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Adapting to climate change: Agricultural system and household impacts in East Africa

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ABSTRACT

The East African region exhibits considerable climatic and topographic variability. Much spatial and temporal variation in the response of different crops to climate change can thus be anticipated. In previous work we showed that a large part of this variation can be explained in terms of temperature and, to a lesser extent, water effects. Here, we summarise simulated yield response in two crops that are widely grown in the region, maize and beans, and investigate how the impacts of climate change might be addressed at two levels: the agricultural system and the household. Regionally, there are substantial between-country and within-system differences in maize and bean production responses projected to 2050. The arid-semiarid mixed crop-livestock systems are projected to see reductions in maize and bean production throughout most of the region to 2050. Yields of these crops in the tropical highland mixed systems are projected to increase, sometimes substantially. The humid–subhumid mixed systems show more varied yield responses through time and across space. Some within-country shifts in cropping away from the arid–semiarid systems to cooler, higher-elevation locations may be possible, but increased regional trade should be able to overcome the country-level production deficits in maize and beans caused by climate change to 2050, all other things being equal. For some places in the tropical highlands, maize and bean yield increases could have beneficial effects on household food security and income levels. In the other mixed systems, moderate yield losses can be expected to be offset by crop breeding and agronomic approaches in the coming decades, while more severe yield losses may necessitate changes in crop types, movement to more livestock-orientated production, or abandonment of cropping altogether. These production responses are indicative only, and their effects will be under-estimated because the methods used here have not accounted for increasing weather variability in the future or changes in the distribution and impacts of biotic and other abiotic stresses. These system-level shifts will take place in a context characterised by high population growth rates; the demand for food is projected to nearly triple by the middle of this century. Systems will have to intensify substantially in response, particularly in the better-endowed mixed systems in the region. For the more marginal areas, the variability in yield response, and the variability in households' ability to adapt, suggest that, even given the limitations of this analysis, adaptation options need to be assessed at the level of the household and the local community, if research for development is to meet its poverty alleviation and food security targets in the face of global change.

1. Introduction

Climate change poses serious threats to development, particularly in sub-Saharan Africa (Scholes and Biggs, 2004). Warming is not only unequivocal (IPCC, 2007), but it is increasingly clear that most of the warming that has occurred over the last 50 years is due to anthropogenic causes (IPCC, 2007). As a result, significant changes in physical and biological systems are occurring on all continents and in most oceans (Rosenzweig et al., 2008). What the impacts may be on agricultural systems and food security, and what options there are for households in vulnerable areas to adapt, are questions that are driving a great deal of work by research organisations, development agencies, and governments. Even so, considerable knowledge gaps remain concerning the interacting and multiple stresses on the vulnerability of the poor in Africa. There is a rapidly growing literature on vulnerability and adaptation to increased climatic variability and climate change, but there is still much to do to improve understanding of the implications of climate change for poverty reduction as well

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as to be able to assess adaptation initiatives and how these might be appropriately targeted.

The focus of most of the work done to date on climate change impacts on agriculture has been carried out at relatively low spatial resolution, often at the scale of the globe, region, or country (for example, Parry et al., 2004; Cline, 2007; Lobell et al., 2008). Particularly for organisations that work with a "pro-poor" mandate in developing countries, more detailed information is needed on the impacts of climate change on agricultural systems, as well as the effects of land-use changes on climate (Moore et al., 2009), so that effective adaptation options can be appropriately targeted.

In a previous paper (Thornton et al., 2009), we investigated in some detail the different types of crop response to climate change in East Africa as represented by a combination of two climate models and two contrasting greenhouse-gas emission scenarios, to the middle of the current century. East Africa is not only highly heterogeneous spatially, but is characterised by a rapidly-expanding human population, increasing urbanisation, and changing socio-economic circumstances and expectations. Such factors make for a highly dynamic situation, with potential economic growth opportunities as well as potential increases in vulnerability for sectors of the population. The results of the study showed that crop yield responses to the changing rainfall amounts and patterns and the generally increasing temperatures projected by General Circulation Models (GCMs) are heterogeneous. They may vary by crop type, by location, and through time. Results also indicate that under the four GCM-scenario combinations considered, the aggregate production decreases are projected to be rather modest to 2050. These aggregate production changes, however, hide a large amount of variability, and under the higher-emission scenario, substantial maize and bean yield reductions can be expected in 50–70% of potentially cropped pixels. At the same time, the highland areas in many parts may see increases in yield potential. Part of this heterogeneity in this response can be explained by temperature effects. At high altitudes, yields may increase as temperatures increase, but at most lower elevations, yield changes also depend on water balances, and many places will see increasing water stress in cultivated crops, all other things being equal. We concluded that relatively localised assessments of adaptation options were needed, that look in more detail at the physical system responses as well as at the heterogeneity of farm households with respect to socio-economic factors.

In this paper, we summarise the simulated production impacts of climate change to 2050 on maize and beans in the region, and assess the production changes by system. We then discuss how these production changes might be dealt with in the future, at two levels: the agricultural system, and the producer household. We consider the types of adaptation options that may be available to deal with either decreases or increases in yield potential, as simulated using crop models, and to start to quantify the impacts of these options on regional food security and incomes of typical producer households. We then briefly discuss the implications of the results in the light of projected increases in demand for food and livestock feed to the middle of this century.

2. Methods

Details on the methods used to simulate production changes are given in Thornton et al. (2009). To summarise, we used the data set TYN SC 2.0 to look at different scenarios of climate change to 2030 and 2050 (Mitchell et al., 2004), using four combinations of two GCMs and two greenhouse-gas emission scenarios (SRES, Special Report on Emissions Scenarios; Nakicenovic et al., 2000). The monthly GCM output data were downscaled to a resolution of 10 arc-minutes (about 18 km) using WorldCLIM (Hijmans et al., 2005) and interpolation methods described in Jones and Gladkov (2001) and Jones and Thornton (2000). From the TYN SC 2.0 data set we used the Hadley Centre Coupled Model version 3 (HadCM3, Mitchell et al., 1998) and the European Centre Hamburg GCM version 4 of the Max Planck Institute for Meteorology, ECHam4 (Roeckner et al., 1996). Relatively, ECHam4 is a wetter model, while HadCM3 is a drier model. For emission scenarios, we chose a low-emission scenario (B1) and a high-emission scenario (A1FI), which span the range of best estimates of temperature change to 2090–2099 relative to 1980–1999 (IPCC, 2007). To generate daily data characteristic of whichever set of climate normals was being used, we used the weather generator MarkSim (Jones and Thornton, 2000) to generate daily rainfall amounts. It also estimates daily maximum and minimum air temperatures from monthly means using the methods originating with Richardson (1981), and solar radiation is estimated from temperatures, longitude and latitude using the model of Donatelli and Campbell (1997).

The work here is part of a broader project designed to address questions of how land-use change affects climate, and how climate change affects land use, by looking at societal and environmental systems across space at multiple scales in East Africa, from the global climate to regional vegetative dynamics to local decision-making by farmers and herders (Olson et al., 2008). The study region includes all of Kenya, Uganda, Tanzania, Rwanda and Burundi, and parts of Ethiopia, Democratic Republic of Congo, Malawi and Mozambique. We used maize as a test crop, because of its prevalence in the study region. To identify the likely (current and possibly future) maize-growing areas in the region, we eliminated those pixels with growing seasons shorter than 40 days and with soils of no agricultural potential (FAO, 1995) To simulate the growth, development and yield of the maize crop in these pixels, we used the model CERES-Maize (Ritchie et al., 1998), as currently implemented in version 4 of the Decision Support System for Agrotechnology Transfer (DSSAT; ICASA, 2007). Simulations were run using a relatively short-season Kenyan variety as a proxy for a well-adapted generic maize variety. Planting was assumed to occur automatically, once the soil profile had received a thorough wetting at the start of the primary rains, and the crop was planted at a typical density of 3.7 plants per square metre. A nominal amount (5 kg per ha) of inorganic N was applied to the crop at planting.

Regarding the impacts of carbon fertilisation on crop yields, there is considerable on-going debate as to the size of the effects on the physiology of crops (Ainsworth et al., 2008), and there are more uncertainties concerning yield benefits in low-input, rainfed subsistence production systems such as those that prevail in the study region. There are also substantial knowledge gaps concerning the impacts of CO_2 concentrations and how they may interact with changing ozone concentrations and with other biotic and abiotic stresses (Challinor et al., in press). Carbon fertilisation effects are incorporated to some degree in the DSSAT models, but given the uncertainty surrounding this issue, we decided not to use them. Accordingly, for all simulations, carbon dioxide concentrations were held constant at 330 ppm.

In parts of the study region it is possible to grow two or more crops per year, either because of the bimodal rainfall patterns that occur or because there is one growing season that is sufficiently long. For these areas, we simulated bean production also. We used the version of the BEANGRO crop model (Hoogenboom et al., 1994) as currently implemented in the DSSAT version 4. As for maize, simulated cultural practices reflect regional management. We grew one well-adapted variety throughout the region, planted at a typical 8 plants per square metre. The cropping systems observed in the region can be complex: maize and beans are often intercropped, for example, and many households grow a wide variety of other crops as well. The original analysis in Thornton et al. (2009) was designed to investigate potential impacts of climate change on contrasting crops (a C_3 and a C_4 crop) with different responses, in places where climatic and soil conditions are such that both crops could be grown. Attempting to simplify the cropping systems in this way may result in some discrepancies in the analysis below: for example, beans rather than maize may be grown in areas with shorter growing seasons. As discussed below, however, crop model results here are overlaid on a broad agricultural systems' classification and scaled to match national production data, in the absence of reliable crop distribution maps for the region, and so these discrepancies should not be large.

For all simulations, we used representative soil profiles from the International Soils Reference and Information Centre's World Inventory of Soil Emission Potentials (WISE) database (Batjes and Bridges, 1994), as modified and reformatted by Gijsman et al. (2007).

In Thornton et al. (2009) we mapped simulated mean yields of maize and beans from 30 replicates (different weather years) for the baseline, using current (nominally 2000) climate normals, and five time slices (2010, 2020, 2030, 2040, and 2050) for each of the four combinations of two GCMs (HadCM3 and ECHam4) and two SRES scenarios (A1FI and B1). We also identified pixels where statistically significant trends (at the 5% level) in yield were simulated, whether they were linear or quadratic, increases or decreases.

The object of the analysis presented here is to investigate the differences in productivity and production of maize and beans in different production systems, and then to assess different options of adapting to these changes in the future, on the basis of differing locations and situations. The obvious starting point is to consider where maize and beans are actually grown in the region. At present, there is little reliable detail on crop distributions in East Africa, although the methods of You and Wood (2006) on taking sub-national data and reallocating them via an appropriate spatial model should rectify this gap before long. One alternative in the meantime is to use a land cover data layer such as GLC 2000 (JRL, 2005) or the crop distribution layers of Ramankutty et al. (2008), and use these to define crop land in the region. There is considerable variability in estimates of cropped areas from different sources, however.

We proceeded as follows. In the study region here, there are five entire countries and pieces of several others: the entire countries are Burundi, Kenya, Rwanda, Tanzania and Uganda. These five countries occupy more than 65 percent of the land area of the region between longitude 28°E to 42°E and latitude 12°S to 6°N. Table 1 shows data for maize and beans for these five countries (FAO, 2008), in terms of average area, yield and production for the years 2005, 2006, and 2007. In order to allocate production spatially within each country, we cannot use the triage of pixels described above, as this will grossly over-estimate cropland, because there are many competing uses for the land which have not been taken into account. Given that there are currently no appropriate regional databases with sub-national crop distribution data, we decided to use a classification of agricultural systems that was developed for other purposes. This is essentially the livestock-based systems classification of Seré and Steinfeld (1996), modified to incorporate some of the systems of Dixon and Gulliver (2001). Details are given in Thornton et al. (2006), and the classification was mapped for current climatic conditions using WorldClim (Hijmans et al., 2005). We assume that maize and beans are grown in the cropping areas of this classification, which is shown in Fig. 1 for the study region. (This will still grossly over-estimate crop area, because much <100% of each "cropped" pixel will be sown to crops.)

For calculating system-specific production changes to 2030 and 2050, we overlaid simulated maize and bean yields on the systems classification, and summed crop production from those pixels that have maize suitability or maize and bean suitability (in terms of length of growing period and soil suitability) and that also correspond to areas within the mixed rainfed classification. In effect, we take national data (FAO, 2008) on the area sown to each crop, and adjust the area within each pixel that we assume is sown to maize and bean, using a pro-rata within-country percentage, to match the national data. While this is somewhat crude, the analysis already takes into account agro-climatic suitability, and the crop model results further take into account the weather conditions in each place. This method would be easily improvable with sub-national crop areas, however. In effect, for the maize and bean crops in each country we calculate production as the product of area and yield, and by keeping the cropped area constant through time (to 2030 and 2050), we calibrate national production with model-simulated production, and then calculate changes in (calibrated) production in relation to spatial and temporal yield changes derived from the crop models. This enables us to calculate country total production for the baseline (current conditions), with spatial variation in relation to yields from the models, with areas adjusted on a per-pixel basis so that the total production at the national level matches the country totals shown in Table 1.

In addition to grain yields, we also calculated system- and country-specific production changes in maize stover for the four GCM-emission scenario combinations. For a small number of selected pixels in the triage, some further simulations were carried out to investigate the effects of changes in planting dates and in substituting sorghum and millet for maize, using the appropriate crop models in the DSSAT v4 (ICASA, 2007).

3. Results

Results are presented and discussed in three sections: projected production changes by agricultural system; production changes and impacts at the household level; and impacts of maize grain and maize stover production changes to 2050 in the light of possible future regional demand for food and feed.

3.1. Simulated production changes by agricultural system

The agricultural systems in the five entire countries in the region are shown in Table 2, in terms of percentage of land area that is classified as mixed crop-livestock systems, livestock-only

Table 1
Maize and bean production data for Burundi, Kenya, Rwanda, Tanzania and Uganda, average of 2005–2007 (FAO, 2008).

	Maize			Beans		
	Area (ha)	Production t	Yield (kg ha^{-1})	Area (ha)	Production t	Yield (kg ha^{-1})
Burundi	115,667	120,334	1040	240,000	220,001	917
Kenya	1,753,103	3,130,923	1786	1,009,956	483,036	478
Rwanda	111,412	93,021	835	336,467	237,678	706
Tanzania	3,000,000	3,353,667	1118	378,333	290,001	767
Uganda	814,333	1,230,000	1510	849,000	445,668	525

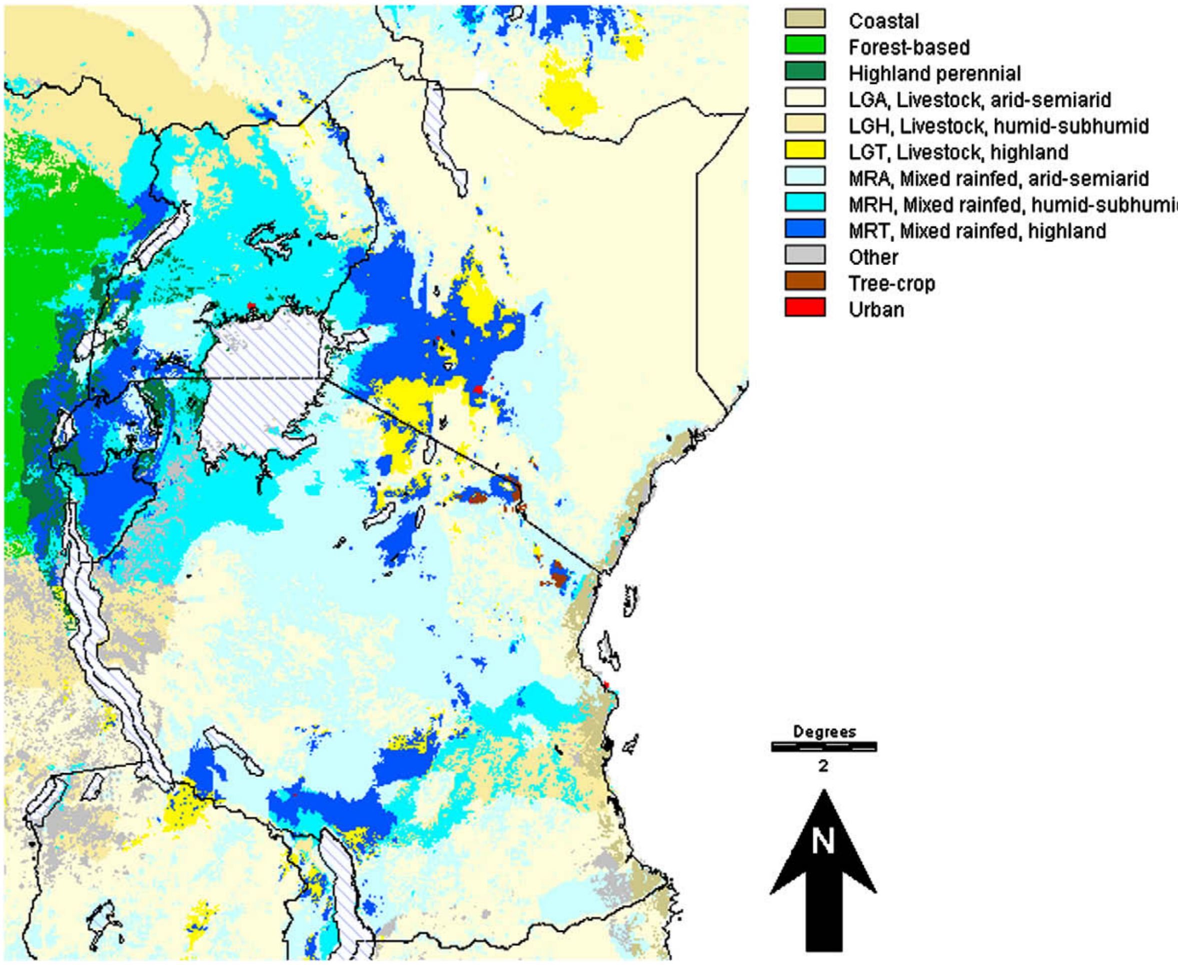

Fig. 1. Agricultural systems of the study region, based on Seré and Steinfeld (1996) and Dixon and Gulliver (2001) as described in Thornton et al. (2006).

Table 2
System areas for Burundi, Kenya, Rwanda, Tanzania and Uganda, showing the country percentage of mixed rainfed systems, of which the temperate/tropical highland (MRT), humid–subhmid (MRH) and arid–semiarid (MRA) systems make up the percentages shown in column "All".

	Mixed rainfed				Livestock Only	Other	Total Area (km^2)
	All	MRT	MRH	MRA			
Burundi	87	75	24	1	0	13	27,278
Kenya	26	45	8	47	71	2	582,721
Rwanda	96	72	11	17	0	4	25,580
Tanzania	56	10	21	69	33	10	939,138
Uganda	68	12	64	24	16	15	244,318
Average or total	49	–	–	–	42	8	1,819,034

systems (i.e. rangelands), and "other", which includes urban areas and other non-livestock systems (e.g. forest-based agricultural systems). Table 2 indicates the proportion of the mixed rainfed system in each country that is classified as arid–semiarid (MRA), humid–subhumid (MRH), and temperate or tropical highland (MRT). The agro-climatic definitions of these classes are as defined in Seré and Steinfeld (1996) and mapped in Kruska et al. (2003): the arid–semiarid regions have a length of growing period (LGP) of less than or equal to 180 days; humid–subhumid, a LGP of more than 180 days; and the tropical highlands have a daily mean temperature, during the growing period, of between 5 and 20 °C (the temperate regions are areas that have one or more months with monthly mean temperature below 5 °C, corrected to sea level).

Results of this country-by-system breakdown are shown for maize and beans in Table 3, in terms of the percentage change in production by system by country to 2030 and 2050, assuming that the cropped areas for maize and beans remain the same through time. For ease of presentation, we have averaged the results for the four combinations of GCM and SRES scenario (strictly, results from each scenario and each GCM are equally likely, so there are no a priori grounds for supposing one combination to be "better" than any other). Simulated crop yield differences associated with each GCM and emissions scenario are summarised in Thornton et al. (2009).

There are two other assumptions that should be noted. First, it is assumed that all beans are grown in the secondary season areas of each country; maize is assumed to be the main crop, grown at the start of the major growing season. Beans contribute only in those places where the growing seasons are long enough on average to support the maize crop and then the bean crop. Second,

Table 3
Percentage production changes to 2030 and 2050, mean of the four combinations of HadCM3 and ECHam4 model simulations and of higher- and lower-emission scenarios (A1FI and B1), by country and system, assumptions as in text. Blank cells indicate that there are no (or very few) pixels in that country associated with maize or bean production in that system.

	National Production		MRT		MRH		MRA	
	2030	2050	2030	2050	2030	2050	2030	2050
Maize								
Burundi	9.1	9.1	14.4	18.1	−1.8	−8.8	–	–
Kenya	15.0	17.8	33.3	46.5	−4.6	−9.8	−1.1	−8.4
Rwanda	10.8	14.9	13.4	18.8	5.4	3.6	1.1	2.7
Tanzania	−3.1	−8.1	7.5	8.7	−1.6	−6.4	−5.1	−11.1
Uganda	−2.2	−8.6	4.9	3.1	−4.6	−12.9	−1.1	−6.3
Beans								
Burundi	21.8	23.7	29.0	35.9	5.2	−4.2	–	–
Kenya	14.2	16.7	18.2	23.6	0.3	−6.8	–	–
Rwanda	14.6	16.4	16.9	19.7	0.1	−4.7	–	–
Tanzania	6.7	−0.6	35.7	57.4	4.0	−5.0	4.5	−5.7
Uganda	−1.5	−18.1	11.0	4.0	−3.7	−20.8	5.7	−13.1

MRT, mixed rainfed temperate/tropical highland.
MRH, mixed rainfed humid–subhumid.
MRA, mixed rainfed arid–semiarid.

average yields by country are not calibrated directly to observed average yields; it is just total simulated and observed production data that are matched. There are several sources of uncertainty involved in the analysis (such as the real distribution of maize and bean cropping in the region, the known limitations of the crop models and the soils and climate data, and the problems associated with downscaling GCM data to relatively high spatial resolutions), and accordingly there are several reasons why the simulated average national yields for the five countries may not be directly comparable with the average yields shown in Table 1. The results shown are thus merely indicative of directional changes in yields and hence in national production.

As expected, the results in Table 3 demonstrate considerable spatial variation: some systems in some countries see increases in production, while others see declines. For these combinations of GCM and emissions scenario, national maize production in Burundi is projected to increase from the baseline (Table 1) by 9% to 2050, but this is made up of a larger increase (18%) in the MRT system in that country and a decrease of 9% in the MRH system. The overall impact on national production is positive because the area of the MRT system in the country is three times the area of the MRH system (Table 2), although the relationship is complicated by the relative yields in each system, which are dependent not only on weather but also on soil conditions. These country-level results may be compared with the aggregate production losses for the entire study region (i.e., the entire area shown in Fig. 1, not just the five entire countries), averaged across all four combinations of GCM and emissions scenario, of 8% (Thornton et al., 2009).

Table 3 shows some temporal switches also. Bean production in the MRH system in Tanzania is projected to increase by 4% to 2030, but then to decline by 5% to 2050, presumably because of average temperatures increasing beyond the threshold of 20–22 °C (Thornton et al., 2009). Nationally, both maize and bean production are projected to increase to 2050 in Burundi, Kenya and Rwanda, and to decrease in Tanzania and Uganda, assuming constant (average of 2005–2007) crop areas.

3.1.1. Responses to system-level shifts in production

Table 3 indicates that there are specific production systems in different places that are likely to suffer relatively more from the impacts of climate change. It also suggests two types of possible response to these projected changes. There are countries in which internal shifts of production can take place, from lower-producing systems to higher-producing systems, to offset projected decreases in production. For example, Kenyan bean production could increase by 17% to 2050 over its 2005–2007 level as a result of yield increases, but the yield increases occur only in the MRT system, not the MRH (in Kenya no beans are simulated to be grown in the MRA system because of inadequate season length to accommodate a maize crop first; see Section 3.1 above). If some bean production shifted to MRT systems, which are characterised by cooler temperatures, then some of the bean production losses projected to occur in the MRH systems in Kenya could be offset.

A second type of response would be to offset projected production losses through increased regional trade. Decreases in both bean and maize production are projected in the MRH and MRA systems in Uganda to 2050. The amount of production that could be shifted to the MRT system areas in the country, which are projected to show some increases in yield, is likely to be limited, as only 12% of the mixed systems in Uganda are in this category (Table 2). For both Tanzania and Uganda, the area of maize in the MRT systems would need to nearly treble in 2050 if production losses in the MRH and MRA systems were to be offset so that national production levels in 2050 were the same as currently. Cropping shifts of this magnitude are unlikely to be feasible. The importance of domestic and regional markets has been thrown into sharp relief by the recent increases in food prices globally. In the study region, domestic food prices are determined as much by local and regional demand and supply conditions as by international market prices (Karugia et al., 2008). Considerable potential for increased regional trade exists. For example, total trade in maize in the Common Market for Eastern and Southern Africa (COMESA), of which the study region is a part, is worth more than US$ 1 billion, but less than 10 percent of this trade has been intra-regional. Rising global market prices present several countries in the region with the opportunity to expand domestic production and supply regional markets (Karugia et al., 2008).

Total maize production for the five countries is currently 7.1 million ton (Table 1). Using the assumptions above, including that of constant crop areas, total production for the same five countries in 2050 is projected to be 8.1 million ton, so all other things being equal, regional trade could cover the shortfalls projected for Tanzania and Uganda. Similarly, bean production stands at about 1.7 million ton currently, and this is projected to increase via spatially explicit yield changes to about 1.8 million ton in 2050. Thus for both maize and beans, increased regional trade could overcome the national production deficits projected here as a result of climate change. The implications of these results in relation to the likely increases in regional demand to 2050 are discussed briefly below.

3.2. Production changes and impacts at the household level

The results presented in the previous subsection indicate that at the systems' level within each of the five countries, the impacts on crop yields of climate change are highly variable, but that overall, the aggregated production changes arising because of increasing temperatures and shifting rainfall patterns and amounts are relatively modest. In this subsection we discuss impacts at the household level, in relation to the three general situations identified in Jones and Thornton (2003):

1. Crop yields decrease, but to an extent that can be handled by breeding and agronomy.
2. Crop yields increase due mostly to gradual warming in the coming decades, presenting smallholders with opportunities for increased income generation.
3. Crop yields decline drastically, so that major changes may be needed to the agricultural system.

3.2.1. Moderate crop yield declines

In Thornton et al. (2009) we showed that maize and bean yield declines can be explained to some extent in relation to average temperature increases to 2050. Many households at lower elevations would be projected to experience moderate declines in crop yields to 2050. What might some of the household responses be? The history of agriculture research and crop breeding in sub-Saharan Africa would suggest that, depending on circumstances and the crops involved, yield losses of 25–40% could potentially be dealt with without great difficulty, through management options and use of improved varieties. For example, there have been periods during the history of maize breeding in East and southern Africa when yield growth rates have been sustained at nearly 5% per year over several years (Smale and Jayne, 2003). Such rates are probably not common, and more modest figures have been used in recent global assessments. In the simulations of Rosegrant et al. (2009), for example, the global yield growth rate for all cereals is projected to decline from 1.96% per year in 1980–2000 to 1.02% per year in 2000–2050, although there are considerable regional variations. At the same time, area expansion is a significant component of projected food production growth in sub-Saharan Africa (28%) (Rosegrant et al., 2009). Yield trends for maize and beans in the five study countries over the recent past suggest that substantial public investment may be needed to attain and maintain these rates of yield growth (FAOSTAT, 2008). Nevertheless, considerable progress is being made in drought tolerance breeding in maize, for example (Bänziger et al., 2006), and drought-tolerant crop varieties are bound to play a major role in adapting to climate change in the region in the coming decades. The incorporation of drought- or heat-tolerant characteristics into the appropriate parameters in the maize and bean models is not straightforward, and it is difficult to quantify the impacts that such new varieties may have directly (Hoogenboom, personal communication).

It is not clear what role other management changes to cropping systems may have in offsetting potential yield reductions that are due largely to temperature increases. We carried out some other crop model runs to see if changing the date of planting in response to shifting weather patterns might be effective in some circumstances. We selected some pixels in an ad hoc fashion out of those that exhibited statistically significant yield reductions in maize of at least 20% to 2050 compared with current conditions. Location, elevation, annual rainfall and average daily temperature for four of these pixels are shown in Table 4. As noted above, crop simulations were usually run with planting occurring automatically, once the soil profile had received a thorough wetting at the start of the primary rains. To look at any influence of planting date on yield reductions, we carried out runs with planting at specified dates, for the four test pixels corresponding to the average planting date of the previous automatically-planted simulations. We varied these dates (which were different for each pixel) by 12 days either side of the average date, and the changes in percentage yield response for the four pixels are shown in Table 4. Changing planting dates in this way made little difference to the yield reductions obtained, an effect that appeared to be independent of the soil type of the pixels chosen. In general, given the relatively limited seasonal variation in daily temperatures during the wet seasons in this region, planting date modifications may have only limited ability to offset the yield-decreasing action of higher temperatures.

3.2.2. Yield increases

Temperature increases in the MRT systems in the region may lead to increased yield potential in some places (Table 3). In previous work, we have undertaken detailed household modelling work for one such area in the MRT system in Kenya. This can give some indications of the household-level impacts of increases in crop yields. Vihiga district in western Kenya lies between 1300 and 1500 m above sea level and has well-drained soils that support the growing of various cash and food crops. The average household has 15 persons living on 0.89 ha of land, and is highly dependent on agriculture. Production is mainly subsistence orientated, and farm areas are largely devoted to maize and other food crops. Some households have local Zebu cattle in open grazing systems. Tea is the main cash crop. Vihiga has a high incidence of poverty: average total income was KSh 56 (about € 0.70 in 2006) per household per day, more than 65% of which was from wages and remittances (Waithaka et al., 2006).

Vihiga is one of the areas in the MRT system in Kenya where yield increases are projected to 2050 for both maize and beans. The impacts of these yield increases at the household level could be considerable. The study of Waithaka et al. (2006) involved data collection from participating households, the biophysical modelling

Table 4
Simulated yield response to changes in planting dates in four individual pixels with substantial maize yield losses to 2050 (HadCM3 + A1FI).

Location	Latitude (°)	Longitude (°E)	Elevation (m)	Current annual rainfall (mm)	Current average daily temperature (°C)	Current mean yield (kg/ha)	Yield change to 2050 (%)		
							Normal planting	Earlier planting	Later planting
NE Tanzania	−4.40	38.25	603	724	23.3	1587	−43	−37	−35
Coastal Kenya	−1.72	40.76	42	603	27.0	1223	−58	−62	−51
Central Uganda	2.82	32.76	1016	1362	23.7	1022	−44	−44	−42
NW Tanzania	−2.26	34.58	1291	873	21.9	981	−47	−53	−55

Normal planting date: average planting date over 30 replicates.
Earlier and later planting dates: the normal planting date adjusted by 12 days either side.

of crop and livestock enterprises, and running a mathematical-programming-based household model to maximize the household's objectives subject to constraints of land, labour and capital. These objectives were elicited from householders and ranked in the order food security, generating cash to meet the household's food requirements, maintaining some maize production and fuelwood trees for cultural reasons, and maintaining the fertility of the soil, if at all possible. Waithaka et al. (2006) found that maize and beans were grown almost exclusively for home consumption, and that currently yields of both are often very low. The study involved the design of "ideal farms" by the farmers and the researchers, that would meet their objectives as nearly as possible within the constraints that households faced. A typical farm has a total area of 0.8 ha, of which 0.33 ha is devoted to food crops, and a household size of 10 people. Readily-attainable maize and bean yields in these conditions are 1.5 and 0.2 ton per ha, respectively. Thus under current conditions, such a household could grow 495 kg of maize in each of two seasons per year; assuming 10 kg of maize per person per month, the maize needs of the household are 1200 kg per year. For such an idealised farm, there is thus currently a slight maize deficit for the household; for real (rather than idealised) households in Vihiga, crop yields are often much lower than those reported above, and most households can grow enough food to satisfy only 2–6 months of their annual food requirements (Waithaka et al., 2006). The balance has to be purchased. For the idealised farm, applying the yield increases in Table 3 to maize and beans, the household would then be producing 725 kg of maize per season, leaving a surplus of some ($2 * 725–1200$) 250 kg per year that could be sold for cash. For these (admittedly idealised) households, the climate change impacts projected to 2050 could mean that household food security objectives could be attained then, which cannot be attained now, all other things being equal. Increased maize and bean yields could also improve the protein content of household diets and generate additional income for the family. Greater quantities of maize stover would also be produced, with implications for livestock feeding (this issue is returned to below). For other districts in the MRT system of the region, where poverty rates are currently high, yield increases of this order of magnitude could have beneficial effects on household food security and poverty levels.

3.2.3. Severe crop yield declines

Croppers and livestock keepers in sub-Saharan Africa have a long history of dealing with the ever-changing production potential of their land. They are already highly adaptable to the vagaries of the weather. One response to declining yields, either as a result of inter-annual variability or of longer-term climate change, is to switch varieties and species. Ben Mohamed et al. (2002) describe efforts to target different millet varieties in relation to their duration (the number of heat units required to reach physiological maturity), in response to shifting isohyets in southern Niger. In times of drought, livestock keepers in arid-semiarid rangeland systems in both East and West Africa may switch from cattle to small ruminants such as sheep and goats when forage is scarce (Nyong et al., 2007). O'Brien and Vogel (2003) have documented shifts to more drought-tolerant crops such as millet and sorghum in southern Africa in the face of below-average rainfall. At the same time, farmers in wetter regions may actually reduce the area planted to maize in anticipation of too much rainfall, while croppers in the drier regions may plant significantly more maize than in normal years, to capture the anticipated benefits of above-average rainfall (O'Brien and Vogel, 2003).

Strong associations have been found between year-to-year variability in the El Niño Southern Oscillation (ENSO) and yields of maize, sorghum, millet and groundnuts in some parts of Africa (Stige et al., 2006). Many climate models project more ENSO-like conditions in the future, and it has been suggested that this variation, even at the regional level, could be used to adapt cropping patterns if likely conditions are known ahead of time (Stige et al., 2006). For example, cassava and sorghum in particular have wide agro-climatic adaptability, including tolerance to drought, and these could be more widely planted in likely drought years in particular areas in response. There is substantial regional variation, however; Stige et al. (2006) note that in southern Africa, their analysis indicates that the impacts of drought years on sorghum were almost as large as the impacts on maize. Clearly, there are limits to all cropping strategies in extreme years; in northern Nigeria, for example, farmers mentioned that seasons of abnormal drought are relatively rare, but during such years, it matters little which crops are planted, as almost all will fail (Adejuwon, 2005).

For the four pixels shown in Table 4, we carried out some more simulations to examine the effect of growing pearl millet and sorghum instead of maize. Detailed results are not shown here, but in all cases, mean yields of sorghum and millet were lower than the corresponding yields of maize for both current weather conditions and future scenarios. Whether planting millet and sorghum in these areas under future conditions could lead to increased yield stability, compared with maize, is not known. For our simulations, in all but one case, the coefficient of variation of annual simulated maize yield for current conditions was lower than that for either millet or sorghum, and Cooper et al. (2008) note that historical yields of pearl millet in Kenya are both lower and more variable than historical yields of maize.

A second response may be to consider a more radical livelihood shift, to more of a dependence on livestock rather than cropping. In another analysis (Jones and Thornton, 2009), areas of sub-Saharan Africa (SSA) were identified where a shifting in emphasis between marginal cropping and livestock keeping might occur. It might reasonably be assumed that the choices people make between cropping and keeping livestock in agropastoral areas are related to some extent to the risk of cropping season failure. As the probability of complete crop failure increases, shifts to livestock keeping, and/or more dependence on livestock keeping, are increasingly likely. Jones and Thornton (2009) suggested that under even a moderate greenhouse-gas emission scenario for the coming decades, there are likely to be substantial shifts in the patterns of African cropping and livestock keeping to the middle of the century. Southern coastal Kenya is one such potential livelihood transition zone, where maize production is likely to become increasingly risky. In general, poverty rates in many of these transition zones are already higher than average. For these areas that are relatively close to large human settlements, there may be options for integration of livestock systems into the market economy and for off-farm employment. For areas that are more remote, both market and off-farm employment opportunities may be much more limited. Some parts of coastal East Africa are close to large urban centres, but other parts are much more remote. For these latter areas particularly, substantial changes may be required to people's livelihood and agricultural systems if food security is to be improved and incomes raised (Jones and Thornton, 2009). In all these cases where crops and livestock are integrated to some degree, there are issues related to the production and utilisation of crop residues in these systems. Assessing changes in these complex situations has to be done at the household level, and a tool such as a household model (as in the Vihiga study above of Waithaka et al. (2006), for example) can have a significant role to play in addressing these issues.

3.3. Future regional demand for maize grain and maize stover

The results presented above indicate that climate change impacts on maize production at the regional level may be relatively modest to 2050. As noted already, the regional perspective hides a great deal of local variability, however; simulation results

Table 5
Availability of maize stover per head of cattle in 2000 and 2050 (assumptions as in text).

	2000				2050			
	Cattle (1000)[a]	Maize HI (%)[b]	Stover (Mt)[c]	Stover (kg per head)	Cattle (1000)[d]	Maize HI (%)[e]	Stover (Mt)[c]	Stover (kg per head)
Burundi	321	44.1	153	476	419	40.5	193	461
Kenya	12,078	44.1	3965	328	16,002	44.5	4597	287
Rwanda	764	47.4	103	135	995	45.0	131	131
Tanzania	17,306	40.3	4968	287	21,075	35.9	5498	261
Uganda	5972	42.6	1657	277	7906	38.1	1825	231

[a] FAOSTAT data for 2000 from Rosegrant et al. (2009).
[b] Simulated average maize harvest index (the weight of grain as a percentage of total plant weight) from the baseline maize model runs (see text).
[c] Estimated stover production (simulated national above-ground biomass minus national grain yield).
[d] Data for the "reference run" for 2050 from Rosegrant et al. (2009).
[e] Simulated maize harvest index, the average of the four GCM-scenario combinations to 2050 (see text).

Table 6
Demand for maize grain for human consumption in 2000 and 2050 (assumptions as in text).

		2000		2050	
	Maize consumption (kg per person)[a]	Population (million)[b]	Demand for maize ($t * 1000$)	Population (million)[b]	Demand for maize ($t * 1000$)
Burundi	24	6.67	160	28.31	679
Kenya	88	31.25	2750	84.76	7459
Rwanda	9	8.18	73	22.63	204
Tanzania	73	33.85	2471	85.08	6211
Uganda	31	24.69	765	92.93	2881
Total		104.64	6220	313.71	17,434

[a] Data for 2003 from FAOSTAT (2008).
[b] Data from UNPD (2008).

suggest that some areas may see increased agricultural potential as a result of climate change, while others may be negatively affected quite heavily. In this subsection we present and discuss results in relation to possible future demand for maize for both food and feed.

Taking the feed demand first, Table 5 shows the availability of maize stover per head of cattle in 2000, and then recalculated for 2050 using results from the maize model simulations. Cattle numbers from Rosegrant et al. (2009) were used for both 2000 (which were based on FAO data for that year) and for 2050. Rosegrant et al. (2009) simulate a scenario to 2050 that quantifies global economic growth and shifts in the demand and supply of agricultural products, that imagines a world developing in the coming decades much as it does today (the "reference world"). Table 5 indicates that cattle numbers in the region are projected to increase by some 32% by 2050. The increases in demand for livestock products that is projected (demand for meat in SSA doubles to 2050 in the reference world) are met through a combination of increasing livestock numbers but particularly increasing productivity per animal. Stover production by country was estimated by calculating the average harvest index (percentage of total above-ground biomass that is grain) from all the simulations (the baseline 2000 run and the four combinations of GCM and emission scenarios), and scaling national production accordingly. For the 2050 data, the assumption was made (as above) that maize production would take place on the same land area in 2050 as in 2000. While this is clearly not likely to occur (as indicated above, Rosegrant et al. (2009) project an increase in the area of cropped agriculture in SSA of 28% to 2050), the results give an indication of the possible impacts of climate change on stover production. Total stover production increases in all countries (Table 5), although the harvest index is simulated to decrease in all countries except Kenya. The end result is a moderate decrease in most countries in the availability of maize stover per head of cattle to 2050, compared with 2000, although the decrease in Uganda is projected to be about 20%.

The potential increases in demand for maize stover as an animal feed are dwarfed by the possible increases in demand for maize grain by the human population. Table 6 shows the changes in demand for maize grain in the region, assuming that maize consumption per person in the early 2000s remains the same to 2050. Human population is projected to triple by 2050, compared with 2000 (UNPD, 2008), and demand for maize as a consequence increases by a factor of 2.8. In SSA, dietary shifts away from maize are projected, with 20% more reliance on rice and wheat in 2050 (Rosegrant et al., 2009), although these other cereals still will have to be grown somewhere or imported. If we take the 6.2 Mt demand for maize in 2000 (Table 6), increase it by 28% to account for increased cropping area (Rosegrant et al., 2009), decrease the result by 8% as the aggregate change in maize productivity arising from climate change for the entire region, and decrease demand in 2050 by 20% to account for dietary switches away from maize, then if maize demand is to be satisfied, an annual production increase per ha of 1.3% per year will be required – or regional imports will have to expand dramatically. Near-doubling of maize yields over 50 years in the East African region is certainly entirely possible from a technical viewpoint, given current yield levels, but it means that substantial intensification will be needed, particularly in the higher-potential cropping systems.

4. Discussion and conclusions

The results presented here support the idea that in regions such as East Africa that are facing continuing population increases, specialisation of agricultural systems is inevitable if regional food security is to be assured (Rosegrant et al., 2009). Large gains will be needed in agricultural productivity because of increasing demand and rising (albeit slowly) incomes. These productivity gains, conditioned by climate change effects, will need to come not only from the more intensive mixed systems that are close to markets, but also from the more extensive mixed systems, where yield gaps are still wide and considerable potential exists for productivity increases (Herrero et al., 2009). This intensification will need to be supported by infrastructural development that improves accessibility to input and output markets, and by technology developments in relation to input use and resource-use efficiency gains. It will also need to be supported by judicious crop improvement and well-targeted genetic resources conservation: Burke et al. (in press) show that the majority of African countries will have novel climates over at least half of their current crop area by 2050, and analogues of some (but by no means all) of these climates currently exist in other African countries.

If system intensification in the better-endowed mixed systems is inevitable, the impacts of climate change in the coming decades are such as to render the more marginal extensive systems increasingly risky to the point where livelihoods may have to change substantially. Climate change will exacerbate the problems for the vulnerable and poor people who live in these marginal areas. Many of these households may need diversified livelihood options if cropping becomes increasingly difficult: livestock may become more important, and in some circumstances other options such as payments for ecosystem goods and services may be able to contribute to household incomes (FAO, 2007). Studies on such payments and their impact on household income are now being done (see Antle and Stoorvogel (2008), and González-Estrada et al. (2008), for example).

At the same time, there are limitations to the analysis outlined here, and it is likely that the impacts of climate change have been under-estimated. While these results indicate relatively modest production changes at the regional level in response to changing long-term means of climate, the effects of increasing climate and weather variability have not been included. Additional system and household-level impacts can thus be anticipated, and these are likely to be uniformly negative, mostly (IPCC, 2007). Tools and methods are increasingly becoming available to better understand and characterise the household implications of increasing climate variability (Cooper et al., 2008), but there are still real difficulties in making the connections between relatively coarse climate models and the spatial and temporal scales at which appropriate adaptation information is really needed (Wilby, 2007). Another limitation to this analysis is that no account has been taken of possibly large shifts in the prevalence and risk of human, livestock and plant diseases as a result of changing climate, all of which may affect rural households, but in ways that for many diseases are essentially unknown.

There are also considerable uncertainties associated with the climate models still. While the GCMs and scenarios used here indicate that rainfall in the region may increase, in line with other model analyses such as those of Doherty et al. (2009) and Moore et al. (2009) as well as the IPCC (2007), other work suggests that climate models to date have probably under-estimated warming impacts of the Indian Ocean and thus may well be over-estimating rainfall in East Africa during the present century (Funk et al., 2008). If this is so, then the notion that East Africa will be become wetter in the coming decades may not be correct. In any case, Thornton et al. (2009) and Burke et al. (in press) show that increased rainfall will not necessarily translate into increased agricultural production because of temperature increases. Funk et al. (2008) suggest that the region will need modest investments in agricultural development; the results presented here lend weight to the idea that the investments needed in agricultural development will need to be both large and well-targeted, given the variability in yield response and in households' ability to adapt, if research for development is to meet its poverty alleviation and food security targets in the face of global change.

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