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Climate variability and climate change and their impacts on Kenya's agricultural sector

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Mario Herrero,[1] Claudia Ringler,[2] Jeannette van de Steeg,[1]
Philip Thornton,[1] Tingju Zhu,[2] Elizabeth Bryan,[2] Abisalom Omolo,[1]
Jawoo Koo,[2] and An Notenbaert[1]

[1]International Livestock Research Institute, PO Box 30709, Nairobi, Kenya
[2]International Food Policy Research Institute, 2033 K Street, Washington, DC, USA

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International Livestock Research Institute

P O Box 30709, Nairobi 00100, Kenya
Phone + 254 20 422 3000
Email ILRI-Kenya@cgiar.org

P O Box 5689, Addis Ababa, Ethiopia
Phone + 251 11 617 2000
Email ILRI-Ethiopia@cgiar.org

www.ilri.org

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Executive summary

This document was produced as an output of the project '*Climate change adaptation for smallholder agriculture in Kenya*' funded by The World Bank and executed by the International Food Policy Research Institute, the International Livestock Research Institute, the Kenyan Agricultural Research Institute and the University of Georgia.

The objective of this report is to provide an assessment of the impact of climate change and variability on the agriculture sector and economy of Kenya as an initial task to devise adaptation strategies for smallholders in selected agro-ecological zones of the country. The following tasks were carried out:

1. a review of the historic performance of the Kenyan agricultural sector under varying climate
2. climate variability and climate change impact analyses with special reference to Kenya
3. assessments of the impacts of climate change on crop yield, production, and livestock yield and numbers using crop and livestock simulation models
4. assessment of the wider effects on the economy using IFPRI's IMPACT model.

Main observations

- **Kenya might get wetter.** In Kenya, as in most of East Africa, there are very few places where rainfall means are likely to decrease. The increase in rainfall in East Africa, extending into the Horn of Africa, is robust across the ensemble of GCMs, with 18 of 21 models projecting an increase in the core of this region, east of the Great Lakes.
- **The increases in rainfall and temperature will only translate in increased agricultural productivity in specific locations.** Increases in rainfall may not lead to increases in agricultural productivity in lowland regions since increases in temperature will also increase evapotranspiration and offset any potential increase in productivity. On the other hand, increases in temperature may remove crop growth constraints in the highlands, thus potentially leading to higher yields. However, to really capitalize on the potential yield increases it will be necessary to invest in these regions in inputs and services.
- **Overall, Kenya will experience country-wide losses in the production of key staples.** There seems to be large uncertainty about the magnitudes of the country-wide staple production losses. These vary between minus 10–55% depending on the scenario, crop model and GCM run. Even with modest increases in maize and bean production in the highlands, the country-wide impacts will be a decrease in the production of the major staples due to the large areas where evapotranspiration could increase.
- **However, trade in key staples is likely to offset reductions in crop production due to climate change.** Trade in cereal production is likely to increase as a result of climate change to satisfy internal consumption. Under climate change, maize and total cereal imports would be much higher for two out of the three scenarios examined, by between 21 and 44%. Under the Hadley scenario, on the other hand, maize imports would be 63% below the scenario without climate change.
- **However, prices of key staples are likely to increase** and this will dampen demand for food, as affordability of nearly all agricultural commodities—including basic staples and livestock products declines under climate change. As a result, per capita calorie availability in Kenya is likely to decline under all climate change scenarios.
- **Lower food accessibility due to increased commodity prices is likely to translate in increases in malnutrition, especially of young children.** Climate change is likely to increase the number of malnourished children in both 2025 and 2050. Without climate change, child malnutrition levels are projected to decline from 19% in 2000 to 15% by 2025 and 11% by 2050. Under climate change, child malnutrition levels increase under all alternative climate change scenarios. These effects will probably be exacerbated in areas of high vulnerability, like in the arid and semi-arid areas Kenya.
- **Increased drought frequencies to more than a drought every five years could cause significant, irreversible decreases in livestock numbers in arid and semi-arid areas.** Results indicate that a drought once every five years (i.e. representative of current conditions) keeps herd sizes stable in ASALs, and this has in fact been observed in places like Kajiado for a long time. Increased probability of drought to once every three years, could decrease herd sizes as a result of increased mortality and poorer reproductive performance of the animals. This decrease in animal numbers would affect food security and would compromise the sole dependence of pastoralists on livestock and their products, as well as the additional benefits they confer. This simple analysis shows that under increased climate variability, the need for diversification of income, a strategy often (and increasingly) observed in pastoral areas, becomes ever-more important. Climate change and increasingly climate variability will have substantial impacts on environmental security as well, as the conflicts (usually over livestock assets) often observed in these regions are likely to escalate in the future.
- **Kenya will have significant areas in the ASALs where cropping might no longer be possible as a result of climate change and where the role of livestock as a livelihood option is likely to increase.** Even

under 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. Potential livelihood transition zones can be identified, and these zones differ in their accessibility, which may have considerable impacts on the type of adaptation options that may be viable. For transition zones that are remote, both market and off-farm employment opportunities may be limited. Substantial changes may be required to people's livelihoods and agricultural systems if food security is to be improved and incomes raised. There will be an increasing need in these areas for highly-targeted schemes that promote livestock ownership and facilitate risk management where this is appropriate, as well as efforts to broaden income-generating opportunities in parts of the continent where this is feasible.

1 Background

The climate of Africa is warmer than it was 100 years ago and model-based predictions of future GHG-induced climate change for the continent clearly suggest that this warming will continue and, in most scenarios, accelerate (Hulme et al. 2001; Christensen et al. 2007). Observational records show that during the 20th century the continent of Africa has been warming at a rate of about 0.05°C per decade with slightly larger warming in the June–November seasons than in December–May (Hulme et al. 2001). By 2000, the five warmest years in Africa had all occurred since 1988, with 1988 and 1995 being the two warmest years. This rate of warming is not dissimilar to that experienced globally, and the periods of most rapid warming—the 1910s to 1930s and the post-1970s—occur simultaneously in Africa and the rest of the world (IPCC 2001).

The projections for rainfall are less uniform. Hulme et al. (2001) illustrated the large regional differences that exist in rainfall variability. East Africa appears to have a relatively stable rainfall regime, although there is some evidence of long-term wetting. There is likely to be an increase in annual mean precipitation in East Africa (Christensen et al. 2007).

Many of the impacts of climate change will materialize through changes in extreme events such as droughts and floods. Such extremes result in severe human suffering, and hamper economic development and efforts at poverty reduction. Unfortunately, assessments of climate change are often limited to mean temperature and precipitation. Knowledge of changes in extremes is sparse, particularly for Africa. In some regions, different models project different trends in wet and dry extremes. In other regions, however, models show clear trends such as increasing drought in the Kalahari and increasing floods in East Africa (KNMI 2006).

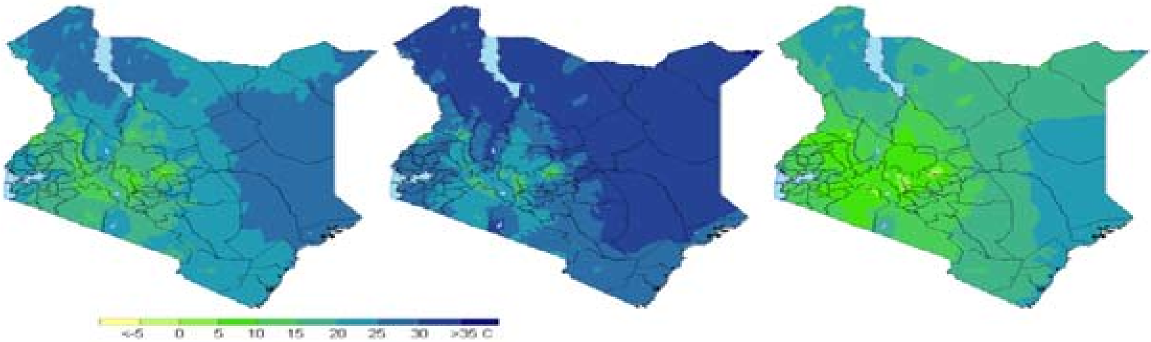
The challenges climate change poses for development are considerable (Thornton et al. 2006). Despite the uncertainties that exist in long-term climate predictions, it is necessary to explore the sensitivity of the environmental and social systems, and economically valuable assets to climate change (Hulme et al. 2001). High levels of vulnerability and low adaptive capacity in areas of Africa have been linked to factors such as limited ability to adapt financially and institutionally, low per capita gross domestic product (GDP) and high poverty rates, and a lack of safety nets. For example, sub-Saharan Africa (SSA) is predicted to be particularly hard hit by global warming because it already experiences high temperatures and low (and highly variable) precipitation, the economies are highly dependent on agriculture, and adoption of modern technology is low (Kurukulasuriya et al. 2006).

This document gives an overview of available literature on climate variability and climate change in Africa, and specifically in Kenya. First a description is given of the current climate in Kenya, followed by an overview of the range of predictions on climate change. We conclude with an analysis of the agricultural impacts of climate variability and climate change.

Section 2 has been adapted from van de Steeg et al. (2009).

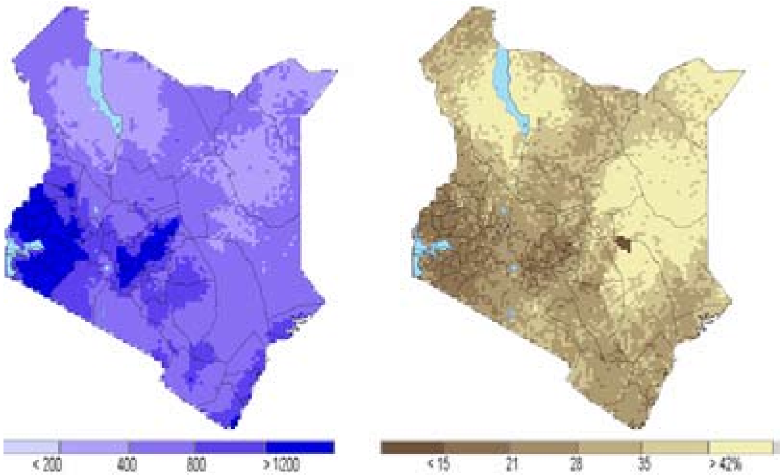
2 Current climate characteristics

In East Africa large water bodies and varied topography give rise to a range of climatic conditions, from a humid tropical climate along the coastal areas to arid low-lying inland elevated plateau regions across Ethiopia, Kenya, Somalia and Tanzania. The presence of the Indian Ocean to the east, and Lake Victoria and Lake Tanganyika, as well as high mountains such as Kilimanjaro and Kenya induce localized climatic patterns in this region (KNMI 2006). Mean temperature varies with elevation. In Figure 1 the difference between the lowest minimum and maximum temperatures for highland regions is in the order of 8–10°C.



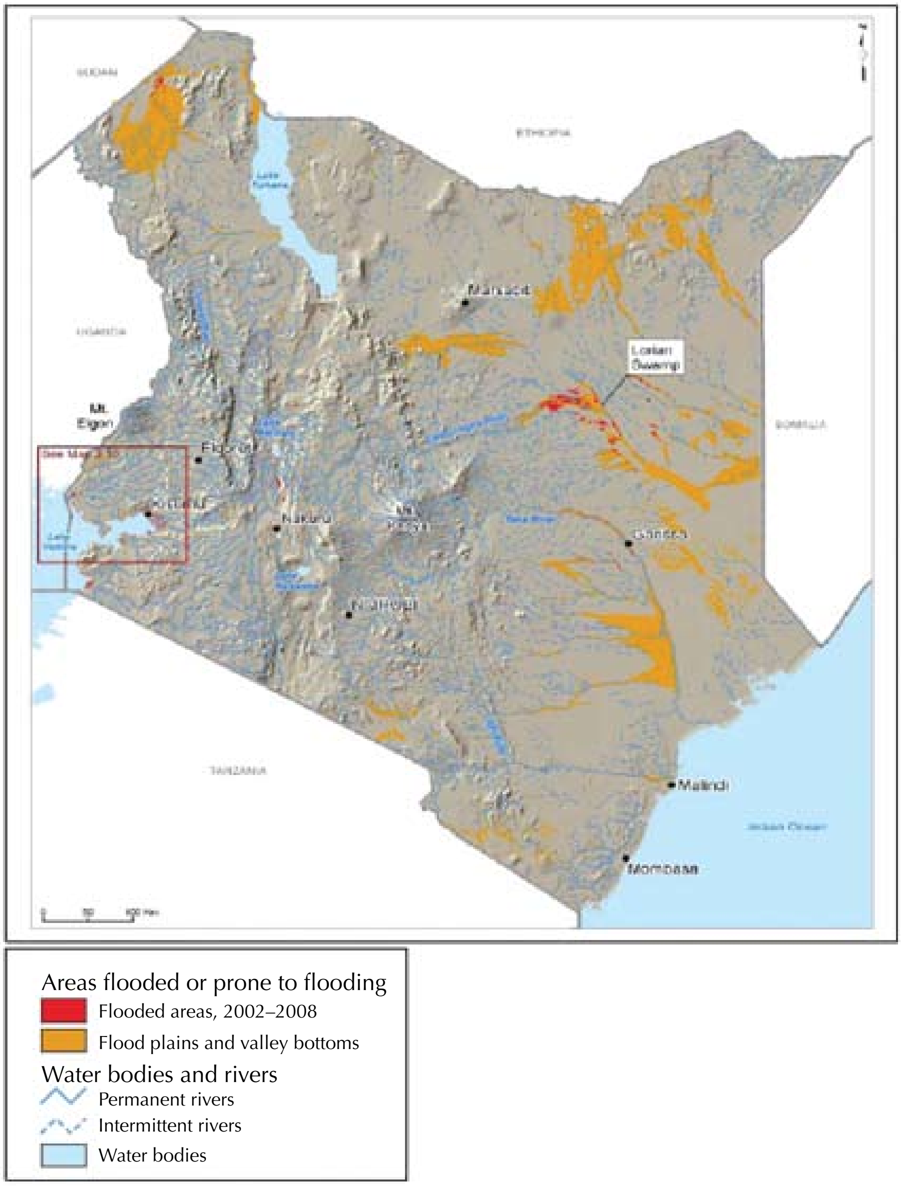
From left to right: The mean average of monthly data on temperature, maximum temperature of warmest month, and minimum temperature of coldest month (Hijmans et al. 2005).
Figure 1. *Current conditions for temperature (2000).*

Kenya's climatic conditions vary from a humid tropical climate along the coast to arid areas inlands. While mean temperature varies with elevation, the more remarkable climatic variation is with respect to precipitation (Figure 2). Kenya experiences a bimodal seasonal pattern as it lies astride the equator: the long rains season starts around March and runs through to June, with the peak centred on March to May; the short rains run from September and taper off in November or December (coinciding with the shifting of the Inter-Tropical Convergence Zone). The annual rainfall and the simulated coefficient of variation of annual rainfall (the standard deviation of annual rainfall divided by the mean expressed as a percentage) at a resolution of 10 arc-minutes are shown in Figure 2. Rainfall is correlated to topography; for example the highest elevation regions receive up to 2300 mm per year whilst the low plateau receives only 320 mm. Over two-thirds of the country receives less than 500 mm of rainfall per year, particularly areas around the northern parts of the country (Osbahr and Viner 2006). The figure shows as well that rainfall is highly variable, especially in the arid and semi-arid regions, and unreliable for rainfed agriculture and livestock production.



Left, mean annual rainfall (Hijmans et al. 2005). Right, the coefficient of variation of annual rainfall (Thornton and Jones 2008).
Figure 2. *Current conditions for rainfall (2000).*

The rainy seasons can be extremely wet and often either at rapid onset or late, bringing floods and inundation, such as in 2000 (Anyah and Semazzi 2007). Major floods periodically afflict the Winam Gulf of Lake Victoria, the Lower Tana River basin and the coastal regions (see Figure 3). Rainfall in this region is strongly linked to the El Niño-Southern Oscillation (ENSO) (Ropelewski and Halpert 1987; Ogallo et al. 1988; Indeje et al. 2000; Mutai et al. 1998). Links between El Niño events and climate variability have been suggested, and it is a common perception that high coefficients of variation in rainfall may be attributed to El Niño effects (Anyah and Semazzi 2007). However, currently it is not clear whether a relationship exists between both El Niño or La Niña events and prolonged drought or particularly wet periods over much of the Greater Horn of Africa (Thornton et al. 2006; Conway et al. 2007).



Source: Otiende (2009) based on WRI (2007).

Figure 3. *Flood-prone regions, Kenya.*

The arid and semi-arid areas (ASALs) that comprise of 80% of total landmass in Kenya are also prone to floods, despite their low levels of rainfall of 300–500 mm annually (WRI et al. 2007). Otiende (2009), citing UNEP (2009) stated that flood-related fatalities account for 60% of all disaster victims in Kenya (see Table 1). However, this statement needs to be seen in the light that drought-related damage data are seldom well accounted for (personal communication, EM-DAT disaster database).

Table 1. *Areas affected and number of people affected by floods*

Year	Region Affected (Provinces)	No of People Affected	
		Displaced	Fatalities
2009	Nyanza (Kisumu town)	150 families	5
2008	Nyanza, Northeastern, Rift Valley, Coastal	12,000	5
2007	Western, Nyanza	20,610	9
2006	Nyanza, Western, Coast and Eastern	723,000	66
2005	Western, Nyanza, Eastern, Northeastern	35,000 including 25,000 refugees in Daadab	20
2004	Widespread	2,500	50
2003	Western, Eastern,	1,000,000	77
2002	Western, Nyanza, Eastern, Coastal	150,000	14
2001	Nairobi	Missing data	4
1997-98	Widespread	1,500,000*	53

Table showing regions and flood victims from recent floods in Kenya
*Figure includes people affected in 4 East and Horn of Africa Countries including Kenya, Somalia, Ethiopia and Tanzania including over 2000 deaths

Source: Government of Kenya (2007) and Dartmouth Flood Observatory (DFO), September 22, The Standard Newspaper

Source: Otiende (2009).

Kenya experiences major droughts every decade and minor ones every three to four years. In recent years, critical drought periods in the country were experienced in 1984, 1995, 2000 and 2005/2006 (UNEP/GoK 2000). Kenya faced a major drought in 2009 that affected all regions; leading to hunger and starvation of an approximate 10 million of people countrywide after a poor harvest, crop failure and rising commodity prices (Kenya Red Cross 2009). The impacts of these droughts on the population are increasing (Table 2) due to high population growth and increasing encroachment of agricultural activities in the arid and semi-arid regions, classified as ASALs. The arid and semi-arid regions are intensifying, and changing from rangeland to mixed systems. This transition from pastoralism to agropastoralism is ongoing in many places throughout Africa (Reid et al. 2004, 2008). This is also demonstrated by the reductions in land area in the rangeland based systems towards increases in areas of mixed systems, and the substantial increases in the livestock populations in the mixed systems leading to more intensive types of production systems (Herrero et al. 2008). In Kenya, changes from pastoral to mixed systems are projected to occur at rates of 1.2–2% per year in terms of area (Herrero et al. 2008). This is not dissimilar to the trends observed up to now.

The droughts are often followed by periods of intensive rainfall. Torrential rainfall experienced during the wet months often translates into high stream/river flow (runoff) in permanent and intermittent streams/rivers across the country resulting to seasonal floods (Otieno 2009). Major floods periodically afflict the

Winam Gulf of Lake Victoria, the Lower Tana River basin and the coastal regions. Rainfall in this region is strongly linked to the El Niño-Southern Oscillation (ENSO) (Ropelewski and Halpert 1987; Ogallo 1988; Mutai et al. 1998; Indeje et al. 2000). Osbahr and Viner (2006) indicated that rainfall seasons can be extremely wet and erratic resulting to both large and small river devastating floods like the El Niño floods of 1997/98 with significant socio-economic impacts. The 1997/98 El Niño flood was associated with one of the largest flood losses in the country in 50 years (Mogaka et al. 2006). The economic and financial losses associated with the El Niño flood is in the range of up to USD 800 million (Karanja et al. 2002).

Table 2. *Number of people in Kenya requiring relief in the worst flood and drought disasters since 1971*

Year	Type of disaster	No. of people affected
2009*	Floods	750,000
2009*	Drought	3,800,000
2006	Floods	723,000
2006	Drought	3,000,000
2005	Drought	3,500,000
2003	Floods	45,000
2002	Floods	60,000
2001	Drought	3,400,000
2000	Drought	2,740,000
2000	Floods	125,000
1998	Floods	539,000
1997	Floods	212,000
1993	Drought	1,200,000
1992	Drought	2,700,000
1984	Drought	600,000
1979	Drought	40,000
1971	Drought	130,000

*Data since 2006 based on estimated Kenya Food Security Steering Group.

Source: Osbahr and Viner (2006).

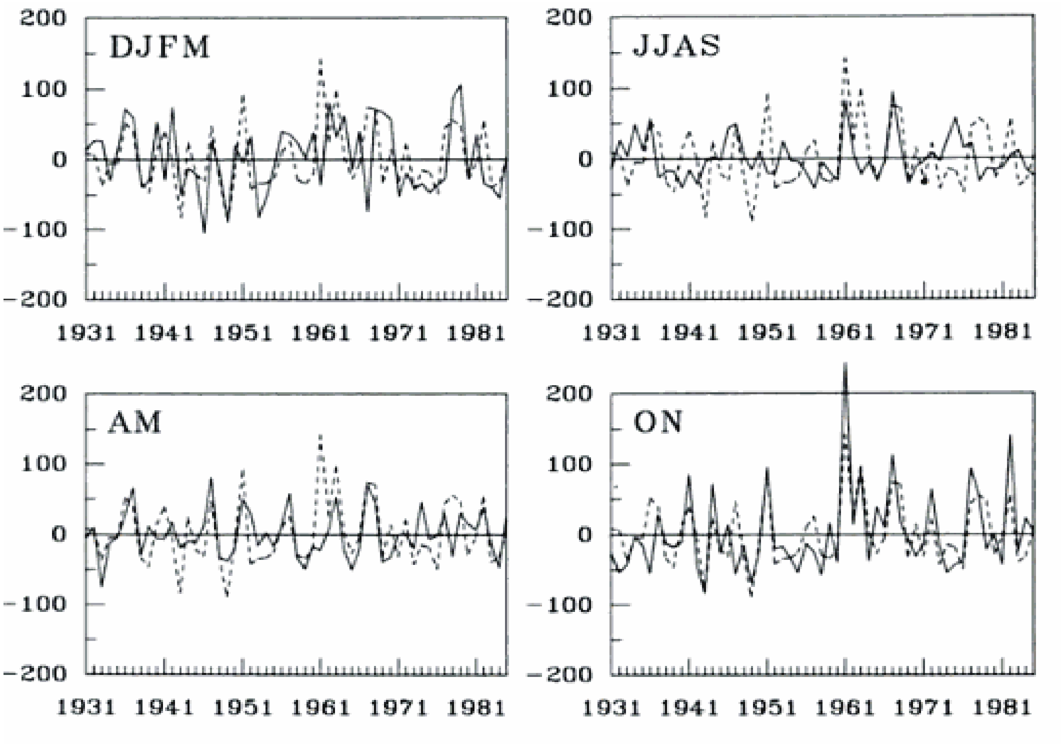
The 2000 and 2006 droughts were the worst in at least 60 years, and between these two extreme years, several other rainy seasons have failed. Climate change introduces an additional uncertainty into existing vulnerabilities in the ASALs (Osbahr and Viner 2006). At the same time, the number of flood events has increased in frequency and magnitude of people affected. Since 2002, there has been significant flood damage every year in the country. The most significant floods—in terms of number of people affected—occurred in 1997 and 2006. However, compared to droughts, floods continue to affect relatively few people in the country. The increased incidence of floods and droughts might well be a sign of climate change.

What are the economic impacts of floods and droughts? Mogaka et al. (2006) reported that the 1997/98 El Niño floods and the 1999/2000 La Nina drought cost, on average, at least 14% of Kenya's GDP each year of the events; and average annual, long-term costs of extreme events at 2.4% of GDP. Another World Bank estimate amounted to 11% of GDP for the 1997/98 flood losses and 16% of GDP losses attributable to the 1999/2000 drought (Hirji, no date).

Climate variability

As mentioned, large regional differences exist in rainfall variability. The long rains (March–May) are less variable, so interannual variability is related primarily to fluctuations in the short rains. These are also linked more closely to large-scale, as opposed to local, atmospheric and oceanic factors. Rainfall fluctuations show strong links to ENSO phenomenon, with rainfall tending to be above average during ENSO years (Nicholson 1996).

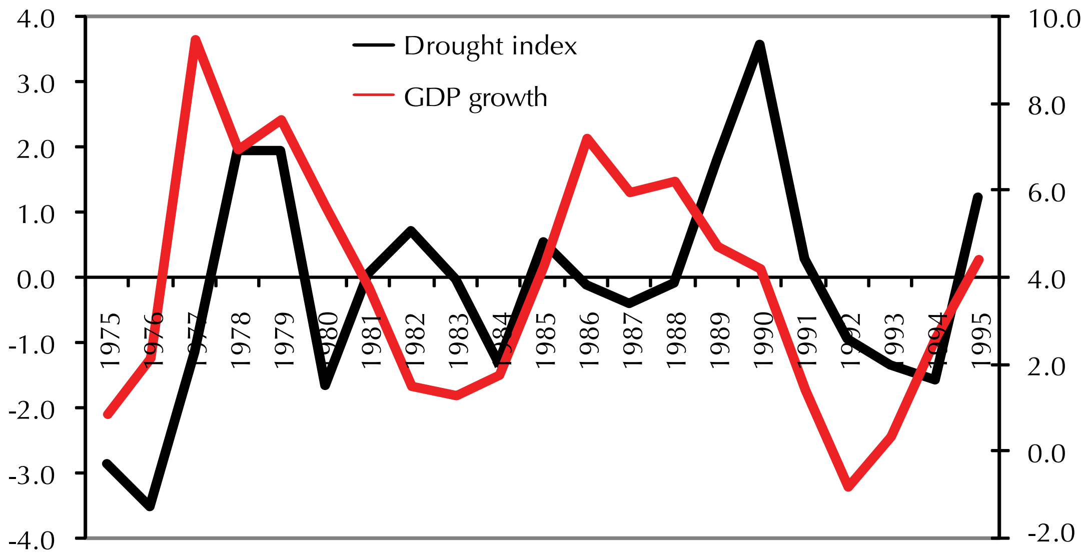
The importance of short rains for interannual variability is underscored in Figure 4, which compares annual time series of rainfall for the region as a whole with the corresponding time series for four seasons. A visual comparison shows that the similarity is strongest with October–November rainfall. This is confirmed by linear correlation coefficients: the correlation between October–November departures and annual departures is 0.71, compared to 0.53 between April–May and annual rainfall departures (Nicholson 1996).



DJFM = December, January, February and March; JJAS = June, July, August, and September; AM = April, May; ON = October, November.
Source: (Nicholson 1996).
Figure 4. *Time series of rainfall departures for individual seasons (solid lines) compared with the annual rainfall departure series.*

Data are representing eastern Africa as a whole, and are expressed as a percent standard departure.

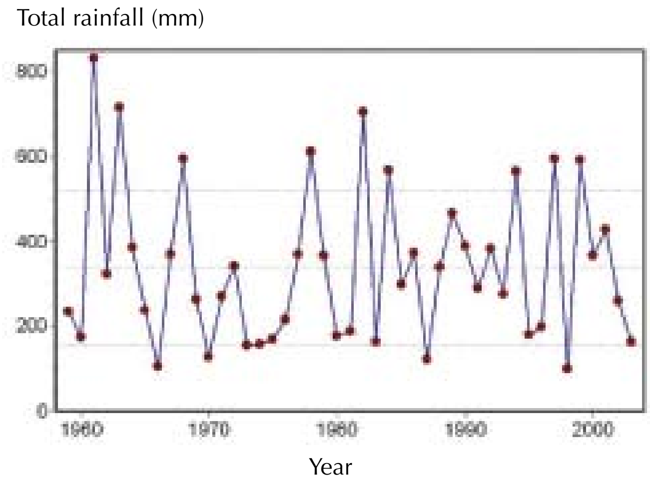
As Figure 5 shows, climate has been a robust determinant of agricultural sector, and thus general economic performance in Kenya (and elsewhere in rainfed SSA). With agriculture accounting for about 26% of the GDP and 75% of the jobs, the Kenyan economy is sensitive to variations in rainfall. Rainfed agriculture is and will remain the dominant source of staple food production and the livelihood foundation of the majority of the rural poor in Kenya. There is a need for the development of the scientific and economic capacity to better understand and cope with existing climate variability (Washington et al. 2006).



Source: IFPRI (2006).

Figure 5. *Linkage between the Palmer Drought Severity Index (PDSI) and GDP growth, Kenya, 1975–1995.*

Rainfall amounts and distribution are of paramount importance to rainfed agriculture in Kenya. Figure 6 illustrates season-to-season variability of rainfall totals, for the short rainy season at Makindu (van de Steeg et al. 2009). As expected, there is great variability in rainfall totals (<150 mm to >800 mm) with a mean of 370 and standard deviation of 180 mm (CV of 49%). Regression lines were fitted to check for evidence of trends in rainfall totals but no statistically significant trend was extractable from the rainfall data.



Note: Horizontal lines show the mean (370 mm) and ±1 standard deviation (180 mm) from the mean. Regression lines were fitted to check for evidence of trends in total rainfall. There were no trends that approached statistical significance. The proportion of variation explained by the line was less than 1%. The actual slope was –0.33 mm per year for the rainfall totals.

Figure 6. *Seasonal rainfall totals for the short rainy season (October, November, December) at Makindu, Kenya (1959–2004).*

Rainfall seasonality of this magnitude affects agricultural production and the livelihoods of people, especially in the arid and semi-arid regions, like Makindu (van de Steeg et al. 2009). Pastoralists have diverse strategies to maintain livestock production. There are several studies that compare how people perceive climate variability, climate change and drought frequency to actual measurements of rainfall variability (Meze-Hausken 2004; Cooper et al. 2008). In the Makindu example, the general public perception was that local climate had been changing during the last few decades. However, rainfall measurements do not show a downward trend in rainfall (Meze-Hausken 2004; Cooper et al. 2008). Reasons for the divergence between perceptions and rainfall measurements can be associated with changes in peoples' need for rainfall or be linked to various environmental changes which cause reduced water availability or simply a confusion of the drivers of change in agricultural production and access to resources (i.e. increases in population density might have reduced availability of water per family in the region).

There is a great variety of possible adaptive responses available to deal with climate variability. These include technological options (such as more drought-tolerant crops), behavioural responses (such as changes in dietary choice), managerial changes (such as different livestock feeding practices), and policy options (such as planning regulations and infrastructural development) (Thornton et al. 2009). For example, in the ASALs, livestock herders migrate with their animals in search of pasture and water, with the average distances trekked tripling in drought years. Herding communities typically reserve some pastures back at their homesteads for grazing by vulnerable animals left under the care of women during migration seasons. The herders also ensure that the composition, size and diversity of their animal herds (e.g. a mix of browsers and grazers) suit their variable feed resources and serve to protect them against droughts that could otherwise wipe out their animal stock.

3 Projected climate change

The climate model simulations under a range of possible emissions scenarios suggest that for Africa in all seasons, the median temperature increase lies between 3°C and 4°C, roughly 1.5 times the global mean response. Half of the models project warming within about 0.5°C of these median values (Christensen et al. 2007). The summary output of 21 Global Circulation Models (GCMs) used by IPCC in their latest report to predict the annual changes in temperature and rainfall that will occur by the end of the 21st century is presented in Table 3. Maximum and minimum predictions of change are given together with the 25, 50 and 75 quartile values from the 21 GCMs (Cooper et al. 2008). Whilst all models agree that it will become warmer, the degree of warming predicted is quite variable.

Table 3. *Regional predictions for climate change in Africa by the end of the 21st century*

Region	Season	Temperature response (°C)					Precipitation response (%)				
		Min	25	50	75	Max	Min	25	50	75	Max
West Africa	DJF	2.3	2.7	3.0	3.5	4.6	–16	–2	6	13	23
	MAM	1.7	2.8	3.5	3.6	4.8	–11	–7	–3	5	11
	JJA	1.5	2.7	3.3	3.7	4.7	–18	–2	2	7	16
	SON	1.9	2.5	3.3	3.7	4.7	–12	0	1	10	15
	Annual	1.8	2.7	3.3	3.6	4.7	–9	–2	2	7	13
East Africa	DJF	2.0	2.6	3.1	3.4	4.2	–3	6	13	16	33
	MAM	1.7	2.7	3.2	3.5	4.5	–9	2	6	9	20
	JJA	1.6	2.7	3.4	3.6	4.7	–18	–2	4	7	16
	SON	1.9	2.6	3.1	3.6	4.3	–10	3	7	13	38
	Annual	1.8	2.5	3.2	3.4	4.3	–3	2	7	11	25
Southern Africa	DJF	1.8	2.7	3.1	3.4	4.7	–6	–3	0	5	10
	MAM	1.7	2.9	3.1	3.8	4.7	–25	–8	0	4	12
	JJA	1.9	3.0	3.4	3.6	4.8	–43	–27	–23	–7	–3
	SON	2.1	3.0	3.7	4.0	5.0	–43	–20	–13	–8	3
	Annual	1.9	2.9	3.4	3.7	4.8	–12	–9	–4	2	6

DJF = December, January and February; MAM = March, April, May; JJA = June, July and August; SON = September, October and November.
Note: Temperature response indicates the projected increase in temperature over current values.
Source: (IPCC 2007).

For precipitation, the situation is more complicated. Precipitation is highly variable spatially and temporally, and data are limited in some regions (IPCC 2007). As indicated by Sivakumar et al. (2005) changes in total volume of rainfall in Africa projected by most GCMs are relatively modest, at least in relation to current rainfall variability. Seasonal changes in rainfall are not expected to be large. Great uncertainty exists, however, in relation to regional-scale rainfall changes simulated by GCMs. The problem involves determining the character of the climate change signal on African rainfall against a background of large natural variability compounded by the use of imperfect climate models (Sivakumar et al. 2005). In East Africa, there are very few places where rainfall means are likely to decrease (Thornton et al. 2006). The increase in rainfall in East Africa, extending into the Horn of Africa, is robust across the ensemble of GCMs, with 18 of 21 models projecting an increase in the core of this region, east of the Great Lakes (Christensen et al. 2007; Doherty et al. 2009). There is still some uncertainty about this trend, however, as other work suggests that climate models to date have probably underestimated warming impacts of the Indian Ocean and thus may well be overestimating rainfall in East Africa during the present century (Funk et al. 2008). If this is correct, then the idea that East Africa will become wetter in the coming decades may be erroneous.

Hulme et al. (2001) discussed two fundamental reasons why there is much less confidence about the magnitude, and even direction, of regional rainfall changes in Africa. Two of these reasons relate to the rather ambiguous representation of climate variability in the tropics in most GCMs via mechanisms such as ENSO, for example, which is a key determinant of African rainfall variability. Another reason is the omission in all current global climate models of any representation of dynamic land cover–atmosphere interactions. Such interactions have been suggested to be important in determining African climate variability during the Holocene and may well have contributed to the more recently observed desiccation of the Sahel (Hulme et al. 2001). Work is now underway, however, to incorporate such links in regional climate models (see, for example, Moore et al. 2009).

Limited information on climate change is available for East Africa at country level or local scale. Rainfall projections in Kenya are inconsistent; a range of models and scenarios suggest both increases and decreases in total precipitation (Osbahr and Viner 2006). Thornton et al. (2006) used changes in aggregate monthly values for temperature and precipitation. For this study possible future long-term monthly climate normals (rainfall, daily temperature and daily temperature diurnal range) were derived by downscaling GCM output to WorldClim v1.3 climate grids at 18 km^2 resolution (Hijmans et al. 2005). The outputs from several GCMs and SRES scenarios (Special Report on Emissions Scenarios; IPCC 2000) were used to derive climate normals for 2000, 2005, 2010, 2015, 2020, 2025 and 2030, using the downscaling methodology described in Jones and Thornton (2003). These normals were then used with the weather generator MarkSim (Jones and Thornton 2000) to generate daily weather data characteristic of the appropriate climate normals.

We used the above mentioned climate grid data (Thornton et al. 2006) to examine the projected changes in temperature and precipitation for Kenya. While looking at the total annual precipitation projections for Kenya increases in total rainfall in the order of 0.2–0.4% per year were found. These figures for Kenya correspond with findings of long-term wetting by Christensen et al. (2007) and Hulme et al. (2001). However, the regional variations in precipitation are large; the coastal region is likely to become drier, while the Kenyan highlands and Northern Kenya are likely to become wetter.

According the UNDP Climate Change Country Profile for Kenya (McSweeney et al. in press), the projections of mean rainfall are consistent in indicating increases in annual rainfall in Kenya. Area average time series show observed climate combined with an ensemble of 15 model simulated recent and future climate under three SRES emissions scenarios (A2, A1B, and B1). The ensemble range spans changes of –1 to +48% by the 2090s. An example of the output is given in Appendix A for the A2 scenario. The projected increases in total rainfall are largest in October–December, but annually these increases are in the order of 20–40 mm per year to 2090 for the arid districts of Kenya. These small increases may be overshadowed if rainfall variability and the frequency of rainfall extreme events increases in the future.

Projected changes in extreme events

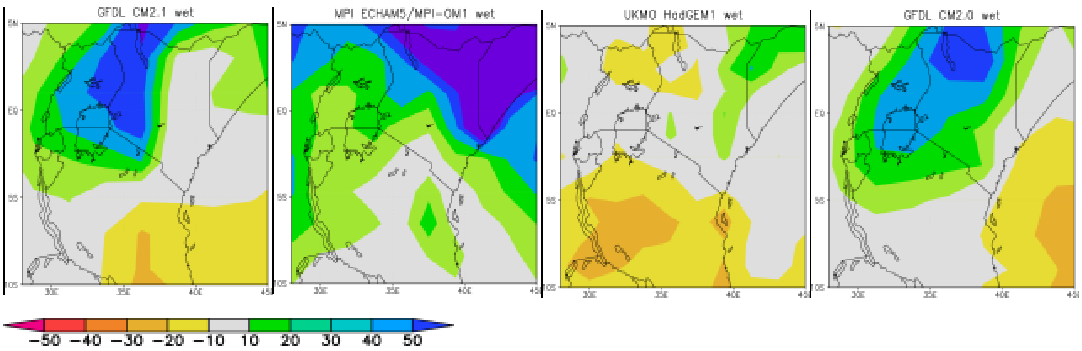
As stated in the Millennium Ecosystem Assessment (2005), natural hazards and disasters are products of both natural variability and human–environment interactions. The extremes of the variability are defined as hazards when they represent threats to people and what they value and defined as disasters when an event overwhelms local capacity to cope. Research on changes in extremes specific to Africa, in either models or observations, is limited. Little can be said yet about changes in climate variability or extreme events in Africa (Sivakumar et al. 2005; Christensen et al. 2007). A general increase in the intensity of high rainfall events, associated in part with the increase in atmospheric water vapour, is expected in Africa, as it is in other regions (Christensen et al. 2007). The increase in the number of extremely wet seasons is increasing to roughly 20% (i.e. 1 in 5 of the seasons are extremely wet, as compared to 1 in

20 in the control period in the late 20th century) (Christensen et al. 2007). Dry extremes are projected to be less severe than they have been during September to December but the GCMs do not show a good agreement in the projected changes of dry extremes during March to May (KNMI 2006; Thornton et al. 2006). Most climate models simulate drier conditions during the 21st century in eastern Sudan and in Ethiopia. This drying was prevalent during the last decades of the 20th century in these regions. There is little consensus among the models with respect to their simulated changes in extreme rainfall events. A spatially coherent pattern is the increase in 10-year highest rainfall events over northern Somali and the Horn of Africa, and more severe dry events over the same areas. Thus extreme events are likely to become more intense over much of northeastern East Africa (KNMI 2006).

As noted above, for Kenya there are indications of an upward trend in rainfall under global warming. Wet extremes (defined as high rainfall events occurring once every 10 years) are projected to increase during both the September to December rainy season and the March to May rainy season, locally referred to as the short and long rains respectively. Dry extremes are projected to be less severe in the northern parts of the region during September to December, but the models do not show a good agreement in their projected changes of dry extremes during March to May (Thornton et al. 2006). KNMI (2006) showed the projected variations in wettest events that occur once every 10 years on average. It should be kept in mind that climate models all underestimate the strength of the long rains in the current climate, limiting the confidence of these projections (KNMI 2006; Thornton et al. 2006). KNMI (2006) used 12 models, on the basis of the realism with which they represent the observed 20th century pattern of African precipitation variation (interannual variability and its amplitude). For those models, KNMI investigated the likely changes in precipitation (mean and extremes) using the runs forced with the Special Report Emission Scenario (SRES) A1B scenario.

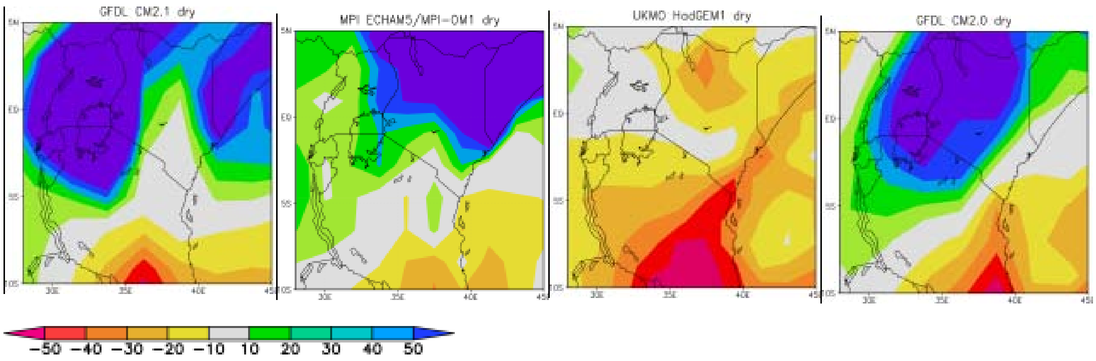
Short rains (September–December)

In the warmer climate around 2100, the GCMs show evidence of an increase in the intensity of extreme rainfall events in much of East Africa, notably in Burundi, Kenya, Rwanda, southern Somali and Uganda. During the short rains, there are indications of the possibility of increases in excess of 50% in 10 year high rainfall events over the north of East Africa. In southern Tanzania the wettest rainfall events are projected to decrease by 0 to 20% (Figure 7) (KNMI 2006).



From left to right, GCM: GFDL CM2.1, MPI ECHAM5, UKMO HadGEM1, and GFDL CM2.0 (KNMI 2006).
Figure 7. *Percentage changes in the amount of rainfall around 2100 in short rains high rainfall events that occur once every 10 years.*

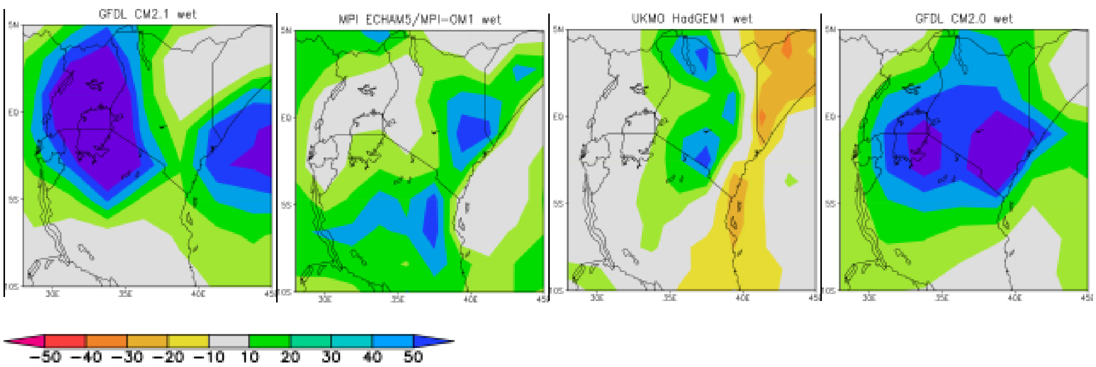
Simulated changes in low rainfall extremes (Figure 8) show that these events are becoming less severe in Burundi, Rwanda, Uganda, northern Kenya and southern Somali during the September to December season in the most realistic models (with the exception of the Rift Valley in HadGEM1). The simulated increase is far more than 50% in certain parts of the region. Noting that increases in both the wettest and the driest rainfall events have been found over the same areas, this shows an overall shift in the rainfall distribution, with floods becoming more likely than the opposite extreme (KNMI 2006).



From left to right, GCM: GFDL CM2.1, MPI ECHAM5, UKMO HadGEM1, and GFDL CM2.0 (KNMI 2006).
Figure 8. *Percentage changes in the amount of rainfall around 2100 in short rains lowest rainfall events that occur once every 10 years.*

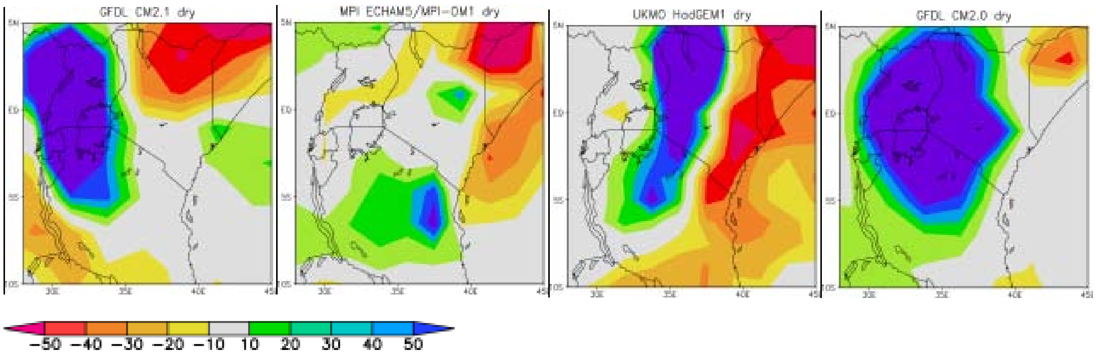
Long rains (March–May)

Even during the long rains, the GCMs continue to simulate an increase in the 10 year highest rainfall events in large parts of East Africa (Figure 9). Over northeastern Kenya and southern Somali during this season only HadGEM1 does not simulate large increases in the amount of rain in extremely wet seasons. Over southern Tanzania, most models give an indication of an increase in high rainfall events. So while some models show an increase in the severity of extremely low rainfall events in northern Kenya, others simulate a decrease over the same areas. However, these climate models all severely underestimate the strength of the long rains in the current climate, limiting reliability of these projections (KNMI 2006).



From left to right, GCM: GFDL CM2.1, MPI ECHAM5, UKMO HadGEM1, and GFDL CM2.0 (KNMI 2006).
Figure 9. *Changes in the amount of rainfall around 2100 in long rains high rainfall events that occur once every 10 years.*

However, there is no consensus between the GCMs on the likely changes in the severity of dry events (Figure 10). While some models show an increase in the severity of extremely low rainfall events in northern Kenya, others simulate a decrease over the same areas. Since the model simulations of the 20th century climatology during this season are inaccurate, model projections of future climate during this season are currently unreliable (KNMI 2006).



From left to right, GCM: GFDL CM2.1, MPI ECHAM5, UKMO HadGEM1, and GFDL CM2.0 (KNMI 2006).
Figure 10. *Changes in the amount of rainfall around 2100 in long rains lowest rainfall events that occur once every 10 years.*

Osbahr and Viner (2006) specified that increases in temperatures would have a significant impact on water availability, and are thus expected to exacerbate the drought conditions already regularly experienced and predicted to continue. The unpredictability of Kenya's rainfall and the tendency for it to fall heavily during short periods are also likely to cause problems by increasing the occurrences of heavy rainfall periods and flooding.

Beside the effects of climate change itself, the coastal areas of Kenya should anticipate changes in sea level due to global warming. The projection that sea level rise could increase flooding, particularly on the coasts of eastern Africa, will probably increase the high socio-economic and physical vulnerability of coastal areas. A rise in sea level in Kenya will have a damaging impact to the production of tree crops situated along the coast (mangoes, cashew nuts and coconuts) and other agriculture based enterprises. A rise in sea level will also affect ecosystems of coastal Kenya, e.g. mangroves and coral reefs with additional consequences for fisheries and tourism (Boko et al. 2007).

4 Impacts of changes on agricultural production

This chapter examines the impacts of climate change on agricultural production in Kenya. The chapter is divided into three subsections. It first analyses the importance of different crop and livestock products for the Kenyan economy and discusses the evolution of production trends over time. Secondly, it uses GIS tools to examine the spatial distribution of crops and livestock in different agro-ecological zones of Kenya, while the third subsection assesses the impacts of potential climate change under a range of scenarios on key Kenyan commodities using the DSSAT crop models (Jones et al. 2001). These data are used as input into the IMPACT model (Rosegrant et al. 2007) for examining the effects of climate change impacts on agricultural production changes and on the wider economy (trade and commodity prices) and human well-being outcomes (malnutrition, kilo-calorie availability).

Importance of agricultural commodities for Kenya

A wide range of commodities are produced in Kenya, the relative importance of these different agricultural commodities varies both spatially and temporally. To assess the relative importance of agricultural commodities, the value of agricultural production was determined (van de Steeg et al. 2009). A better understanding of the sensitivity of the agricultural sector can be assessed by calculating the value of production (and therefore importance) of different agricultural commodities. This could help target investments and adaptation options for the different commodities and regions (Freeman et al. 2008).

The value of production (VOP) was calculated using the formula:

$$\text{VOP } i = \sum(\text{Prod } i * \text{Price } i)$$

where: VOP i = Value of production for commodity i (USD)

PROD i = Production of commodity i (t)

PRICE i = Price of commodity i (USD/t).

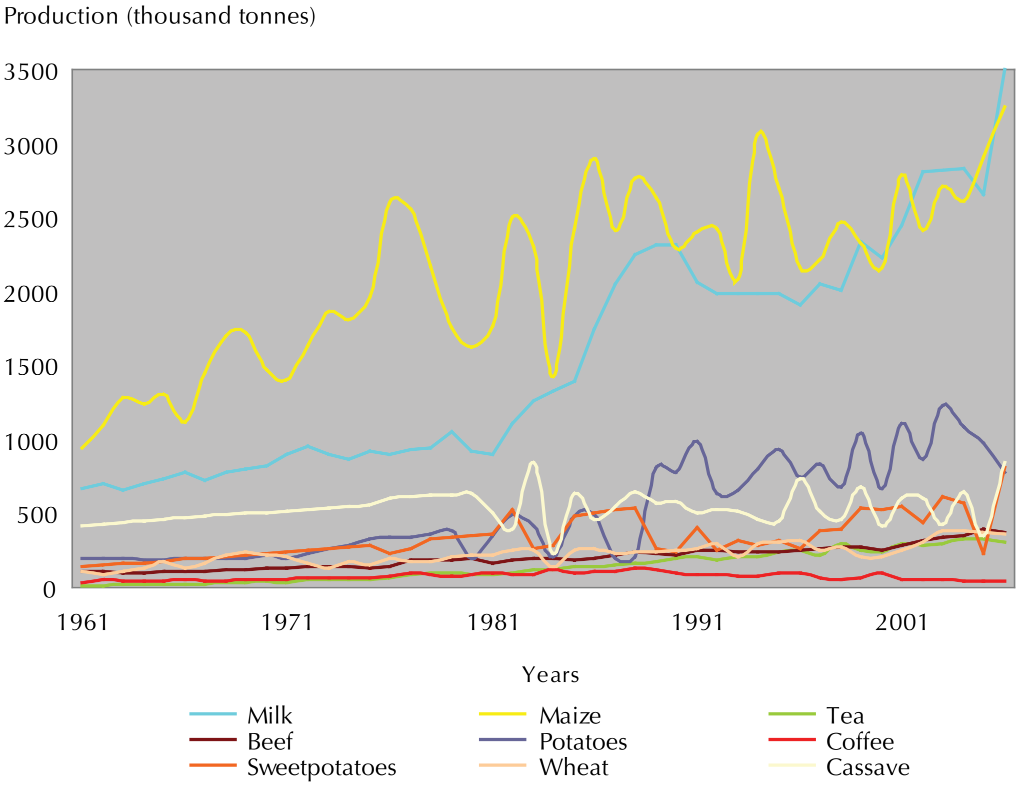
The production data and prices were derived from the FAO statistical database (FAOSTAT) for 2004 to 2006. An average value for these years was used to reduce outliers and large annual fluctuations.

Table 4 shows the total production, average price and value of production for main agricultural commodities in Kenya (van de Steeg et al. 2009). Maize and tea are the most important crops in terms of VOP, contributing up to 17% and 15%, respectively. Both milk and meat from cattle contribute to 28.3% to the agricultural VOP. The meat comes mostly from extensive cattle production in pastoral systems and most of the sold milk from semi-intensive mixed systems. Milk is also an essential source of nutrition in the more subsistence-based pastoral systems where it is mostly consumed by the family directly. Other important crops are potatoes, sugarcane and coffee.

Table 4. *Kenya—The total production, average price and value of production for main agricultural commodities, average values for years 2004 to 2006*

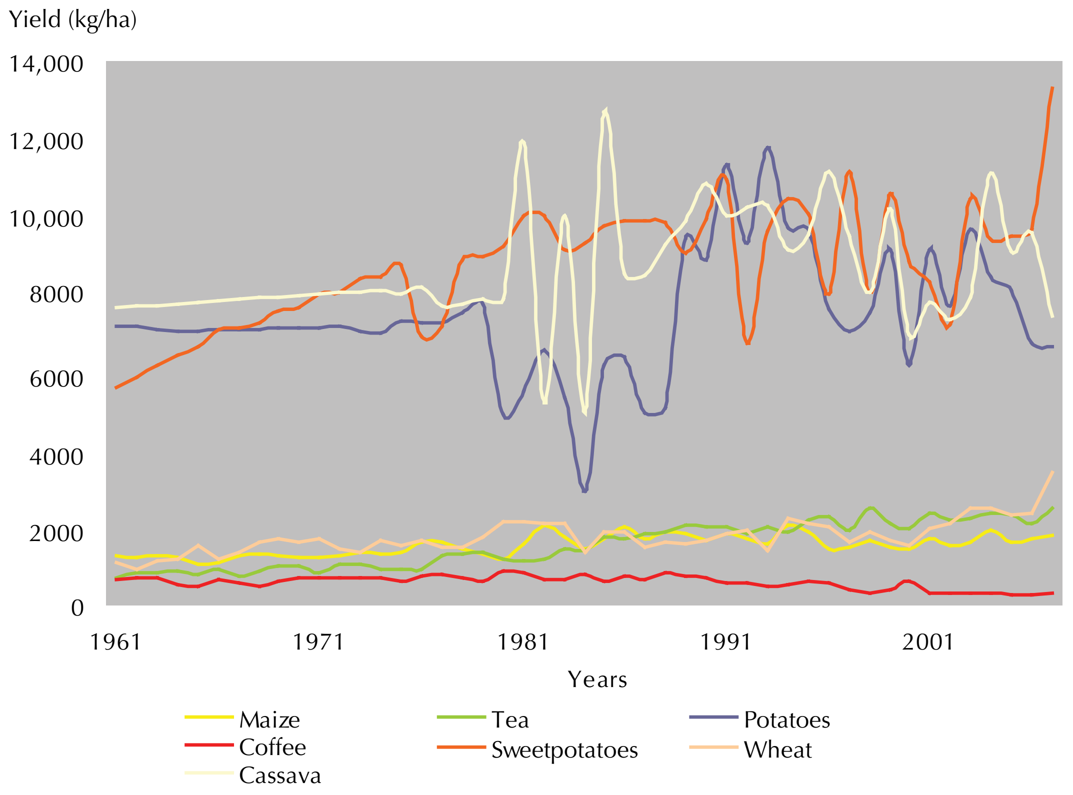
	Commodity	Production (t)	Price (USD/t)	VOP (USD)	Contribution (%)
1	Milk	2,993,300	221	662,237,692	18.4
2	Maize	2,919,966	203	592,373,502	16.5
3	Tea	321,227	1729	555,412,685	15.4
4	Beef	374,217	948	354,845,973	9.9
5	Potatoes	949,453	369	350,613,881	9.8
6	Sugarcane	4,798,218	25	121,810,761	3.4
7	Coffee	47,310	2365	111,908,336	3.1

Figure 11 shows the evolution of production of the main agricultural commodities over the last four decades. The figure shows that maize and milk have dominated the increases in production over time. This has happened as a result of intensifying practices in dairy systems and a conducive policy environment for the production of milk, mostly in highland regions (Staal et al. 2003). Coffee areas have not increased due to market and price instability for this crop. Maize production has increased mostly as a result of area expansion and increased adoption of this crop in both mixed and pastoral areas (Herrero et al. 2010a). Figure 12 shows that overall, technological change and yield increases for the main commodities produced in Kenya has been slow. As with maize, in most areas, agricultural expansion has been the main means to increase production. This is a reflection of the lack of support for agricultural production in the last decades and the lack of inputs, services and market environment to support the intensification of crop production systems.



Source: FAOSTAT (2009).

Figure 11. *The production of main agricultural commodities in Kenya over time.*



Source: FAOSTAT (2009).

Figure 12. *The yield of main agricultural commodities in Kenya over time.*

Agro-ecological zones of Kenya

The potential for agricultural production is determined by physical factors, primarily by soil and climatic conditions, and a complex interaction of socioeconomic, cultural and technological factors, such as farm sizes, level of farming and livestock inputs, management practices including soil conservation and enhancement, veterinary services, economic factors like market prices and access, credit availability, education and extension services (FAO 1978–81).

The climatic resource inventory of Kenya records both temperature and soil moisture conditions. This inventory was carried out as part of the Exploratory Soil Map of Kenya (KSS 1982), at a scale of 1:1 million. Quantification of moisture conditions was achieved through the concept of reference length of growing period (LGP). The moisture availability zones is divided into seven classes (Table 5). The quantification of temperature attributes was achieved by defining reference temperature zones. To cater for differences in temperature adaptability of crops, pasture and fuelwood species, nine thermal zones were distinguished (Table 5).

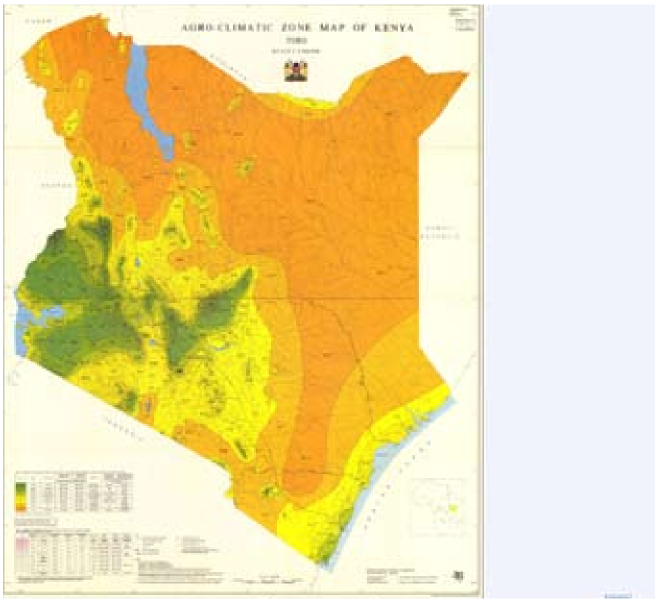
The agro-climate zone map resulted into a map with more than 300 mapping units and 40 different combinations of moisture availability and thermal zones classes (Figure 13).

Table 5. *Descriptions of different moisture availability and temperate zones, used for the agro-climate zone map of Kenya*

zone	r/Eo (%)	classification	r average annual rainfall (mm)	Eo average annual potential evaporation (mm)	vegetation	potential for plant growth	risk of failure of an adapted maize crop
			excluding areas above 10,000 ft altitude			assuming that soil conditions are not limiting	
I	> 80	humid	1100 - 2700	1200 - 2000	moist forest	very high	extremely low (0 - 1%)
II	65 - 80	sub-humid	1000 - 1600	1300 - 2100	moist and dry forest	high	very low (1 - 5%)
III	50 - 65	semi-humid	800 - 1400	1450 - 2200	dry forest and moist woodland	high to medium	fairly low (5 - 10%)
IV	40 - 50	semi-humid to semi-arid	600 - 1100	1550 - 2200	dry woodland and bushland	medium	low (10 - 25%)
V	25 - 40	semi-arid	450 - 900	1650 - 2300	bushland	medium to low	high (25 - 75%)
VI	15 - 25	arid	300 - 550	1900 - 2400	bushland and scrubland	low	very high (75 - 95%)
VII	< 15	very arid	150 - 350	2100 - 2500	desert scrub	very low	extremely high (95 - 100%)

zone	mean annual temperature (°C)	classification	mean maximum temperature (°C)	mean minimum temperature (°C)	absolute minimum temperature (°C)	night frost	altitude (feet)	altitude (meters)	general description
9	less than 10	cold to very cold	less than 16	less than 4	less than –4	very common	more than 10,000	more than 3050	Afro-Alpine Highlands
8	10 - 12	very cool	16 - 18	4 - 6	– 4 to – 2	common	9000 - 10,000	2750 - 3050	Upper Highlands
7	12 - 14	cool	18 - 20	6 - 8	– 2 to 0	occasional	8000 - 9000	2450 - 2750	
6	14 - 16	fairly cool	20 - 22	8 - 10	0 - 2	rare	7000 - 8000	2150 - 2450	Lower Highlands
5	16 - 18	cool temperate	22 - 24	10 - 12	2 - 4	very rare	6000 - 7000	1850 - 2150	
4	18 - 20	warm temperate	24 - 26	12 - 14	4 - 6	none	5000 - 6000	1500 - 1850	Midlands
3	20 - 22 *	fairly warm	26 - 28	14 - 16	6 - 8	none	4000 - 5000	1200 - 1500	
2	22 - 24 *	warm	28 - 30	16 - 18	8 - 10	none	3000 - 4000	900 - 1200	
1	24 - 30 *	fairly hot to very hot	30 - 36 **	18 - 24 **	10 - 16	none	0 - 3000	0 - 900	Lowlands

Source: KSS (1982).



Source: KSS (1982).

Figure 13. *The agro-climate zone map of Kenya.*

The Food and Agriculture Organization of the United Nations (FAO), with the collaboration of the International Institute for Applied Systems Analysis (IIASA), developed a land resources database and a methodological framework to assess food production and population supporting potentials in developing countries, FAO (1971–81, 1976, 1978–80). In the 1990s, FAO undertook an AEZ case study of Kenya, with the concurrence of the Kenyan Government and IIASA's participation (FAO/IIASA 1994). The AEZ within this methodology are mainly based on the length of growing period (LGP).

Based on a similar approach, but with more recent data, ILRI derived an LGP map for Kenya (Thornton et al. 2002) that resembled the main agro-ecological zones of Kenya. This map is used in subsequent analyses for determining the magnitude of the expected climate change impacts on agricultural production. The LGP was divided into four classes to resemble the key agro-ecological zones (Figure 14):

LGP <90 days: Arid zone

$90 \geq LGP \leq 180$ days: Semi-arid zone:

$180 \geq LGP \leq 210$ days: Subhumid zone

LGP > 210 days: Humid zone

Note that especially the subhumid and humid zones encompass a mixture of highland and lowland areas.

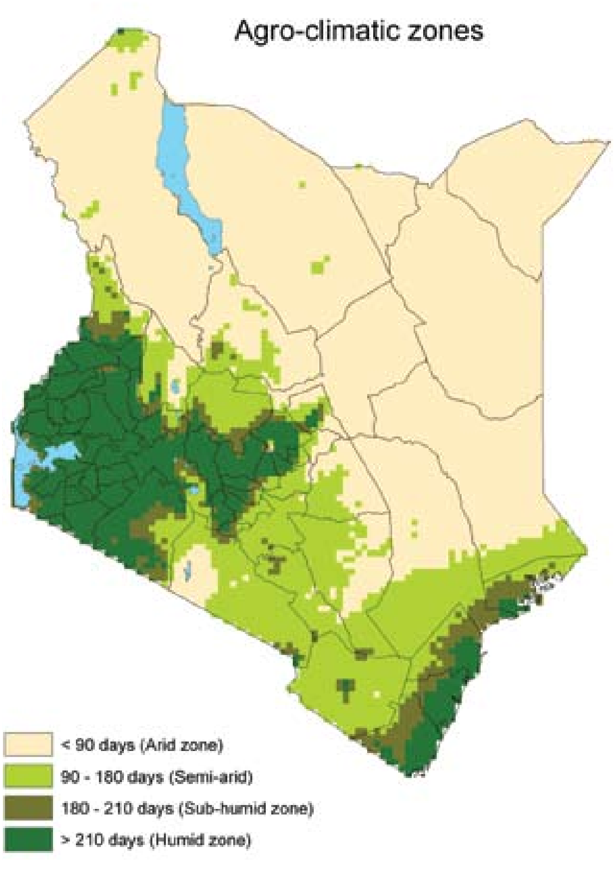


Figure 14. *The agro-climate zone map of Kenya, based on LGP classes.*

Most people in Kenya live in the humid and subhumid areas (central highlands, humid lowlands around lake Victoria, coastal zones) (Table 6) which have a higher potential agricultural productivity, are closer to larger cities and their services, markets and other infrastructure (health centres, schools etc). These are the areas where most crop production occurs in Kenya (Table 7). While the area under this agro-ecological zone is small relative to the drylands (arid and semi-arid areas), they have large concentrations of cattle, mostly in mixed systems with some degree of dairying and a significant number of free-ranging sheep and goats. In the past decades, significant human migrations to humid and subhumid areas has created a significant pressure on natural resources, notably land and soils. For example, farm sizes in places have reduced to the point where farming is no longer viable as a sole activity to support families (Waithaka et al. 2006). In these areas soil fertility problems and land degradation have also been notorious to the point where crops no longer respond to fertilizer applications due to lack of organic matter in some cases (Tittonell et al. 2009).

Table 6. *Human population and livestock numbers in different agro-ecological zones of Kenya*

Agro-climatic zone	Human population	Cattle	Goat	Sheep	Area (km^2)
Arid (LGP <90 days)	2,516,000	2,665,750	4,005,340	2,882,090	351,347
Semi-arid (LGP 90–120 days)	4,377,000	2,751,580	2,500,690	1,969,670	123,436
Subhumid (LGP 180–210 days)	2,808,000	1,129,430	722,522	772,678	32,203
Humid (LGP > 210 days)	20,373,000	7,210,830	2,263,680	2,803,410	83,490

Table 7. *Production of key agricultural commodities by agro-ecological zone*

Agro-ecological zone	Production in tonnes ('000s), 2000								
	Cassava	Coffee	Maize	Potatoes	Sugarcane	Sweetpotatoes	Wheat	Sorghum	Millet
Arid (LGP <90 days)	20	11	171	95	1,441	16	3	29	8
Semi-arid (LGP 90–120 days)	111	45	703	222	1,096	69	4	35	15
Subhumid (LGP 180–210 days)	83	13	292	74	424	29	5	17	4
Humid (LGP > 210 days)	267	25	1,036	223	1,299	421	165	43	21
Total	480	95	2,203	614	4,260	536	177	126	47

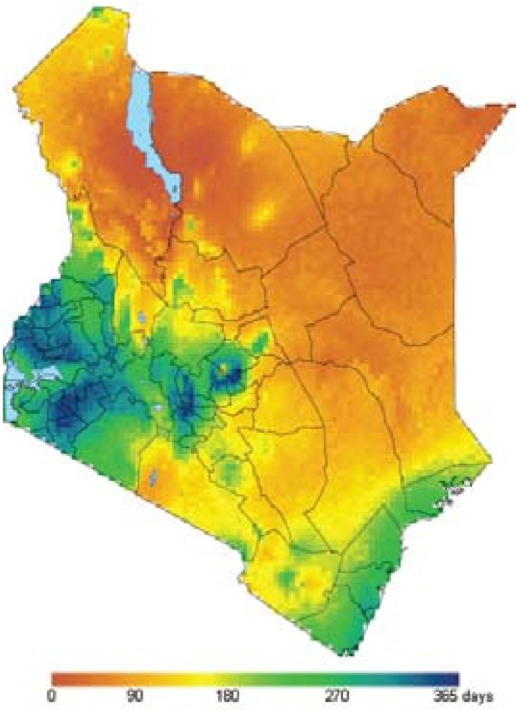
In contrast, the vast arid and semi-arid districts are home to about 15% of the population, 40% of the cattle and 60% of the small ruminants of the country (Table 6). These areas produce most of the dryland crops (sorghum and millet) of the country (Table 7). These largely neglected areas are characterized by a high degree of poverty and food insecurity, increased conflicts, high rainfall variability and significant production risk, all of which have led to significant human migrations to cities in higher potential areas (Nairobi, Nakuru, Kisumu etc.) in search of employment. Interestingly, the semi-arid areas present the highest yield gaps for crops, which suggests that with adequate programs to support agriculture, investment in infrastructure and market development, and adoption of risk management practices, these areas could significantly increase crop and livestock production (Herrero et al. 2010).

Maps of the spatial distribution of human population, crop production and livestock densities by agro-ecological zone of Kenya can be found in Appendix A.

Understanding climate change impacts on crop and livestock production—The length of growing period

Like Fischer et al. (2002) and Jones and Thornton (2003), we assessed the impact of climate change on agro-ecological characteristics by looking at changes in length of growing period (LGP), as an initial proxy for agricultural impacts. Changes in rainfall patterns, in addition to shifts in thermal regimes, influence local seasonal and annual water balances and in turn affect the distribution of periods during which temperature and moisture conditions permit agricultural crop production. Such characteristics are well reflected by the LGP since Kenya mostly relies on rainfed agriculture (Fischer et al. 2002; Comprehensive Assessment 2007). The use of this indicator supplemented with crop modelling work provides a framework for studying the impacts of climate change on crop yields and production.

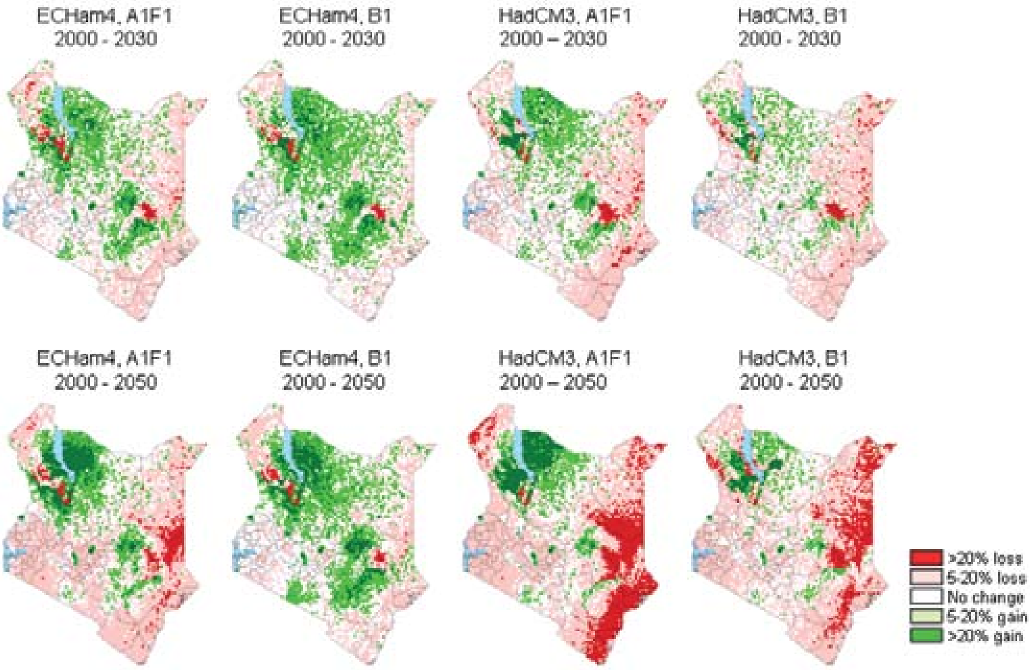
LGP was calculated as described by Thornton et al. (2006). In this study, for each 10 minute pixel in Kenya climate normal data, monthly values for average daily temperature (°C), average daily diurnal temperature variation (°C), and average monthly rainfall (mm), were read from the appropriate gridded file and interpolated to daily data using the method of Jones (1987). LGP is actually the total number of days in a year when there is enough water to support crop growth. It does not deal well with bimodal rainfall regimes when the two seasons are actually interspersed with a dry period. However, bimodal rainfall patters are less pronounced in Kenya than in the past (Thornton et al. 2006). Figure 15 shows the LGP for 2000.



Source: Thornton et al. (2006).

Figure 15. *The length of growing period (in days) for 2000.*

Thornton et al. (2006) presented LGP changes for the whole of Africa to 2050 under various model projections, showing few differences in projections under two SRES scenarios (A1F1 and B1). The 'A' scenarios place more emphasis on economic growth, the 'B' scenarios on environmental protection. The '1' scenarios assume more globalization. For this part of the report revised spatial data layers are utilized (Thornton and Jones 2008). LGP changes to 2030 and 2050 are projected for Africa using downscaled outputs of coarse-gridded GCM, using methods outlined in Jones and Thornton (2003), using the datasets of WorldCLIM (Hijmans et al. 2005), TYN SC 2.0 dataset (Mitchell et al. 2004), and the outputs from the Hadley Centre Coupled Model version 3 (HadCM3) (Mitchell et al. 1998) and ECHam4 (Roeckner et al. 1996), associated with A1FI and B1 (IPCC 2001). Figure 16 shows maps of projected changes in LGP from 2000 to 2030 and 2050, from downscaled outputs of the ECHam4 and the HadCM3 GCM for scenarios A1F1 and B1. Following IPCC (2001) map legends, these changes were classified into five: losses in LGP of >20% ('large' losses); of 5–20% ('moderate' losses); no change (± 5% change); gains of 5–20% ('moderate' gains); and gains of >20% ('large' gains).



Source: Thornton et al. (2006).

Figure 16. *The percentage change in length in growing period to 2030 and 2050 in Kenya.*

As discussed by Thornton et al. (2006), various points can be made about these maps. First, it should be noted that some of the large losses and large gains are located in areas with LGP less than 60 days (arid agro-ecozone), i.e. in highly marginal areas for cropping but important for pastoralists. This implies that pastoralism will continue to be a significant livelihood option in these regions *vis-à-vis* crop expansion in marginal lands under current circumstances but that there is a need to support them with mechanisms to deal with potentially greater variability (risk reduction, insurance based schemes, development of safety nets etc.). Second, there is considerable variability in results arising from the different scenarios, and there is also variability in results arising from the different GCMs used. Third, if anything could be generalized about these different maps, it is that under the range of these SRES scenarios and the GCMs used, many parts of Kenya are likely to experience a decrease in LGP, and in some areas, the decreases may be severe. In other words, projected increases in temperature and projected changes in rainfall patterns and amount (increases in rainfall amounts are projected in many areas) combine to suggest that growing periods will decrease in many places. There are also a few areas, especially in the highlands (humid and subhumid zones) where the combination of increased temperatures and rainfall changes may lead to an extension of the growing season.

Differences in projected changes (Figure 16) make it quite challenging to come to a general consensus over climate change trends for Kenya, or certain areas within Kenya. Although the projected increases in rainfall might appear to be good news for arid and semi-arid districts, the increasing temperatures cause a substantial increase in evaporation rates, which are likely to balance and exceed any benefit from the increase in precipitation (Osbahr and Viner 2006). This means that the increases in LGP might only translate into very modest, if at all, increases in rangeland or crop productivity in these areas. To elicit the responses of different crops to these changes, the next sections delve further by using crop simulation models to determine plausible impacts of climate change on agricultural production.

Impacts of climate change on crop production

The impacts of climate change on crop production for Kenya were studied using the methods described by Rosegrant et al. (2009). In summary, statistically downscaled climate data was obtained from the NCAR (NCAR-CCSM3) and CSIRO models under the A2 scenario from the IPCC 4th Assessment report; and also from United Kingdom Meteorological Office Hadley Centre's Coupled Model, version 3 (HadCM3), using the A2a scenario from IPCC's Third Assessment Report. Data were used to run the DSSAT suite of crop models for four key staple crops (maize, wheat, groundnuts [as a proxy for beans], and irrigated rice) to 2050. A single crop variety was chosen for each crop, but management practices were distinguished on the basis of regionally differentiated agricultural practices and fertilizer inputs. The crop area extent for each crop was determined using the crop layers of You and Wood (2004). Results were summarized for each agro-ecozone and displayed in maps accordingly. Since the differences observed in model X scenario combinations is important, we present individual maps for the different combinations in Figure 17 to aid the interpretation of the responses.

All SRES scenarios have higher temperatures in 2050 resulting in higher evaporation of water. When this water vapour eventually returns to the earth as precipitation, it can fall either on land or the oceans. The NCAR model is 'wet' in the sense that average precipitation on land increases by about 7%. For Kenya, the NCAR scenario predicts a 45% increase in annual rainfall from 2000 to 2050. The CSIRO model (like the Hadley model) envisages a much drier future climate. Globally, rainfall is projected to increase by about 1% under the CSIRO scenario from 2000 to 2050 and to decline by 0.4% for the HadCM3 scenario. For Kenya, the CSIRO annual rainfall change is an increase by 5% and for the HadCM3 scenario an increase of 0.2%.

Projected impacts to 2050 result in lower rainfed maize yield for Kenya in 4 out of 6 scenarios. Maize yields are likely to vary modestly according to the CSIRO and NCAR models (± 5 to 20%). In general terms, most modest changes are observed in the humid and subhumid areas and small gains can be observed in certain highland areas in the humid and subhumid zones. These results seem to be in line with the data of Thornton et al. (2009). The arid and semi-arid regions show in most cases variable reductions in yields, with the Hadley model estimating the largest decreases (up to 50% in some parts).

In four out of six scenarios (NCAR and CSIRO models), large decreases in yields (between 20–50%) are observed for groundnuts and wheat irrespective of agro-ecozones. The DSSAT runs with the HadCM3 downscaled climate data show different effects by agro-ecozone: potential gains in yields for groundnuts of 5–20% in the humid and subhumid areas but potential reductions of 20–50% in the arid and semi-arid areas. With the current varieties, these levels of reduction may force farmers to rethink the feasibility of planting this crop in these areas. A similar but reverse story is observers for wheat: modest gains of 5–20% are observed in semi-arid areas, while large losses are predominantly in the humid and subhumid zones. A similar case is observed for irrigated rice.

The variability in the results for groundnut and wheat, for example, shows the difficulties in making generalizations about the impacts of climate change on particular crops in particular places. Current best practice in climate change and crop modelling dictates the use of as many model X scenario combinations to try to reduce the uncertainty in the magnitude of the impacts, the locations and the direction of change in yields, whether they are increasing or decreasing.

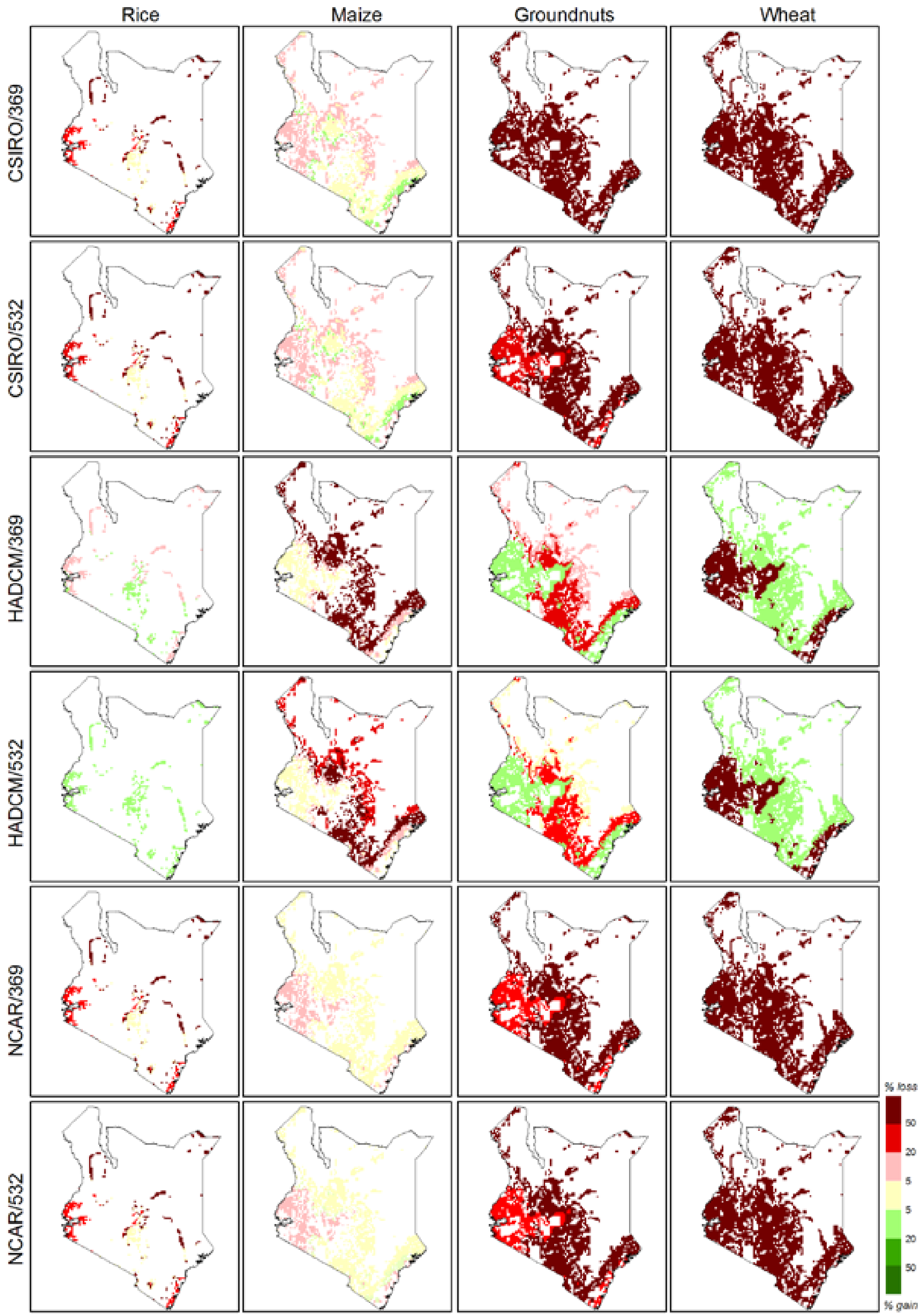


Figure 17. *Climate change impacts on yields of key commodities in Kenya to 2050 as projected by six different model X scenario combinations.*

Thornton et al. (2010) analysed the spatial differences in simulated main season maize and secondary season *Phaseolus* bean yields to 2050, and attempted some simple characterization of crop response. GCMs show an heterogeneous response of crop yield to the changing amounts and patterns of rainfall, and to the generally increasing temperature. As shown by Thornton et al. (2010) 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, as shown in Figure 17. Several studies indicated the uncertainty of crop models in the response of yield to climate change is comparable in magnitude to the mean simulated yield change (Challinor and Wheeler 2007; Thornton et al. 2010). However, the results suggested that we need to keep on monitoring the effects of climate change on crop yields. Thornton et al. (2009) demonstrated that maize yields to 2050 are reduced by 20% for the more semi-arid areas of Kenya and Tanzania where maize cropping is possible. Most of these losses are in the range of 200–700 kg/ha. Production losses of maize to 2050 could be in the order of 8.4% in the mixed rainfed systems in the arid and semi-arid areas and 9.8% in the mixed rainfed systems in the humid and subhumid areas of Kenya. By contrast, maize yields are projected to increase in the central and western highlands of Kenya, mostly by 200 to 700 kg/ha. By 2050, the production of maize is likely to increase by 46.5% in the mixed rainfed systems in the temperate areas of Kenya (Thornton et al. 2010), but total country production will still decline as these areas contribute modestly to the total country production.

Scarce information is available on the impacts of climate change on cash crops in Kenya. According to maps provided by UNEP-GRID, a 2ºC increase in temperature would make much of the current tea area in Kenya unsuitable to tea production, in particular, the tea areas in the Mount Kenya, Aberdares, and Kisumu area (Simonett 1989). In the short term, recent declines in tea production have been directly linked to erratic rainfall patterns and drought.

Wider effects on the economy

Climate change impacts, in the form of yield declines, may be less severe in SSA than in Asia. This is primarily because yields in SSA are much lower and their absolute reductions therefore smaller than in Asia. However, SSA is one of the most vulnerable regions to climate change as a result of its low adaptive capacity (Thornton et al. 2009), linked to high levels of poverty and poor infrastructure, as reflected in the high dependence on rainfed agriculture.

SSA faces increased net food imports even under historic climate as a result of growing populations, faster economic growth compared to the past, and growing urbanization, coupled with slow improvement in agricultural productivity. According to Gerald et al. (2009), climate change will likely further increase net food import demand in the region.

Thus, Kenya will not only be affected by local impacts, but also by climate change impacts in other countries. If climate change impacts are larger in other countries than in Kenya, food imports that might otherwise have been available for SSA in general and Kenya in particular might be redirected to those countries and regions experiencing even sharper declines in food production as a result of climate change. Kenyan agricultural development strategies need to take into account food price and trading environments under climate change in their assessment of climate change impacts and for the development of appropriate adaptation strategies.

To assess these issues for Kenya, we are using an integrated modelling framework.

Results on yield changes of different commodities and their spatial distribution are taken from the previous section on crop modelling and used as inputs into a partial equilibrium model of the agricultural sector called IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade). Model details are presented in Appendix 3. The flow of the analysis is presented in figure 18.

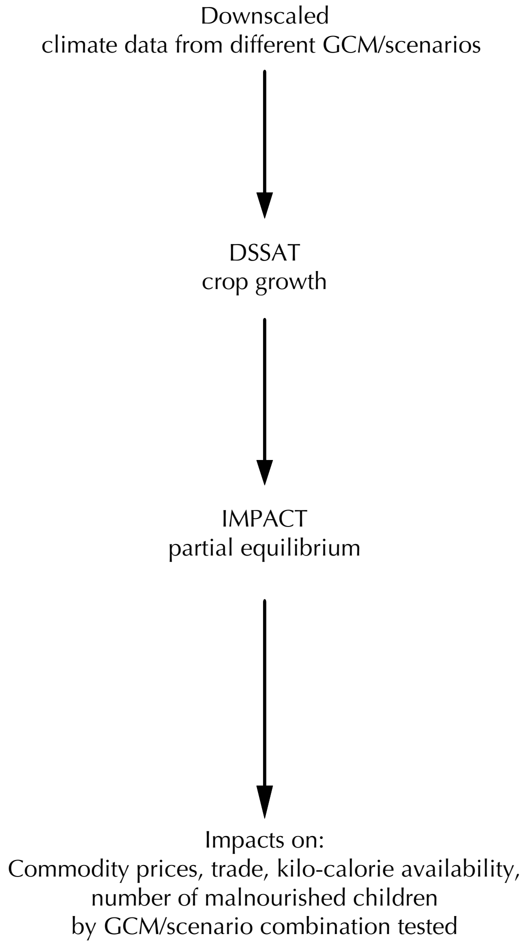


Figure 18. *Models used and flow of the analysis of the impacts of climate change on crop yields and the wider impacts on the economy of Kenya.*

Biophysical climate change effects on crop productivity enter into the IMPACT model by affecting both crop area and yield. IMPACT integrates impacts on crop production from altered temperature and precipitation patterns, changes in irrigation water availability and evapotranspiration potential; it also includes the effects of technological change over time, and economic feedback effects through changes in international food prices, which lead to a series of (autonomous) supply and demand responses. Thus, three impacts on crop production from climate change are considered: first, direct effects on rainfed yields through changes in temperature and precipitation; second, indirect effects on irrigated yields from changes in temperature and changes in water availability for irrigation (including from precipitation); and third, autonomous adjustments to area and yield due to price effects and changes in trade flows in the economic model. With comparisons of IMPACT projections with and without climate change scenarios, the 'net' impacts of climate change on agricultural production, demand, trade and prices can be obtained.

World prices are a key indicator of food affordability and security and also of the effects of climate change on agriculture. Table 8 shows the price effects under the three scenarios for 2025 and 2050.

Climate change will increase world prices of cereals, grains, and meats compared to a scenario with historic climate. Adverse impacts on food prices are even higher for some crops if the carbon fertilization effect is included, with the exception for rice, soya bean and sweetpotato for 2025 and rice and soya bean for 2050. The carbon fertilization effect has much lower benefits for the African continent as few crops receive adequate fertilization. By 2025, maize prices increase most under the NCAR 369 A2 scenario, followed by the Hadley scenario; by 2050, maize prices are similarly highest under NCAR 369 A2 scenario, followed by the CSIRO 532 A2 scenario.

Table 8. *Agricultural commodity prices, alternative climate change scenarios (USD/t) and percentage change under alternative climate scenarios*

		Year 2025					Year 2050				
	2005	No climate change	Hadley 369	NCAR 369	CSIRO 369	CSIRO 532	No climate change	Hadley 369	NCAR 369	CSIRO 369	CSIRO 532
	USD/t		%				USD/t	%			
Beef	2,146	**2,336**	–9	2	–14	1	**2,836**	–29	9	–25	7
Pigmeat	911	**1,033**	6	3	–10	2	**1,272**	–15	15	–20	13
Sheep and goat	2,996	**3,100**	–11	0	–25	0	**3,275**	–39	6	–39	5
Poultry	1,191	**1,396**	–7	4	–13	3	**1,688**	–20	17	–20	14
Rice	211	**255**	17	19	10	7	**310**	26	36	12	11
Wheat	134	**144**	33	48	28	33	**162**	48	106	43	66
Maize	102	**124**	27	29	16	23	**155**	27	52	14	35
Millet	310	**324**	11	52	–6	13	**281**	21	22	–30	22
Sorghum	121	**144**	14	230	8	19	**146**	11	41	–5	32
Soya beans	214	**306**	10	7	2	0	**347**	13	14	6	0
Groundnuts	501	**529**	20	–67	17	19	**487**	20	52	16	35
Other grains	88	**88**	39	57	24	44	**83**	43	123	17	84
Potatoes	226	**188**	38	58	49	50	**158**	56	118	90	101
Sweetpotatoes	549	**567**	2	46	38	38	**624**	–7	94	50	64
Cassava and other roots and tubers	69	**71**	15	42	23	27	**68**	16	97	41	56

Price increases are somewhat lower for meat and dairy products; however, this analysis does not incorporate the impact of climate change on grazing lands and pastures, nor animal heat stress. If these impacts were included, price effects for these commodities would likely be larger.

Climate change affects the agriculture sector directly and indirectly through impacts on crop productivity and production, and resulting shocks on the economic system, and alteration of prices, which in turn affect food demand, calorie availability, and, ultimately, human well-being. Figure 19 presents the aggregated changes in maize yield under alternative climate change scenarios taking into account a) technological change through time; b) autonomous adaptation as a result of higher food prices and thus dampened demand and pressure on increasing supplies; and c) some balance between supply and demand as a result of changes in trade-flows. In Kenya, compared to 2000 rainfed maize yields of 1.6 t/ha, yields by 2050 without climate change are projected at 2.4 t/ha, at an annual yield growth rate of 0.86%, compared to historic overall maize yield growth (rainfed and irrigated) of 0.73% per year from 1962 to 2006 (three-year centered moving average). This exogenous technological change is justified by a long history of crop improvements over time as a result of agricultural research (new varieities) and enhanced crop inputs; globally crop yields are expected to improve by 1% per year.

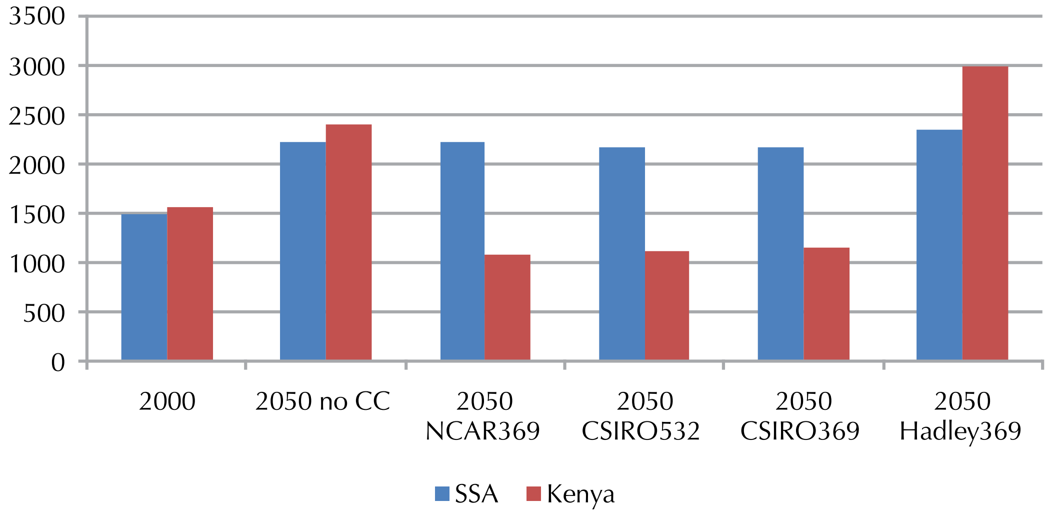
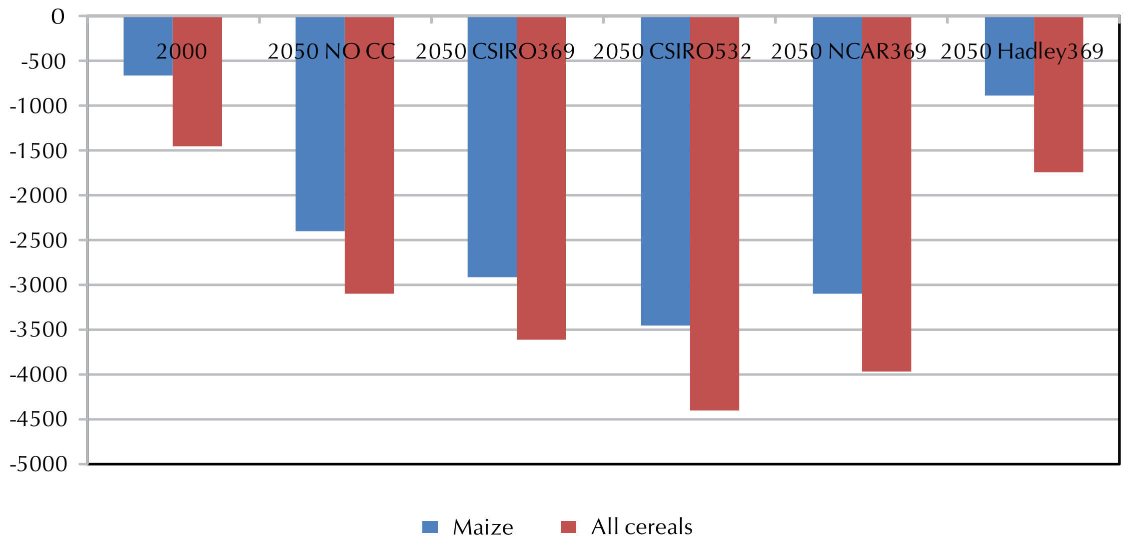


Figure 19. *Maize yield, historic climate and alternative climate change scenarios (kg/ha).*

Under climate change, yields change dramatically for Kenya, whereas average changes in SSA are much smaller, as adverse impacts in parts of SSA are compensated by beneficial impacts elsewhere in the region. Compared to a situation with historic climate, Kenyan maize yields drop by 51–55% under the NCAR 369, CSIRO 369, and CSIRO 532 A2 scenarios, compared to 2050 yields with historic climate. On the other hand, yields increase by 25% under the Hadley 369 A2a scenario. These results somehow differ from the yield changes from other studies (i.e. Cline 2007). The main reason is that the yield changes presented in Figure 19 come from a detailed integration of spatially explicit biophysical modelling with projected technological change, supply/demand aspects and trade. Therefore, they represent more than just biophysical impacts.

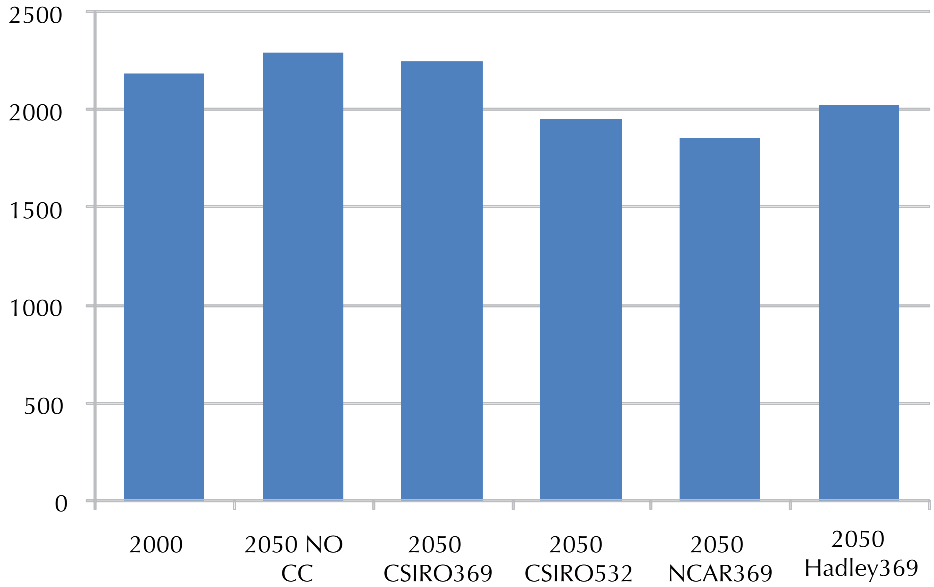
Research on the effects of climate change on world agricultural markets is still relatively limited. Crop and animal production are affected both by changes in temperature and precipitation. Climate change alters comparative advantage, setting up the possibility of changes in trade flows as producers respond to changing opportunities. More generally, agricultural trade flows depend on the interaction between inherent comparative advantage in agriculture, which is determined by climate and the resource endowments, and a wide-ranging set of local, regional, national and international trade policies. As with any change in comparative advantage, unfettered international trade allows comparative advantage to be exploited to the fullest. Figure 20 presents changes in net cereal trade and net maize trade for Kenya. As expected, net imports increase under historic climate for both maize and all cereals. Maize imports are expected to almost quadruple, from 663,000 t to 2,404,000 t; and total cereal imports are projected to increase from 1.5 to 3.2 million tonnes. Under climate change, maize and total cereal imports would be much higher for two out of the three scenarios examined, by between 21 and 44%, thus increasing the future dependency and vulnerability of local food systems under climate change. Under the Hadley scenario, on the other hand, maize imports would be 63% below the scenario without climate change. Trade flows are changing as a result of changing comparative advantage of locations of food production and demand. As mentioned earlier, trade flows have been increasing gradually and continually over time with small drop offs as a result of recessions/depressions, but the trend is clearly upward. Under climate change scenarios, the majority of additional supply is produced in the developed countries, chiefly North America and Europe, but also Latin America—with variations across scenarios. This is not necessarily a win–win situation. Trade will be able to buffer deficits, but at a social cost as prices rise and the poor are excluded from the benefits of consuming the available food due to their low incomes.



Source: IFPRI Impact Simulations (2009).

Figure 20. *Change in net cereal and maize trade, Kenya, alternative climate change scenarios (thousand tonnes). Negative numbers indicate net imports.*

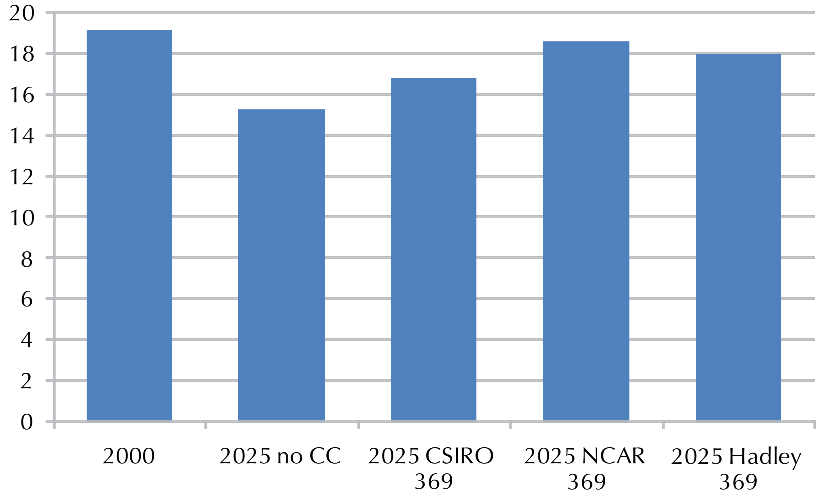
Higher food prices due to increased trade, dampen demand for food as affordability of nearly all agricultural commodities—including basic staples and livestock products—declines under climate change. As a result, per capita calorie availability in Kenya declines under all climate change scenarios, even the Hadley scenario that postulates significant yield growth for Kenya. In 2000, average per capita calorie availability for Kenya was estimated at 2186 calories per day, just slightly above the minimum 2000 calories per capita per day that are considered necessary to lead a healthy and productive life. By 2050, little improvement is expected in calorie availability for the country, with availability estimated to increase to 2295 calories per capita per day without climate change. Under climate change, on the other hand, calorie availability would decline by –2 to –19% (Figure 21). Under both the CSIRO 532 A2 and the NCAR 369 A2 scenarios, calorie availability would fall below the 2000 kilocalorie threshold, and only the CSIRO 369 A2 scenario is above the calorie availability level achieved in the year 2000.



Source: IFPRI Impact Simulations (2009).

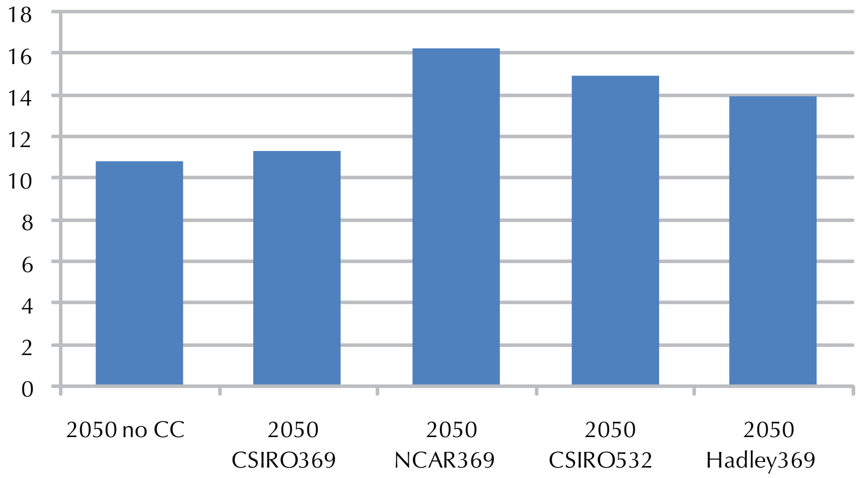
Figure 21. *Per capita calorie availability per day, alternative climate change scenarios, Kenya.*

Food and nutrition security are closely tied to agricultural productivity. Increased food production increases local food availability. Higher production from one's own farm or herds increases access to food and enhances household food security. The nutritional quality of the food produced is also an important consideration in reducing malnutrition, particularly for households who acquire most of their food from their own fields and herds. Particularly in SSA, the most potent force for reducing malnutrition is raising food availability through increased agricultural productivity, as well as trade. Key non-food determinants of child malnutrition include the quality of maternal and child care, female secondary education, and health and sanitation (Smith and Haddad 2000). Depressed food demand translates into direct increases in malnutrition levels, with often irreversible consequences for young children. Projections show that climate change increases the share of malnourished children in both 2025 and 2050, compared to a non-climate change scenario (see Figures 22 and 23).



Source: IFPRI (2009).

Figure 22. *Kenya: share of malnourished children, historic climate and alternative climate change scenarios, 2025 (percentage).*



Source: IFPRI Impact Simulations (2009).

Figure 23. *Kenya: share of malnourished children, historic climate and alternative climate change scenarios, 2050 (percentage).*

Without climate change, the share of malnourished children is projected to decline from 19% in 2000 to 15% by 2025 and 11% by 2050. Thus, Kenya's child malnutrition levels are significantly below the average in SSA in 2000 (28%) and projected in 2025 (29%). Under climate change, child malnutrition levels increase under all alternative climate change scenarios, with levels raising highest under the NCAR 369 A2 scenario, and lowest under the CSIRO 532 A2 scenario.

5 Variability, vulnerability and livelihoods

As has been noted already, currently there is little that can be said concerning the details of the increases in climate variability that, it is envisaged, will affect East Africa (indeed all places) during this century. This section contains two brief examples of some of the impacts that increased climate variability may bring about in livestock systems: one looks at possible impacts of increasing climate variability on herd structure, and the other at possible shifts in livelihoods that may be induced by changes in climate and climate variability.

Impact of increased climate variability on livestock assets of pastoralists

(This subsection was adapted from Thornton and Herrero 2010, with additional analyses)

In general, pastoralists live in regions where the impacts of climate change are likely to be large (Thornton et al. 2006), including the Sahelian rangelands, southern Africa, and parts of East Africa. These are some of the most vulnerable livestock keepers on the planet. Livestock provide many benefits to pastoral families in the form of milk, meat, hides, manure, and socio-cultural capital. At the same time they represent a considerable asset that can be traded or sold in hard times or for purposes such as paying school fees or providing a dowry (Nkedianye et al. 2009). The impact of drought on herd performance and asset values have been widely documented. In large areas of Africa, highly variable climate with frequent droughts can decimate herds and displace pastoralists. Emergency services and humanitarian relief efforts are often needed to support pastoralist families during considerable parts of the year in these regions.

We ran a herd dynamics model (Lesnoff 2007) to investigate the potential impacts of increased climate variability, represented here as increased drought frequencies, on herd dynamics and livestock numbers. We used baseline information on mortality, reproduction and herd structures from pastoralist herds in Kajiado, Kenya (Boone et al. 2005). The model was run over 20 years assuming a herd baseline size of 200 animals, of which 60 were adult females. We ran two scenarios: a baseline scenario simulating realistic climate variability of one drought every five years and an alternative scenario of increased frequency of droughts, one in three years. Such increases in climate variability may be anticipated as a result of global warming. In years of drought, animal mortality rates increase and reproductive performance of adult females declines, potentially resulting in lower numbers of offspring and a declining herd size.

Results indicate that a drought once every five years (i.e. representative of current conditions) keeps herd sizes stable (Figure 24), and this has in fact been observed in Kajiado for a long time (Rutten 1992). At the same time, the district has seen substantial increases in human population, meaning that the proportion of the population that can thrive in a pastoral setting has plummeted, because animal numbers per adult equivalent are simply not sufficiently high to support pastoralism. This might reflect that the ecosystem simply cannot support more animals (except at the possible expense of wildlife, with other income-related effects).

When we increased the probability of drought to once every three years, herd sizes decreased as a result of increased mortality and poorer reproductive performance (see Figure 24). This decrease in animal numbers would affect food security and would compromise the sole dependence of pastoralists on livestock and their products, as well as the additional benefits they confer. This simple analysis shows that under increased climate variability, the need for diversification of income, a strategy often (and increasingly) observed in pastoral areas, becomes ever-more important. Climate change and increasingly climate variability will have substantial impacts on environmental security as well, as the conflicts (usually over livestock assets) often observed in these regions are likely to escalate in the future (Bocchi et al. 2006).

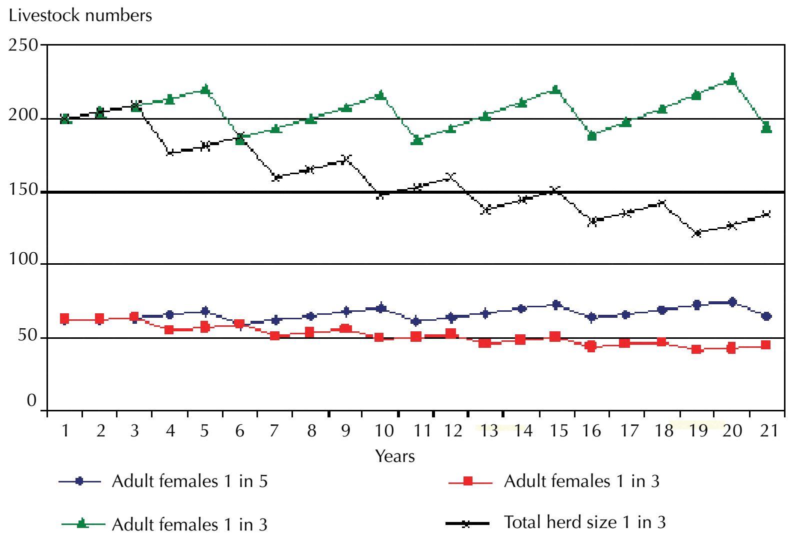


Figure 24. *Evolution of total herd size and the number of adult females under two scenarios of climate variability: (1) a drought every five years, and (2) a drought every three years.*

We upscaled the results to the ASAL regions in Kenya and estimated that 1.8 million animals would be lost by 2030 due to increased drought frequencies (Table 9). In terms of economic losses, the biggest losses are in terms of the livestock assets, as in these regions milk and meat production are low. This is important as livestock accumulation represents an important risk management strategy for pastoral societies as animals can be sold in times of hardship. They also play an essential cultural role (prestige, dowry) or for paying school fees, food purchases etc.

Table 9. *Economic impacts of increased drought frequencies in pastoral and agropastoral systems in arid and semi-arid regions of Kenya*

Indicator	Value
Cattle numbers in 2000 (million TLU*)[1]	5.6
Cattle numbers in 2030 drought 1 in 5 years (million TLU)[1]	5.9
Cattle numbers in 2030 drought 1 in 3 years (million TLU)[2]	4.1
Animals lost due to increased drought frequency (million TLU)[2]	1.8
Cumulative milk production lost (million kg)[3]	837
Cumulative meat production lost (million kg)[4]	1.4
Value of lost animals (million USD)	458
Value of lost milk production (million USD)[3]	167
Value of lost meat production (million USD)[4]	5
Total economic losses (million USD)	630

* Tropical livestock units (1 TLU = 250 kg bodyweight).
1. Data from Herrero et al. (2008).
2. Estimated with the model of Lesnoff (2007).
3. Assumptions: price of 1 animal USD 250, milk production 150 kg/year, 20% females in milk, milk price 20 KES/kg (Note that on 14 June 2011, USD 1 = KES 89.45).

4. Assumptions: 10% offtake, 50% dressing percentage, meat price 250 KES/kg.

It is essential to increase the resilience and adaptation of agropastoralists to protect their livelihoods if these kinds of extreme events increase in frequency (Herrero et al. 2010b). This can be done in many ways. Some examples are by: a) implementing schemes to protect their assets such as index-based insurance schemes, or the development of easy to implement early warning systems, b) creating incentives to incorporate pastoralists into the market economy to generate cash income. This would imply investing in market and value chain development to enhance the ability to obtain inputs and sell livestock products, c) develop safety nets so that disenfranchised people can access food, health services and others in times of hardship. This would involve the development of food storage systems, improving water accessibility and developing institutional networks to support pastoralists (government, civil societies, NGOs, others).

Croppers to livestock keepers: Possible livelihood transitions due to climate change

(This subsection is based on Jones and Thornton 2009)

Various studies estimate that warming and drying may reduce crop yields by 10 to 20% overall by the middle of the century, and increasing frequencies of heat stress, drought and flooding events will result in yet further impacts on crop and livestock productivity. The local effects of climate change may be severe in places, to the point where the existing livelihood strategies of rural people may be seriously compromised. These places are likely to include parts of East Africa that are already marginal for crop production; as these become increasingly marginal, through a combination of increasing temperatures, changing rainfall amounts and patterns, and increasing climate variability, then livestock may provide an alternative to cropping. Some of these areas in SSA have been identified where such transitions might occur. For the currently cropped areas of the continent, a recent study estimated probabilities of failed seasons for current climate conditions, and compared these with estimates obtained for future climate conditions in 2050, using downscaled climate model output for two contrasting greenhouse-gas emission scenarios. Results are shown in Figure 25, in terms of the parts of the continent in the mixed crop–livestock rainfed arid–semi-arid systems in which the number of Reliable Crop Growing Days (RCGD) falls below 90 between 2000 and 2050, as projected using the HadCM3 model and the A1FI high-emissions scenario (Jones and Thornton 2009). RCGDs are an indicator of growing season length and reliability, and are a probabilistic measure related to LGP (see above). Cropping in areas with an RCGD less than 90 becomes highly marginal, and so this value can be used as a cut-off point below which cropping is likely to be too risky for the household. Areas in red in Figure 25 are ‘transition zones’, where cropping may be possible now but will probably not be possible in 2050. For Kenya, these areas are relatively small. They are located around coastal areas and also in transition zones between the highlands and the lowlands. Areas like Machakos, where significant decreases in LGP may force farmers to rely more on livestock, substitute crops and/or diversify into other activities.

Even under 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 in the middle of the century. Potential livelihood transition zones can be identified, and these zones differ in their accessibility, which may have considerable impacts on the type of adaptation options that may be viable. For those that are relatively close to large human settlements, for example, there may be options for both integration of livestock systems into the market economy and for off-farm employment opportunities. For transition zones that are more remote, on the other hand, both market and off-farm employment opportunities may be much more limited. There are currently significant populations of people in these more remote transition zones, and they are widely spread throughout west, east and southern Africa. Substantial changes may be required to people’s livelihoods and agricultural systems if food security is to be improved and incomes raised. The results also highlights the fact that poverty rates in the marginal cropping lands of Africa are already high, and generally increase as accessibility decreases (Jones and

Thornton 2009). There will be an increasing need in these areas for highly-targeted schemes that promote livestock ownership and facilitate risk management where this is appropriate, as well as efforts to broaden income generating opportunities in parts of the continent where this is feasible.

Source: Jones and Thornton (2009).

Figure 25. *Transition zones in the mixed rainfed arid–semi-arid system, in which the Reliable Crop Growing Days (RCGD) falls below 90 between 2000 and 2050, as projected using the HadCM32 model and the A1FI scenario.*

Conclusions

Notwithstanding the uncertainty in analysing the impacts of climate change and variability on the agricultural sector in Kenya, below are a few points that summarize the main conclusions from our report.

In East Africa there are very few places where rainfall means are likely to decrease. The increase in rainfall in east Africa, extending into the Horn of Africa, is robust across the ensemble of GCMs, with 18 of 21 models projecting an increase in the core of this region, east of the Great Lakes.

The increases in rainfall and temperature will only translate in increased agricultural productivity in specific locations. Increases in rainfall may not lead to increases in agricultural productivity in lowland regions since increases in temperature will also increase evapotranspiration and offset any potential increase in productivity. On the other hand, increases in temperature may remove crop growth constraints in the highlands, thus potentially leading to higher yields. However, to really capitalize on the potential yield increases it will be necessary to invest in inputs and services.

Even with modest increases in maize and bean production in the highlands, Kenya will experience country-wide losses in the production of key staples, due to increased evapotranspiration in large cropland areas. There is large uncertainty about the magnitudes of the country-wide staple production losses, but they may be between –10 and 55% depending on the scenario, crop model and GCM run.

Trade in key staples could offset lower crop production caused by climate change. Trade in cereal is likely to increase to satisfy internal consumption. Under climate change, maize and total cereal imports would be much higher for two out of the three scenarios examined, by between 21 and 44%. Under the Hadley scenario, on the other hand, maize imports would be 63% below the scenario without climate change.

However, the whole picture is more complex. Prices of key staples are likely to increase and this will dampen demand for food, as affordability of nearly all agricultural commodities—including basic staples and livestock products declines under climate change. As a result, per capita calorie availability in Kenya is likely to decline under all climate change scenarios.

Lower food accessibility due to increased commodity prices is likely to translate in increases in malnutrition, especially of young children. Climate change is likely to increase the number of malnourished children in both 2025 and 2050. Without climate change, child malnutrition levels are projected to decline from 19% in 2000 to 15% by 2025 and 11% by 2050. Under climate change, child malnutrition levels increase under all alternative climate change scenarios. These effects will probably be exacerbated in areas of high vulnerability, like the ASALs.

Increased drought frequencies to more than a drought every five years could cause significant, irreversible decreases in livestock numbers in arid and semi-arid areas. Results indicate that a drought once every five years (i.e. representative of current conditions) keeps herd sizes stable in ASALs, and this has in fact been observed in places like Kajiado for a long time. Increased probability of drought to once every three years, could decrease herd sizes as a result of increased mortality and poorer reproductive performance of the animals. Pastoralists whose food security and entire livelihood depends solely on livestock would be severely affected by decreased animal numbers.

This highlights how under increased climate variability, diversification of income sources is a key adaptation strategy. There are some signs of livelihood diversification in pastoral areas, but it will need to be encouraged further. Climate change and increasingly climate variability will have substantial impacts on environmental security as well, as the conflicts (usually over livestock assets) often observed in these regions are likely to escalate in the future.

Kenya will have significant areas in the ASALs where cropping might no longer be possible as a result of climate change and where the role of livestock as a livelihood option is likely to increase. Even under 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 in the middle of the century. Potential livelihood transition zones can be identified, and these zones differ in their accessibility, which may have considerable impacts on the type of adaptation options that may be viable. For transition zones that are remote, both market and off-farm employment opportunities may be limited. Substantial changes may be required to people's livelihoods and agricultural systems if food security is to be improved and incomes raised. There will be an increasing need in these areas for highly-targeted schemes that promote livestock ownership and facilitate risk management where this is appropriate, as well as efforts to broaden income-generating opportunities in parts of the continent where this is feasible.

Strengthening the adaptive capacity of vulnerable populations and of the agriculture sector as a whole requires a comprehensive assessment of the impacts of climate change and variability, the risks these changes pose to agricultural production, the constraints to adaptation households and communities face, and the potential policy options that can facilitate adaptation.

Responses to climate change need to encompass several levels, including crop and farm-level adaptations, collective action at the community level, and agricultural and supporting policies and investments at national, regional and global levels. Adaptation will require the involvement of multiple stakeholders, including policymakers, extension agents, NGOs, researchers, communities, and farmers. Potential strategies will include infrastructural investment, water management reform, land-use policy, and food trade.

The fact that the study of climate change is an uncertain discipline is no excuse for inaction. Using the best information available, the Kenyan agricultural sector, donors and other stakeholders need to be responsive and act in a timely, targeted fashion to ensure that millions of smallholders can adapt to climate change and maintain or improve their livelihoods and the ecosystems they rely upon.

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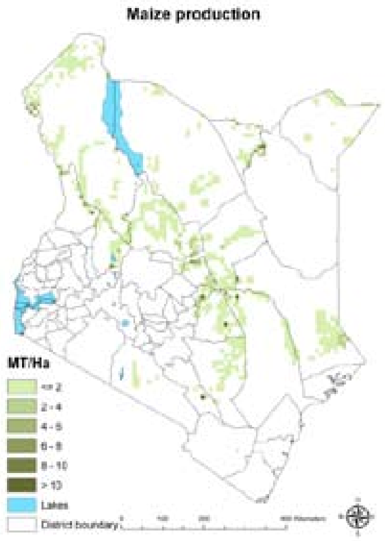
Appendices

Appendix A

Arid



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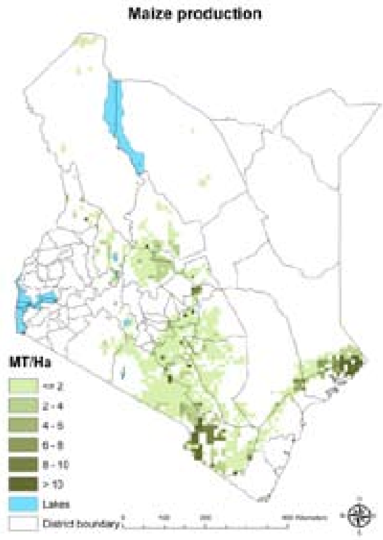

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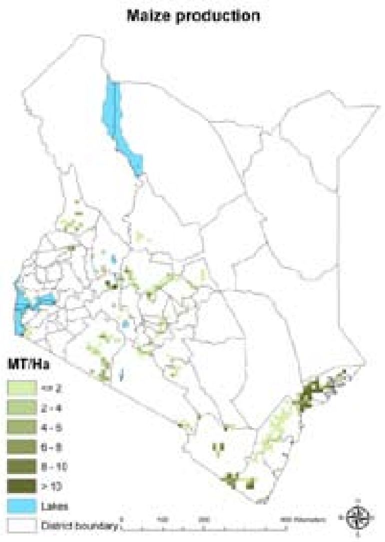

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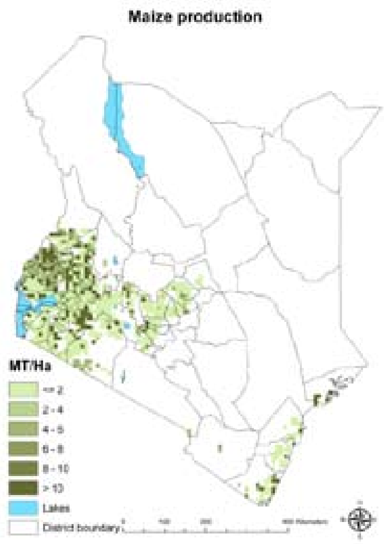

Figure Appendix A1. *Distribution and yield in t/ha of maize, 2000.*

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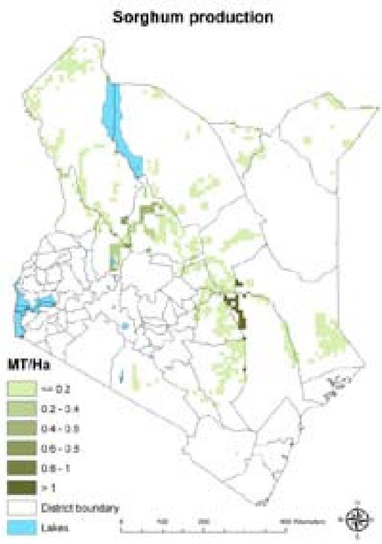

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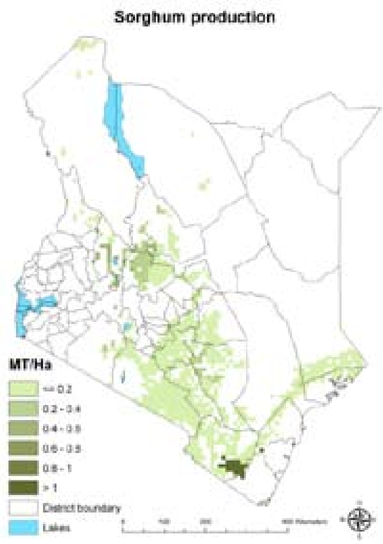

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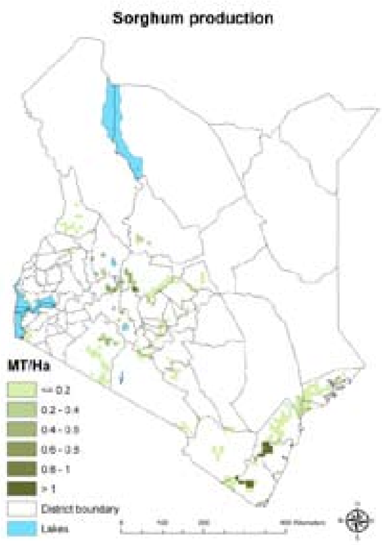

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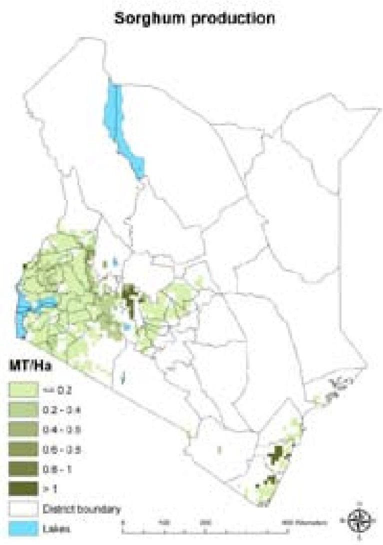
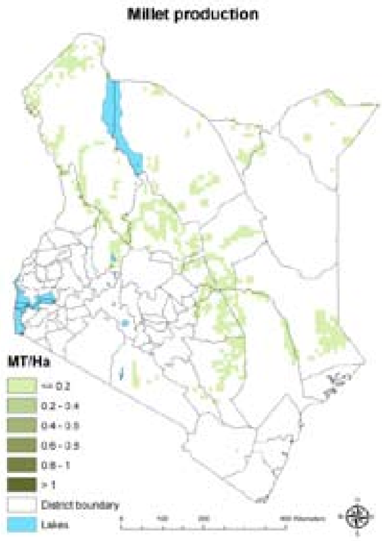


Figure Appendix A2. *Distribution and yield in t/ha of sorghum, 2000.*

Arid



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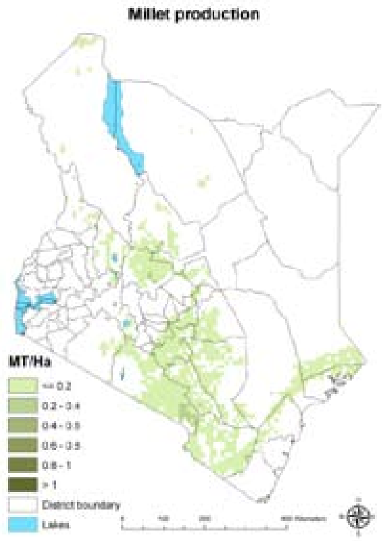

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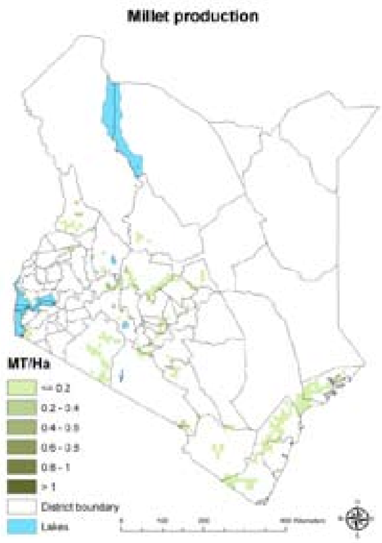

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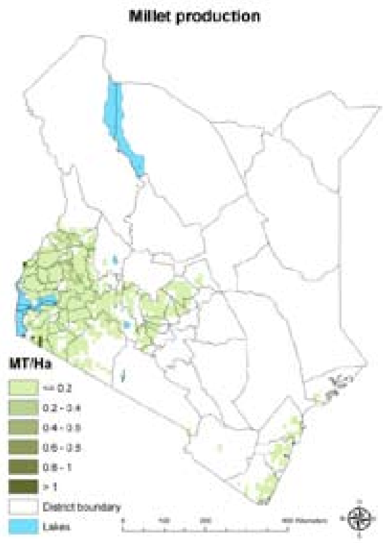
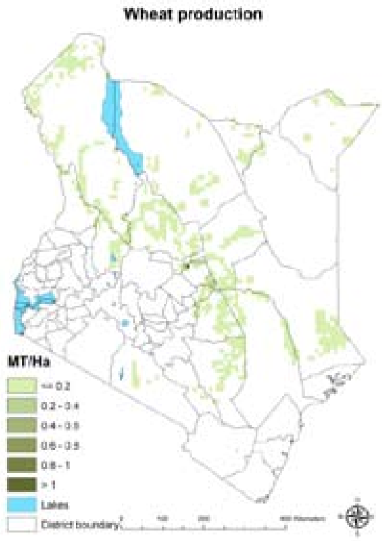


Figure Appendix A3. *Distribution and yield in t/ha of millet, 2000.*

Arid



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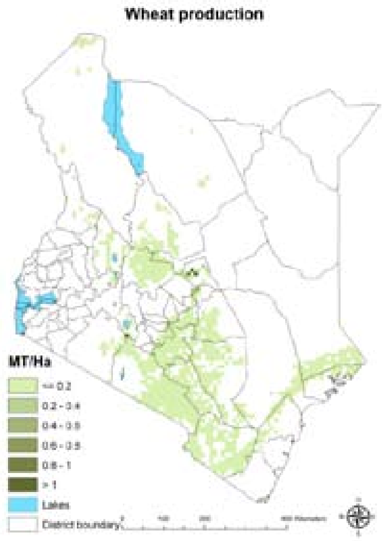

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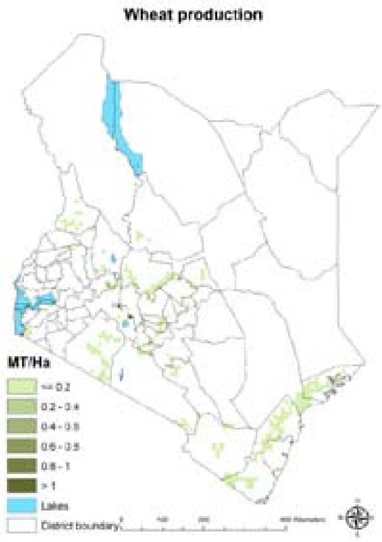

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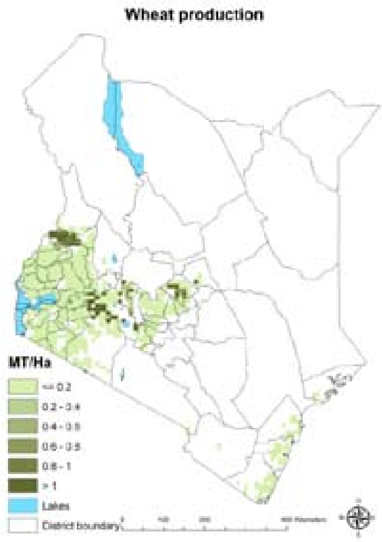
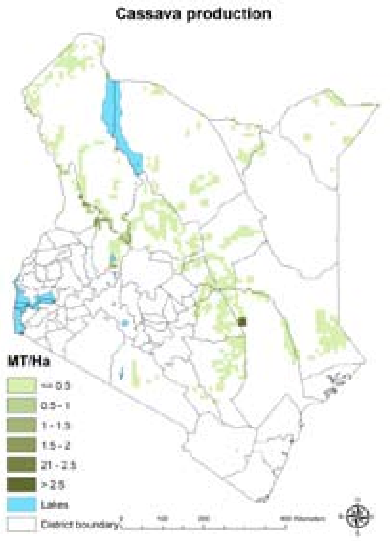


Figure Appendix A4. *Distribution and yield in t/ha of wheat, 2000.*

Arid



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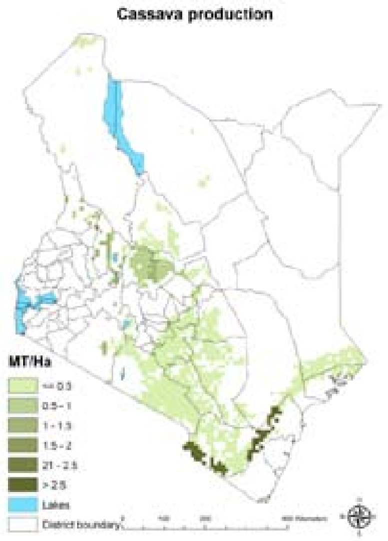

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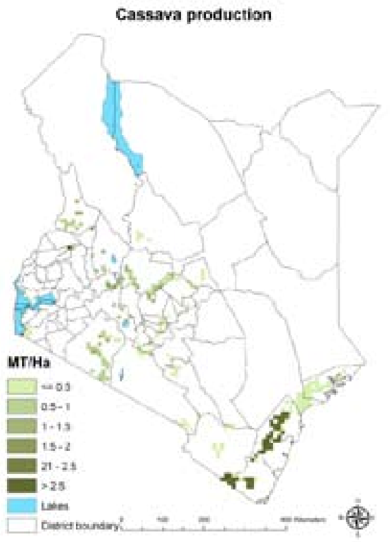

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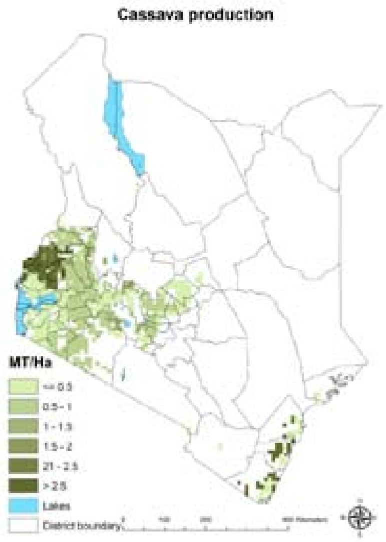
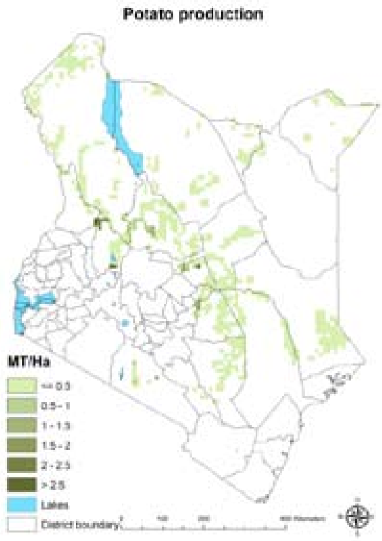


Figure Appendix A5. *Distribution and yield in t/ha of cassava, 2000.*

Arid



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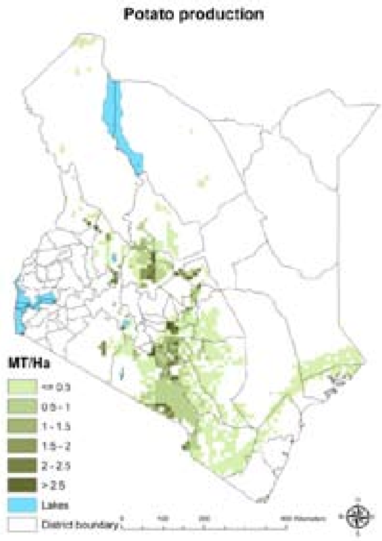

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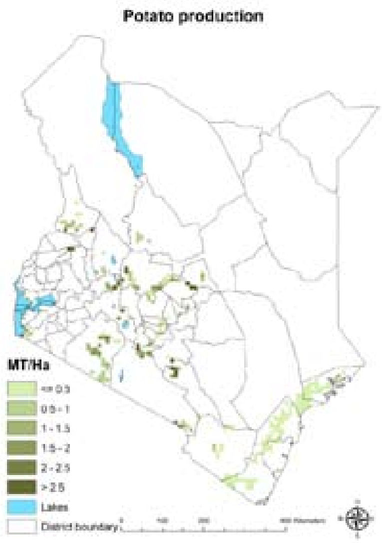

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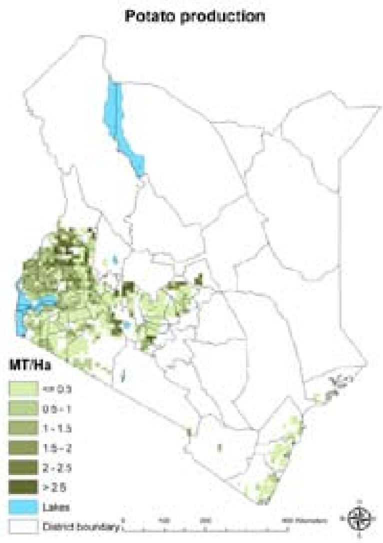


Figure Appendix A6. *Distribution and yield in t/ha of potato, 2000.*

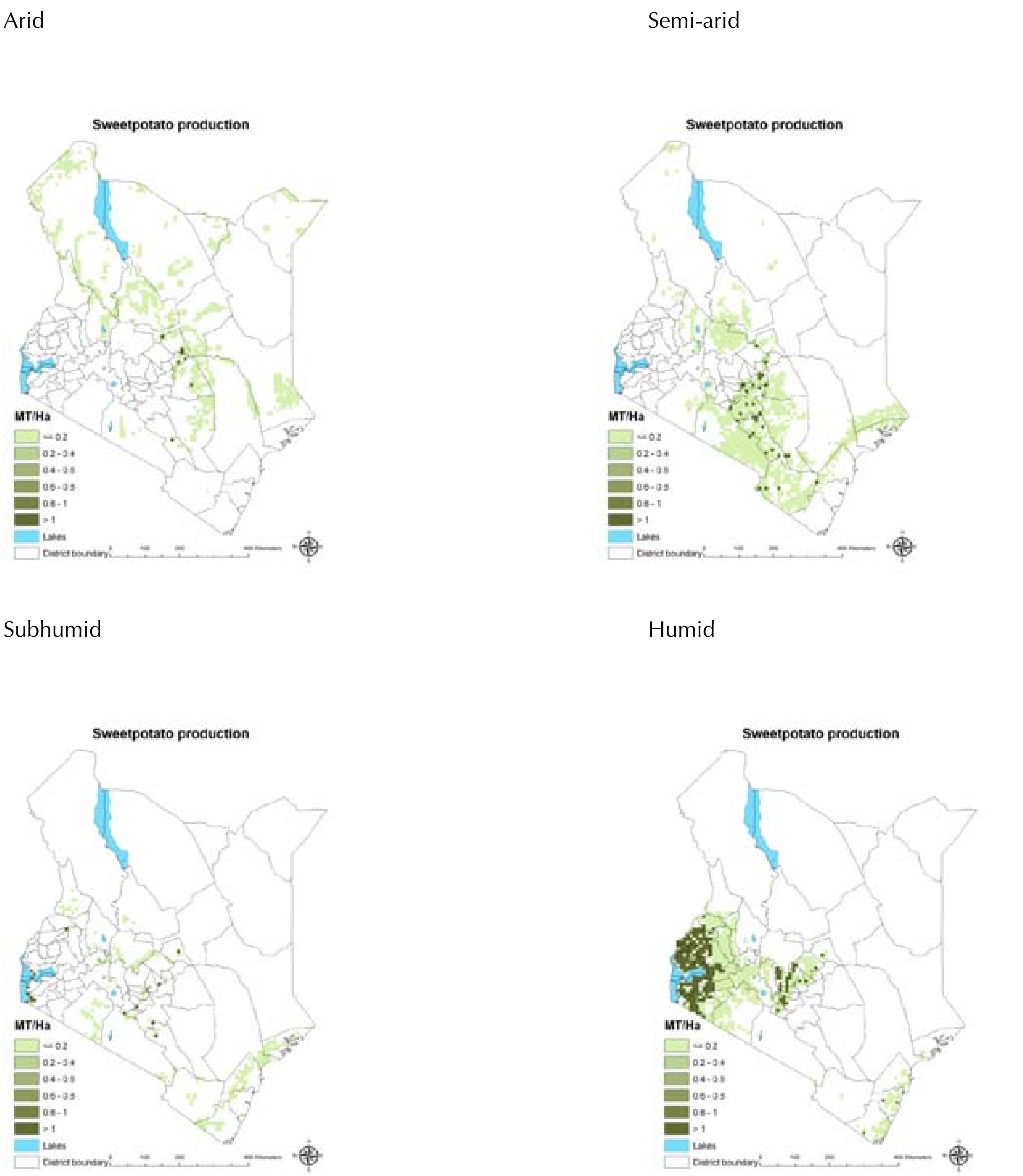
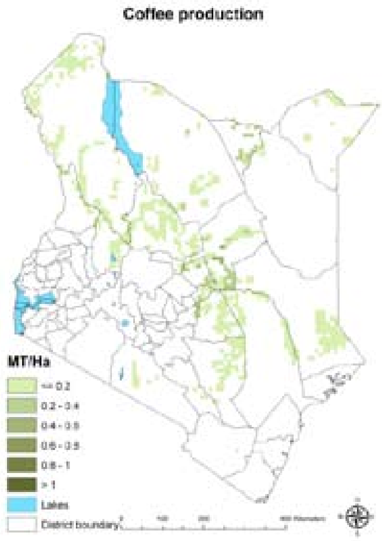


Figure Appendix A7. *Distribution and yield in t/ha of sweetpotato, 2000.*

Arid



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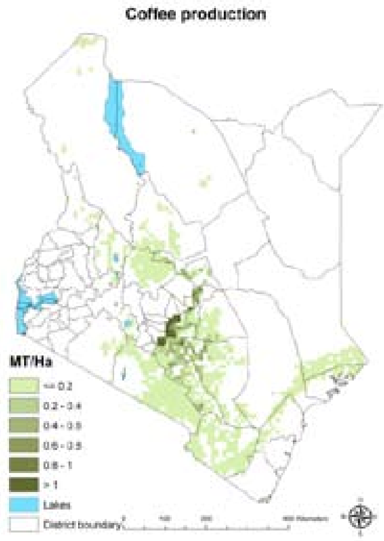

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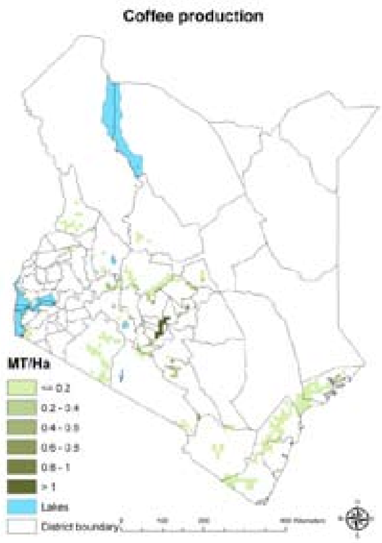

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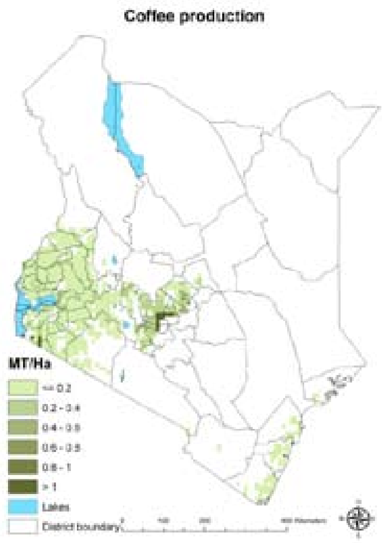
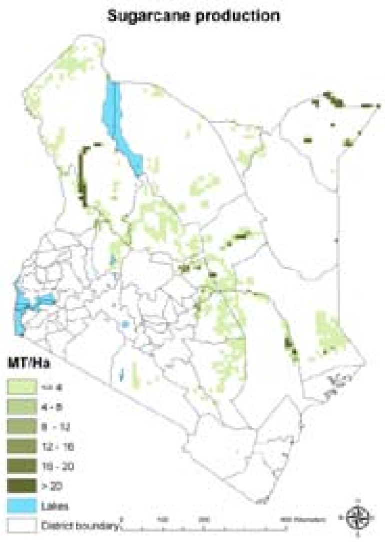


Figure Appendix A8. *Distribution and yield in t/ha of coffee, 2000.*

Arid



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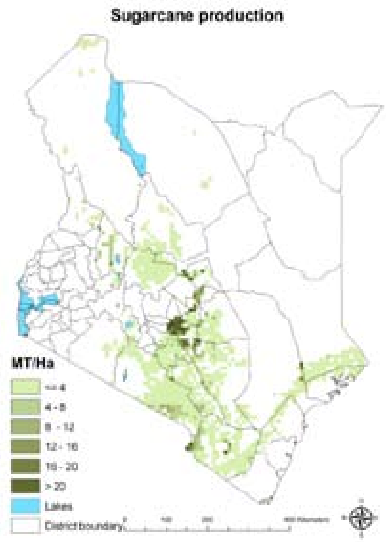

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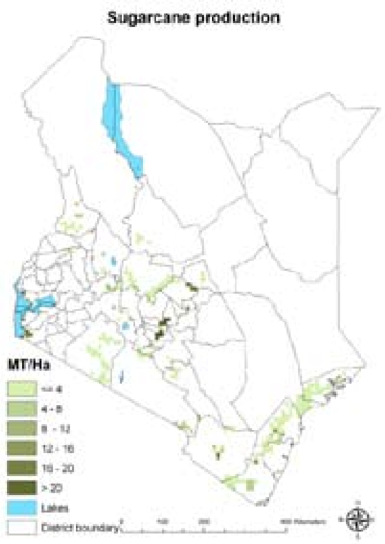

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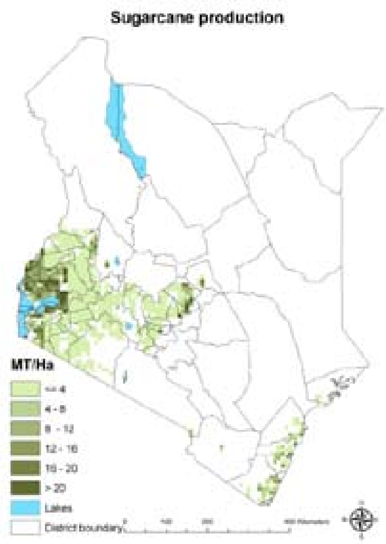


Figure Appendix A9. *Distribution and yield in t/ha of sugarcane, 2000.*

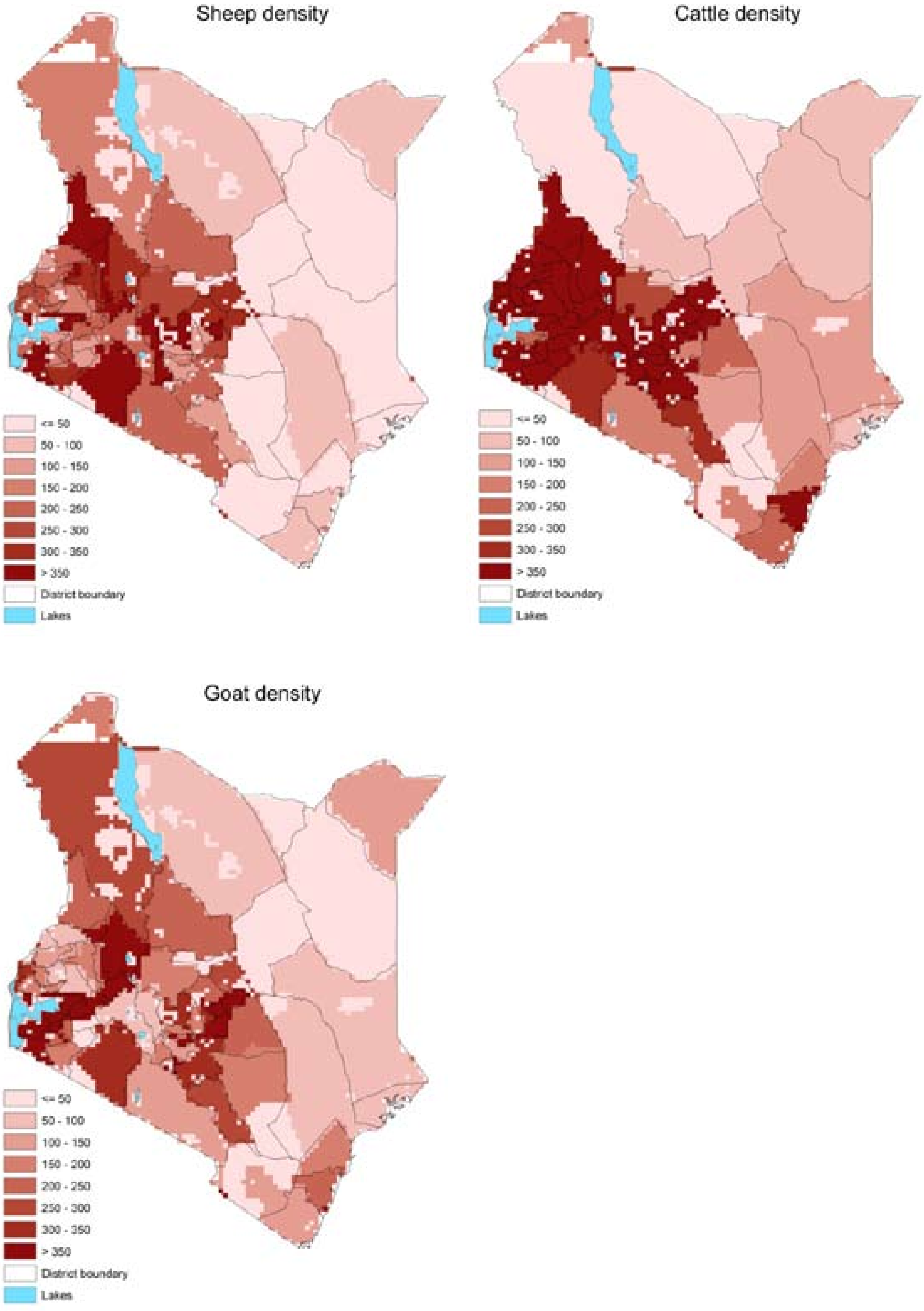
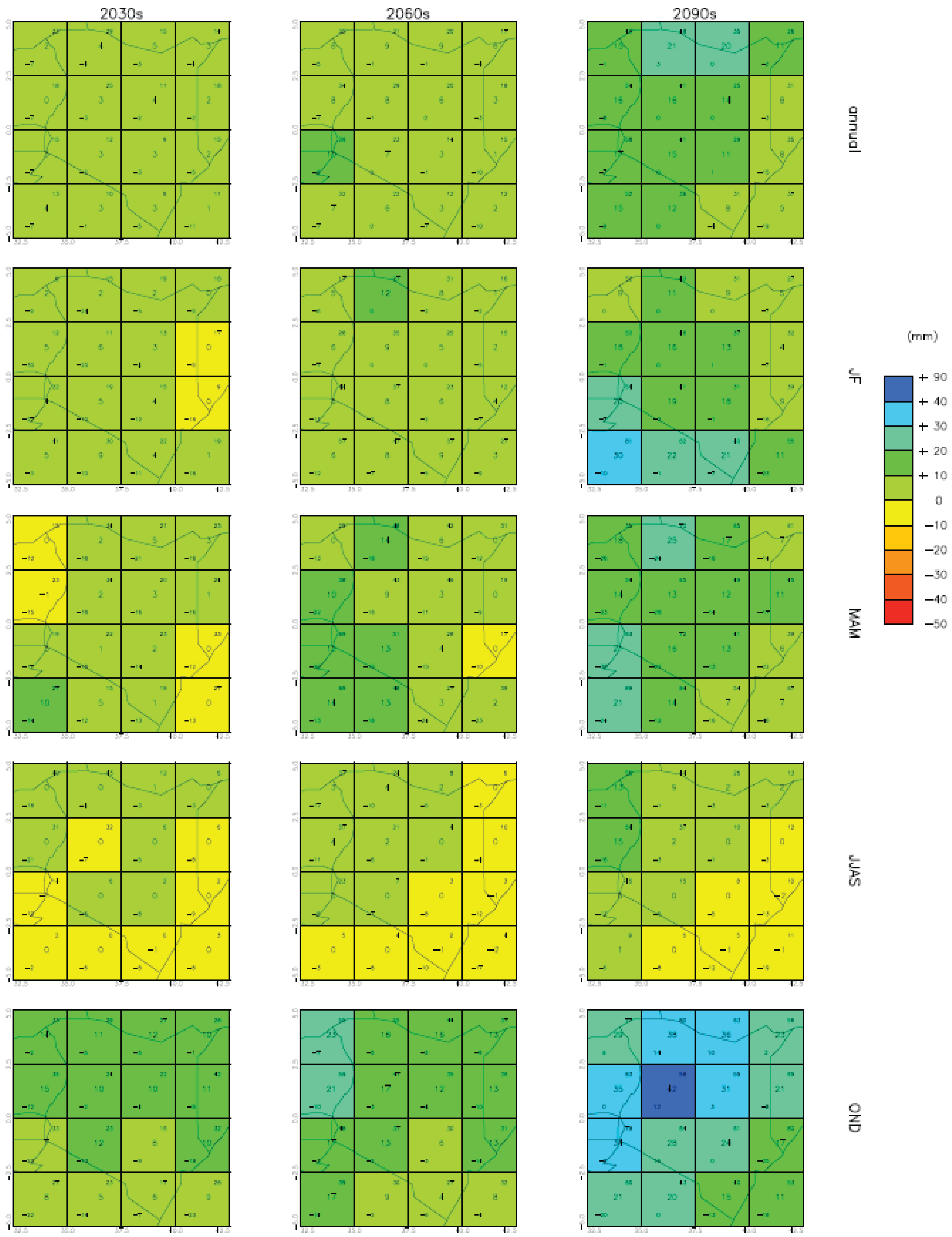


Figure Appendix A10. *Livestock density maps (TLU/km²).*

Appendix B



Source: McSweeney et al. in press, http://country-profiles.geog.ox.ac.uk/.

Figure Appendix B1. *Kenya: Spatial patterns of projected change in monthly precipitation for 10-year periods in the future under the SRES A2 scenario.*

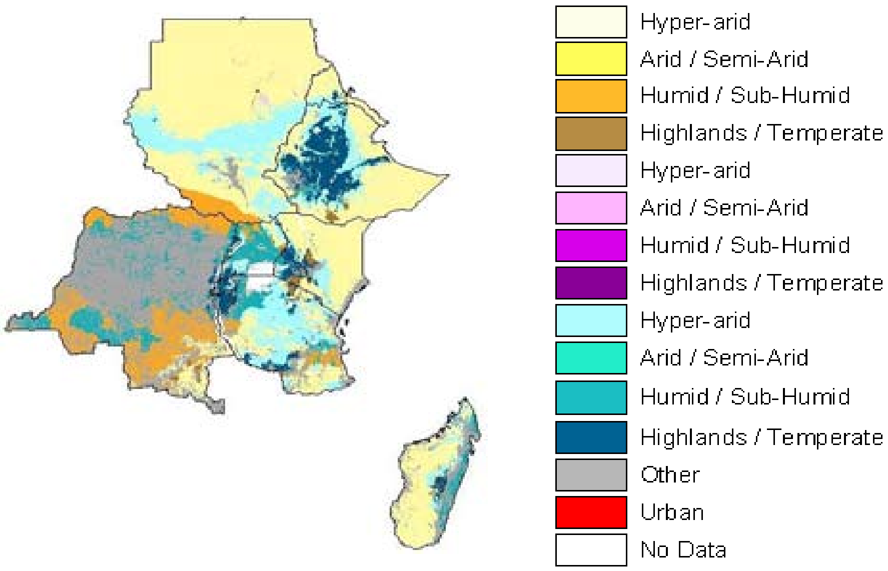
All values are anomalies relative to the mean climate of 1970–1999 .

Appendix C Production systems in Kenya

Livestock production systems consist mostly of pastoralists, while mixed systems represent crop–livestock systems where dairy predominates and where different crops, primarily maize and beans are planted in single stands or intercropped.

Choice of crop is also determined by agro-ecology. In the mixed systems in the highlands maize and potatos predominate together with cash crops such as coffee and tea. Sugarcane, sweetpotato and maize grow mostly in the humid areas while millets and sorghum are restricted to the semi-arid regions.

In terms of livestock, most meat production predominates in arid and semi-arid regions and comes from a mixture of cattle, sheep and goats. Sheep and goat production is growing at faster rates than cattle production in these areas (Herrero et al. 2008). Camels are also replacing cattle in these environments. Dairy predominates in the highlands.



Appendix D Generating plausible crop distribution and performance maps

This text is based on the abstract in 'Generating plausible crop distribution and performance maps for sub-Saharan Africa (SSA) using a spatially disaggregated data fusion and optimization approach' by You et al. (2007).

Agricultural production statistics reported at country or subnational geopolitical scales are used in a wide range of economic analyses, and spatially explicit (georeferenced) production data are increasingly needed to support improved approaches to the planning and implementation of agricultural development. However, it is extremely challenging to compile and maintain collections of subnational crop production data, particularly for poorer regions of the world. Large gaps exist in our knowledge of the current geographic distribution and spatial patterns of crop performance and these gaps are unlikely to be filled in the near future. Regardless, the spatial scale of many subnational statistical reporting units remains too coarse to capture the patterns of spatial heterogeneity in crop production and performance that are likely to be important from a policy and investment planning perspective. To fill these spatial data gaps, You et al. (2007) developed and applied a meso-scale model for the spatial disaggregation of crop production. Using a cross-entropy approach, the model makes plausible pixel-scale assessment of the spatial distribution of crop production within geopolitical units (e.g. countries or subnational provinces and districts). The pixel-scale allocations are performed through the compilation and judicious fusion of relevant spatially explicit data, including production statistics, land use data, satellite imagery, biophysical crop 'suitability' assessments, population density, and distance to urban centers, as wells as any prior knowledge about the spatial distribution of individual crops.

Using the modified spatial allocation model, they generated 5-minute (approximately 10-km) resolution grid maps for 20 major crops across SSA, namely barley, dry beans, cassava, cocoa, coffee, cotton, cowpeas, groundnuts, maize, millet, oil palm, plantain, potato, rice, sorghum, soya beans, sugarcane, sweetpotato, wheat, and yam. An example of estimated distribution maps for sorghum, maize and millet are given in Figure D1. The approach provides plausible results but also highlights the need for much more reliable input data for the region, especially with regard to subnational production statistics and satellite-based estimates of cropland extent and intensity.

Figure Appendix D1. *Estimated crop distribution maps of sub-Saharan Africa.*

Appendix E Crop and economic modelling methods

Generating locale-specific yield responses to climate change

Biophysical yield responses to soil, nutrients and climate change generated by the Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation model distributed across the globe based on crop calendars, soils, and the ISPAM dataset of crop location and management techniques (You and Wood 2006; see also www.mapspam.info).

Distributed crop simulation model results are then aggregated into the 281 food producing units that form the basic elements of IMPACT. On the water side, results from the GCMs are fed into a global hydrologic simulation model to account for impacts on runoff and evapotranspiration from changes in temperature and precipitation patterns.

Modelling climate change impacts

Climate change effects on crop productivity enter into the IMPACT model by affecting both crop area and yield. For example, crop yields are altered through the intrinsic yield growth coefficient in the yield equation as well as the water availability coefficient for irrigated crops. Intrinsic growth coefficients, or technological change depend on crop management system, location, yield trends, and agricultural research investments. For most crops, the average is about 1% per year.

We generate relative climate change productivity effects by calculating location-specific yields for each of the five crops modelled with DSSAT for 2000 and 2050 climate as described above and then constructing a ratio of the two. The ratio is then used to alter the intrinsic rate of technological change. Rainfed crops react to changes in precipitation and temperature as modelled in DSSAT. For irrigated crops, the effect of temperature is derived from the DSSAT results and water stress effects are captured in the hydrology model connected with IMPACT, reducing water availability for irrigation.

The role of carbon fertilization

Scenarios can be run with or without increased carbon fertilization effects. Plants produce more vegetative matter as atmospheric concentrations of CO_2 increase. The effect depends on the nature of the photosynthetic process used by the plant species. C_3 plants use CO_2 less efficiently than C_4 plants, which benefit from elevated atmospheric concentrations of CO_2. Uncertainty remains regarding the translation of mostly laboratory results to actual field conditions. DSSAT has an option to include CO_2 fertilization effects at different levels of CO_2 atmospheric concentration. However, when compared to recent evidence in field trials, it appears that the CO_2 fertilization effects currently embedded in the DSSAT models may overstate the benefits of carbon fertilization (Kenneth J. Boote, Professor, Agronomy Department, University of Florida, March 2009, Personal communication). To capture the uncertainty in actual field effects, we simulate two levels of atmospheric CO_2 in 2050: 369 ppm (the level in 2000) and 532 ppm, the expected CO_2 levels in 2050 for one of the scenarios (A2 for a comparison of results). Thus, we compare a situation with CO_2 fertilization with a situation without.

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