
Poverty rate (%)	40.0	24.9	15.8	39.2	43.5	40.9	33.5	38.4	37.6	49.0	54.1	45.8
Poor population (1000)	12,679	1,468	567	901	11,211	1,030	1,328	1,405	635	3,868	1,066	1,879
Share of poor (%)	100.0	11.6	4.5	7.1	88.4	8.1	10.5	11.1	5.0	30.5	8.4	14.8
Harvest area (1,000 ha)	-	-	-	-	8,209	1,004	951	1,919	605	2,597	411	722
Average farm land (ha)	-	-	-	-	1.63	2.09	1.01	2.75	1.40	2.04	1.16	0.84
Maize	-	-	-	-	0.53	0.74	0.41	1.04	0.27	0.52	0.44	0.34
Sorghum and millet	-	-	-	-	0.18	0.11	0.04	0.15	0.00	0.31	0.05	0.34
Other cereals	-	-	-	-	0.12	0.17	0.05	0.43	0.00	0.15	0.02	0.00
Roots	-	-	-	-	0.24	0.04	0.15	0.22	0.82	0.38	0.10	0.01
Pulses and oilseeds	-	-	-	-	0.29	0.47	0.14	0.57	0.16	0.31	0.43	0.14
Horticulture	-	-	-	-	0.13	0.35	0.12	0.22	0.03	0.14	0.07	0.00
Export crops	-	-	-	-	0.13	0.21	0.11	0.12	0.13	0.24	0.03	0.01

Notes: Population data is from HBS 2000–01 (National Bureau of Statistics 2002). Per capita expenditure is based on consumption spending from the 2007 social accounting matrix. The poverty line identifies the bottom two per capita expenditure quintiles as poor.

Source: Authors' calculations using data from Pauw and Thurlow (2010).

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Table 1: Projected national climate changes in Tanzania by 2041–50

Scenario ID	General circulation model (GCM)	Emissions scenario (SRES)	Average change from baseline, 2040–50		
			Temperature (°C)	Precipitation (%)	CMI (absolute)
HOT	ncar_ccsm3_0	a1b	1.87	5.67	+0.0565
COOL	ncar_pcm1	a1b	1.13	5.37	+0.0157
WET	csiro_mk3_0	a2	1.43	13.3	+0.0243
DRY	ukmo_hadgem1	a1b	1.49	-11.14	-0.0853

Source: Own calculations using GCM results.

Table 2: Changes in mean annual dry-land maize yields, 2041–50

	Change from baseline (%)			
	HOT	COOL	WET	DRY
Northern zone				
Arusha	-15.05	4.06	12.66	-23.1
Kilimanjaro	-13.61	1.87	11.81	-15.55
Manyara	-13.46	3.18	15.28	-16.64
Tanga	-11.29	1.31	8.12	-6.84
Southern highlands				
Iringa	-3.2	-2.72	1.51	-5.51
Mbeya	0.25	-3.02	-3.12	-4.58
Ruvuma	-2.23	3.74	5.51	-5.17
Northern coast				
Dar es Salaam	-1.37	-0.42	0.97	-0.03
Morogoro	-4.49	-3.11	4.15	-5.49
Pwani	-6.25	-1.83	3.64	-5.09
Southern coast				
Lindi	-3.03	-2.97	-2.45	-4.29
Mtwara	0.01	-4.65	-7.47	0.19
Lake Victoria				
Kagera	-4.64	-3.35	-9.35	-16.48
Mara	-6.94	-1.19	-0.33	-16.91
Mwanza	-6.18	1.11	-2.62	-18.27
Shinyanga	-8.14	3.52	-2.76	-19.78
Western zone				
Kigoma	2.03	-7.56	-7.73	-14.27
Rukwa	0.69	-4.57	-8.39	-8.63
Central zone				
Dodoma	-9.45	1.15	13.46	-13.25
Singida	-6.79	0.74	-0.89	-9.8
Tabora	-4.64	-0.91	-12.38	-14.74
Coastal islands				
Kaskazini Pemba	-0.9	-0.52	2.58	-2.39
Kaskazini Unguja	-1.37	-0.42	0.97	-0.03
Kusini Unguja	-1.37	-0.42	0.97	-0.03
Mjini Magharibi	-1.37	-0.42	0.97	-0.03

Source: Results from CLICROP models for Tanzania.

Table 3: Macroeconomic results

	Baseline	HOT	COOL	WET	DRY
Average annual real per capita absorption growth rate, 2007–50 (%)	2.74	2.72	2.73	2.74	2.70
Deviation from baseline	-	-0.02	0.00	0.00	-0.04
Average annual undiscounted value of absorption, 2046-50 (US$ billions, 2007 prices)	95.42	94.69	95.27	95.51	93.82
Deviation from baseline	-	-0.73	-0.16	0.08	-1.60
Deviation as a share of baseline (%)	-	-0.77	-0.16	0.09	-1.71
Accumulated discounted deviation in absorption from baseline, 2007-50 (US$ billions, 2007 prices)	-	-4.21	-0.91	3.03	-12.70
Accrued during 2010s	-	-1.10	-0.45	0.53	-3.38
Accrued during 2020s	-	-0.94	0.11	0.81	-3.61
Accrued during 2030s	-	-0.74	-0.18	0.73	-2.67
Accrued during 2040s	-	-1.00	-0.23	0.26	-2.46
Deviation in average annual net food imports from baseline, 2046–50 (%)		21.34	3.65	-6.49	37.13

Source: Results from the DCGE model for Tanzania.

Table 4: Sectoral results

	Initial GDP share (%)	Deviation in average annual real GDP from baseline, 2046–50 (%)			
		HOT	COOL	WET	DRY
Total GDP	100.00	-0.89	-0.19	0.17	-1.93
Agriculture	27.82	-5.42	-1.19	1.10	-11.51
Cereals	8.31	-6.05	-0.59	1.25	-10.48
Maize	4.42	-5.91	-0.45	1.23	-10.89
Root crops	3.27	-2.44	-1.54	-1.40	-10.13
Pulses and oilseeds	2.71	-2.80	-0.99	0.03	-8.75
Horticulture	5.19	-5.44	-3.22	3.45	-13.92
Export crops	2.79	-6.53	-1.03	1.79	-11.37
Livestock	5.55	-6.96	-0.06	0.04	-13.18
Forestry and fisheries	4.02	0.20	0.03	0.03	0.50
Mining	3.94	0.00	0.00	0.00	0.01
Manufacturing	8.84	-2.05	-0.38	0.26	-4.42
Food processing	4.58	-3.57	-0.62	0.32	-7.84
Construction and energy	10.33	-0.02	0.00	0.02	-0.01
Services	45.05	0.13	0.03	-0.03	0.23

Source: Results from the DCGE model for Tanzania.

Table 5: Regional results

	Initial GDP share (%)	Deviation in average annual real GDP from baseline, 2046–50 (%)			
		HOT	COOL	WET	DRY
National (all regions)	100.00	-5.42	-1.19	1.10	-11.51
Northern zone	21.85	-9.76	-1.89	8.51	-15.51
Arusha and Manyara	10.12	-13.18	-0.69	7.07	-18.89
Kilimanjaro	5.95	-7.88	-4.16	9.49	-15.23
Tanga	5.77	-5.58	-1.66	10.06	-9.75
Southern highlands	15.72	-2.14	-1.88	-0.84	-6.33
Iringa	3.36	-3.35	-2.04	1.49	-6.45
Mbeya	7.53	-0.44	-2.64	-3.08	-6.46
Ruvuma	4.83	-4.15	-0.46	1.27	-6.02
Northern coast	13.48	-3.59	-1.32	5.66	-9.23
Dar es Salaam	0.62	2.20	1.89	5.79	-5.71
Morogoro	8.85	-4.11	-1.85	4.98	-9.37
Pwani	4.00	-3.34	-0.62	7.18	-9.47
Southern coast	3.95	-1.88	0.65	0.10	-6.49
Lindi	1.94	-4.56	-0.11	3.41	-12.48
Mtwara	2.00	1.38	1.57	-3.92	0.77
Lake Victoria	30.21	-6.24	-0.12	-3.53	-13.61
Kagera	7.60	-4.67	-0.58	-7.90	-13.78
Mara	4.95	-5.18	-0.94	-1.16	-12.14
Mwanza	8.99	-6.84	-0.65	-3.14	-13.28
Shinyanga	8.66	-7.66	1.29	-1.41	-14.66
Western zone	6.96	-0.57	-4.04	-5.32	-9.47
Kigoma	4.64	-0.36	-4.18	-4.92	-10.50
Rukwa	2.32	-1.00	-3.78	-6.08	-7.48
Central zone	7.83	-5.39	-0.11	0.05	-10.19
Dodoma	3.07	-6.43	0.80	8.20	-10.05
Singida	2.09	-4.95	0.25	-0.91	-7.36
Tabora	2.68	-4.54	-1.46	-8.66	-12.60

Source: Results from the DCGE model for Tanzania.

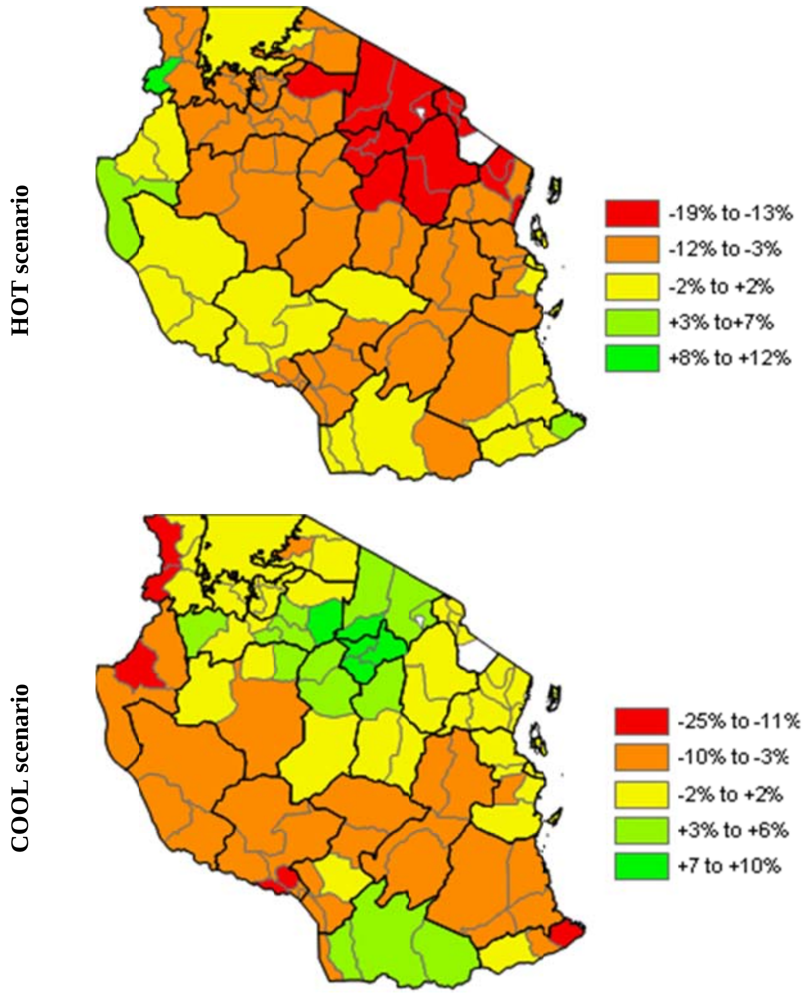
Table 6: Household food consumption results

	Initial food consumption (US$ p.c.)	Deviation in average annual real per capita food consumption from baseline, 2046–50 (%)			
		HOT	COOL	WET	DRY
National (all households)	355	-3.57	-0.78	0.33	-7.95
Farm	303	-3.59	-0.83	0.35	-8.04
Non-farm	582	-3.53	-0.65	0.30	-7.75
Quintile 1	114	-3.72	-1.06	0.39	-8.54
Quintile 2	193	-3.58	-0.92	0.35	-8.11
Quintile 3	272	-3.62	-0.83	0.36	-8.15
Quintile 4	390	-3.55	-0.81	0.35	-7.96
Quintile 5	805	-3.54	-0.67	0.31	-7.75
Northern zone	425	-3.69	-0.90	0.17	-8.42
Arusha and Manyara	430	-3.86	-0.91	0.23	-8.53
Kilimanjaro	477	-4.04	-0.98	0.40	-9.16
Tanga	382	-3.17	-0.83	-0.12	-7.64
Southern highlands	268	-3.64	-0.65	0.33	-7.79
Iringa	260	-3.81	-0.63	0.23	-8.14
Mbeya	214	-3.62	-0.64	0.70	-7.49
Ruvuma	377	-3.53	-0.68	0.01	-7.82
Northern coast	459	-3.18	-0.80	0.28	-7.14
Dar es Salaam	789	-3.10	-0.89	0.36	-7.33
Morogoro	324	-3.45	-0.77	0.35	-7.42
Pwani	649	-2.91	-0.80	0.17	-6.74
Southern coast	412	-3.53	-0.91	0.34	-8.18
Lindi	452	-3.34	-0.94	0.40	-7.93
Mtwara	379	-3.71	-0.88	0.28	-8.43
Lake Victoria	236	-3.60	-0.96	0.54	-8.17
Kagera	226	-4.36	-1.62	1.14	-10.51
Mara	399	-3.53	-0.78	-0.09	-8.40
Mwanza	218	-3.32	-0.64	0.41	-7.18
Shinyanga	200	-3.21	-0.76	0.55	-6.72
Western zone	285	-3.98	-0.64	0.25	-8.64
Kigoma	277	-3.79	-0.76	0.19	-8.51
Rukwa	294	-4.19	-0.51	0.31	-8.79
Central zone	228	-3.59	-0.78	0.45	-7.86

Dodoma	204	-3.16	-0.94	0.08	-7.37
Singida	267	-3.78	-0.75	0.62	-8.08
Tabora	228	-3.85	-0.65	0.69	-8.18

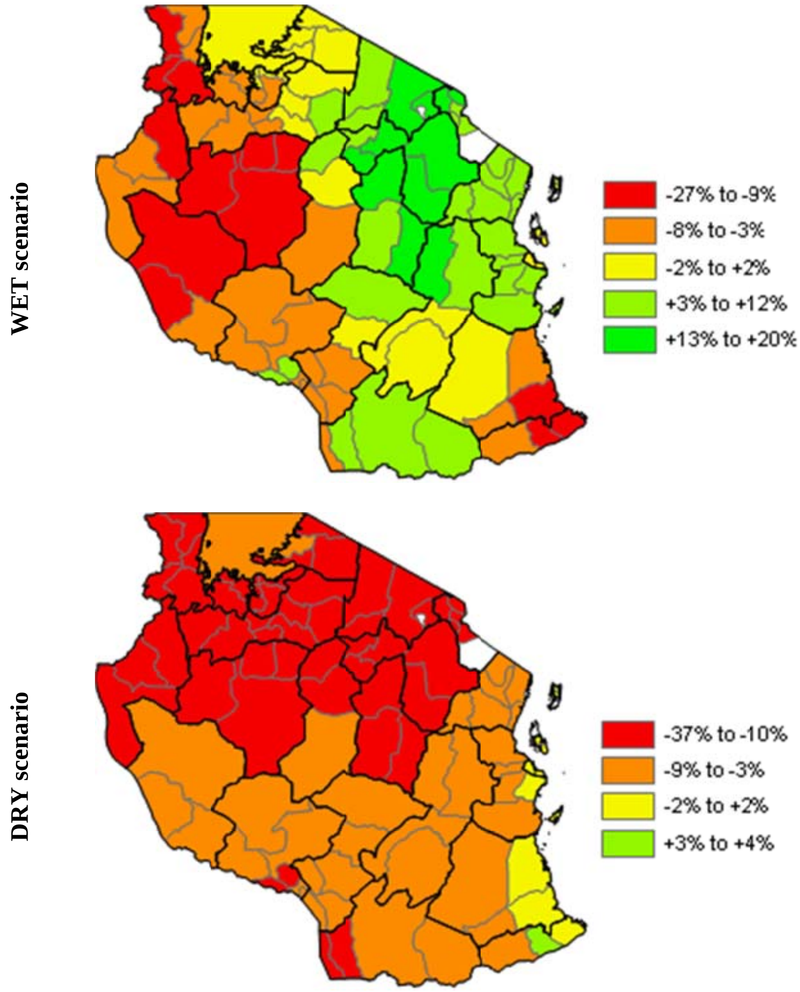
Source: Results from the DCGE model for Tanzania.

Figure 1: Mean annual dry-land maize yield changes for HOT and COOL scenarios, 2041–50



Source: Results from CLICROP models for Tanzania.

Figure 2: Mean annual dry-land maize yield changes for WET and DRY scenarios, 2041–50



Source: Results from CLICROP models for Tanzania.