Chapter 3

Impacts of Climate Variability and Change on Agricultural Systems in East Africa

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Introduction

With growing evidence and increasing awareness that the climate is changing and will continue to change even under reduced greenhouse gas emissions (IPCC, 2013), the focus now shifts to understanding the impacts of the projected changes and to developing strategies that help in adapting to the same. However, adaptation planning requires accurate information about where, when, and how the impacts will be felt and who will be more vulnerable. Agriculture, especially as practiced under rainfed conditions, is one of the most vulnerable sectors to climate variability and change because they are important determinants of its productivity. Among the regions, Africa is considered more vulnerable due to its high dependence on agriculture for subsistence, employment, and income.

In East Africa, agriculture provides 43% of GDP and contributes to more than 80% of employment (Omano *et al.*, 2006). East Africa suffers from both periodically excessive and deficient rainfall (Hastenrath *et al.*, 2007; Webster *et al.*, 1999). Generally the region experiences prolonged and highly destructive droughts that cover large areas at least once every decade and more localized events occur more frequently. Based on the analysis of data from the International Disaster Database (EM-DAT), Shongwe *et al.* (2009) report that there has been an increase in the number of reported disasters in the region; from an average of less than three events per year in the 1980s to over seven events per year in the 1990s and ten events per year from 2000–2006.

The negative impacts of climate are not limited to the years with extreme climatic conditions. Even with normal rainfall, the countries in the region do not produce enough food to meet their needs and many them are net importers of food. Overlaid on this challenging scenario is the dominance of semi-arid to arid climatic conditions, degraded soils, extreme poverty, and lack of infrastructure, which make these countries highly vulnerable to future changes in climate (Fischer *et al.*, 2005; IPCC, 20013).

There is a rapidly growing literature on vulnerability and adaptation to increased climatic variability and climate change, but most of these assessments are based on statistical and empirical models that fail to account for the full range of complex interactions and their effects on agricultural systems (Cline, 2007; Lobell *et al.*, 2008; Parry *et al.*, 2004). For developing and implementing adaptation programs, more detailed information about the components of the prevailing systems (such as which crops and varieties are more vulnerable and which management practices are not viable under the predicted climates) is needed. Several problems hinder such an assessment. First, there is the lack of availability of downscaled local-level climate change projections. While climate models provide various scenarios with higher levels of confidence at global and subregional levels, uncertainty prevails over the exact nature of these changes at local levels (IPCC, 2007). Second, information is lacking on how the projected changes in climate impact agricultural systems, especially smallholder agriculture. Though process-based crop simulation models can serve as tools to capture these interactions and make more realistic assessments of climate effects on agricultural systems, application is often limited to a few location-specific studies mainly because of the intensive data requirements and practical limitations, including the capacity to calibrate, validate, and perform detailed analyses. Third, there is scarcity of information on how the impacts of climate change on the production and productivity of agriculture translate into economic impacts, including food security at household and national levels.

This assessment is aimed at developing more accurate information on how projected changes in climate might affect smallholder farmers through impacts on productivity and profitability of agricultural systems that are widely adopted in East Africa, by using protocols and methods developed by the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig *et al.*, 2013a). The assessment is designed to capture the complexity and diversity that exist in the smallholder farming systems, including the different ways in which the system is managed (Fig. 1). AgMIP has developed methods and protocols that integrate state-of-the-art downscaled climate scenarios, by using crop and economic models (Rosenzweig

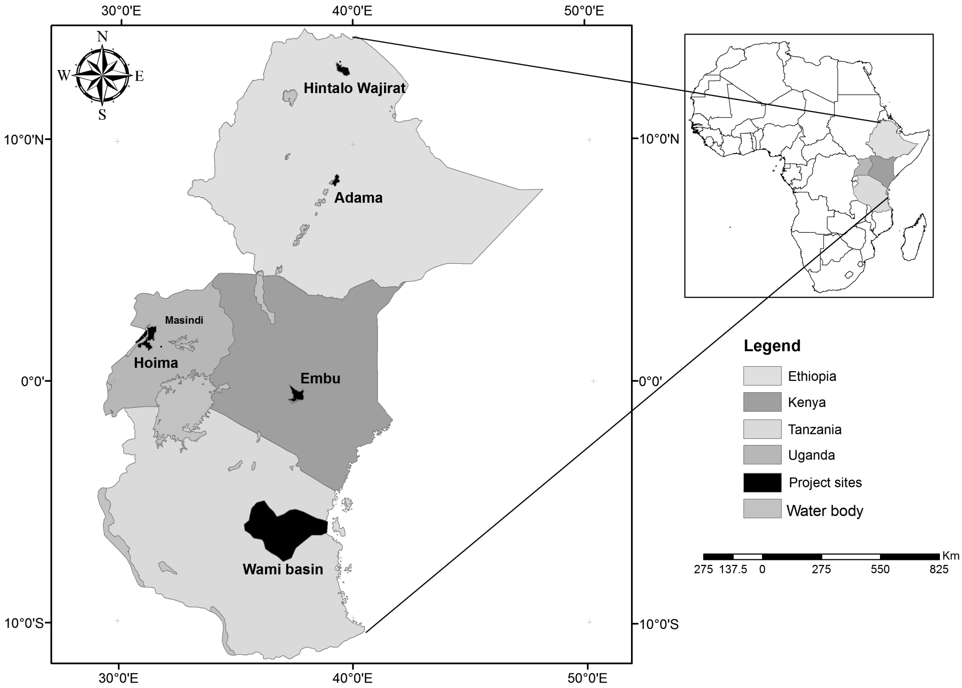

Fig. 1. AgMIP study areas in Eastern Africa.

et al., 2013b). This paper examines the results from the integrated assessment carried out on smallholder farming systems in different agroecological zones (AEZs) of Embu County in Kenya and explores their possible impacts on income, poverty, and food security. It also discusses some of the available options that can be used to mitigate the negative impacts effectively while capitalizing on the opportunities created.

Farming System Investigated

Settings and locations

Embu County in Kenya, which lies on the southeast slopes of Mount Kenya, covers the typical agroecological profile of the region, from cold and wet high-altitude areas to the hot and dry low-altitude areas (Fig. 2). The region is bounded by latitude 0°53'S and longitude 37°45'E. The county slopes from west to east (Jaetzold *et al.*, 2007). According to the 2009 population census, the district had a total population of 543,221 people with an annual growth rate of 1.7%. The National Report on Poverty in Kenya 2000 indicated that 56%of the population in Embu District is absolutely poor while 43.5% of them were categorized as chronically poor. Absolute poverty is a

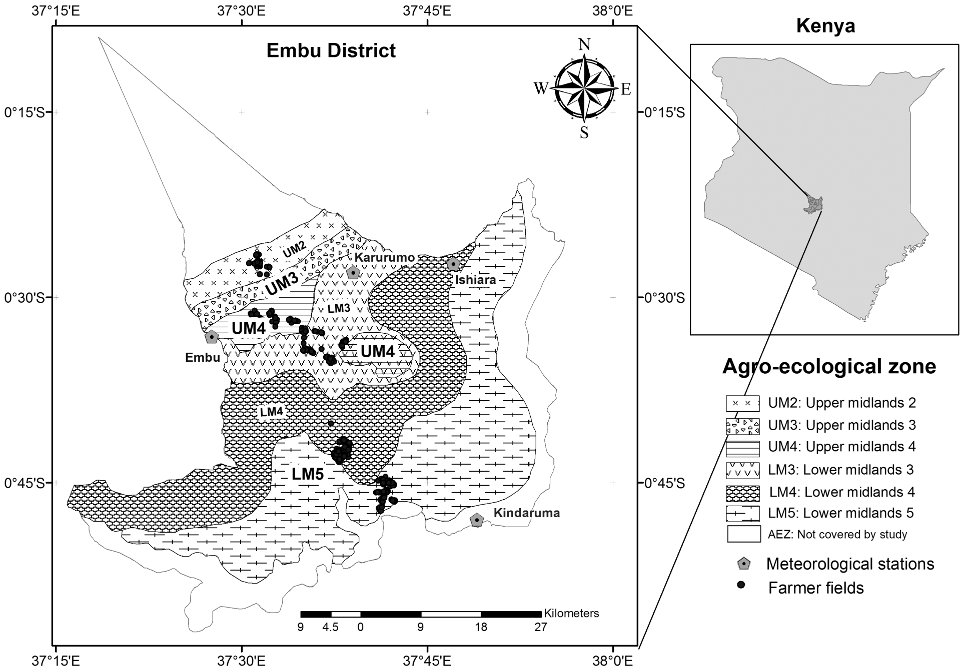

Fig. 2. Target AEZs in Embu County (based on Jaetzold *et al.*, 2007).

condition characterized by severe deprivation of basic human needs, including food, safe drinking water, sanitation facilities, health, shelter, education, and information (UN, 1995). Chronic poverty is a condition whereby an individual or group is in a state of poverty over an extended period of time (Aaberge and Mogstad, 2007).

Agriculture in the county is predominantly rainfed and highly dependent on seasonal rainfall patterns. The seasonality is associated with the annual migration northwards and southwards of the Intertropical Convergence Zone (ITCZ) (Griffiths, 1972; Jackson, 1989; Osei and Aryeetey-Attoh, 1997), which is located over the equator in March to April and again in October to November. Consequently, the areas nearest to the equator, such as parts of Kenya and Tanzania, experience two distinct rainfall seasons during the year. Away from the equator, in south Tanzania and north Ethiopia, there is only one rainy season. Agricultural systems in the region have evolved along these climatic patterns. The average rainfall in the county varies from more than 2200 mm at an altitude of 2500 m to less than 600 mm near the Tana River at 700 m. The average temperatures vary from 28.8°C in the hottest month to 9.6°C in the coldest month (Jaetzold *et al.*, 2007).

The county is divided into 11 AEZs based on the probability of their meeting the temperature and water requirements of the main crops grown (Table 1). The upper highlands (UH0) and lower highlands (LH0) are so wet and steep that forest

Table 1. AEZs of Embu County and climate of the zones (Jaetzold *et al.*, 2007).

AEZ		Altitude (m)	Annual mean temperature (°C)	Annual rainfall (mm)
UH0	Upper highland forest zone	>2500	NA	NA
LH0	Lower highland forest zone	>2500	NA	NA
LH1	Lower highland tea–dairy zone	1900–2100	17.7–15.8	1750–2000
UM1	Upper midland coffee–tea zone	1600–1850	18.9–17.5	1400–1800
UM2	Upper midland main coffee zone	1400–1600	20.1–18.9	1250–1500
UM3	Upper midland marginal coffee zone	1280–1460	20.7–19.6	1000–1250
UM4	Upper midland sunflower–maize zone	1200–1400	20.9–20-0	980–1100
LM3	Lower midland cotton zone	1070–1280	22.0–21.0	900–1100
LM4	Lower midland marginal cotton zone	980–1220	22.5–21.0	800–900
LM5	Lower midland livestock–millet zone	830–1130	23.9–21.7	700–800
IL5	Inner lowland livestock–millet zone	600–850	25.4–24.0	500–710

is the best land use. In the lower highlands zone (LH1) and upper midland zone (UM1), precipitation is 1800 mm or more and average annual temperatures are less than 18°C. The predominant cropping systems there are tea- and coffee-based. The contribution of these AEZs, along with the relatively small inner lowland (IL5) zone, to food production in the county is fairly small. The remaining seven zones, ranging from the upper midland main coffee zone (UM2) to the lower midland livestock–millet zone (LM5), are the main cropping areas. The rainfall during the main crop growing period declines rapidly from UM2 to LM5.

Soil and climate data

Long-term historical climate data for several locations in Embu County for the baseline period 1980–2010 were collected from the archives of the Kenya Meteorological Department (KMD) to characterize variability in the observed climate, develop future scenarios, and to use with the crop simulation models, DSSAT (Decision Support System for Agrotechnology Transfer) and APSIM (Agricultural Production Systems Simulator) (IBSNAT, 1989; McCown *et al.*, 1996). Though the minimum data requirement includes daily records of rainfall, minimum and maximum air temperatures, and solar radiation, the KMD has only one synoptic station located at the Embu Research Farm of the Kenya Agricultural Research Institute (KARI) where data on all the required parameters are collected. At all other stations in the county, only rainfall measurements are taken, and for many of these locations, available data are incomplete. From the available data, four stations for which good-quality data (with less than 10% missing records) are available were selected. These include the synoptic station Embu for AEZs UM2 and UM3 and rainfall stations Karurumo for LM3, Ishiara for LM4, and Kindaruma for LM5. Historical climate

Table 2. Key climate characteristics of the selected AEZs in Embu County.

	AEZ			
Variable	UM2 and UM3	LM3	LM4	LM5
Average rainfall (mm)				
Annual	1248 (26)	1141 (24)	823 (25)	833 (29)
LR season	583 (35)	471 (25)	327 (26)	331 (33)
SR season	490 (39)	565 (37)	431 (37)	407 (43)
Average temperature (°C)				
Annual mean	19.4	19.1	21.2	22.4
Annual maximum	24.5	24.3	26.9	28.1
Annual minimum	14.2	13.8	15.5	16.7
LR season mean	20.5	20.3	22.5	23.8
LR season maximum	25.6	25.6	28.3	29.5
LR season minimum	15.4	15.0	16.7	18.0
SR season mean	19.6	18.9	20.8	22.3
SR season maximum	24.7	24.0	26.4	27.8
SR season minimum	14.4	13.7	15.3	16.7

Note: Figures in parentheses represent coefficient of variation (CV).

data were subjected to quality control by using R-Climdex (Zhang and Feng, 2004), which flagged out the spurious values. Bias-corrected AgMERRA (Ruane *et al.*, 2014) datasets were used to fill the missing values and to replace the spurious ones. The bias correction was achieved by calculating a correction factor between each variable of the MERRA data and the corresponding observations for every month and employing the factor on the MERRA data to estimate the missing values. For the three locations, Ishiara, Karurumo, and Kindaruma (for which only precipitation data is available) other variables were all estimated from the MERRA data by using correction factors for the Embu station.

The Embu and Karurumo sites, which receive more than 1000 mm rainfall annually, are generally considered as high-potential areas, while the Ishiara and Kindaruma sites (with about 800 mm rainfall annually) are considered as medium-to-low potential areas for maize production (Table 2). Rainfall in the region is bi-modal with two distinct rainy seasons, which are locally referred to as the short rains (SR) season from October to December and the long rains (LR) season from March to May.

In general, the SR season receives more rain than the LR season. This is true for all the selected sites except Embu, where rainfall during the LR season is 19% higher than that during the SR season. Rainfall at all sites showed high temporal variability, with a coefficient of variation greater than 25%. Annual rainfall at Embu and Kindaruma sites showed higher variability than that at Ishiara and Karurumo.

At all sites, variability in rainfall during the SR season is higher than that during the LR season. Embu, with an altitude of about 1500 m above mean sea level, is the coolest of the four sites used in this assessment. Temperatures during the LR season are higher compared to the SR season at all sites. The county experiences higher temperatures during the period February to April and lower temperatures during July to September.

The main source of soil data is reports of the Soil Survey Division of KARI. The county is mostly covered by four distinct soil types (Fig. 3) and one representative soil profile for each soil type was selected for use with the DSSAT and APSIM crop models. The first group of soils (RB1, RB2, and RB3) is a well-drained, extremely deep, reddish brown to dark brown, friable and slightly smeary clay, with acid

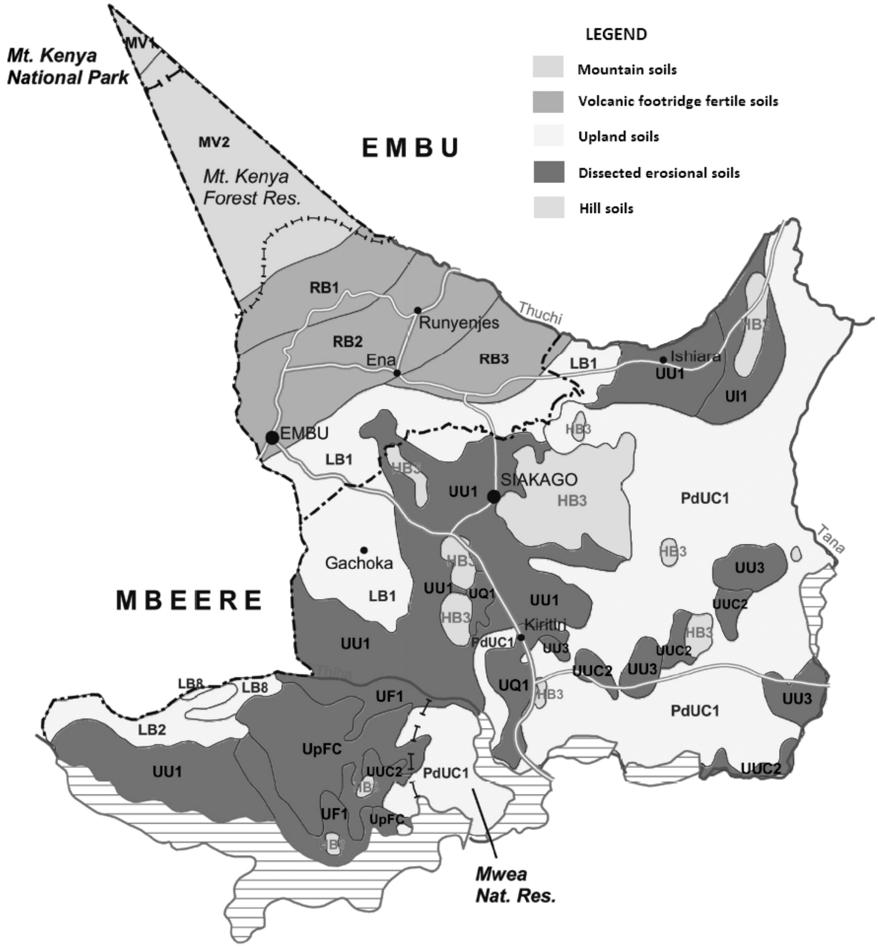

Fig. 3. Distribution of soil types in Embu County (Jaetzold *et al.*, 2007).

Table 3. Properties of soil profiles representing AEZs in Embu County.

Soil Properties	Embu	Kavutiri	Gachuka	Machanga
Target AEZ	UM2	UM3 and LM3	LM4	LM5
Soil type	Typic Palehumult	Othoxic Palehumult	Typic Haplorthox	
Soil layers/depth (cm)	4/102	6/200	4/104	4/80
Sand, silt, clay (percentage in 0–15 cm)	20, 24, 56	20, 26, 54	20, 24, 56	—
Plant available water	93.7	152.2	89.4	100
Organic matter (top three layers)	2.09, 1.49, 0.91	3.61, 2.29, 1.58	2.29, 1.58, 0.92	0.58, 0.5, 0.4

humic topsoil. The soil profile selected to represent this type is Kavutiri. The area demarcated on the map as LB1 is represented by the Embu soil profile, which is a well-drained, very deep, dark red, very friable clay soil. The third soil profile Gachuka represents the area demarcated on the map as PdUC1, which is a complex of well-drained, shallow, dark red to yellowish red, friable to firm, stony, loamy sand to clay soils. The fourth profile, Machanga, covers the region marked on the map as UU. The soils in this area are well-drained, shallow to deep, dark red to yellowish brown, loose loamy sand to friable sandy clay loam with rocky and stony inclusions. These soil types are generally classified as entisols and oxisols.

The profile description taken from the soil survey reports is considered to represent average soil conditions in the study area. Considering the high variability in soil conditions across the farms and the need to account for the same, for each of the soil profiles selected three variants (good, average, and poor) were created by increasing or decreasing the soil organic matter and plant available water contents by 20%. With these variants, a total of 12 soil profiles were created, and a summary of the key characteristics of the profiles under the category "good" is presented in Table 3. These profiles are assigned to individual farms, based on the location of the farm and the perception of the farmer about the fertility status of his farm as captured in the survey. During the survey, farmers were asked to rate the fertility status of their farm as "good", "average", or "poor" when compared to general conditions in the farms of that area.

Farming systems

The most common farming systems in the county are small-scale cash-crop and subsistence farming (Fig. 4). The cropping patterns are determined by the district

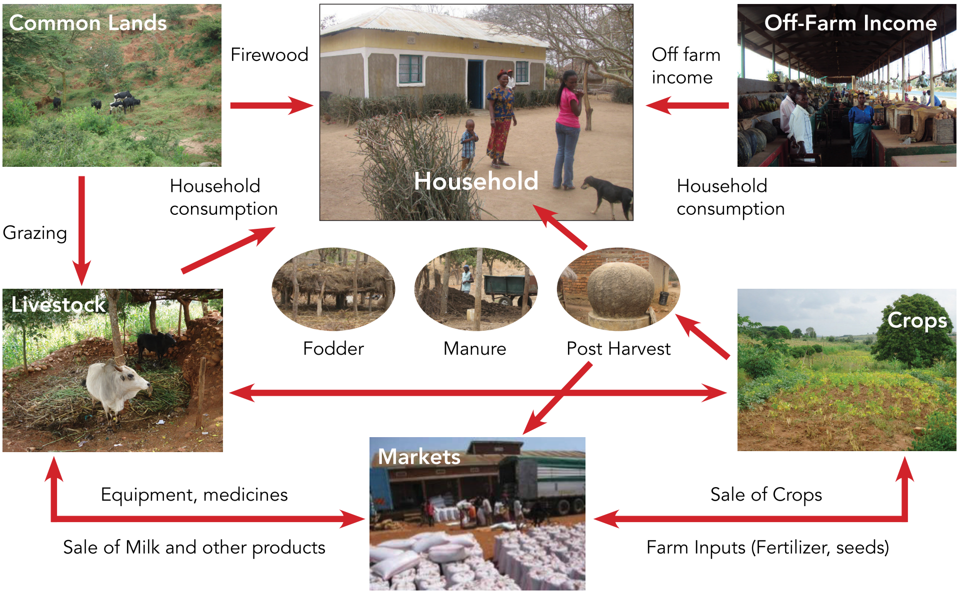

Fig. 4. Typical East African farming system showing main components of the system and their relationships.

Table 4. Characteristics of smallholder farms in AEZs of Embu County.

AEZ	Mean household size	Mean farm size (ha)	Mean dairy herd size	Fertilizer use (kg N/ha)	Dominant maize variety	Average maize yields (kg/ha)
UM2	4.3	0.91	2.29	12.1	DK41, H513	1030
UM3	5.7	2.21	1.79	15.0	Duma, H513	1195
LM3	5.8	1.85	1.83	12.8	Duma, DK43, Katumani,	1021
LM4	6.5	2.43	2.2	9.4	Katumani, Duma, DK43	960
LM5	6.9	1.74	1.88	4.1	Katumani, Duma	525

AEZs. The intensity of land use decreases from upper midland zones to lower midland zones. Some important characteristics of the farming systems in the target AEZ areas are shown in Table 4.

Agriculture in the selected AEZs is characterized by extreme dependence on rainfall. The amount and fluctuations in the temporal distribution of rainfall and surface temperature are the most important determinants of interannual variability in crop production. Farmers practice low-input agriculture that is low in productivity mainly due to the risk associated with erratic and unreliable rainfall during and between the seasons. A mixed crop–livestock system is the most widespread practice.

In UM2, UM3, and UM4, key crops are maize and beans, but farmers also grow coffee as a cash crop. In addition, they also plant bananas, vegetables, and sweet potatoes. Crops grown by farmers in LM3 are similar to those grown in UM2 and UM3 except coffee. Some farmers in this AEZ grow sorghum and millet on small areas. Farmers in LM4 and LM5 plant pigeon peas in addition to other crops grown in LM3. Though farmers in all AEZs grow maize, there are significant differences in the variety grown and in the management employed. Farmers in the high-potential UM2, UM3 and LM3 areas use long-duration high-yielding varieties, while those in the low-potential LM4 and LM5 areas favor short-duration varieties as a drought-escaping strategy. In general, use of fertilizer is very low and the number of farmers using fertilizer, especially in agroecologies LM4 and LM5, is very limited. The areas occupied by various crops also vary from farm to farm and from season to season.

Stakeholder Interactions, Meetings, and Representative Agricultural Pathways

Currently, besides growing maize, farmers in different AEZs of Embu County are involved in various other farming activities. These systems are dynamic and hence there is the need for representative agricultural pathways (RAPs) to predict potential future scenarios both at farm level and also at the household level. The impacts of climate change and vulnerability of the communities are long term in nature and depend on socio-economic developments and on how these developments shape the future agricultural systems. RAPs were developed to project the current production system into the future. RAPs are combinations of economic, technology, and policy scenarios that represent a plausible range of possible futures. They are qualitative storylines that can be translated into model parameters such as farm and household size, prices and costs of production, and policy. To this end, discussions were held with representatives from different government and non-governmental agencies and other organizations about current and future trends in agriculture and other socio-economic developments to map future agricultural systems. The RAPs meeting was held at the World Agroforestry Centre offices in Nairobi in June 2013, and it attracted 16 participants from government agencies, universities, CGIAR organizations, and the local research organization.

In development of the RAPs, we presented the stakeholders with two scenarios; an optimistic one and a pessimistic one as discussed by Claessens *et al.* (2012). In the optimistic one, it is assumed that Kenya follows a more positive economic development trajectory than in the past 30 years, with higher rates of economic growth, movement of labor out of agriculture into other sectors, reductions in rural household size, and increases in farm size. In addition, investments in transportation and communication infrastructure are expected to increase, and more open trade and liberalized domestic policies will be adopted. This scenario also assumes higher real prices for traded agricultural commodities such as maize and also policy changes and infrastructure improvements, which will lead to lower real prices of critical agricultural inputs such as mineral fertilizer and improved seeds.

The pessimistic scenario assumes that Kenya will continue experiencing a low rate of economic growth; population growth rates will remain high, rural populations will increase, farm sizes will decline, and rural household sizes increase. In addition, transportation infrastructure will deteriorate, and the government will adopt trade policies that discourage exports so that prices to farmers remain at current levels. Taxes on imports of critical inputs such as fertilizers are expected to increase and soil fertility and agricultural productivity will continue to decline to an even lower level equilibrium than was observed in the early part of the 21st century.

Given the two projected development paths, the stakeholders agreed to work with the business-as-usual scenario, which was mostly reflected by the optimistic scenario. After identifying the projected development path, stakeholders were presented with a matrix of different bio-physical, socio-economic, institutional, and technological indicators that were expected to change in the future. Discussions were then held on the directions and magnitudes of the different indicators and why they believed this was going to be the case. For some indicators, stakeholders would readily agree, while for others such as change in farm sizes, there were split opinions both on the magnitude and direction.

Data and Methods of Study

The assessment used AEZs representing unique combinations of climatic and soil conditions that are homogeneous with regard to their capacity to support production of a wide range of food and cash crops as the unit for evaluating the impacts of climate variability and change. Relevant data required to calibrate, validate, and apply climate, crop, and economic models for each of the seven target AEZs was collected from various secondary sources which include informal publications such as research reports.

Since data on several parameters required by the crop and economic models are not readily available, a survey was done in Embu County to characterize the smallholder nfarming systems in the target AEZs. The information collected included various enterprises that the farmers are involved with, their management and productivity, as well as sources of non-farm income to the households. The methodology used for data collection was a combination of stratified and multi-stage sampling. The strata for the survey were the selected AEZs, which include UM2, UM3, LM3, LM4, and LM5. At each AEZ, administrative regions were chosen (division, location, and sublocation) and one sublocation representing each AEZ was chosen for

Table 5. Distribution of sampled households by AEZ in Embu County.

AEZ	Division	Number of households
UM2	Kevote, Nembure	81
UM3	Kithimu, Nembure	89
LM3	Riandu, Siakago	107
LM4	Nyangwa, Gachoka	92
LM5	Mavuria, Gachoka	84

sampling. At the sublocation level, data collection was by simple random sampling. The sublocations chosen for sampling were Kevote in UM2, Kithimu in UM3, Riandu in LM3, Nyangwa in LM4, and Mavuria in LM5. A total of 453 households were sampled, as shown in Table 5.

Climate

Observed trends in temperature and precipitation

A clear increasing trend in the maximum and minimum temperatures was observed since 1990 (Fig. 5). Though both maximum and minimum temperatures have increased, the increase in maximum temperatures is higher than that in minimum temperatures. The average annual maximum temperatures during the period 2001–2010 were 0.54°C higher than the temperatures recorded during the period 1980–1989, while the corresponding increase in minimum temperature was 0.30°C. Differences were also observed between the two rainy seasons with higher

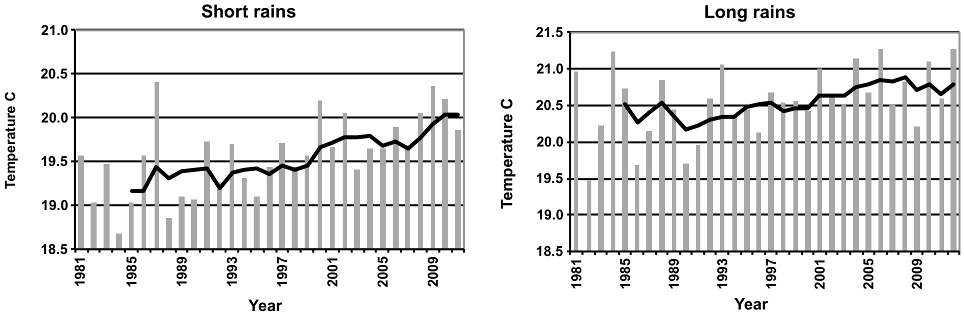

Fig. 5. Variability and trends in average air temperature during short and long rain seasons in Embu County during the period 1980–2010.

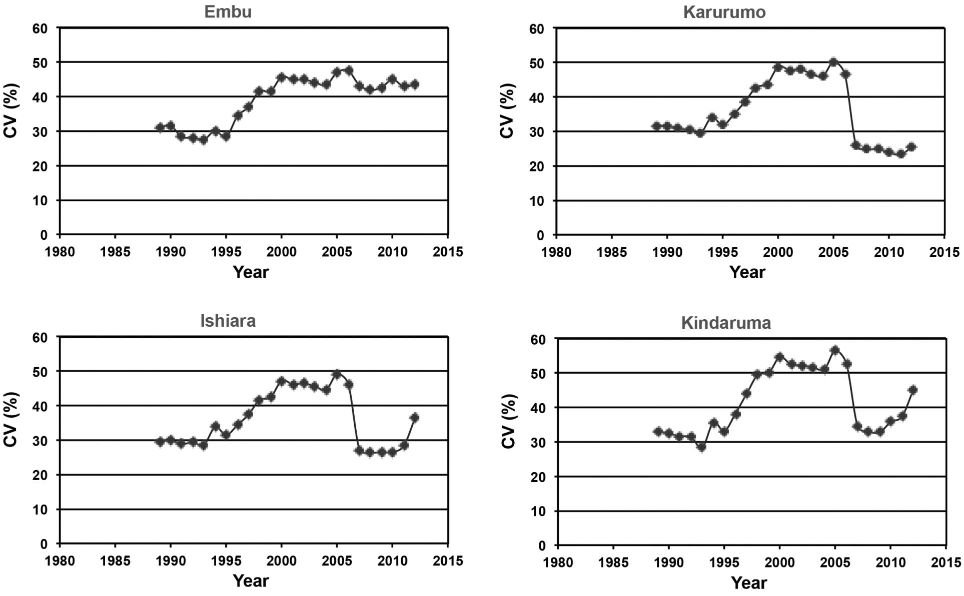

Fig. 6. Ten-year moving coefficient of variation (CV) of rainfall starting from 1980 during SR season at four sites in Embu County.

increase during the SR season in both minimum and maximum temperatures. The average annual temperatures in 2001–2010 were higher by 0.57°C during the SR season and by 0.49°C during the LR season, compared to the 1980–1989 period.

While no clear trend was observed in the amount of rainfall received annually or seasonally during the baseline period from 1980–2010, there are indications that variability in rainfall, as indicated by the trends in the ten-year moving coefficient variation (CV), is increasing during the SR season and decreasing in the LR season (Fig. 6). This is a significant change, since the SR season is the period in which the main food crop (i.e., maize) is grown and is generally considered as more reliable in the region.

The Mann–Kendall tau-b non-parametric function that computes a coefficient representing strength and direction of trend in equally spaced data was used to test the significance of the observed trends in temperature and rainfall (Table 6). The p values from the test indicate that the trends in temperature are significant at less than 0.02; trends in rainfall are less conclusive due to strong interannual and interdecadal variability.

Table 6. Kendall tau significance test for annual and seasonal precipitation and temperature at different locations in Embu County.

		Temperature	Precipitation			
		EMBU	Embu	Ishiara	Karurumo	Kindaruma
Annual	Kendall's tau	0.43	0.22	0.34	0.12	0.38
	p-value	0.00	0.13	0.02	0.45	0.01
SR season	Kendall's tau	0.30	0.26	0.14	0.14	−0.05
	p-value	0.02	0.08	0.36	0.34	0.75
LR season	Kendall's tau	0.35	0.52	0.10	−0.03	0.29
	p-value	0.01	0.00	0.51	0.86	0.05

Climate projections

Since it is not practical to assess impacts of climate change on agricultural systems at the local scale with coarse data from coupled atmosphere–ocean general circulation models (AOGCMs), location-specific climate change scenarios were developed by using a simple delta method in which monthly changes in temperature and precipitation from an AOGCM, calculated on the grid scale, are added to the corresponding observed station data. The delta method assumes that future model biases for both mean and variability will be the same as those in present day simulations (Wilby *et al.*, 2004). Climate change scenarios for mid-century (2041–2070) and end-century (2071–2100) periods were developed for 20 AOGCMS from the Coupled Model Intercomparison Project phase 5 (CMIP5) for two representative concentration pathways (RCPs) 4.5 and 8.5 (Moss *et al.*, 2010; Taylor *et al.*, 2012).

Downscaled CMIP5 projected climate change scenarios showed a general increase in surface temperatures and precipitation for the four locations in Embu County (Fig. 7). However, magnitude of this increase varied over different time-periods and RCPs. Projections by using HadGEM2-CC, HadGEM2-ES, and MIROC-ESM showed higher increase in maximum temperatures, while those from CanESM2, INMCM4, MRI-CGCM3, and NorESM1-M showed very marginal increase. The highest increase in annually average maximum temperature across all scenarios was 4.8°C. Projected minimum surface temperature is also increasing but the increase in minimum temperature is projected to be higher than that in maximum temperature. The BNU-ESM, GFDL-ESM2G, GFDL-ESM2M, and NorESM1-M climate models showed only a marginal increase in temperatures. The maximum increase in minimum temperature is 5.8°C (Fig. 7).

The GFDL-ESM2G, HadGEM2-CC, HadGEM2-ES, MIROC5, and NorESM1-M GCMs project declines in annual rainfall from –0.5% to –25%, while the

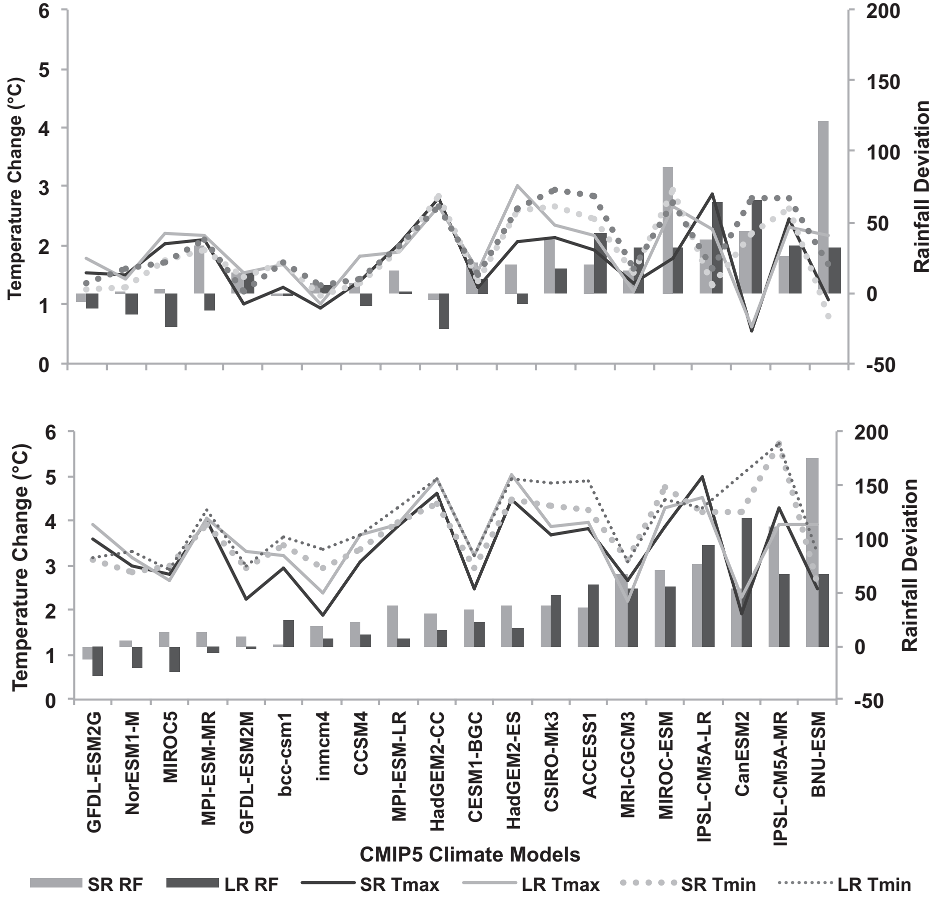

Fig. 7. Projected changes in rainfall (percent deviation from historic rainfall) and temperatures (absolute change) under RCP4.5 and8.5 to mid-century in Embu County (RF=rainfall, SR=short rains, LR=long rains, Tmax=maximum temperature and Tmin=minimum temperature)

other GCMs projected an increase across RCPs and time-periods. The BNU-ESM projected the highest increase in precipitation compared to the other GCMs. Precipitation increases considerably in RCP8.5 compared to RCP4.5.

Projected changes in mean surface temperatures and precipitation for individual months and crop seasons were also investigated. Future projected changes in mean surface temperature and precipitation records for five GCMs (CCSM4, HadGEM2ES, MIROC5, MPI ESM, and GFDL) were anyzed at monthly and seasonal intervals for two RCPs and time-periods as depicted in Fig. 8 for end-century period. In both scenarios the increase in temperature and precipitation is expected to be high during LR season (MAM).

Crops

Crop management parameters used in setting up crop model simulations for individual farms were derived from the results of the survey conducted in the target AEZs. The survey captured, among other things, variety used, date planted, and amount of seed, fertilizer, and manure applied during the 2012 LR and SR seasons, and harvested yields. Farmers in the region used a large number of varieties. The varieties mentioned by farmers during the survey included Local, DK41, DK43, H513, H613, Duma, and Pioneer. In setting parameters for these varieties, we have identified and used an equivalent variety for which data are available to derive model parameters. The identification of the equivalent variety is based on the duration and yield potential of that variety. Table 7 presents the farmer-used variety and its equivalent use in the crop model simulations. Katumani is used as the local variety.

Plant population estimates for individual farms were set based on the amount of seed used by farmers. Previous studies on farmer fields by KARI-Embu have reported that the plant population normally used by farmers varied from 30,000 plants/ha to 50,000 plants/ha. Accordingly, a plant population of 30,000 plants/ha was assigned to farmers using seed rates lower than 15 kg/ha, 40,000 plants/ha for those using 15–20 kg/ha, and 50,000 plants/ha for those using more than 20 kg/ha. The distribution of farmers in these three groups is presented in Table 8. The majority of the farmers were found to be using 30,000 plants/ha. Only 5% of the sampled farmers are in the category of sowing 50,000 plants/ha.

Survey results indicated large differences in the amount of fertilizer used by farmers in different AEZs (Table 9). Similar differences were also observed in the use of manure. While setting up the crop models for individual farms, we used the actual amounts applied by the farmers. The type of fertilizer used by farmers is mainly ammonical (calcium ammonium nitrate, di-ammonium phosphate, and NPK complex). A uniform depth of 5 cm was used for placing the fertilizer, and the entire amount was applied once, at the time of sowing.

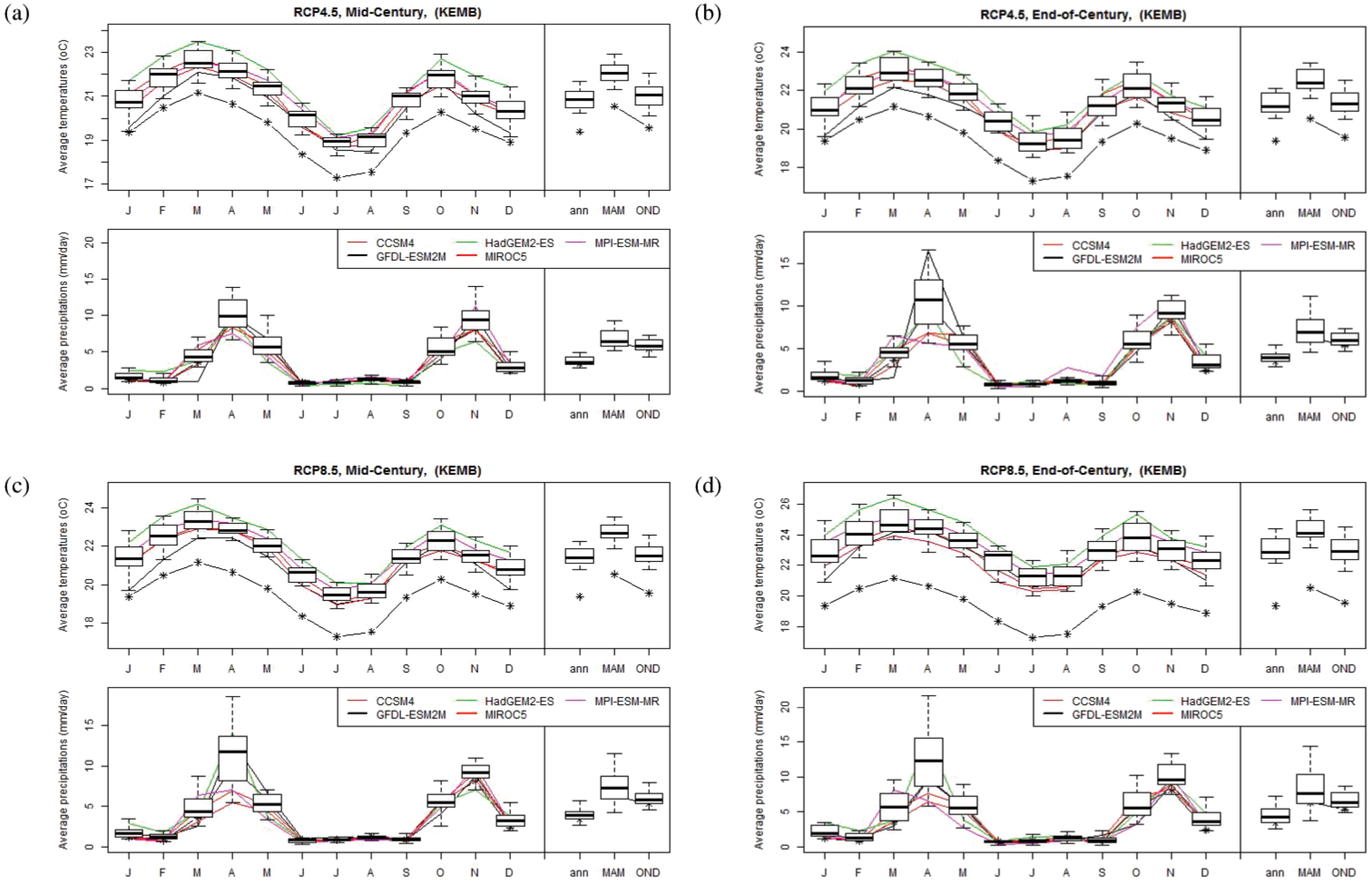

Fig. 8. Projected changes in monthly, seasonal, and annual temperature and precipitation (a) 4.5 mid-century (2014–2070), (b) 4.5 end-century (2071–2100), (c) 8.5 mid-century (2041–2070), (d) 8.5 end-century (2071–2100) at Embu in Kenya.

Table 7. Maize varieties used by farmers in different AEZs in Embu County and their corresponding equivalent cultivar in the model.

Variety used by farmer	Duration (months)	Yields (t/ha)	Variety in crop models used
DK41		5–6	Deka_lb
DK43		6–7	H511
H513	4–5	6–8	H511
H613	6–8	8–10	H513
Local	All		Katumani
Duma	4–5	6–7	H511
Pioneer	5–6	8–10	H513
Others	Considered as local		Katumani

Table 8. Number of farmers using different levels of plant population in different AEZs of Embu County.

Plant population (plants/ha)	UM2	UM3	LM3	LM4	LM5	Total
30,000	31	55	50	69	63	268
40,000	39	27	48	18	18	150
50,000	3	5	8	4	1	21

Table 9. Number of farmers under different levels of fertilizer use (kg/ha) in the five different AEZs of Embu County.

Fertilizer (kg/ha)	UM2	UM3	LM3	LM4	LM5	Total
<10	10	7	16	20	47	100
10–25	25	12	14	27	24	102
25–50	30	24	32	43	25	154
>50	21	38	34	19	5	117

Crop model calibration (DSSAT and APSIM)

The maize varieties H511, H513, Dekalb, and Katumani were selected to represent the varieties used by farmers in the county. DSSAT and APSIM were calibrated for these maize varieties using the unpublished data from a study conducted on the research farm of the KARI-Embu research station. The trial was conducted during the period 2000–2002 over three seasons (SR season of 2000 and SR and LR seasons of 2001) and tested three varieties, *viz.*, H511, H513, and Katumani. Available data included dates of sowing, days to tasseling and flowering, days to maturity, and grain and dry matter yields, at harvest and also during the crop growing periods. For

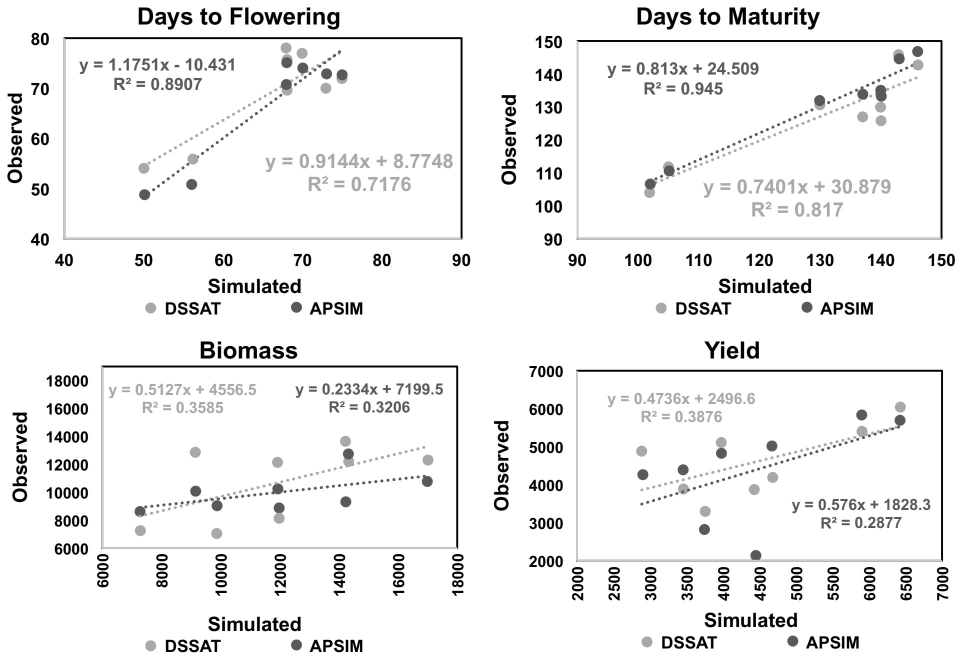

Fig. 9. Relationship between DSSAT and APSIM simulated and observed days to maturity, days to flowering, grain yield (kg/ha), and biomass yield (kg/ha) for the varieties H511 and H513.

the Katumani variety, default parameters already available with APSIM and DSSAT were used without any changes. In the case of H511 and H513, parameters were derived by manipulating the thermal time required to complete various growth stages until the simulated phenology matched the observed phenology. Simulations with the final set of parameters by both crop models indicated a good relationship between observed and simulated days to flowering and days to maturity (Fig. 9). However, the model-simulated biomass and grain yield did not display good agreement with the observed data. This is mainly due to lack of information regarding the management practices employed in these trials and lack of data on initial soil moisture and fertility conditions.

Additional model parameterization and validation

Model sensitivity to various environmental parameters was examined by conducting a matrix of simulations designed to understand the response of DSSAT and APSIM crop models to changes in maximum and minimum temperatures, precipitation, and atmospheric CO_2 concentrations. Embu climate data for 30 years (1980–2010)

Table 10. Response of maize to changes in temperature and rainfall in Embu County as simulated by APSIM and DSSAT.

	APSIM		DSSAT	
Treatment	Biomass yield (kg/ha)	Grain yield (kg/ha)	Biomass yield (kg/ha)	Grain yield (kg/ha)
Effect of temperature and rainfall				
Base Climate	9525	2207	4468	2450
Base+1°C	9181 (–4%)	2326 (+5%)	6711 (50%)	2461 (0%)
Base+3°C	8617 (–10%)	2593 (+17%)	7398 (66%)	2690 (10%)
Base+5°C	8001 (–16%)	2697 (+22%)	7788 (74%)	2811 (15%)
Base+1°C+10%RF	9364 (–2%)	2473 (+12%)	6383 (43%)	2343 (–4%)
Base+3°C+10%RF	8753 (–8%)	2681 (+21%)	7038 (57%)	2549 (4%)
Base+5°C+10%RF	8155 (–14%)	2814 (+27%)	7381 (65%)	2657 (8%)
Base+1°C–10%RF	9021 (–5%)	2187 (–1%)	6992 (56%)	2562 (5%)
Base+3°C–10%RF	8463 (–11%)	2424 (+10%)	7723 (73%)	2842 (16%)
Base+5°C–10%RF	7811 (–18%)	2628 (+19%)	8117 (82%)	2958 (21%)

RF=rainfall

were used for the sensitivity analysis. Table 10 compares the average maize yields simulated by the two crop models under different climatic conditions. In general, APSIM simulated higher biomass yield compared to DSSAT under all conditions. While both models simulated fairly similar responses in grain yield to changes in temperature and rainfall, they differed in the way total biomass was estimated. Simulations with APSIM indicated a decline in the total biomass, while those by DSSAT indicated an increase. A reduction in the crop growing period is considered as the main reason for reduced biomass production in the APSIM simulations, and the main contributor for higher biomass production with DSSAT is unclear since the CO_2 concentration in these simulations kept constant. APSIM is insensitive to changes in atmospheric CO_2.

Crop model results (*DSSAT and APSIM*)

After calibration, the crop models were used to simulate the yields of 440 farmers covered by the survey, by setting up farmer-specific climate, soil, crop, and management parameters. In order to evaluate the performance of the crop models in reproducing maize yields for the season 2011–2012 captured in the survey, simulations were made with DSSAT and APSIM for the short rainy season 2011–2012 for 160 farmers represented by the Embu climate. Since the required daily climate data for this season are not available for the other three meteorological stations (Ishiara, Karurumo, and Kindaruma), simulations were not made for the remaining 280 farms that are covered by these three stations. The simulated yields are generally higher

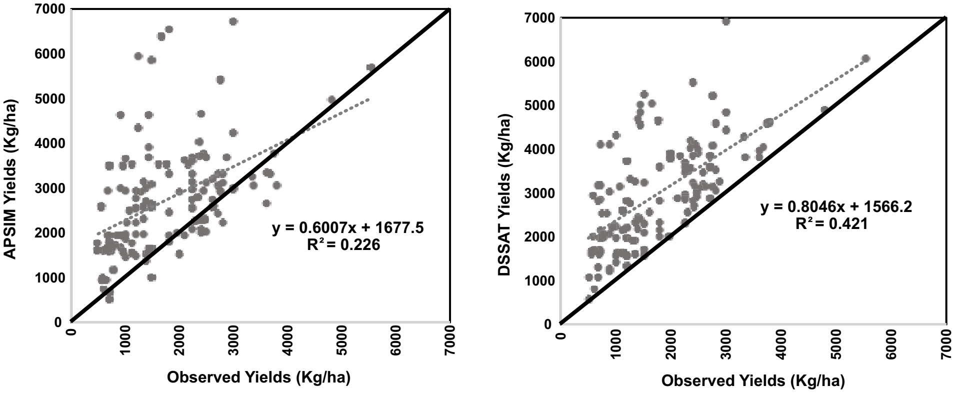

Fig. 10. Relationship between DSSAT and APSIM simulated grain yields and survey yields for the 2010–2011 short rain season in Embu County. (Black line in 1:1.)

than the yields reported by farmers (Fig. 10). The differences between simulated and observed yields varied from as little as 20 kg/ha to as high as 4000 kg/ha. This could be attributed to various factors such as differences in interpreting and translating farmers' descriptions of their resource endowment into model parameters, inability of the models to capture the effects of biotic stresses such as pests, diseases, and weeds, inaccuracies in estimating yields especially in the mixed/intercropping systems that are widely practiced, and inaccuracies in defining the initial conditions. However, the simulated long-term yields of the different AEZs reflected the trends in the yields reported by farmers fairly well, especially in the low-potential LM4 and LM5 AEZs. This is mainly due to high moisture stress experienced by the crops that, to a large extent, masked the effect of management and differences in the resource base.

Economics

Survey data and strata

Farm sizes in the region varied from one AEZ to the other but tend to be smaller in UM2 and larger in LM4 as shown in Table 11. The areas occupied by the different crops also varied from farm to farm and from season to season.

In general, yields of maize are very low mainly due to low levels of inputs used by the farmers. The average yields of maize varied from 1 t/ha in the relatively high-potential areas of UM2, UM3, and LM3 to 0.5 t/ha in the low-potential LM5. Maize yields did not vary significantly between SR and LR seasons in UM2, UM3, and LM3, but varied by about 200 kg/ha in LM4 and LM5 (Table 12). This could be explained by depressed rainfall in the LR seasons in the two AEZs, which received

Table 11. Average farm size of the sample households in different AEZs of Embu County.

AEZs	Mean farm size (ha)	Standard deviation
UM2	0.91	0.75
UM3	2.21	2.80
LM3	1.85	0.97
LM4	2.43	3.41
LM5	1.74	1.22

Table 12. Average maize yields of surveyed households during SR and LR seasons in different AEZs of Embu County.

	Maize yields SR (kg/ha)		Maize yields LR (kg/ha)	
AEZs	Mean	Std. dev.	Mean	Std. dev.
UM2	1029.6	636.7	1187.3	632.6
UM3	1194.8	845.6	1120.8	787.5
LM3	1020.9	719.9	901.4	665.1
LM4	959.9	658.6	739.7	556.4
LM5	525.4	381.9	363.7	309.2

Table 13. Non-agricultural income (Kenya shillings per year) by source of surveyed households in Embu county.

Income source	Number of households	Mean	Std. Dev.	Min.	Max.
Formal employment	45	223,585	200,906	7,000	800,000
Business	221	110,761	118,001	1,800	960,000
Rental income	18	83,889	108,859	1,500	480,000
Off-farm labor	99	27,031	33,675	1,000	240,000
Remittances	39	28,446	44,130	2,000	240,000
Shares	5	49,600	84,468	2,000	200,000
Others	2	26,500	28,991	6,000	47,000
Total	328	122,366	150,009	1,500	960,000

Note: 1 USD=KSh. 85 at the time of survey.

a relatively low amount of rainfall during this season compared to the other three AEZs.

In addition to agriculture, farmers depend on income from other sources, which vary from formal employment and businesses to remittances from family members (Table 13). The key source of non-agricultural income for most farmers is business, followed by off-farm labor.

RAP narrative and development

RAPs were developed against a background of demographic and socio-economic developments in the country such as: (1) devolution of government[1]; (2) increasing population; (3) government plans to invest in fertilizer manufacture; (4) current government subsidies on fertilizers; (5) improved economic performance expected to cause shifts from agriculture to service industries; (6) government plans for expansion of irrigation (from the current 120,000 ha to over 1,000,000 ha); and (7) expected increase in extension services and application of climate information by farmers.

A combination of these factors is expected to change the future outlook and impact of climate change. For example, it is assumed that with increased family-planning campaigns and increases in literacy levels, family sizes are expected to decrease by 30% in future. There is also the expectation that farmers will diversify into other non-farming activities to supplement their incomes, and hence non-farming income will increase by 50%. Given the current family sizes, farm subdivision is expected to continue. However, this will be countered by rural–urban migration, as rural populations move to cities to search for better opportunities. The trend will be accelerated by devolution of political and economic power to the county level. This increased urbanization, lack of interest in agriculture among the youth, and devolution is expected to have a net effect of increasing farm sizes by 30%.

Dairy herd sizes are expected to remain the same, although farmers in LM4 and LM5 might abandon their traditional breeds and opt for higher-yielding breeding so as to increase their milk output. With increased urbanization and growing population, the demand for milk is expected to increase and the price of milk to rise by 50%. However, it is expected that the cost of milk production will increase by 20% due to a shift towards processed feeds, which are more costly.

In crop production, there has been a sustained increase in the price of fertilizers in the past few years. This trend is expected to continue, but there are two factors that might slow it and even overturn it: The planned establishment of a fertilizer factory by the Kenyan government and the discovery of oil in Kenya. The net effect is an estimated 20% decline in fertilizer prices. There has also been an increase in improved maize seed prices due to increased demand by farmers. At the same time, the seed sector has witnessed increased competition due to entry of many competitors, which might slow seed price increases. The AgMIP RAP for the region therefore predicts an 80% increase in seed prices. The other component of variable costs expected to change is the cost of hired labor. This is because many people would opt to work off the farm, as the reward to labor from farming is not giving

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[1] With the promulgation of the new constitution, Kenya has been divided into 47 county governments, and each has a different development agenda. Different policies in areas of agricultural development, food security, and poverty alleviation, etc., are expected to evolve from the different governments.

them enough compensation. Many young men are opting for other jobs such as transporting people and goods using motorbikes (*boda bodas*), and this is taking labor out of agriculture. The cost of labor is therefore expected to increase by 60%. The prices of other crops such as coffee, beans, and sorghum/ millet are expected to increase by 10%. This information is summarized in Table 14 below.

Adaptation Package

Strong trends in climate change showed the increasing scale of potential climate impacts on local crop varieties and crop management practices in the study area. Potential adaptation options vary with the scale of projected impacts. Since maize crop yields are marginally increasing or decreasing in the future projected climate change scenario, we show the implementation of better performing crop varieties with best crop management practices can cope with a harsh and highly variable climate. Developing adaptation measures based on the best performing crop variety, crop management practices, and suitable planting date is likely to have substantial benefits under a moderate climate change scenario.

Adaptation planning incorporates scientific information both from projections of climate and its impacts on crop productivity. There is a high diversity of agricultural practices in the study region because of the range of climate and other environmental variables and economic factors. Here we present a framework of adaption options based on the performance of crop varieties, crop management practices, and planting windows in the study areas. From the above crop simulation results it is evident that both the crop models APSIM and DSSAT show marginal changes in maize crop yields in the future projected climate change scenarios. Local crop varieties with current management practices showed decreased crop yields. Based on the

Table 14. Plausible changes in institutional and socio-economic indicators in the RAPs of Embu County.

Category	Variable/ indicator	Direction of change	Magnitude of change	Change over the period (%)
Institutional/policy/ regulation	Fertilizer prices	Reduced	Moderate	20
	Seed prices	Increase	High	80
	Milk prices	Increase	High	50
	Grain prices	Increase	Very High	200
Socio-economic	Labor cost	Increase	High	60
	Farm sizes	Increase	High	30
	Household sizes	Decrease	High	30
	Non-agricultural incomes	Increase	High	50

Table 15. Main components of the adaptation strategies developed for different AEZs in Embu County.

	Adaptation strategy for LR season				Adaptation strategy for SR season			
AEZ	Planting time	Plant pop.	Variety	Fertilizer	Planting time	Variety	Plant pop.	Fertilizer
LM3	15–30 Mar	50	H513	60	1–15 Oct	Deka_lb	50	80
LM4	15–30 Mar	50	Deka_lb	60	15–30 Oct	H511	50	70
LM5	15–30 Mar	50	H511	60	1–15 Nov	Deka_lb	40	60
UM2	15–30 Mar	50	H513	80	1–15 Nov	H511	40	70
UM3	15–30 Mar	50	H513	70	1–15 Oct	H513	40	60

above analysis, the better-performing crop varieties along with sustainable crop management practices were selected as shown in Table 15.

Core Question 1: What Is the Sensitivity of Current Agricultural Production Systems to Climate Change?

Impact of climate change on crop production

Simulations were carried out with both DSSAT and APSIM for baseline and climate change scenarios for all combinations of RCPs 4.5 and 8.5 and time-periods mid-century (2050s) and end- century (2080s) for all 20 AOGCMs. While both APSIM and DDSAT predicted that maize yields will increase under future climate scenarios, the magnitude of this increase is higher in the case of DSSAT compared to APSIM. Results from the APSIM simulations projected that maize yields would marginally increase in UM2, UM3, and LM3 AEZs and decline in LM4 and LM5. In all AEZs, the projected changes are within ±10% range compared to yields with baseline climate. In the case of DSSAT, except for the LR season in LM4, maize yields increased by more than 10%, mostly in 20–30% range, across all AEZs and in both seasons. The highest increase is predicted in LM3, followed by LM5 and UM3. Though the percentage increase is high in LM5, the yields are very low in this AEZ. Compared to the LR seasons, the increase is higher during the SR seasons. The changes in crop yields varied from –27 to +79% in the LR season and from –36 to +80% in the SR season. LM3, represented by the Karurumo weather station, showed the highest increase. In both seasons, simulated maize yields showed an increase through time, as displayed in Fig. 11.

The predicted increase in maize yields under climate change scenarios is attributed to general increase in rainfall and temperatures remaining within the optimal range for maize production even with an increase of 2.5 to 4.8°C. The higher

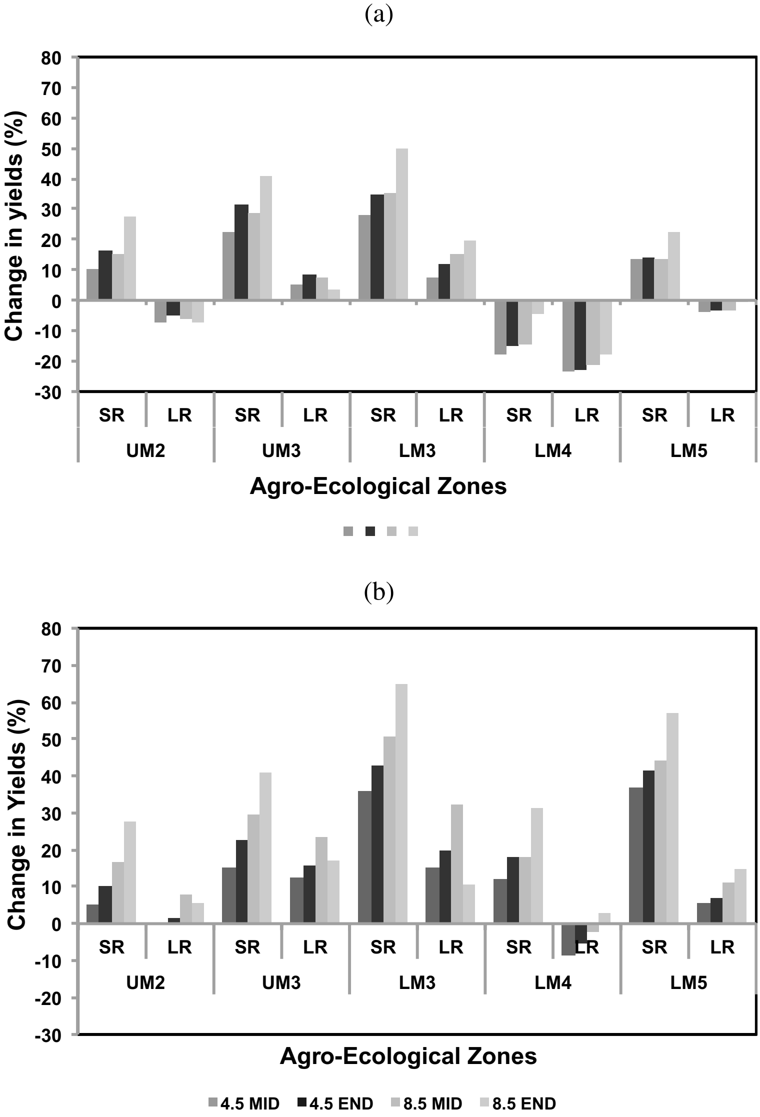


Fig. 11. APSIM (a) and DSSAT (b) simulated changes in average maize yields during SR and LR seasons under different AEZs in Embu County. (4.5 and 8.5 represent RCPs and Mid and End represent mid-century and end-century periods.)

increase observed during the SR season is due to a projected longer rainy season. The average number of rainy days in the LR season is 40 while in the SR it is 58 days as shown in Fig. 12. The fewer rainy days and shorter duration of the LR season exposed maize to water stress especially during the critical stages of flowering and grain-filling. Also most AOGCMs projected a considerably higher increase in rainfall during the SR season compared to the LR season. In the SR season, projected

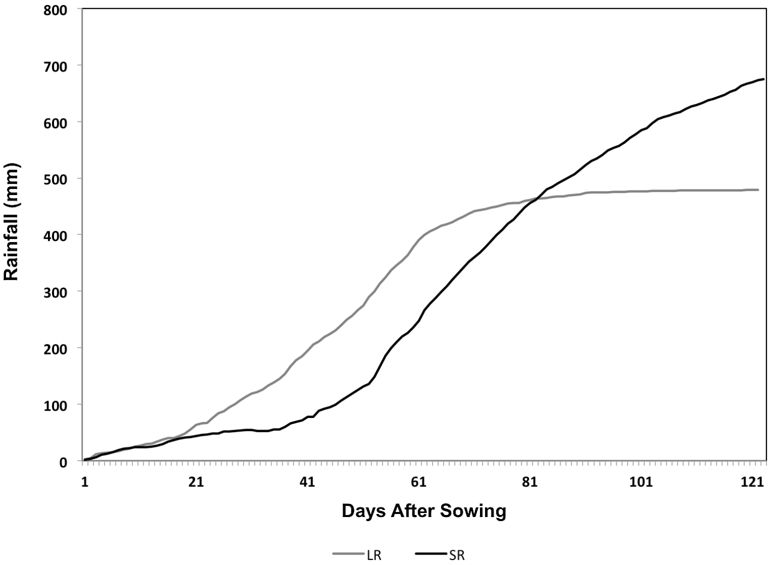


Fig. 12. Average cumulative rainfall during SR and LR seasons in Embu County.

changes in maize yields are as high as +60%, whereas those during LR season are up to a maximum of +30%, except for in LM4 where yields declined under future climate scenarios.

The differences in the yields simulated by APSIM and DSSAT are mainly due to the CO_2 effect. The version of APSIM used in this assessment is insensitive to changes in CO_2 concentration while DSSAT version has CO_2 effects included. To assess the effect of atmospheric CO_2 concentration on growth and yields of maize, simulations were carried out with DSSAT with and without changing CO_2 under projected climates from all the 20 AOGCMs. In the "without" scenario, the atmospheric concentration of CO_2 was set to 380 ppm and in the "with" scenario it was set to 450 ppm for RCP4.5 and 850 ppm for RCP8.5 scenarios. Maize yields showed a greater increase in the scenario in which CO_2 concentration was changed compared to the unchanged CO_2 scenario. The increase is fairly small in UM2 and UM3, as represented by the Embu climate, compared to the other AEZs. The CO_2 effect on maize yields was found to be much higher in the case of Ishiara and Kindaruma compared to Embu and Karuromo. In the case of LM4, represented by Ishiara, maize yields declined without CO_2 effect (Fig. 13) but increased when the CO_2 effect is included. The climate at Ishiara and Kindaruma sites is warmer by 2–3°C compared to that in Embu and Karuromo and use of inputs such as fertilizer is very low. In general, the increase in yields due to increase in CO_2 is in the range of 300–500 kg/ha. The very high percent increase in LM4 and LM5 is due to low level of base yields in these AEZs.

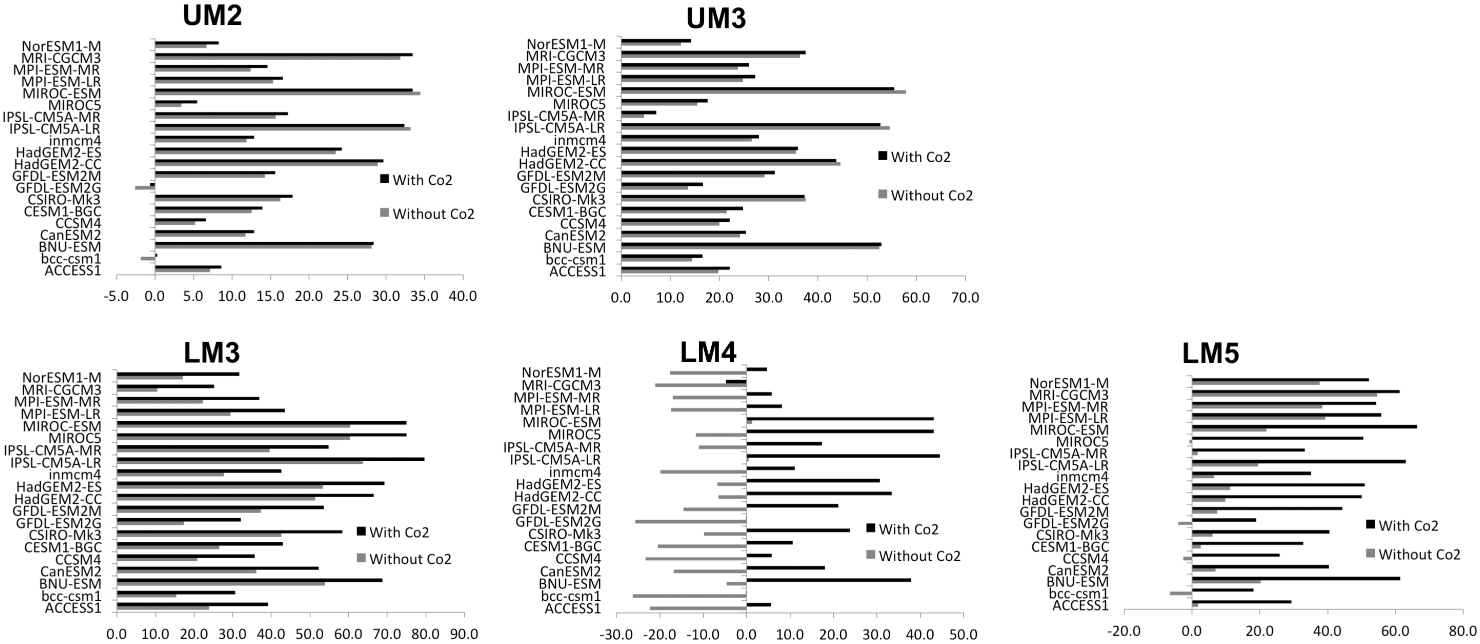


Fig. 13. Comparison of DSSAT projected changes in maize yields (percent deviation from baseline) with and without CO_2 fertilization effect under RCP 8.5 mid-century climate scenarios from 20 GCMs, at different agro-ecological zones of Embu County, Kenya.

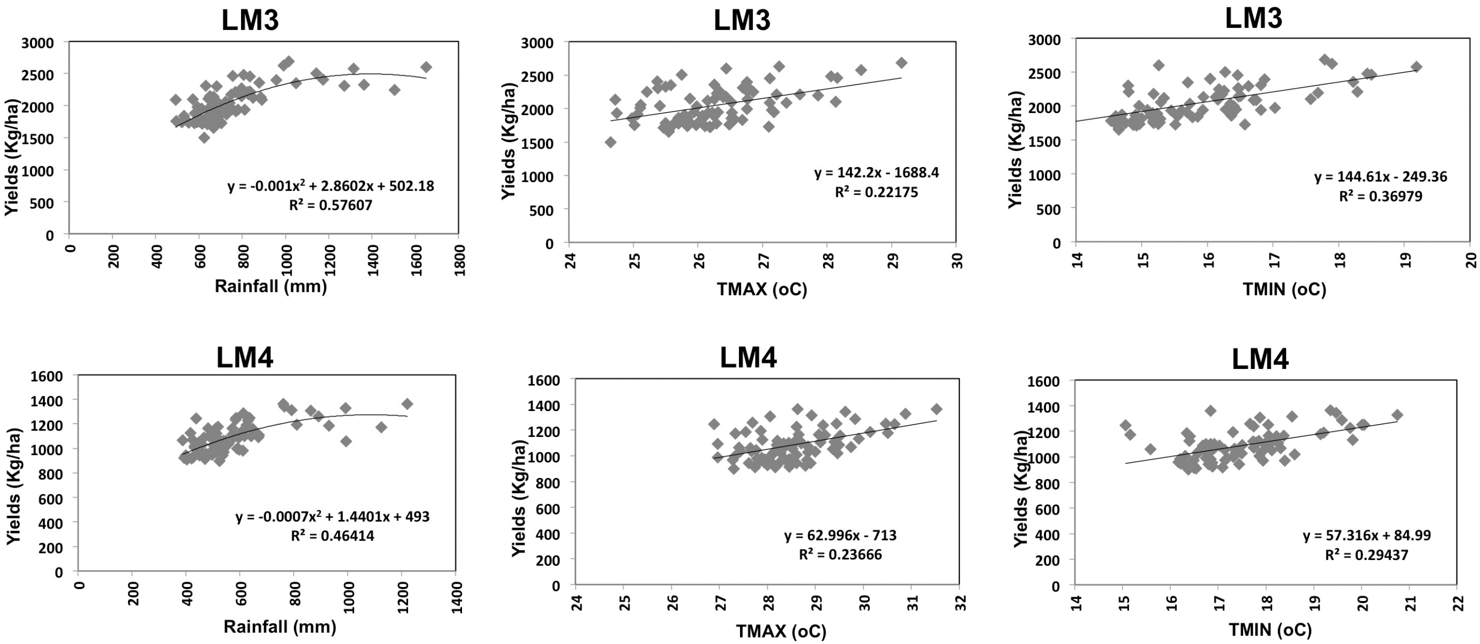


Fig. 14. Effect of rainfall and maximum and minimum temperatures on grain yields as simulated by DSSAT for two contrasting agro-ecological zones LM3 (above) and LM4 (below) in Embu county, Kenya.

Significant relationships between maize yield and rainfall, maximum and minimum temperatures, evapotranspiration, and crop duration were also observed in different AEZs. In all AEZs, maize yields are linearly related to the amount of rainfall during the crop season (Fig. 14). Analysis across the AEZs indicated that yields increased linearly with up to 700 mm rainfall. Further increase in seasonal rainfall apparently has no effect. Maize yields also showed a linear relationship with increase in seasonal maximum temperature between 25 and 30°C and with increase in minimum temperature between 14 and 19°C. Increased temperatures lead to faster growth and reduced duration of the growing season, which showed a negative impact on the performance of the crop.

The impacts of climate change on the performance of maize were also influenced by the management adopted by the farmers, such as crop variety used, planting time, plant population, and amount of fertilizer applied. These effects varied from one AEZ to the other. The local variety, Katumani, which is widely used by the farmers in the study area, is most vulnerable to projected changes in future climate (Fig. 15). Both APSIM and DSSAT simulation results show that Katumani is most vulnerable in the region, especially during the LR season. Katumani is a short-duration variety and further reduction of this growing period adversely affected its performance. In addition, it is a drought-tolerant variety and hence did not respond to the projected increase in rainfall. Farmers using low-input production systems were found to be less affected by changing climate compared to farmers with high-input systems. Adverse impacts of climate change were also observed in the case of farmers who planted late and used low plant populations. Use of higher plant populations seems

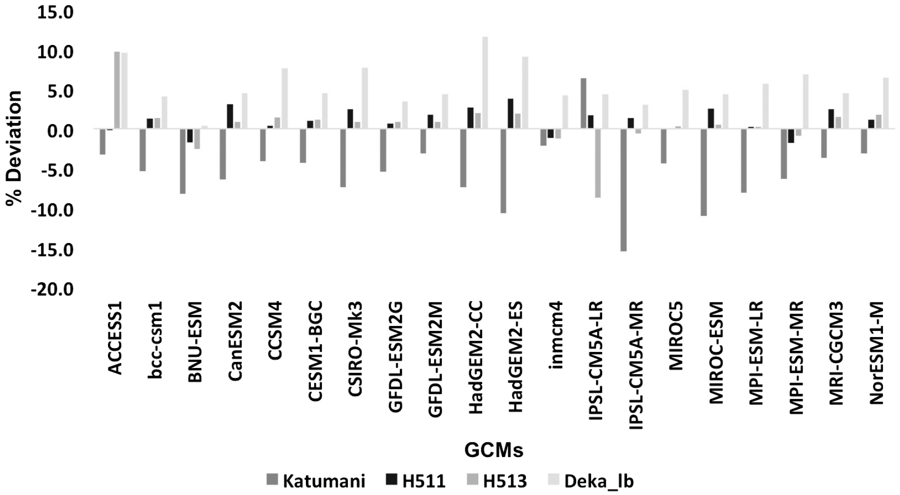


Fig. 15. Impact of projected changes in climate to mid-century under RCP8.5 on performance of different maize varieties in Embu County.

to be an important option in adapting to climate change in the study area since it is able to compensate for the impacts of reduced growth duration and to capitalize on the increased moisture availability.

AgMIP Core Question 1: What is the Sensitivity of Current Agricultural Production System to Climate change?

In order to examine the sensitivity of the current production system to climate change, potential impacts of climate change were evaluated on net farm returns, *per capita* income, and poverty by using economic model Tradeoff Analysis Model for Multi-dimensional Impact Assessment (TOA-MD). The main production system that characterizes the Embu region comprises maize and beans — mainly intercrop — in all AEZs, coffee in UM2 and UM3 and pigeon pea and sorghum in LM4 and LM5. To assess the sensitivity to climate change we considered two systems:

- System 1 = current climate-current technology.
- System 2 = future climate-current technology.

This implies that the current production system under current climate and current technology (system 1) is perturbed with climate change (system 2) to determine how it responds to climate shock. Impacts of climate change for maize were simulated using crop simulation models and perturbed weather data corresponding to different climate scenarios. The ratio of future and base simulated yields is the relative yield which is used as a correction factor for observed (survey) data on maize yields.

For non-modeled crops, i.e. beans, coffee, pigeon pea and sorghum, expert opinion and secondary sources were used to specify expected changes. For instance with climate change, bean production is expected to increase by 10% in UM2, UM3, LM3 and decline by 10% in LM4 and LM5. Coffee is grown in UM2 and UM3, both of which gain from climate change, hence its production is expected to go up by 20% in both AEZs. Pigeon pea and sorghum are drought-tolerant crops grown in marginal areas and are not expected to be adversely affected by climate change. In fact, the increment in rainfall and temperature simultaneously in the region is expected to boost pigeon pea and sorghum production by 20% and 15%, respectively, in LM3 and decrease production of both crops by 10% in LM4 and LM5. Dairy production is also expected to increase by 10%. Output prices — both for crops and dairy — were also held constant for this scenario, but production costs are expected to change as production changes. Other household characteristics such as farm size, herd size, non-agricultural income, etc. are assumed to remain constant. Any change between the two systems is therefore purely the effect of climate on the current system.

From Table 16, if the current agricultural system is exposed to a climate shock, APSIM results for CCSM4 and MPI_ESM indicate that maize farmers in LM4 and LM5 will loose from climate change, while small positive changes are expected in UM2, UM3, and LM3. DSSAT results for CCSM4 and MIROC-5 indicate losses in maize production in LM4, while all other models indicate gains in maize production in all AEZs. The impact of climate change on non-modeled crops is illustrated in Table 17.

Results from TOA-MD simulations show that, if the current production system in Embu County is perturbed by climate change most of the AEZs would have positive impacts, except in the AEZs LM4 and LM5 where the percent of losers range between 25.8% and 62.3%.

APSIM simulations show that about 36.4% to 56.2% of the farmers in LM5 and 33.8% to 62.3% in LM4 are expected to be worse off than they are today if the current system was to be subjected to climate change (Table 18). The figures are lower for the same AEZs using DSSAT estimations. The percent losers in AEZs UM2, UM3 to LM3 are lower in both APSIM and DSSAT for all GCMs.

Climate change is expected to increase net farm returns as can be seen by comparison between net farm returns with and without climate change for the different GCMs (Fig. 16). In APSIM analysis, in all AEZs (except CCSM4 for AEZ LM4 and MPI-ESM for AEZs LM4 and LM5), climate change will cause an increase in net farm returns. With projections by some GCMs, maize production recorded declines and the positive incomes could be explained by rising returns from other crops (coffee, beans, pigeon peas, and sorghum), which are expected to increase in yields in some AEZs due to climate change. Examples of this are in CCSM4 in UM2 and MIROC-5 in LM4 which record a decline in maize production but increased net farm returns. In instances where loss in maize production and loss in other crops was recorded, net farm returns also recorded a decline e.g. CCSM4 for AEZ LM4; and MPI-ESM for AEZs LM4 and LM5. The gains in net returns are highest in LM3 and UM3 and lowest in LM5 (Fig. 16a). Results from the DSSAT model indicate gains in net farm returns in all AEZs and the trends are similar to those of APSIM, though higher (Fig. 16b).

Figures 17a and 17b show the gains and losses from climate change as a percent of net farm returns for the different models. APSIM simulations (Fig. 17b) indicate that GFDL recorded the highest net impact but also recorded the largest losses. The high net impact is comparable with the net impacts under DSSAT. HadGEM recorded the highest net impact from DSSAT simulations as can be seen in Fig. 17b, but the net impacts in DSSAT are similar. In both models, the magnitudes of gains and losses varies for the different GCMs, and this highlights the uncertainty in the analysis.

Table 16. Mean and standard deviation of relative yield of maize under climatic conditions predicted by five GCCMs under RCP8.5 to mid-century period in different AEZs of Embu County.

		Scenario 1: Sensitivity of current agricultural production systems									
		APSIM Time-averaged relative yield ($r = s2/s1$)					DSSAT Time-averaged relative yield ($r = s2/s1$)				
AEZ	Observed mean maize yield (kg/ha)	CCSM4	GFDL	HadGEM_2ES	MIROC-5	MPI_ESM_MR	CCSM4	GFDL	HadGEM_2ES	MIROC-5	MPI_ESM_MR
Upper Midland (UM2)	2191.20	0.97 (0.18)	1.06 (0.08)	1.07 (0.16)	1.06 (0.11)	1.03 (0.14)	1.12 (0.08)	1.17 (0.09)	1.07 (0.08)	1.11 (0.30)	1.23 (0.08)
Upper Midland (UM3)	2273.20	1.00 (0.20)	1.02 (0.22)	0.98 (0.20)	1.02 (0.16)	0.99 (0.17)	1.35 (0.43)	1.39 (0.43)	1.27 (0.42)	1.28 (0.64)	1.44 (0.48)
Lower Midland (LM3)	1935.09	1.02 (0.28)	1.03 (1.11)	1.00 (0.26)	1.02 (0.23)	1.00 (0.26)	1.32 (0.45)	1.51 (0.56)	1.63 (0.63)	1.24 (0.44)	1.41 (0.50)
Lower Midland (LM4)	1675.40	0.75 (1.14)	1.05 (1.64)	1.06 (0.52)	0.91 (1.27)	0.88 (0.45)	0.98 (0.33)	1.12 (0.39)	1.30 (0.43)	0.92 (0.32)	1.06 (0.35)
Lower Midland (LM5)	877.04	0.98 (0.39)	1.06 (0.44)	1.07 (0.52)	1.02 (0.56)	0.89 (0.39)	1.13 (0.27)	1.27 (0.37)	1.27 (0.47)	1.29 (1.68)	1.23 (0.33)

**Figures in brackets are standard deviations*

<1 *indicates that climate change has a negative impact on production*

>1 *indicates that climate change has a positive impact on production*

$r = s2/s1$ *is the relative yield; where* $s2$ *is the future simulated yield and* $s1$ *is the base simulated yield*

Table 17. RAPs for relative yields of non-modelled crops in different AEZs.

Crop	Beans	Coffee	Pigeon pea	Sorghum
Upper Midland (UM2)	1.1	1.2	N/A	N/A
Upper Midland (UM3)	1.1	1.2	N/A	N/A
Lower Midland (LM3)	1.1	N/A	1.1	1.15
Lower Midland (LM4)	0.9	N/A	0.9	0.9
Lower Midland (LM5)	0.9	N/A	0.9	0.9

Table 18. Percentage of farmers expected to be worse off (losers) with climate change in different AEZs in Embu County.

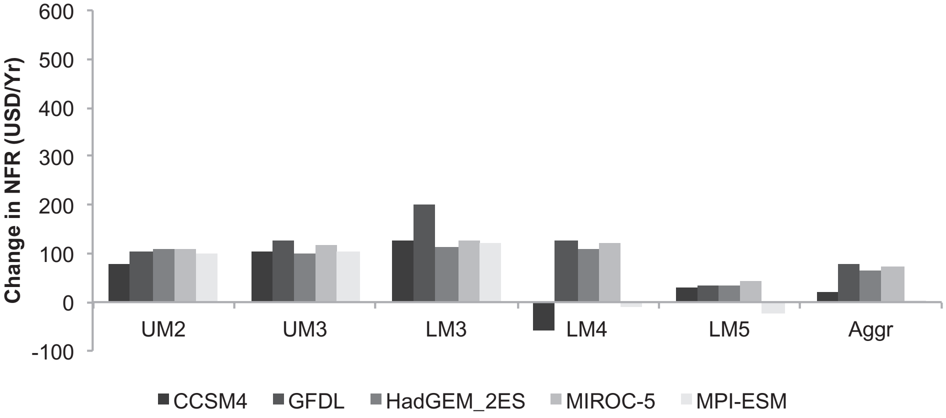
	APSIM					DSSAT				
AEZ	CCSM4	GFDL	HadGEM_2ES	MIRO C-5	MPI-ESM	CCSM4	GFDL	HadGEM_2ES	MIRO C-5	MPI-ESM
Upper Midland (UM2)	32.25	28.28	27.23	27.46	28.64	25.39	23.83	27.65	28.42	21.67
Upper Midland (UM3)	32.97	35.10	33.84	31.36	33.37	20.58	19.50	22.58	28.26	19.74
Lower Midland (LM3)	28.59	40.50	32.40	28.90	31.37	19.17	16.55	15.51	22.69	17.58
Lower Midland (LM4)	62.30	44.30	33.77	45.04	52.52	43.92	34.35	25.79	48.45	37.96
Lower Midland (LM5)	37.59	36.39	38.62	38.17	56.20	33.19	29.58	33.34	33.92	31.69
Aggregate	44.04	38.96	36.10	38.90	51.21	34.49	29.29	28.80	36.99	31.59

AgMIP Core Question 2: What Is the Impact of Climate Change on Future Agricultural Production Systems?

This scenario "translocates" the current production system into the future where production technology, prices and other biophysical and socio-economic conditions are changed. To assess the impact of climate change on this future system we incorporated information from RAPs discussed above, including yield and price trends. The two systems to analyze are defined as:

- System 1 = current climate-future technology with RAPs and trends.
- System 2 = Future climate-future technology scenario with RAPs and trends.

(a)



(b)

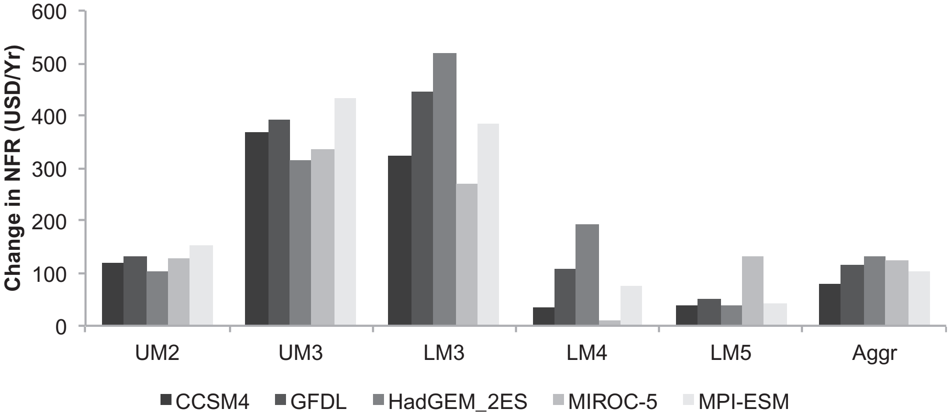


Fig. 16. Changes in net farm returns of farmers in different AEZs of Embu County, with and without climate change based on APSIM (a) and DSSAT (b) simulated yields.

Besides the RAP discussions from the country stakeholders, the global impact model also predicts future trends of production and prices for various crops. For instance, the model predicts that maize yields will increase by a factor of 1.4 while maize prices will increase by 1.35 in a situation without climate change and 1.95 for a situation with climate change. The yield trend factor for sorghum according to the global impact model is 2.00, while prices without and with climate change in the future are expected to increase by 1.19 and 1.48, respectively. Using historical information and expert opinion, we used yield trend factors of 1.5, 1.25 and 1.9 for beans, coffee and pigeon peas, respectively. For dairy production, we used a production factor of 1.4 for both systems. The costs of production in the future were assumed to follow the same trends as the commodity prices. The yield and price

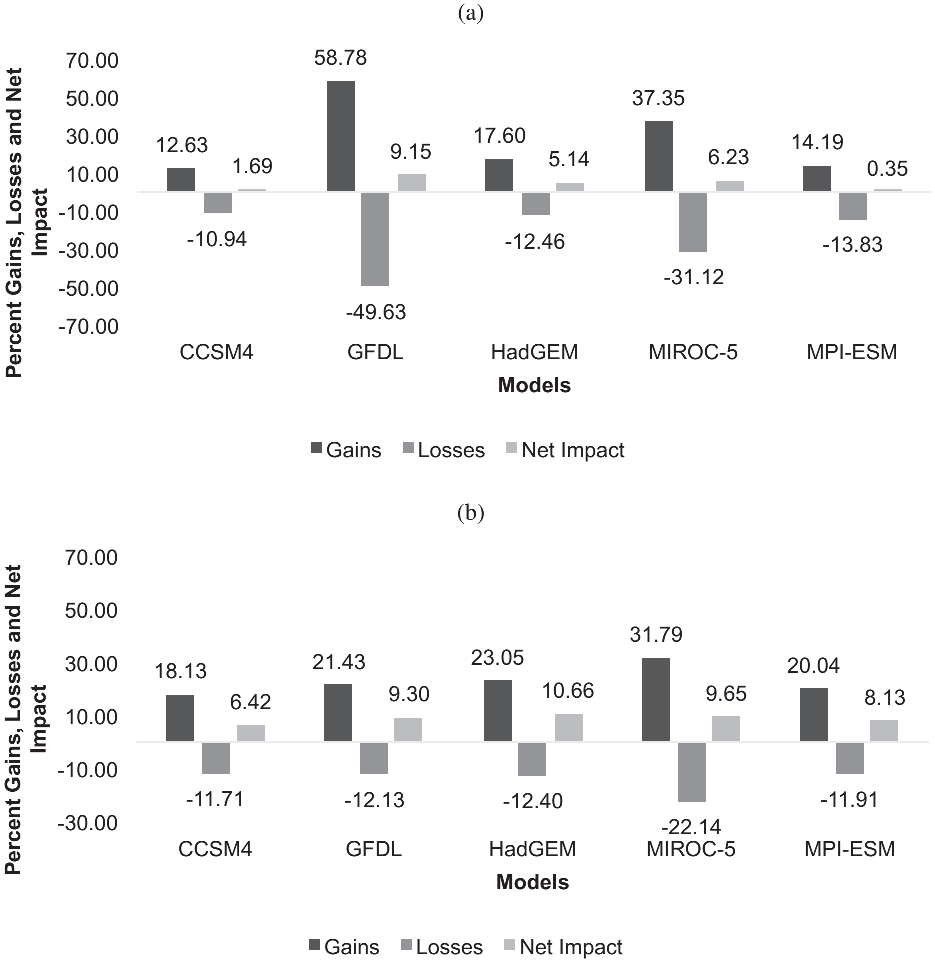


Fig. 17. Overall gains, losses and net impact as percent of net farm returns in Embu County, based on APSIM (a) and DSSAT (b) simulated yields.

inflation factors for both systems are shown in Table 19 below and were used to project the future systems with and without climate change

Results show that if the future agricultural production systems in Embu County are subjected to climate change, there will be losers from climate change in all AEZs. However, a comparison of the percent losers in this scenario is much lower than in Core Question 1. A comparison across the AEZs indicates that LM4 and UM3 will have the highest number of losers both for DSSAT and APSIM, while LM5 has the least number of losers. APSIM and DSSAT results seem to agree on the AEZs with the highest and lowest number of losers (Table 20). GFDL and MIROC-5 in

Table 19. Changes in yield and prices of different crops used in assessing the economic impacts of climate change.

Activity	Yield trends	Prices/costs System 1 Without climate change	Prices/costs System 2 With climate change
Maize	1.40	1.35	1.95
Beans	1.50	1.40	1.80
Coffee	1.25	1.60	2.00
Pigeon Pea	1.90	1.40	1.80
Sorghum	2.00	1.19	1.80
Dairy	1.40	1.50	2.00

Table 20. Losers from climate change under RAPs based future production systems in Embu County.

	APSIM				
AEZs	CCSM4	GFDL	HadGEM_2ES	MIROC-5	MPI-ESM
Upper Midland (UM2)	8.44	8.29	8.13	8.03	8.22
Upper Midland (UM3)	11.03	13.20	11.73	10.93	11.48
Lower Midland (LM3)	8.57	28.26	9.89	8.80	9.21
Lower Midland (LM4)	19.40	38.23	15.99	35.75	11.25
Lower Midland (LM5)	2.36	2.33	5.33	2.26	2.23
Aggregate	8.67	16.33	9.36	13.64	6.17
			DSSAT		
Upper Midland (UM2)	7.83	7.53	7.86	9.78	7.87
Upper Midland (UM3)	11.64	11.41	12.07	16.62	12.11
Lower Midland (LM3)	9.09	9.08	9.08	9.71	9.00
Lower Midland (LM4)	11.85	11.60	10.56	13.13	11.47
Lower Midland (LM5)	2.06	2.15	2.06	15.82	2.07
Aggregate	6.25	6.20	5.87	14.33	6.15

APSIM, and MIROC-5 in DSSAT are recording higher number of losers for some AEZs. The rationale behind the decline in the number of losers is the high trend values used for prices and yields to depict technological advancement and increased prices as we move in to the future. Technological changes and increases in food prices will ensure that farmers will have better yields and better incomes even in a future with climate change, but this is also countered by climate change impacts in some AEZs and increased cost of production. It should be noted that although costs are increasing, their magnitude is small compared to increase in revenue. This could be because of low agricultural input use in the area.

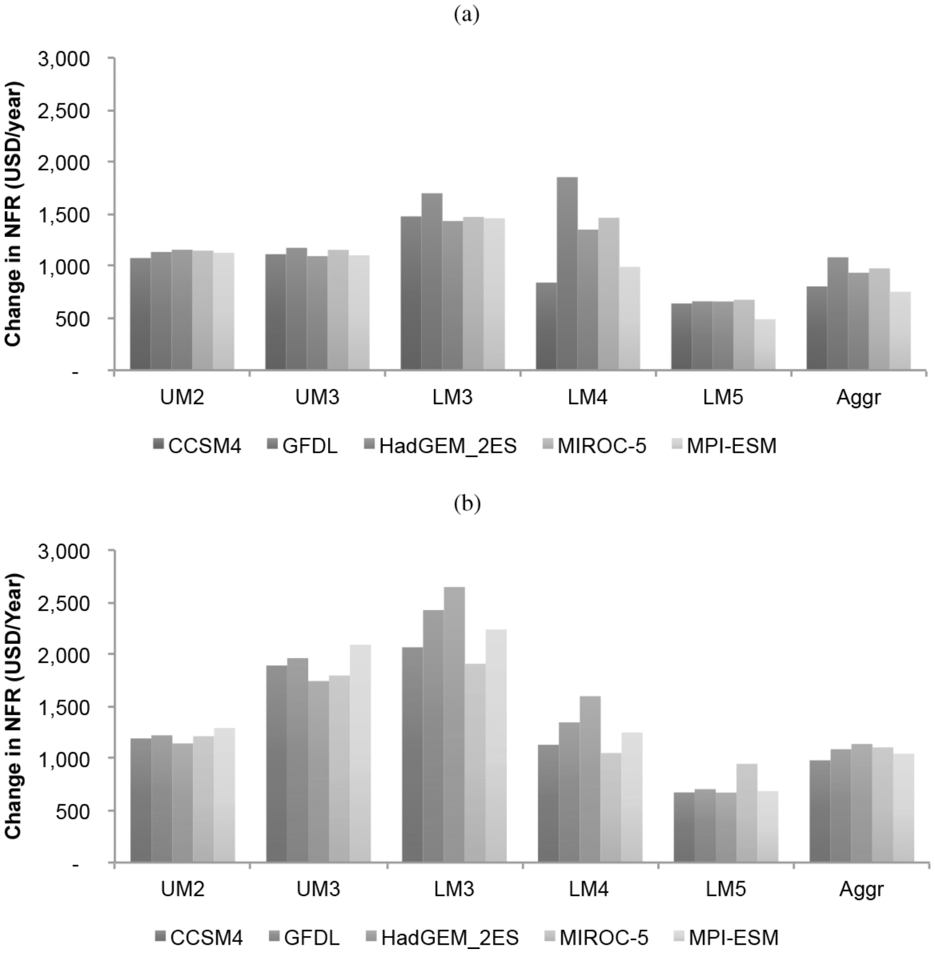


Fig. 18. Change in net farm returns in different AEZs of Embu County based on APSIM (a) and DSSAT (b) simulated yields and RAPs based future production systems.

The change in net farm returns are also significantly higher compared to those in Core question 1. The highest gains are in LM3 for APSIM, and UM3 and LM3 in DSSAT (Figs. 18a and b).

Figure 19 shows the gains and losses from climate change as percent of net farm returns for the different models. Both APSIM and DSSAT show higher increment in the net impact compared to simulations in Core Question 1. This is an indication that climate change in future will impact agriculture in the region more positively. However, this positive net impact could be attributed more to the trend values from the impact model than the impacts of climate change. These positive impacts in production and prices result in high farm net returns, increased *per capita* income and decrease in poverty rates. However, Figs. 19a and b show sizeable losses as well.

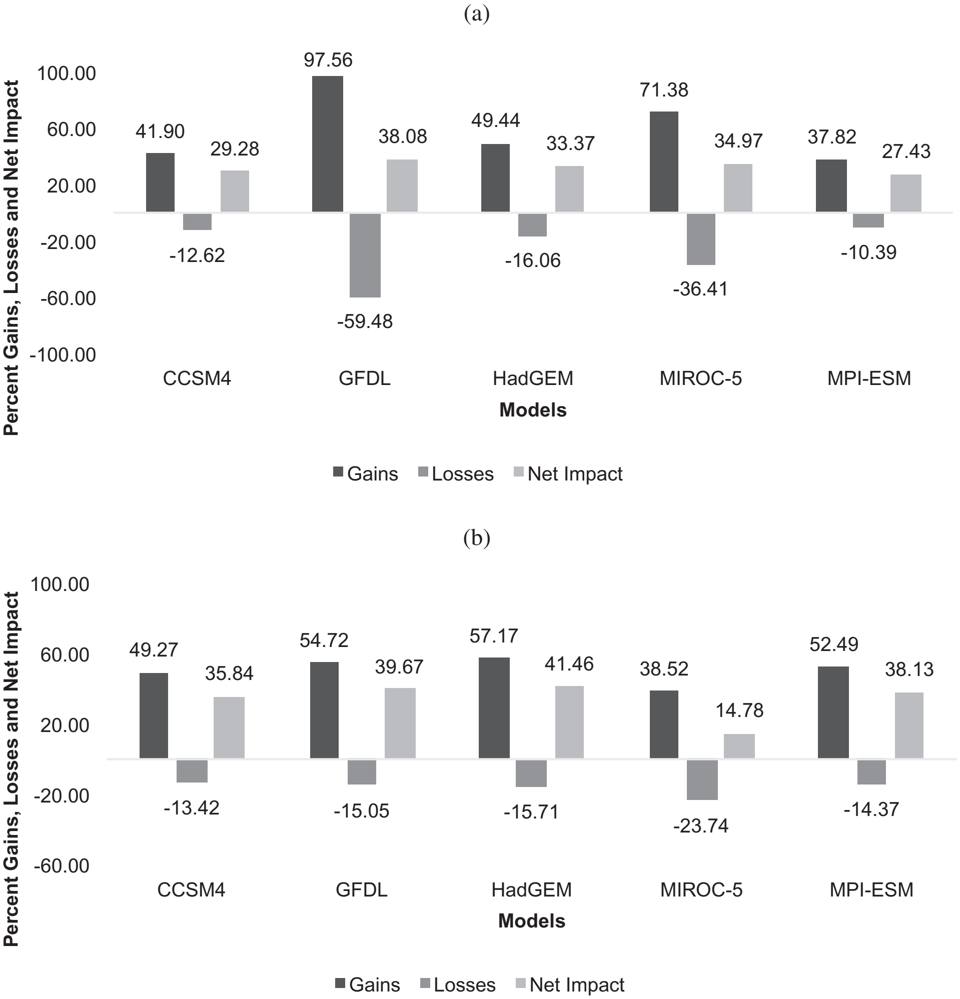


Fig. 19. Overall gains, losses and net impact as percent of net farm returns in Embu County, based on APSIM (a) and DSSAT (b) simulated yields and RAPs based future production systems.

The net impacts with APSIM simulations varied from 27.4% to 38.1% (Fig. 19a) while those under DSSAT (Fig. 19b) varied from 14.8% to 41.6%.

Sensitivity to Trends Assumptions

Projection of current systems to the future requires altering yield levels, commodity prices and production costs. To test how the results are sensitive to these assumptions, we lowered the trend factors for technology and prices, but increased the costs as shown in Table 21.

Table 21. Yield, commodity prices, and production costs used in the sensitivity analysis.

Activity	Production	Prices System 1	Prices System 2	Costs System 1	Costs System 2
Maize	1.15	1.3	1.6	1.6	2.0
Beans	1.2	1.4	1.6	1.5	2.1
Coffee	1.2	1.5	1.7	1.8	2.2
P Pea	1.2	1.4	1.6	1.6	1.9
Sorghum	1.1	1.2	1.4	1.8	2.1
Dairy	1.2	1.4	1.6	1.7	2.0

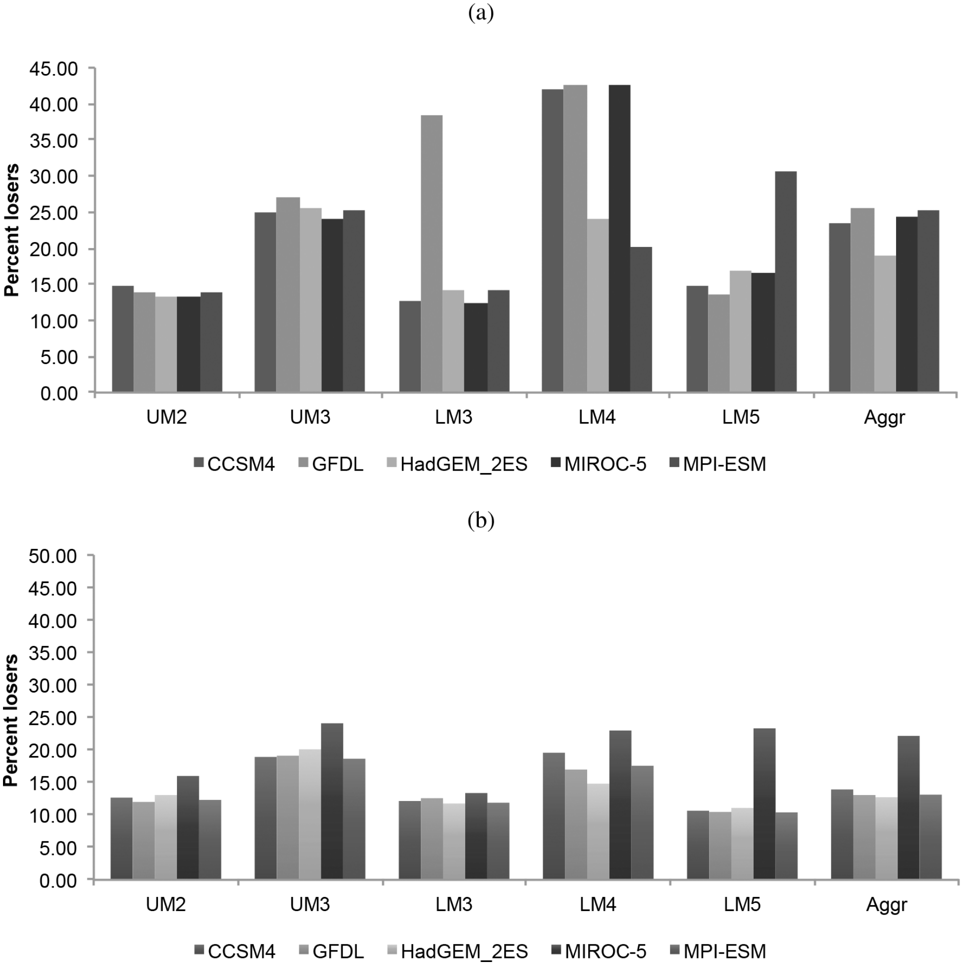


Fig. 20. Sensitivity of net impact of APSIM (a) and DSSAT (b) simulated yields under climate change to changes yield levels, prices and costs.

We then compared the net impact of these changes as a percent of mean net returns with those obtained with figures in Table 18. Results indicate significant differences in the number of losers for both APSIM and DSSAT (Figs. 20a and b), with the number being smaller in DSSAT.

In both models, the net impacts have reduced significantly, with net impacts reducing by almost half in all the GCMs (Fig. 21). This is an indication that model results are very sensitive to projected trends in yield, commodity prices, and production costs. Under or over estimation of these trends could lead to large differences in the economic impacts. Note that the relative yields of non-modeled crops have

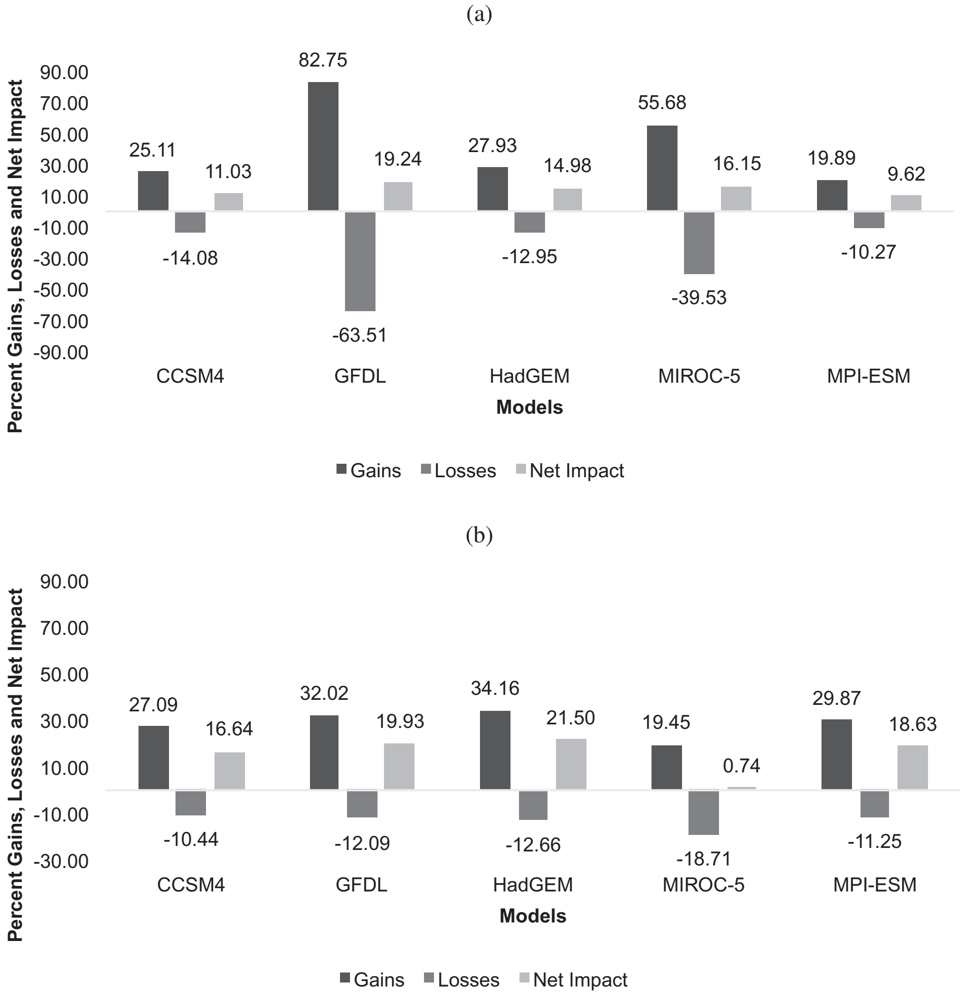


Fig. 21. Sensitivity of net impact of APSIM (a) and DSSAT (b) simulated yields under climate change to changes yield levels, prices, and costs.

not been changed. Changing them together with the trend factors can completely alter the results.

Core Question 3: What Are the Benefits of Climate Change Adaptations?

Impact of adaptation on crop productivity

Simulation analysis was carried out with both APSIM and DSSAT, with the new crop management strategies and selected varieties using baseline climates, and the downscaled CMIP5 AOGCMs future climate projections. DSSAT simulated maize-crop yields with adapted technology projected a significant increase across all the AEZs under RCP8.5 (Fig. 22) to mid- and end-century periods. With RCP8.5, maximum and minimum temperatures are projected to increase by 4.0 and 4.8°C, respectively and crop season precipitation amounts are projected to increase by +7% to end century.

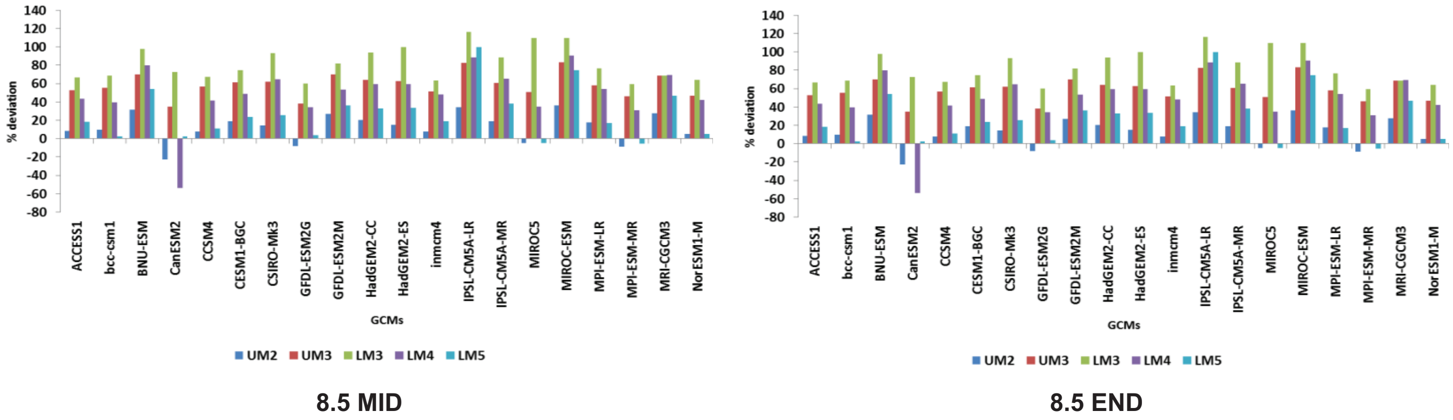
Benefits of adaptation

In this scenario, the question we are answering is how the various indicators of net farm returns, income poverty and *per capita* income change if households in future system under climate change take up an adaptations package. Using TOA-MD, we assessed the impacts of the proposed adaptation package on *per capita* income, net farm returns and poverty. The assessment also determined the percentage of farmers in each AEZ who would adopt the proposed adaptation strategy. This scenario compares a future climate with future technology against a future climate-future technology with adaptations i.e.

- System 1 = Future climate-future technology with all RAPs discussed earlier and yield and price trend.
- System 2 = future climate-future technology with adaptation, RAPs and trends.

The adaptation package described above involves higher utilization of fertilizer and higher seeding rates, both of which imply increases in cost of production to the farmer. For this reason, the total variable cost of production is expected to increase. All the parameters corresponding to the other non-adapted production activities and household data were held constant.

From Table 22, we find that adaptation to climate change is expected to increase maize yields in all AEZs, with LM5 gaining the most from adaptations. A part of this increase is due to increased use of fertilizer and other inputs compared to current low levels of use by farmers in the region. With the increase in input use coupled with positive changes in climate, it is possible for farmers in the Embu County to double or triple their yields as shown in Table 22.



8.5 MID

8.5 END

Fig. 22. DSSAT projected changes in maize crop yields for RCPs 8.5 and time-periods mid-century (2040–2070) and end-century (2070–2100) periods in Embu County.

Table 22. APSIM and DSSAT simulated mean maize yields (kg/ha) with adaptations in different AEZs of Embu County.

AEZ	Projected future mean maize yield (Kg/ha)	Question 3: The benefits of climate change adaptations									
		APSIM Time-averaged relative yield ($r = s2/s1$)					DSSAT Time-averaged relative yield ($r = s2/s1$)				
		CCSM4	GFDL	HadGEM_2ES	MIROC-5	MPI_ESM	CCSM4	GFDL	HadGEM_2ES	MIROC-5	MPI_ESM
UM2	5,151	1.61	1.50	1.68	1.61	1.56	1.17	1.24	1.25	1.05	1.00
UM3	5,377	1.52	1.48	1.52	1.53	1.50	1.70	1.45	1.77	1.64	1.59
LM3	5,136	1.10	1.07	1.10	1.09	1.09	1.47	1.28	1.66	1.44	1.36
LM4	4,060	1.60	2.04	1.84	1.46	1.57	1.66	1.96	1.99	2.09	1.58
LM5	1,941	2.96	3.14	3.15	2.85	2.92	2.01	1.89	2.40	1.70	1.70

<1 *indicates that climate change has a negative impact on production*

>1 *indicates that climate change has a positive impact of production*

$r = s2/s1$ *is the relative yield; where s2 is the future simulated yield and s1 is the simulated base yield under current climate with current technology*

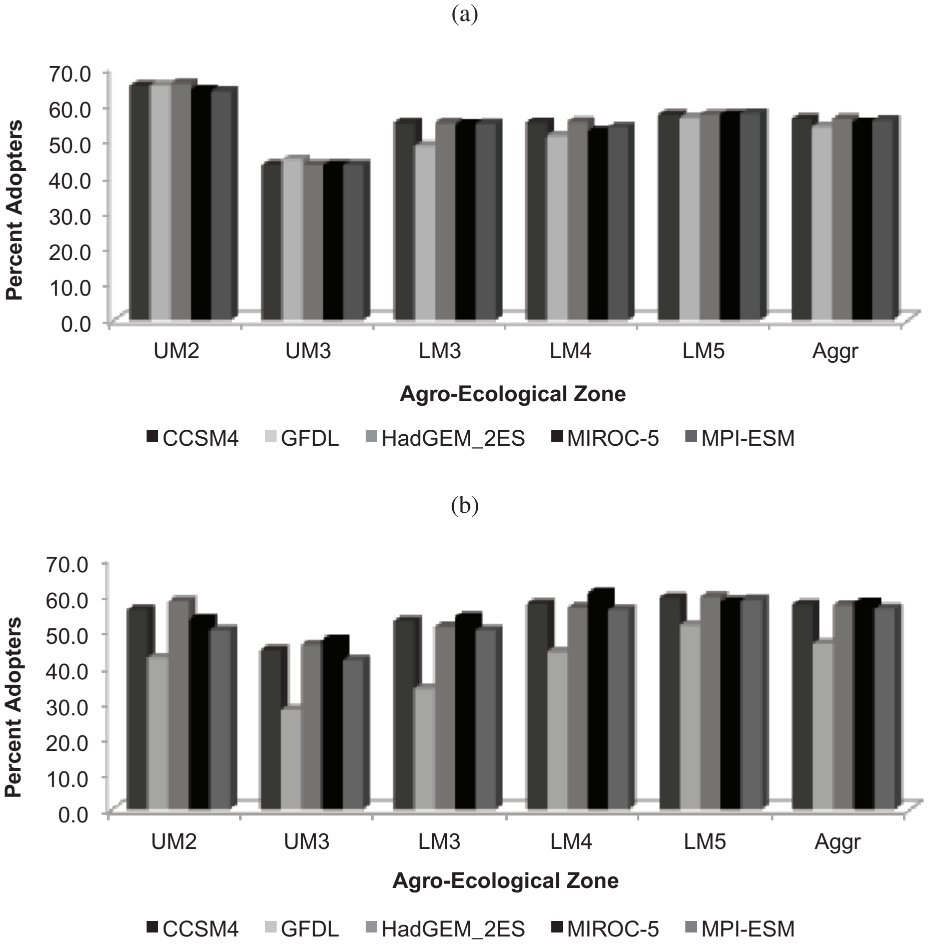


Fig. 23. Future adopters (%) of adaptation package in different AEZs of Embu County, based on APSIM (a) and DSSAT (b) simulated yields with adaptations.

We expect the high potential gains in yields to be matched by high percentages of adopters in all the GCMs. However, it is not expected that all farmers should adopt as autonomous adoption is a decision based on farmers' perceived gains from adopting the new technology. Simulations show that if the proposed adaptation strategy was to be introduced in future, APSIM predicts that farmers in UM3 would adopt the least while those in the other AEZs would take up the technology in larger numbers (Fig. 23a). The adoption rates are comparable in both models except for UM2 where APSIM is predicting significantly higher adoption rates than DSSAT (Fig. 23b).

The results show that there are substantial increases in net returns for farmers in LM4 and LM5 (both in DSSAT and APSIM) after adapting to climate change

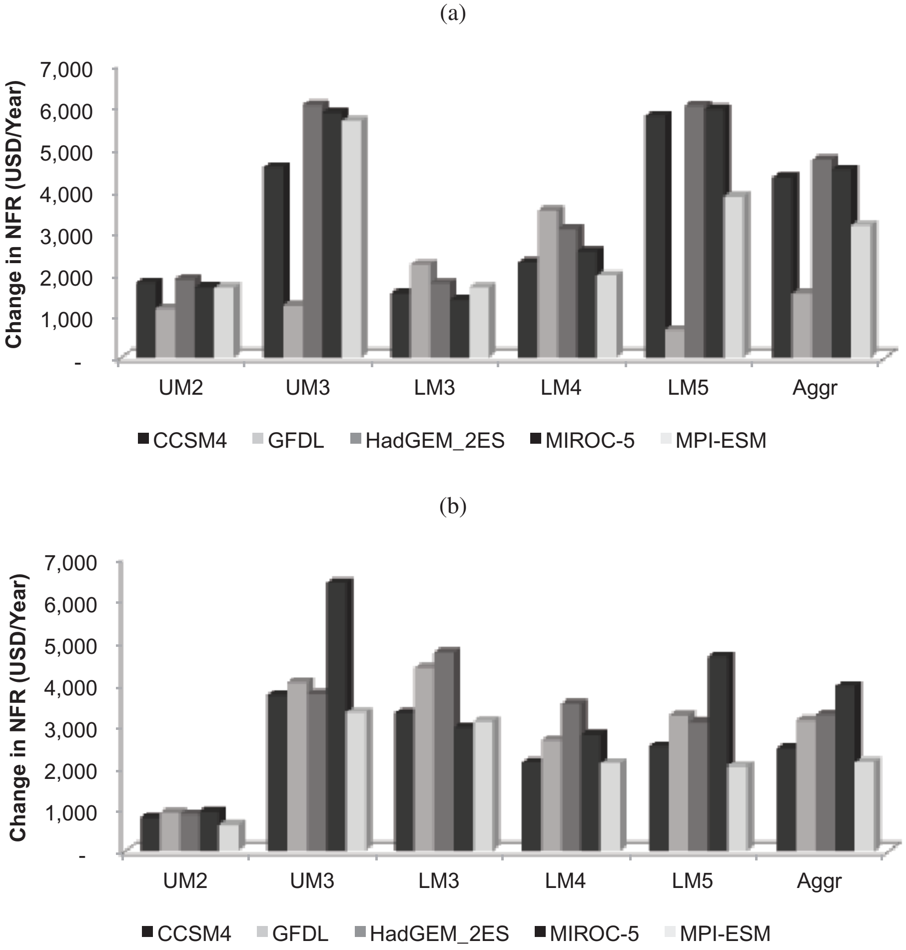


Fig. 24. Future net farm returns (USD/year) in different AEZs of Embu County based on APSIM (a) and DSSAT (b) simulated yields with adaptations.

(Figs. 24a and b). The farmers in these two AEZs have the highest yield gaps[2] and adaptation to climate change would substantially increase their returns. From Table 22, adaptation in these AEZs would increase yields by a factor of 1.58 to 3.15 depending on the model and the GCM.

Core Question 1 presented the gains/losses from climate change on future agricultural systems. However, if farmers decide to adapt to climate change, then there are extra benefits in net farm returns as indicated in Figs. 24a and b. Therefore

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[2] This is the difference between actual and potential yield levels.

the adaptation benefits e.g. increased net returns, increased *per capita* income, and reduced poverty levels are over and above those under Core Question 1.

Conclusions and Next Steps

Realistic assessment of impacts of climate change on smallholder agricultural systems is a challenging exercise. Crop productivity in smallholder agricultural systems is a function of complex interactions of various suboptimal resources with large variations between fields, partly from inherent differences in soil types and partly due to differences in management. To estimate crop productivity under such circumstances, crop models must be sensitive enough to simulate the effects of biophysical heterogeneity and management strategies. Crop simulation models such as DSSAT and APSIM have the capabilities to capture these differences but require detailed data on climate, soil, and management. An additional challenge is to translate these impacts on productivity into socio-economic impacts on poor smallholder farmers who derive their livelihoods form these systems. This AgMIP regional assessment addressed this complexity in a comprehensive way by integrating the best available knowledge and modeling tools in the areas of climate, crop, and socio-economics. This probably is one of the first attempts in the region to assess the impacts of climate change on smallholder farming systems in a holistic and systematic way.

Despite data constraints and limitations, this assessment has demonstrated that it is possible to make a more reliable and credible assessment of impacts of climate variability and change on smallholder farming systems that can aid in planning for adaptation. The analysis provided good insights into the climate sensitivity of the various components of the smallholder farming systems in Embu County and identified the regions and components that are more vulnerable to projected changes in climate. It highlighted the differential impacts that the changes in climate can have on different AEZs within a small area that cannot be captured in the large-scale assessments made using aggregated empirical models.

The assessment further highlights the fact that in Eastern Africa, impacts of climate change will not be uniform, and that there will be losers and gainers depending on the environment they are operating in and the management employed. The assessment also reveals that to a large extent the negative effects of climate change can be minimized and benefits from the positive impacts can be maximized by making simple adjustments to the existing practices such as changing varieties, plant densities and soil fertility management. The planning and effectiveness of adaptation strategies can be greatly enhanced by this type of information, which helps in identifying the most appropriate interventions and also in targeting the most vulnerable

AEZs and people. In addition to technological advancement, predicted future prices can also offset negative climate impacts.

Contrary to conventional expectations where climate change is expected to have negative impact on agricultural production, this study has shown that climate change can have positive impacts in some locations. Embu, for instance is on the slopes of Mt. Kenya, and it is not representative of Kenya which comprises about 80% semi-arid lands. The temperatures in the area are also suboptimal for crop production. In fact for most GCMs in the region, improved temperatures would boost maize production. If this study is extended to other regions in the country e.g. the semi-arid regions, the results would be different. It is also feasible that the study over-estimated net farm returns due to low costs and high trend factors used to project prices and technology. The low costs could be due to low utilization of inputs among smallholder farmers, and also the feasibility that all production costs were not captured.

The methods and tools developed under this project proved to be extremely valuable in understanding and characterizing how smallholder agriculture in developing countries is going to be impacted by the projected changes in climate and by developing more appropriate site-specific adaptation strategies. Efforts are now required to further define the resource endowment and management employed by the farmers as accurately as possible to capture the diversity that exists among the farms. Once established, this will serve as a valuable platform to assess impacts of current schemes as well as future climate conditions. The framework will also serve as a means to develop climate-based agricultural forecasting and early-warning systems that can enable governments and humanitarian organizations to use appropriate responses to protect rural communities from the impacts of adverse extremes. The current assessment is limited to the impacts on maize only; this can be extended easily to cover most of the other enterprises that the farmers are involved with in the regions and to enable a more comprehensive assessment of the system.

Finally, there is a need to create awareness amongst the policymakers and decision-makers about the results and assessment capabilities, and to ensure that the relevant agencies and departments receive and utilize this information in planning various interventions, from adapting to impacts of climate change to providing food security assessments and early warnings.

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