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REVIEW

Climate change and eastern Africa: a review of impact on major crops

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Abstract

Global warming has become one of the major challenges in maintaining global food security. This paper reviews the impacts of climate change on fourteen strategic crops for eight sub-Saharan Africa countries. Climate change is projected to increase median temperature by 1.4–5.5°C and median precipitation by −2% to 20% by the end of the 21st century. However, large levels of uncertainty exist with temporal and spatial variability of rainfall events. The impact of climate change on crop yields in the region is largely negative. Among the grain crops, wheat is reported as the most vulnerable crop, for which up to 72% of the current yield is projected to decline. For other grain crops, such as maize, rice and soybean, up to 45% yield reductions are expected by the end of this century. Two grain crops, millet and sorghum, are more resilient to climate change for which projected impacts on crop yields are <20%. Root crops, such as sweet potato, potato and cassava are projected to be less affected than the grain crops with changes to crop yields ranging from about −15% to 10%. For the two major export crops, tea and coffee, up to 40% yield loss is expected due to the reduction in suitable areas caused by temperature increase. Similar loss of suitable areas is also expected for banana and sugarcane production, however, this reduction is due to rainfall variability in lowland areas. Other crops such as cotton and sugarcane are projected to be more susceptible to precipitation variation that will vary significantly in the region. In order to mitigate the long-term impacts of climate change on agricultural sectors, the development of small-scale irrigation systems and water harvesting structures seems promising, however, affordability of such measures remains a key issue.

Introduction

Evident from the increase in frequency of extreme climatological events, climate change has become unequivocal, impacting water resources, agricultural, and food systems (Bates et al. 2008; Brown and Funk 2008; Hartmann et al. 2013). Historical records show an increase in global temperature since the late 19th century (Hartmann et al. 2013). The last three decades have been reported to be successively warmer than all previous decades, and the first decade in 21st century has been the warmest decade on record. On an average, global temperature has increased 0.72°C since 1950 (Hartmann et al. 2013). With the increase in temperature, frequency of cold days, cold nights, and frost have decreased, while frequency of hot days, hot nights, and heat waves have increased. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) projects a continuous increase in global temperature if greenhouse gas (GHG) emissions persist unabated. IPCC further predicts an increase in temperature between 0.3°C and 0.7°C over the next two decades and an increase of 0.3–4.8°C by the end of the 21st century, depending upon emission scenarios (Collins et al. 2013; Kirtman et al. 2013). Along with increases in temperature, global warming is associated with changes in large-scale hydrological cycle elements, such as an increase in atmospheric water vapor, shifting precipitation patterns, changes in precipitation intensity and extreme events, reduced snow cover and extensive melting of ice, and variations in soil moisture content and runoff (Bates et al. 2008; Hartmann et al. 2013). Precipitation has generally increased from 1900 to the 1950s between 30°N and 85°N latitude and has significantly increased between 10°N to 30°N, but has declined after 1970 to present (Bates et al. 2008).

Sub-Saharan Africa (SSA) is one of the poorest regions in the world, where an estimated 386 million people (48% of the region's total population) live on less than $1.25 a day (Ravallion 2012). This group of people is considered the most vulnerable to climate change as they possess minimum financial and technical resources to cope with climate change (Eriksen et al. 2007; Wheeler and von Braun 2013). In SSA, hydro-meteorological disasters, especially droughts and floods, are the most common forms of natural disasters. As such, drought and floods represent 80% of the loss of life and 70% of economic losses related to natural hazards in SSA (Bhavnani et al. 2008). As a consequence of climate change, the frequency and intensity of floods and droughts are projected to increase in the future (Bernstein et al. 2008). Meanwhile, agriculture is a major economic sector in the region, employing 65% of the labor force and contributing 32% to the countries' national gross domestic products, and is characterized by low productivity and lack of modern farming technologies (Chauvin et al. 2012). Despite being a large sector of the national economies, agricultural production systems in SSA are largely rainfed and thus, their success is sensitive to climate variability. In addition, the rapidly growing population in the region has further increased pressure on the food production systems.

This paper reviews the impacts of climate change on fourteen staple and cash crops in SSA. Special focus is given to eight countries in East Africa: Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, and Zambia, which were selected by the United States Agency for International Development (USAID) for the Feed the Future (FtF) program. These countries were selected by the USAID based on prevalence of poverty and hunger, potential for agricultural-led growth, opportunities for regional cooperation, commitment, will, leadership and governance of the host country, and availability of resources (Ho and Hanrahan 2011). This review includes projected climate change in East Africa, the current status of the staple and cash crops in the region, how climate change is projected to impact the yield of these crops, and possible climate change adaptation measures. By compiling numerous studies in a single review, this paper lays the foundation for planning adaptation measures in the region, especially concerning food security and climate change.

East African Agriculture

Agriculture is a major contributor to the national economies in the study area. Agriculture in East African countries is dominated by smallholders who contribute up to 90% of agricultural production (Salami et al. 2010; Wiggins and Keats 2013). Among the eight countries examined, agriculture accounts for 21–42% of the national gross domestic products (FAO 2013b). Currently, of all the crops grown in SSA, a cereal-legume mixed cropping pattern is the dominant system that includes maize, millet, sorghum, and wheat (Van Duivenbooden et al. 2000). As presented in Figure 1, the maize mixed cropping system covers over 40% of the area, followed by pastoral (14%), root crop (12%), and cereal-root crop mixed system (11%). Other major crops in the region include cassava, banana, and rice, while teff is a major crop in the Ethiopian highlands. In drier parts of East Africa, the mixed cropping system is based on millet; while in the humid regions mixed cropping systems are based on maize and cassava (Francis 1986). Coffee, tea, cotton, tobacco, and sugarcane are the major cash crops in most of the FtF countries in SSA.

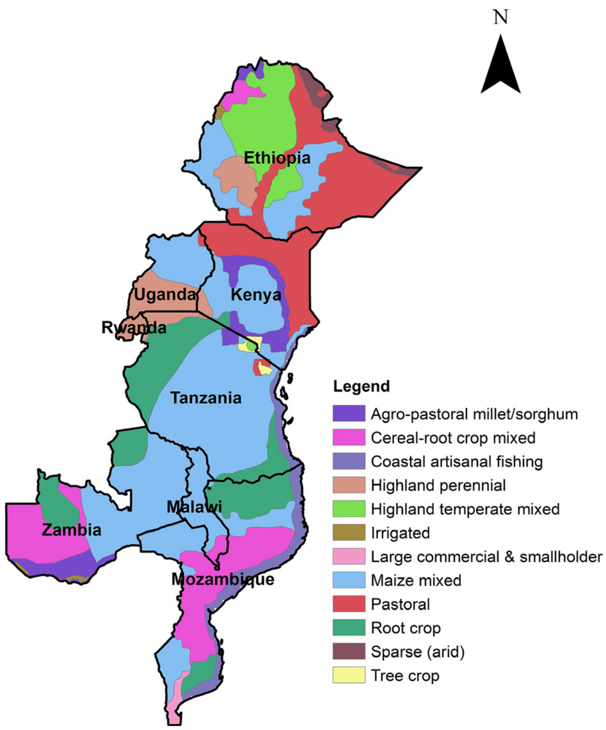

Figure 1. Landuse map of the study area (FAO 2002).

Despite the large contribution to national economies of SSA, yield of major crops remains below the global average (Fig. 2). In general, water availability is considered the primary limiting factor in semiarid sub-Saharan Africa (Barron et al. 2003). Only 18% of the potentially irrigable land or 3.5% of total cultivated area in SSA is irrigated (Foster and Briceno-Garmendia 2010). Lack of irrigation makes the agricultural system in the region vulnerable to rainfall variability and dry spells even during rainy seasons (Mupangwa et al. 2006). As such, low production of the rainfed agricultural systems in SSA are not due to low annual rainfall, but uneven distribution of the rainfall across the seasons (Barron et al. 2003). In addition to water availability, inadequate fertilizer application and continuous farming has resulted in removal of large quantity of nutrient from the soil, resulting in declined crop yield (Sanchez et al. 1997). Furthermore, current temperature in the region can be a limiting factor for some crops (such as wheat) if it is higher than optimum temperature (Liu et al. 2008). Lastly, majority loss of crop in East Africa is due to limited pest and weed control practices (Oerke 2006).

Climate Change in East Africa

Climate change is projected to increase temperature and precipitation variability in East Africa. Temperature in Africa is projected to rise faster than the rest of the world, which could exceed 2°C by mid-21st century and 4°C by the end of 21st century (Niang et al. 2014). Country-specific median projected change in temperature and precipitation for the 2090s (2080s for Rwanda) are presented in Figure 3. The projection for Rwanda was obtained from Cole (2011) and the rest were obtained from United Nations Development Programme (UNDP) Climate Change Country Profiles (McSweeney et al. 2010a ,b,c,d,e,f,g,h). Report for Rwanda represents an ensemble of 19 Global Circulation Models (GCMs) while UNDP studies comprise of an ensemble of 15 GCMs under three climate scenarios (B1: Rapid economic growth; focus on sustainability and environmental health; population growth peaks in 2050 and declines after; prevalent nonfossil fuel energy source use; relatively low increase in GHG emissions, A1B: Rapid economic growth and global economic development with balanced use of fossil fuels and nonfossil energy sources; population growth peaks in 2050 and declines after; moderate increases in GHG emissions, and A2: Economic development is regionally divided; global population continually grows; consistent fossil fuel use; relatively higher increase in GHG emissions). As shown in Figure 3, projected median increase in temperature by the end of this century is quite uniform across the region and ranges from 2°C to 3°C under the B1 scenario to above 4°C under the A2 scenario. However, large uncertainty exists in the temperature projection and the minimum and maximum projected rise in temperature range from 1.4°C to 5.5°C by 2090s.

IPCC AR5 reported that the future precipitation projections are more uncertain but likely to increase in the eastern Africa and decrease in the southern part (Niang et al. 2014). UNDP reports suggest general increase in annual precipitation in East Africa similar to IPCC AR5. Contrary to the general increase in median precipitation in the region, median precipitation is projected to decrease

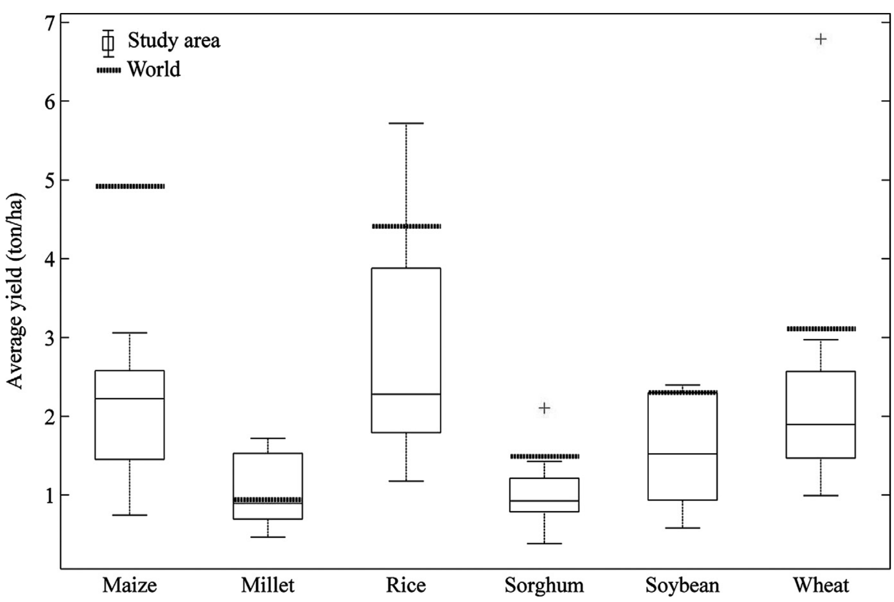

Figure 2. Average yield of major crops in study area and the world (2012) (FAO 2013a). (+ indicates outlier).

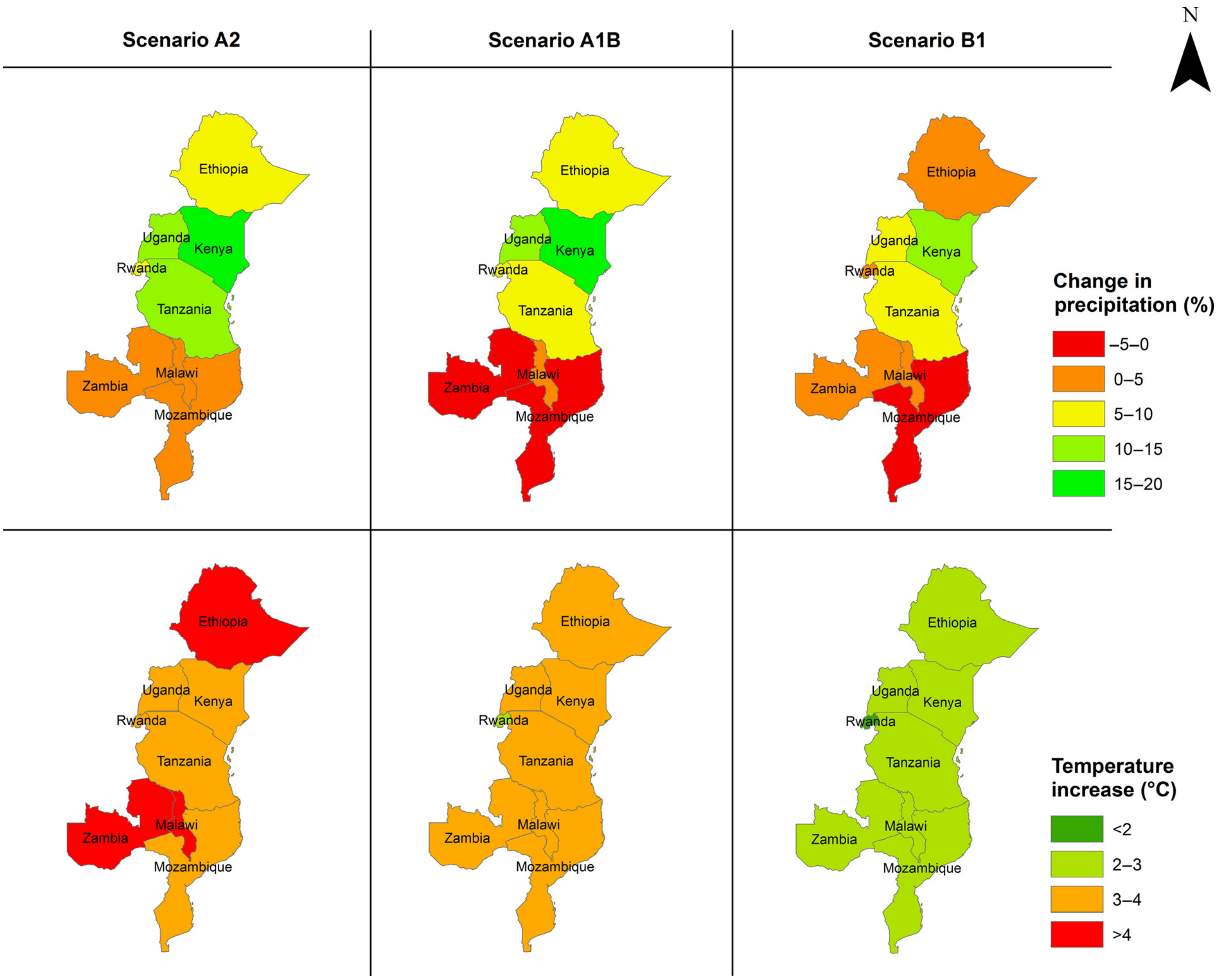

Figure 3. Median projected temperature and precipitation change in East Africa for 2090s (2080s for Rwanda). Temperature and precipitation projections are from an ensemble of 19 GCMs for Rwanda and 15 GCMs for the rest of the countries under B1, A1B and A2 emission scenarios (McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011).

in Mozambique (B1 and A1B scenarios) and Zambia (A1B scenario). In addition to median value, the range of precipitation changes are important to consider as large uncertainty exists in the precipitation projections. Among the countries studies by UNDP, projected change in precipitation range from −15% to +27% by 2060s and −16% to +49% by 2090s. Apart from uncertainty in annual precipitation, large variation in seasonal change has also been reported. For example in Ethiopia, projected annual changes in precipitation vary from −6% to +42%, while projected precipitation change in January-February-March months range from −42% to +78% under the three climate scenarios (B1, A1B, and A2). Likewise, in October-November-December, projected change in precipitation ranges from −10% to +70% in Ethiopia. These examples imply that even though projected annual change in precipitation is largely positive, seasonal variation should be closely monitored especially during the growing season. Since this has major impacts on water availability and crop production.

Climate Change Impact on Agriculture

Climate change is projected to overall decrease the yields of cereal crop in Africa through shortening growing season length, amplifying water stress and increasing incidence of diseases, pests and weeds outbreaks (Niang et al. 2014). Among the various environmental changes brought about by the climate change that limit crop yields, heat and water stresses are considered the most important (Prasad et al. 2008). Heat stress during development phases leads to fewer and smaller organs, reduced light interception due to shortened crop life, and altered carbon-assimilation processes including transpiration, photosynthesis, and respiration (Stone 2001). Heat stress during flowering and grain filling stages results in decreased grain count and weight, resulting in low crop yield and quality (Bita and Gerats 2013). Increase in temperature also increases saturation vapor pressure of air, thereby increasing evaporative demand. Plants close their stomata as a response to increased evaporative demand, thereby reducing photosynthesis rate and increasing vulnerability to heat injury (Lobell and Gourdji 2012). Even short duration heat shock can reduce crop yield substantially, especially if it coincides with the reproductive stage (Teixeira et al. 2013). Meanwhile, water stress leads to the shortening of the crop reproduction stage, reduction in leaf area and closure of stomata to minimize water loss, reducing crop yields (Barnabás et al. 2008). Water stress also increases pollen sterility that leads to reduced grain yield and quality (Alqudah et al. 2011). Water stress is frequently accompanied by heat stress, as dehydration of the plant tissue leads to overheating (Henckel 1964). The occurrence of water and heat stresses adversely impact plant growth and productivity, which is more pronounced than the individual impacts (Prasad et al. 2008). However, in areas with excess water and heat (due to climate change) it is projected that pathogen, weed, and insect infestation will further damage the agricultural systems (Ziska et al. 2011). In addition, rise in the CO_2 level is projected to benefit C3 crops, such as wheat, rice, and soybean, while no substantial effect is expected for C4 crops such as maize, sugar cane, millet, and sorghum (Conway 2009).

Concerning the impacts of climate change in the area of study, in high altitude regions such as mountainous lands in Ethiopia and Kenya, where temperature is the limiting factor for plant growth, a rise in temperature possibly will increase crop yield, but in lowland areas, will increase the risk of water stress (Thornton et al. 2009). Precipitation variability due to climate change results in increased irrigation water demand (Nelson et al. 2009). In addition, precipitation variability is expected to intensify the magnitude and frequency of flood and drought events that are both detrimental to agricultural industry. (Pachauri and Reisinger 2007). These events will likely further decrease crop water availability and threaten the productivity of the rainfed agriculture system in East Africa. Water and heat stress are projected to temporally decrease the length of the growing season while spatially shrinking the suitable areas for agricultural production, especially along the boundaries of arid and semiarid regions in Africa (Conway 2009; CIAT 2011b). Climate change is also projected to reduce the value of cropland by shifting high value agro-ecological zones to low value agro-ecological zones (Kurukulasuriya and Mendelsohn 2008). Increased rainfall intensity is projected to accelerate the rate of soil erosion in the future (Nearing et al. 2004), further threatening the crop productivity.

To better understand the spatial extent and magnitude climate change on agricultural production, we performed cluster analysis to assess the effect of temperature on five major crops. We used the temperature-crop yield relationships for maize (Muchow et al. 1990), wheat (Hatfield et al. 2008), rice (Baker and Allen 1993), sorghum (Hatfield et al. 2008), and soybean (Boote et al. 1998) to estimate the impacts of future climate scenarios (B1, A1B, A2) on the percent change (Table 1) and actual change in yields (Table S1). These values were applied to the spatial yield map obtained from HarvestChoice to compute the future yields (HarvestChoice 2015a,b,c,d,e). The multilevel thresholding method (Otsu 1975) was used to cluster the crop yields into three classes of high, medium, and low (Figs. 4 and S1–S4) and the results are presented in their respective sections.

Table 1. Projected percent change in yield under three climate change scenarios (B1, A1B and A2) by the 2090s (Muchow et al. 1990; Baker and Allen 1993; Boote et al. 1998; Hatfield et al. 2008; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011).

Country	Maize			Rice			Wheat			Sorghum			Soybean		
	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2
Ethiopia	–7	–10	–12	–6	–11	–14	–9	–14	–17	–18	–27	–33	–6	–9	–10
Kenya	–6	–9	–11	–7	–12	–15	–8	–12	–15	–16	–23	–29	–5	–8	–10
Malawi	–7	–10	–13	–5	–8	–11	–9	–14	–17	–17	–27	–34	–3	–6	–8
Mozambique	–6	–9	–12	–7	–11	–14	–8	–12	–16	–16	–24	–30	–5	–8	–10
Rwanda*	–6	–9	–10	–1	–2	–2	–13	–19	–20	–15	–23	–25	39	36	35
Tanzania	–6	–10	–12	–5	–9	–12	–8	–13	–16	–16	–25	–30	–5	–8	–10
Uganda	–7	–10	–11	–5	–9	–11	–9	–13	–15	–17	–26	–30	–5	–8	–9
Zambia	–7	–11	–13	–5	–9	–12	–10	–15	–18	–19	–29	–35	–3	–6	–8

*By the 2080s for Rwanda.

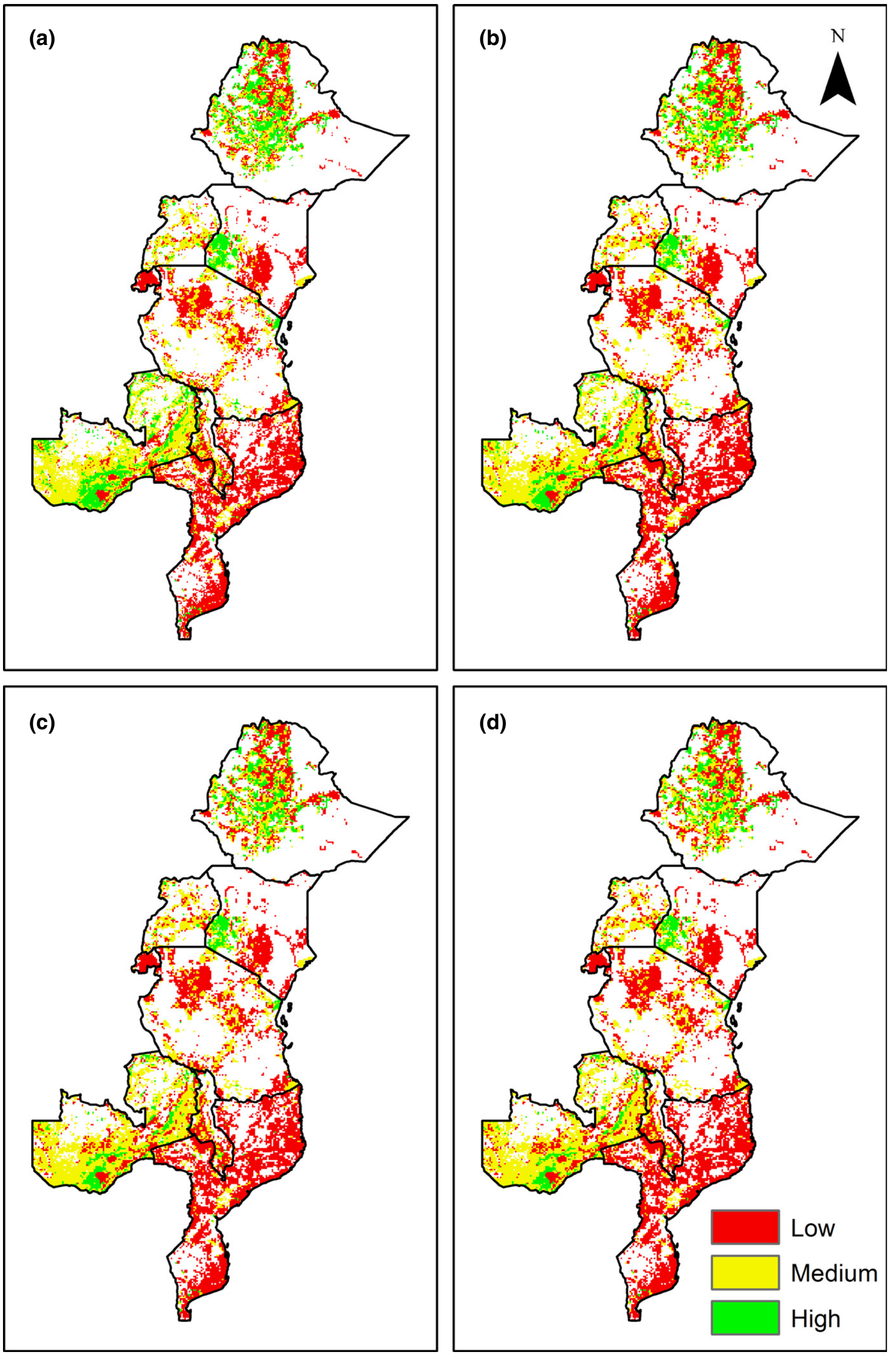

Figure 4. Current (a) and projected maize yield by the end of 21st century under B1 (b), A1B (c) and A2 (d) scenarios (Muchow et al. 1990; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011; HarvestChoice 2015a).

Major Crops and the Impacts of Climate Change

Maize

Maize, the most widely cultivated staple crop in SSA, is primarily grown by smallholders and 77% of the total production in SSA (excluding South Africa) is consumed as food (Smale et al. 2011). Maize is cultivated on about 25 million hectares in SSA, which accounted for 27% of total cereal area and 34% of cereal production between 2005 and 2008 (Smale et al. 2011). Maize is the most important source of dietary protein and the second most important source of calories in eastern and southern Africa (Broughton et al. 2003).

Maize is one of the crops for which climate change impact has been widely studied. Schlenker and Roberts

(2009) reported increased maize yield with an increase in temperature up to 29°C followed by a sharp decline in yield with further temperature increases. However, Liu et al. (2008) reported the optimum maize-growing temperature to be 25°C. Each degree day spent above 30°C has been found to reduce final maize yield by 1% even under optimal rainfed conditions (Lobell et al. 2011). Other report suggests that a 1°C increase above norm reduces maize yield by 10% (Brown 2009). Using worldwide temperature and yield trends, Lobell and Field (2007) reported a decrease of 8.3% in maize yield per 1°C rise above normal. Easterling et al. (2007) plotted multiple crop yield projections against temperature rise, and reported that in low-latitude regions, where the majority of countries studied in this report lie, even a single degree increase in temperature results in about 3% loss in maize yield. Muchow et al. (1990) studied the effect of temperature in maize yield in the United States, where mean daily temperature ranged from 18°C to 29°C, and reported 4–8% yield reduction with a 2°C rise in temperature and 8–16% yield reduction with a 4°C rise in temperature. Runge (1968) found that daily maximum temperatures between 32.2°C and 37.8°C is beneficial to corn yield provided that adequate moisture is available. The authors reported that high temperature (when maximum temperature was 35°C) resulted in 9% reduction in maize yield per 1 inch reduction in rainfall. These findings suggest that at elevated temperature, maize not only suffers from temperature stress, but also becomes sensitive to moisture availability. Rainfed agriculture combined with potential variations in rainfall distribution under climate change, available soil moisture may not be able to meet increasing water demand.

Overall, maize production will decrease under future climate scenarios, though the degree of impact differs among simulations. Using the CERES-Maize model, Jones and Thornton (2003) predicted a 3–19% reduction in maize yield in the FtF countries by 2055 compared to 2000, where Ethiopia and Mozambique were projected to experience the least and greatest decrease in maize yield, respectively. Thornton et al. (2009) simulated maize and bean yield in East Africa, which extends to all FtF countries except Zambia, under A1FI (rapid economic growth and global economic development with intensive fossil fuel use; population growth peaks in 2050 and declines after; the highest increases in GHG emissions) and B1 storyline using the HadCM3 and ECHam4 models. A 3–15% reduction, depending on scenario and GCM, was projected on combined maize and bean production by 2050. Furthermore, the authors projected spatial heterogeneity for maize production with larger areas experiencing reduced yield as compared to the areas with yield gains in East Africa. By 2050, 9–33% of land was projected to observe reduced maize yield by more than 20%. Meanwhile, 39–68% of the simulated area was projected to increase yield by more than 5% depending on the scenario and GCM combination. Using the same models and scenarios, Thornton et al. (2010) predicted yield gains in Kenya and Rwanda and declines in Tanzania and Uganda in 2030 and 2050. Yield gains projected in Kenya and Rwanda were 15% and 11% by 2030 and 18% and 15% by 2050, respectively, while yield losses projected in Tanzania and Uganda were 3% and 2% by 2030 and 8% and 9% by 2050, respectively. Yield gains in Kenya and Rwanda were attributed to the beneficial temperature increases, which would bring growing season temperatures close to optimum temperature in temperate/tropical highlands. However, yield losses in Tanzania and Uganda occurred due to growing season temperatures rising past optimum temperatures. Without considering carbon fertilization, Nelson et al. (2009) projected 7–10% reduction in maize yield under the A2 storyline by 2050 in sub-Saharan Africa. Fischer (2009) included carbon fertilization and adapted crop varieties to estimate the yield of rainfed maize and projected a 1–9% increase in eastern Africa and 43–45% reduction in Southern Africa by 2050s under A2 climate change scenario. Even under optimum rainfed conditions, a 1°C increase in temperature is projected to reduce maize yield in 65% of the present maize cropping areas and under drought conditions, all areas are expected to experience yield loss (Lobell et al. 2011). Based on the relationship presented by Easterling et al. (2007) and considering the temperature projections as shown in Figure 3, yield reduction could be as much as 8–12% (B1), 16–30% (A1B), or 16–40% (A2) by the end of this century without adaptation. Based on the temperature-maize yield relationship presented by Lobell and Field (2007), maize yield in East Africa will be reduced by 16–20%, 24–31%, and 27–37% under B1, A1B and A2 storylines, respectively. Based on Muchow et al. (1990) and considering the area with similar mean daily temperature, maize yield in East Africa will be reduced by 6–7%, 9–11%, and 10–13% under B1, A1B and A2 storylines, respectively (Table 1). The maize yield percentage reduction translates into a loss of 38 kg/ha (Rwanda) to 225 kg/ha (Zambia) depending on field location (Table S1). In general, climate change has minimal impacts on shifting yield classes. The southern part of the study area has lower yield while the northern part has higher yield both under current and future climate scenarios (Fig. 4).

Despite large variations in projected impact on maize yield, there is a general consensus that climate change will adversely affect maize yield in East Africa. Multiple studies indicated that East Africa could lose as much as 40% of its maize production by the end of the 21st century.

Wheat

Wheat is generally cultivated as a winter rainfed crop in the highlands of Ethiopia, Kenya, Uganda, Rwanda, and Tanzania and as a winter irrigated crop in Zambia, Malawi, and Mozambique (Negassa et al. 2012). Wheat is a cool season crop and increasing temperature shortens its growth period by accelerating phonological development, resulting in reduced yield (You et al. 2005; Asseng et al. 2011). In SSA, average annual temperature in 1990 was 20.3°C in wheat harvest areas, which already exceeded the optimum wheat-growing temperature of 15–20°C (Liu et al. 2008). The exact level of the effects of climate change differ by location, but some studies suggest that a 1°C increase in temperature above norm reduces wheat yield by 10% (Brown 2009). Another study reported 3–4% reduction in wheat yield for every 1°C increase in temperature above 15°C (Wardlaw et al. 1989). Without considering the temperature effect on photosynthesis and grain-set, Hatfield et al. (2008) reported 7% yield reduction per 1°C increase in air temperature between 18 and 21°C and 4% reduction per 1°C increase above 21°C. Analyzing global wheat yield data, Lobell and Field (2007) reported a 5.4% wheat yield reduction per 1°C increase in temperature. By plotting the multiple simulation studies from low-latitude areas, Easterling et al. (2007) reported a linear relationship between an increase in temperature and the reduction in wheat yield with about 7% decrease for a 2°C rise in temperature and 34% yield decrease for a 4°C rise in temperature.

As wheat has a lower optimum temperature than rice, maize, millet, cassava, and sorghum (Liu et al. 2008), many simulation studies have projected a greater impact on wheat yield compared to other crops in East Africa (Liu et al. 2008; Fischer 2009; Nelson et al. 2009; Ringler et al. 2010). Fischer (2009), using HadCM3 under the A2 storyline, projected 63% and 44% yield reduction for rainfed wheat in eastern and southern Africa, respectively, by the 2050s even under carbon fertilization and adapted crop cultivars. Using the CSIRO climate model under the same storyline, the author projected 30%, 48%, and 72% yield reduction for rainfed wheat in eastern Africa by 2020s, 2050s, and 2080s, respectively, even considering carbon fertilization. Meanwhile, other crops such as rainfed maize and sorghum, were projected to experience 4% yield gains by the 2050s and a yield decline <2% by the 2080s. Liu et al. (2008) projected a 16–18% yield decrease in SSA by the 2030s, while increases in millet, rice, and maize yields were projected. Using the National Center for Atmospheric Research (NCAR) and CSIRO models and without considering carbon fertilization, Nelson et al. (2009) projected 34% to 36% reduction in wheat under the A2 scenario by 2050 in SSA. Tatsumi et al. (2011) modeled a number of crops using the Improved Global Agro-Ecological Zones method with the A1B storyline and projected a 15% yield loss in wheat in eastern Africa by 2090s compared to the 1990s. Using comprehensive climate change scenarios, which consisted of 17 GCMs, Ringler et al. (2010) simulated a number of crop yields and projected the greatest negative impact on wheat yield in SSA by 2050. Based on Easterling et al. (2007) and projected mean temperature increase (Fig. 3), wheat production in East Africa will decrease by 7–20%, 20–34%, and 20–40% under B1, A1B and A2 storylines, respectively, by the end of the 21st century. According to the report, even with adaptive measures, a 4°C rise in temperature will result in a 15% decrease in wheat production in low latitudes. Based on the global temperature-wheat yield relationship presented by Lobell and Field (2007) and temperature projections in Figure 3, East Africa could experience 10–13%, 16–20%, and 17–24% wheat yield decrease by the end of the 21st century under B1, A1B and A2 storylines, respectively. Considering the temperature projections (Fig. 3) and the relationship presented by Hatfield et al. (2008), wheat yield in East Africa will decrease by 8–13%, 12–19%, and 15–20% under B1, A1B, and A2 storylines, respectively (Table 1). The wheat yield percentage reduction translates into a loss of 69 kg/ha (Rwanda and Mozambique) to 1098 kg/ha (Zambia) depending on field location (Table S1). Spatial yield maps (Fig. S1) show lower yields in northern and southern regions of the study area with no major change in yield classes under future climate change scenarios considered.

The results presented above indicate that wheat is one of the most sensitive crops to climate change. Projected impacts in East Africa vary widely, but without climate change adaptation, eastern Africa could lose about two-thirds of the wheat productivity by the end of the 21st century.

Rice

Rice is a vital crop in East Africa where it is primarily grown by smallholder farmers as a rainfed crop (excluding Kenya, where the majority of rice is irrigated). It is the second most important crop in Tanzania and Malawi and the third most important crop in Kenya and Zambia (EUCORD 2002; Saka et al. 2006; FoDiS 2010). Rice is grown as upland rice, lowland rainfed rice, mangrove swamp rice, floating rice, and irrigated rice (EUCORD 2002). As most of the rice in East Africa is not irrigated, climate change-induced rises in temperature and increased variability in rainfall may impact production. The extent of this impact will vary by production system. Upland and lowland rice production, which constitute about 80% of rice production area in Africa, are projected to be the most vulnerable (Bimpong et al. 2011). Manneh et al. (2007) determined that climate change will affect rice production in Africa by increasing heat stress, drought, flooding and submergence, and salt stress. In rainfed production systems, drought is the most important production-limiting factor due to its sensitivity to moisture stress: yield is significantly reduced even under a mild drought (Guan et al. 2010). Similarly, heat stress results in high spikelet sterility, low tillering, stunting, and accelerated development, which eventually leads to reduced yield (Bimpong et al. 2011). A 1°C increase in temperature above norm reduces rice yield by 10% (Brown 2009). According to Liu et al. (2008), rice has an optimum growing temperature of 25°C, and temperature increases should result in higher rice yield in a majority of FtF countries. Correlating global rice yield with global temperature, Lobell and Field (2007) reported a 0.6% decrease in rice yield per 1°C increase in temperature. Easterling et al. (2007) plotted multiple simulation studies against temperature and projected a 2.6% yield increase with 1°C temperature rise to about 16% yield reduction for a 4°C rise in temperature. Baker and Allen (1993) found a quadratic relationship between temperature and rice yield at 330 ppm of CO_2 with zero yield at 37°C. Being a C3 crop, rice is expected to benefit from increased atmospheric CO_2 concentrations. However, increases in temperature have the potential to negate any benefit of elevated CO_2 in rice yield (Ainsworth 2008).

Projections of the impact of climate change on rice in the region vary among studies. Lobell et al. (2008) used 20 GCM models and projected a slight increase (<5%) in rice production in East Africa by 2030 as compared to 1998–2002. Using the Impact model, Ringler et al. (2010) projected a 0.24% increase in rice yield in eastern Africa and a 2.32% reduction in southern Africa by 2050. Another study by Tatsumi et al. (2011) using the Improved Global Agro-Ecological Zones method under A1B storyline also projected about 1% yield gain in rice in eastern Africa by 2090s compared to 1990s. Nelson et al. (2009) used the NCAR and CSIRO models and projected about a 15% reduction in yield under the A2 storyline by 2050 in SSA without considering carbon fertilization. Variations in rice yield projections among different studies are likely due to the difference in scenarios and models used in the prediction. Based on the temperature projection in Figure 3 and the relationship reported by Easterling et al. (2007), eastern Africa could lose 4–8%, 8–13%, and 8–16% of rice yield under B1, A1B and A2 scenarios, respectively by the end of the 21st century. However, based on Lobell and Field (2007) model, significantly lower yield loss is expected (between 1–3%) for B2, A1B, and A2. However, based on the Baker and Allen (1993) model and median temperature projections for the region, East African rice yield will decrease by 1–7%, 2–12%, and 2–15% under B2, A1B, and A2 storylines, respectively (Table 1). Compared with the current yield, the rice yield percentage reduction translates into a loss of 35 kg/ha (Malawi) to 397 kg/ha (Kenya) depending on field location (Table S1). Spatial yield maps show no major change in yield classes under future climate change. In general southern regions (Mozambique, Malawi, and Zambia) have lower yields while the rest of the region has higher yields (Fig. S2).

Overall, rice appears to be more resilient to climate change than maize or wheat. Nonetheless, climate change is projected to have negative impact on rice yield and eastern Africa could lose as much as 16% of its current rice production by the end of the 21st century.

Sorghum

In terms of quantity, sorghum is the second most important crop in Africa after maize and is the most important crop in the semiarid tropics (Obalum et al. 2011). Major sorghum-growing areas in FtF countries include much of north central, northwestern, western, and eastern mid-altitude areas of Ethiopia, Rwanda, northern and eastern Uganda, central Tanzania, and the areas in Kenya and Tanzania east of Lake Victoria (Wortmann et al. 2009). The importance of sorghum to Africa lies in its inherent ability to resist drought and withstand periods of high temperatures (Taylor 2003). Maiti (1996) reported the optimum vegetative growth temperature of sorghum is 26–34°C and an optimum reproductive growth temperature is 25–28°C. Currently, most of the sorghum in the region is grown under sub-optimum temperatures. About 54% of the sorghum is produced below 24°C (Wortmann et al. 2009). Based on Maiti (1996) and Wortmann et al. (2009), sorghum production should increase in the region with slight increases in temperature. However, some researchers have projected climate change to negatively impact sorghum yield. In a global simulation of sorghum yield, Lobell and Field (2007) reported an 8.4% decrease in sorghum yield for 1°C increase in temperature. Similarly, Hatfield et al. (2008) reported a 7.8% decrease in sorghum yield for 1°C rise in temperature from 18.5°C to 27.5°C. Water deficiency is another constraint in the region that has been cited as the most important sorghum production constraint (Wortmann et al. 2009). Water deficit may increase with increases in temperature and variability in rainfall and may offset yield gains associated with temperature increases. Being a C4 crop, sorghum may not benefit significantly from increased atmospheric CO_2 (Liu et al. 2008).

Combining the temperature projections in Figure 3 and the Lobell and Field (2007) projected yield model, sorghum production in East Africa will be reduced by as much as 16–20%, 24–31%, and 27–38% under B1, A1B, and A2 storylines, respectively, by the end of the 21st century. The Hatfield et al. (2008) crop yield model also produced similar results and showed decrease in sorghum production by 15–19%, 23–29%, and 25–35% under B1, A1B, and A2 storylines, respectively (Table 1). These yield losses are equivalent to 86 kg/ha (Mozambique) to 595 kg/ha (Uganda) when compared to the current crop yields (Table S1). Spatial yield maps show that high-yielding northern regions of the study area will be more impacted by the future climate change than the low-yielding southern regions (Fig. S3). However, comparing these findings to other studies conducted in the region, the yield losses are overpredicted. Knox et al. (2012) reported only a 15% sorghum yield reduction in the African continent by the 2050s. Most other simulation studies that focused on SSA or East Africa predict small changes in future sorghum production in East Africa. Liu et al. (2008) simulated sorghum yield in SSA and Lobell et al. (2008) simulated sorghum production in East Africa and both projected only small changes in sorghum production in the 2030s compared to the 1990s and 2000s. Fischer (2009) projected a 4% yield gain in rainfed sorghum in the 2020s and 2050s and a 2% reduction in 2080s in East Africa with CO_2 fertilization. Using NCAR and CSIRO models without carbon fertilization, Nelson et al. (2009) projected a 2–3% reduction in sorghum under the A2 storyline by 2050 in SSA.

These findings suggest that sorghum is more resilient to climate change than maize or wheat and will be minimally impacted (<5%) by the middle of this century.

Millet

Millet is cultivated mostly in the semiarid tropics and subtropics of Africa; however, it is also cultivated in other drought-prone sub-humid and medium-high altitude areas (Obilana 2003). Millet is a hardy crop that requires few inputs, is less susceptible to pests and diseases, and can be grown in the areas that are too hot and dry for sorghum (Cagley et al. 2009). Pearl millet and finger millet are the most commonly grown millet varieties, where pearl millet is grown in all sub-Saharan countries and finger millet is grown in eastern, southern and central Africa (Obilana 2003). Pearl millet is grown as a dry-land crop in semiarid regions, while finger millet is generally grown in uplands and sub-humid areas (Gari 2002). Millet is important for SSA's food security due to its adaptation to drought and heat, high nutritive, value and ability to be stored for long periods without quality degradation. In SSA, the average temperature in millet harvest areas in 1990 was 27.3°C, which was below the optimum millet-growing temperature of 30°C (Liu et al. 2008). Climate change is expected to raise the temperature in millet-growing areas closer to the optimum temperature, leading to a general increase in millet yield. However, similar to sorghum, millet is not expected to gain much from elevated atmospheric CO_2 levels.

Quantitative projections show both negative and positive impacts of climate change on millet yield. The discrepancy might be attributed to the difference in scenarios, models and time periods used in future projections and the extent of the area considered in the study. Ringler et al. (2010), using comprehensive climate change scenarios consisting of 17 GCMs, simulated crop yields and projected a slight increase (<5%) in millet yield in SSA in 2050. Compared to the 1990s, Liu et al. (2008) projected a 7–27% increase in millet yield in SSA by 2030s under the A1FI, A2, B1 and B2 storylines. Using NCAR and CSIRO models without considering carbon fertilization, Nelson et al. (2009) projected a 7–8% reduction in millet yield under A2 storyline by 2050 in SSA. Using 16 models under the A1B storyline, Schlenker and Lobell (2010) projected a median decrease of 17% in millet yield in SSA by 2050s. These findings are similar to those reported by Knox et al. (2012), who reported a 10% decline in millet yield in Africa by the 2050s.

Based on these studies, millet is more resilient to climate change than maize or wheat but less resilient than sorghum. It is expected that there will be about a 15% yield loss in East Africa by the middle of the century.

Dry beans and soybean

In eastern and southern Africa, beans are the second most important source of dietary protein following maize and the third most important source of calories after cassava and maize, with annual consumption exceeding 50 kg per person (Wortmann et al. 1998; Broughton et al. 2003). Beans are produced in over 20 countries in eastern and southern Africa covering over four million hectares, where Ethiopia, Kenya, Rwanda, Tanzania, and Uganda are among the major producers (Wortmann et al. 1998; Asfaw et al. 2009). Cultivation areas are concentrated in cooler highlands and warmer mid-elevation areas with altitudes greater than 1000 m above sea level. However, due to population pressure, the cropping area is being extended to lower elevations (Katungi et al. 2009). Schlenker and Roberts (2009) conducted a study on the effect of temperature on soybean production and reported a threshold temperature for soybean to be 30°C; increases in temperature up to 30°C gradually increased yield but temperatures beyond the threshold resulted in a sharp decline in soybean yield. In eastern and southern Africa, 80% of the bean-producing area has a mean annual temperature of 15–23°C, which is below the threshold temperature, favoring bean production (Wortmann et al. 1998). However, using global yield data and temperature, Lobell and Field (2007) reported 1.3% decline in soybean yield per 1°C increase in temperature. Boote et al. (1998) reported an optimum temperature of 22°C for soybean yield and a linear reduction thereafter until 30°C. Elevated CO_2 and ozone levels alter the type of soybean diseases prevalent and higher daily temperature has been found to increase disease incidence in soybean (Eastburn et al. 2010). As a C3 crop, beans are expected to benefit from elevated atmospheric CO_2 concentration. Ainsworth et al. (2002) reported a mean increase of 24% in soybean yield with elevated atmospheric CO_2, which was mainly due to pod number increases. Soybean yield is also affected by precipitation and subsequent moisture availability. In 65% of the bean-producing area in the region, the mean rainfall exceeds 400 mm during the three months after sowing, while in other areas yield is severely impacted by moisture deficit (Wortmann et al. 1998). When precipitation falls below 300 mm during the growing season, yield decline in beans is estimated to be 1000 kg/ha (Wortmann et al. 1998). Hence, in eastern and southern Africa, rainfall variability and soil moisture content, rather than rising temperature, are the crucial factors in determining the effect of climate change in soybean production.

Using 20 GCM models, Lobell et al. (2008) projected a slight decrease (<5%) in bean production in East Africa by 2030 as compared to 1998–2002. Thornton et al. (2009) used the HadCM3 and ECHam4 models and the A1FI and B1 storylines to model bean production in East Africa and projected that up to 13% bean cultivation area by 2030 and 56% of area by 2050 will experience greater than 20% yield reduction depending upon scenarios and models. Using the same models and scenarios, Thornton et al. (2010) projected yield gains of up to 36% in 2030 and up to 57% in 2050 in rainfed highlands. The authors projected mixed effects with minor variations in 2030 and up to 20% yield decline in 2050 in rainfed humid-sub-humid regions. Arid and semiarid regions of Tanzania and Uganda were predicted to gain yields in the 2030s and decline in the 2050s. Tatsumi et al. (2011) used the Improved Global Agro-Ecological Zones method under the A1B storyline and projected 12% decline in soybean production in East Africa by 2090 compared to 1990. However, only considering the impact of median temperature rise on soybean yield, the Lobell and Field (2007) model predicts a 2–6% reduction in East Africa by the end of this century across the B1, A1B, and A2 storylines. This is similar to the projections based on Boote et al. (1998) and temperature projection in East Africa (Fig. 3), which shows a yield reduction between 3% and 10% across all scenarios by the end of this century, except for Rwanda (Table 1). In Rwanda, the projections show a yield increase of 35–39% across all storylines as rise in temperature would bring the soybean-growing temperature close to the optimum temperature. These percentage changes would be equivalent to 226–252 kg/ha yield gain in Rwanda, and 11–134 kg/ha yield loss in rest of the countries (Table S1). Spatial cluster analysis shows shift from low yield to medium yield in Rwanda under climate change but no major change in yield class for other countries (Fig. S4).

These results suggest that bean yields in East Africa are more sensitive to rainfall variations than temperature rises. Projections based on climate change scenarios indicate that lowland areas could lose up to 20% of the current beans production but highland areas can gain up to 57% in bean productivity by the middle of the century. However, due to the ratio between lowland and highland areas, there will be a general decrease in dry beans and soybean productions.

Cassava

Cassava is the most important crop in SSA in terms of caloric intake (Rosenthal and Ort 2012). In East Africa, cassava is also the most important staple food crop in terms of total production, where production is concentrated in mid-altitude areas in the African Great Lakes region and the coastal zones of Tanzania and Kenya (Fermont 2009). Cassava is also traditionally cultivated in the northern part of Zambia, while about 70% of farmers in Mozambique cultivate cassava (Nielson 2009). The crop is more resilient to climate change due to its tolerance of high temperatures and intraseasonal drought (Jarvis et al. 2012). However, if a prolonged drought period (>2 months) falls during the root thickening initiation state, a root yield reduction of up to 60% may occur (Jarvis et al. 2012). Cassava shows better yield gain than grain crops at higher CO_2 concentrations, can recover from very long drought periods, and exhibits increases in optimum growth temperature under elevated CO_2 levels (Rosenthal and Ort 2012). These qualities make cassava a suitable crop in a future that is projected to experience elevated CO_2, increased temperature, and variable rainfall patterns. The findings are supported by other researchers who projected minimum impact, if not positive, or at least better performance of cassava than other crops.

Using a geographical information system-based model, Liu et al. (2008) projected small changes in sub-Saharan cassava production by 2030; a 2% reduction to 1% increase depending on scenario. Lobell et al. (2008) also projected a positive impact due to climate change with a slight increase on cassava production in in East Africa by 2030 compared to 2000. Using 16 models under the A1B storyline, Schlenker and Lobell (2010) projected 8% yield reduction for cassava compared to 17–22% reductions in maize, sorghum, millet, and groundnut by the mid-21st century in SSA. Tatsumi et al. (2011), using the Improved Global Agro-Ecological Zones method under the A1B storyline, projected a 10% increase in cassava yield in eastern Africa by 2090s compared to 1990s. Studies conducted by the International Food Policy Research Institute (IFPRI) using the IMPACT model, which takes global food supply, demand, price, etc. along with climate change into account, has also projected increase in cassava production between 40% and 100% in Malawi, Rwanda, and Uganda with no significant change in Mozambique and Tanzania in 2050 (Bashaasha et al. 2012; Kilembe et al. 2012; Maure et al. 2012; Saka et al. 2012; Tenge et al. 2012). Using the same model, Ringler et al. (2010) projected a 0.42% increase in cassava production in eastern Africa and a 0.75% reduction in cassava production in southern Africa in 2050. Furthermore, under different climate change scenarios, projected cassava yield performed better than or at least equal to (in the worst case scenario) maize, sorghum, millet, beans, potato, and banana (Jarvis et al. 2012) making it a potential candidate to ensure future food security in the region.

Based on different projection scenarios, cassava is projected to lose up to 8% or gain up to 10% of its yield in the future. Overall, cassava yield appears to be the least impacted by the climate change.

Sweet potato

One of the most widely grown crops in SSA, sweet potato is an important crop in the areas surrounding the Great Lakes in eastern and central Africa, such as Malawi and Mozambique (Shonga et al. 2013). Sweet potato is a major staple crop in Uganda, Rwanda, and parts of Tanzania, while it is a secondary food source in Kenya and most of Tanzania and Ethiopia (Smit 1997). Mainly cultivated by smallholders, sweet potato is the third most important source of carbohydrates in Uganda, while the country is the third largest producer of sweet potato in the world (Muyinza et al. 2012). Although the crop grows from semiarid lowlands to high-altitude zones, cultivation of sweet potato is most intense in altitudes of 800–1900 m (Smit 1997). Sweet potato is a tropical or a subtropical plant, which has an optimum-growing temperature of 20–25°C, but can be grown in temperatures ranging from 15°C to 33°C (Ramirez 1992). Lower nighttime temperature is required for tuber formation, while higher temperature in the day helps vegetative growth. Susceptibility of sweet potato to drought stress and lower nighttime temperature required for tuber formation makes the crop vulnerable to climate change (Ramirez 1992; Agili 2012). However, being a C3 crop, sweet potato benefits from elevated atmospheric CO_2 concentration levels (Mortley et al. 1996).

Information is sparse regarding the impact of climate change on sweet potato production. Using the IMPACT model, Ringler et al. (2010) projected 1.06% gain in eastern Africa and 1.14% gain in southern Africa in sweet potato yield by 2050. However, while considering the whole sub-Saharan region, the same crop was the second most impacted after wheat. In contrast to previous findings, using five GCM models under the A1B storyline and the Improved Global Agro-Ecological Zones model, Tatsumi et al. (2011) projected a 15% decline in sweet potato production in eastern Africa in 2090s compared to 1990s.

The studies on the impact of climate change on sweet potato in East Africa are not adequate to draw conclusions on the potential yield impact. However, susceptibility of sweet potato to high temperatures at night and climate-induced water stress suggest that the crop might be negatively impacted in the future.

Potato

Mostly grown by smallholders, Malawi was previously the biggest potato producer in SSA (Maganga 2012). Recent statistics shows that Kenya has surpassed Malawi with over 5 million tons of potato production in 2012 (FAO 2013a). In Kenya, potato is the second most important crop following maize. Here it is cultivated by about 500,000 smallholders, making it one of the most important sources of income and employment in rural areas (Obare et al. 2010). In Rwanda, potato is the second major food crop after banana, where it is grown mainly in the highlands in the southwest and north of the country (Muhinyuza et al. 2012). Potato is cultivated in all of the FtF nations, where cultivation is mainly concentrated in highland areas. In terms of total annual production, Rwanda (2.3 million tons) and Tanzania (1.8 million tons) rank third and fourth among the FtF nations, while Zambia is the lowest producer with only 30,000 tons per year (FAO 2013a). Optimum temperature for potato cultivation is 17°C; above which potato production is reduced through either lower plant development and productivity due to heat stress or decreased partitioning of assimilates to the tubers (Wolf et al. 1990). Likewise, moisture stress reduces potato yield by shortening the growing and dormancy period and by reducing the total number and size of potato tubers (Karafyllidis et al. 1996). Being a C3 crop, elevated atmospheric CO_2 levels increase potato yield by increasing the number of tubers.

However, under limited fertilization and a water stressed environment, actual yield gains may be insignificant (Miglietta et al. 1998; Ainsworth and McGrath 2010).

There are very few studies on the impacts of climate change on potato production in East Africa. Haverkort et al. (2013) used six coupled GCMs under the A2 storyline in four potato-growing agro-ecosystems in South Africa. The authors predicted that the positive effects of elevated CO_2 on water use efficiency and crop yield were more than adequate to compensate for the negative effects of increased temperatures and reduced water availability in 2050s. Similarly, IFPRI (Tenge et al. 2012) using the IMPACT model, predicted up to a 100% increase in potato yield and a 50% increase in cultivation area in Rwanda in 2050 compared to 2010. As a result, the authors predicted doubling or tripling the potato production by 2050. However, these predictions are based on IMPACT model, which considers global food supply, demand, price along with climate change. Contrary to previous findings, Jarvis et al. (2012), using 20 GCMs under the A1B storyline, projected about 15% reduction in potato yield in Africa by 2030. Similarly, Tatsumi et al. (2011), using five GCM models under the A1B storyline, projected a 17% decline in potato yield in eastern Africa in 2090s compared to 1990s. As a consequence of climate change, potato yield in most of East African countries (except Rwanda) will decrease due to heat and water stress.

Banana

The Great Lakes region in East Africa is the largest banana-producing and consuming region in Africa (AATF 2009). Banana is the most important food crop in Uganda and Rwanda, where annual per capita consumption exceeds 135 kg (FAO 2013a). Major banana-growing areas in East Africa include southwestern and central Uganda, most parts of Rwanda, the northern, southern, and eastern highlands in Tanzania, and the central and Kisii regions in Kenya (AATF 2009). Studies conducted in some of the FtF countries have revealed that drought stress is either the most important or the second most important constraint in banana production in the region (Van Asten et al. 2011). Optimal banana production is believed to require a constant and ample supply of water due to its permanent green vegetation and shallow root system (Robinson 1996). Though banana can survive water stress for long periods of time, low soil moisture and extended exposure to extreme temperatures (above 35°C) can reduce banana production (Thornton and Cramer 2012). As such, in the East African highlands, where annual rainfall is below 1100 mm, drought-induced yield reduction on rainfed bananas can reach up to 65% compared to wetter areas (Van Asten et al. 2011).

Eastern and Southern Africa, where banana production is limited by low temperature, are projected to experience increases in suitable area ranging from 1% to 11% by 2020 (Ramirez et al. 2011). However, variability in rainfall is expected to result in a loss of suitable areas in the lowlands (Ramirez et al. 2011). Though higher temperatures may increase suitable areas, rises in temperature also result in increased water demand, limiting banana cultivation to the areas projected to receive increased rainfall (Thornton 2012). Meanwhile, highland bananas are projected to observe significant yield loss due to increased risk of pest and diseases if the temperature increases by 2°C (Thornton and Cramer 2012).

Quantitative measures of banana yield under future climate change are limited. In general, moderate temperature rise in highlands would be beneficial for banana yield. However, rainfall variability in lowlands will limit the suitable areas for banana cultivation in the future.

Tea and coffee

Tea and coffee are grown throughout the FtF countries, mostly by smallholders as a cash crop. The production system employs millions of people in the region. Most of the countries export tea and coffee, which contributes significantly to national foreign exchange earnings. While Arabica and Robusta are the two dominant commercially produced coffee varieties grown around the world, Arabica is dominant in East Africa. Kenya, Ethiopia, Rwanda, Malawi, and Zambia primarily grow Arabica. Uganda predominantly grows Robusta, while Tanzania grows both types, mostly Arabica. Optimum-growing temperature for Arabica is 18–23°C while for Robusta is 22–26°C (ICO 2009). Hence, Arabica is cultivated in high altitudes while Robusta is cultivated in lowlands. Higher temperature hastens development and ripening of the cherry, impacting both productivity and quality of coffee.

Based on a study by the International Coffee Organization (ICO 2009), future coffee production is likely to decrease worldwide under the A1F1, A2, B1, and B2 storylines, although the magnitude varies between scenarios. Tanzania's Initial Communication to the UNFCCC (URT 2003) projected no impact with up to a 2°C rise in temperature in coffee production in the country. Variability in precipitation was identified as the decisive factor and the report concluded that an increase in precipitation could increase coffee yield by as much as 17%. In Kenya, the optimal coffee-producing zone is predicted to move upward from 1600 m to 1700 meter above sea level by 2050 (GIZ 2010). The report also projected a decrease in suitable coffee-producing area in the country from the current 50–70% to 30–50%. Jaramillo et al. (2011) predicted shrinkage in coffee-growing areas in most of Kenya, Uganda and Rwanda due to the prevalence of the coffee berry borer caused by increases in temperature, and expansion of suitable area in Tanzania and Ethiopia by 2050 under A2 and B2 storylines.

Similar to coffee, the optimum tea-growing area is projected to shift toward higher altitudes and total suitable area for tea cultivation is projected to shrink. In Kenya, as a result of rise in temperature and variation in precipitation, suitable areas for tea production are predicted to decrease from the current 60–80% to 35–55% and the current optimum tea production zone (1500–2100 m above sea level) is projected to shift to higher altitudes (2000–2300 m above sea level) by 2050 under the A2 storyline (CIAT 2011a). Another report projects that a rise in temperature by 2°C would render large areas in Kenya currently suitable for tea production unsuitable and that smallholders may not be able to cope with the effects of climate change (Simms 2005). Similar to Kenya, optimum tea-growing areas in Uganda are projected to shift from the current 1450–1650 meter above sea level to 1550–1650 meter above sea level under A2 storyline (CIAT 2011b). Due to the lack of high altitude areas, total areas available for tea cultivation are projected decrease by 2050 (CIAT 2011b). Total area suitable for tea cultivation is also projected to decrease from the current 60–80% to 20–40% by 2050. Similar shift in optimum tea and coffee-growing area and shrinkage in total suitable area can be expected in other coffee and tea-producing East African countries.

Overall, future climate change is projected to impact tea and coffee production negatively although quantitative results are limited. Optimum tea and coffee-growing area will shift to higher altitudes. This will limit the production of these crops due to several factors including land ownership, social preference, and land availability.

Cotton

Cotton is grown in most of the FtF countries and is an important cash crop for many smallholders. It is primarily grown in arid and semiarid regions in Kenya, northern and eastern regions in Uganda, Western and Eastern Cotton zones in Tanzania, the lowlands and mid-altitude regions in Ethiopia, southern parts of Malawi, central, eastern and southern provinces in Zambia, and many regions in Mozambique. Cotton is also among the major export commodities in Uganda, Tanzania and Mozambique. To some extent, cotton can tolerate high temperature and drought, although it is sensitive to water availability, especially during flowering and boll formation (Ton 2011). Higher temperatures are reported to decrease boll maturation period, reduced boll size, reduce the number of seeds per boll, reduce fiber length, and ultimately reduce cotton yield (Reddy et al. 1999; Meredith 2005; Pettigrew 2008). Optimum-growing temperature for cotton ranges from 23.5°C to 32°C (Burke et al. 1988). Hatfield et al. (2008) reported that cotton has an optimum-growing temperature of 25°C and the crop completely fails at a temperature of 35°C. Based on the findings and current mean annual temperature, a moderate increase in temperature is beneficial for cotton production in most of the FtF countries. Being a C3 crop, cotton is expected to experience yield increases with the increase in atmospheric CO_2 concentration as long as the temperature does not exceed optimum-growing temperature range (Yoon et al. 2009).

Data on the projected impacts of climate change on cotton production in the region is scarce. One study conducted in Zimbabwe (Gwimbi 2009) reported a decrease in cotton yield with decreasing precipitation and increasing temperature; an 80% decrease in precipitation resulted in a 38% decline in cotton yield. In another study conducted in Cameroon (Gerardeaux et al. 2013), cotton yields were projected to increase by 2050 under the A1B storyline as a result of a slight increase in temperature, and an increase in atmospheric CO_2 with no changes in rainfall. Studies conducted in Cameroon and Mali (Sultan et al. 2010) concluded that onset and duration of rainy season were the major drivers of temporal and spatial distributions of cotton productivity. The authors reported that the relationship between rainfall and cotton productivity depended on mean climatic conditions, as drier regions were most sensitive to climate variability. In Tanzania, a study projected no impacts on cotton production with an annual temperature rise of 2.7°C as the temperature still remained within the optimum-growing temperature (URT 2003). However, the areas projected to receive increased precipitation by 37% were predicted to experience up to a 17% increase in cotton yield, while the areas expected to receive decreased precipitation were projected to experience up to 17% yield loss.

Since it is expected that the rainfall variability will significantly increase by the end of the 21st century, there is a high probability that cotton production will be negatively impacted. However, there is an overall gap in quantitative analysis of climate change and cotton yield in the region.

Sugarcane

Sugarcane production is an important sector in all the FtF countries, where most of the sugarcane is grown either by large estates or by smallholders around the estates, also known as outgrowers. Exceptions are Ethiopia and

Kenya: in Ethiopia about 35% of the sugarcane is produced by smallholders, whereas in Kenya about 85% of sugarcane is produced by smallholders (KSB 2009; Assefa et al. 2010). Sugarcane is extensively grown in the Lake Victoria basin of Kenya and Uganda and is considered the most important cash crop in the region (Netondo et al. 2010). Sugarcane requires a temperature of 30–32°C during the main growing season, while temperature above 35°C is detrimental to plant growth (Blackburn 1984; Hunsgi 1993). Additionally, a 2–3°C increase in temperature was reported have a positive impact on sucrose yield, while decreases in rainfall had a negative impact on sucrose yield (Kiker 2002). Being a C4 crop, sugarcane will receive limited benefits from carbon fertilization, but De Souza et al. (2008) demonstrated increased sugarcane production under carbon enriched environments, indicating a positive impact of climate change.

Under the A1FI, A2, B1 and B2 storylines, Liu et al. (2008) projected increases in temperature ranging from 28.30°C to 28.54°C, which is below the optimum sugarcane-growing threshold. Hence, variation in precipitation and water availability seem to be the key factor in quantifying the effect of climate change on sugarcane in the region. In Ethiopia, sugarcane grown by smallholders is irrigated (Assefa et al. 2010), and hence climate change should have minimal effects on production. In Kenya, climate change is projected to increase frequency of drought (ROK 2002), which may result in moisture deficit affecting sugarcane production. Lukorito and Ouma (2010) also concluded that rainfall variability during the grand growth stage of sugarcane is a major factor affecting productivity in sugarcane-based areas. Studies conducted by IFPRI using the IMPACT model projected a 0.31% increase in yield for eastern Africa and a 1.09% increase in southern Africa by 2050 (Ringler et al. 2010). Using 20 GCM models, Lobell et al. (2008) projected a slight decrease (<5%) in sugarcane production in East Africa by 2030 as compared to 1998–2002. Reports on the effects of climate change on sugarcane production in other countries are lacking, although irrigated sugarcane production systems developed by estates should be more resilient in light of changing climate.

Sugarcane is resilient to temperature rise but is vulnerable to rainfall variability. Projected climate change impact on sugarcane is minimal and it is expected to be within 5% of the current yield.

Adaptation Options

The application of different adaptation techniques in East Africa should aim to improve several critical components including soil health, water conservation, livelihood diversification and the capacity of local institutions (FAO, 2014). In addition, effective management of land, water and soil resources should always be considered while planning adaptation measures, as these resources provide a safety net to the vulnerable groups (Paavola 2008).

It is evident from this review that some crops in eastern Africa will be primarily affected by heat stress in the future. For crops, such as wheat that are more impacted by heat stress switching to heat-resistant and drought tolerant crops, such as sorghum and millet, may mitigate temperature stress-related crop failure. As an adaptive measure to climate change, farmers in Africa have already begun selecting a combination of crops based on the prevailing climate (Kurukulasuriya and Mendelsohn 2006).

However, many crops will be more affected by water stress, caused by increased evapotranspiration and variability in rainfall, rather than heat stress. As such, rainfed farming in SSA is typically limited to 3–6 months during the rainy season and the crop yields are subjected to weather-driven fluctuations (Burney and Naylor 2012). Construction of new irrigation schemes and rehabilitation of existing schemes are possible options to reduce future water stress. Of the six million hectares equipped for irrigation in SSA, one million hectares need rehabilitation; more than 30%, 50%, and 60% of irrigation-equipped area in Uganda, Malawi, and Mozambique, respectively, are in need of irrigation rehabilitation (You 2008). In SSA, large-scale irrigation schemes have proven to be expensive and environmentally unsustainable (Ngigi 2003). Furthermore, the construction of large-scale irrigation projects is limited by both natural and social constraints such as water source availability, geography, and conflicting interests among stockholders (Fujiie et al. 2011). This has made the development of large-scale irrigation schemes implausible in SSA. However, the development of small-scale irrigation schemes is a more feasible option for maintaining future crop productivity. For smallholders, shallow and hand-dug wells could supplement water limitations, especially during the dry season (Ngigi 2009). Rainwater harvesting and storage from ground surfaces and rooftops for use during the dry season is another option to cope with rainfall variability (Elliot et al. 2011). The development and dissemination of drought tolerant crop cultivars could also help minimize the climate change impact in drought-prone areas.

Future climate change impacts on water resources in East Africa show that runoff will increase in the northern regions and decrease in the southern regions (Adhikari et al. 2015). Furthermore, groundwater sources will be less impacted by near-term climate change providing an alternative source of water for all regions (Bonsor et al. 2010). However, due to the lack of studies evaluating the impacts of climate change on groundwater by the end of the century, the feasibility of groundwater irrigation systems is uncertain. This means that for the near-future both northern and southern regions will have access to water for irrigation. However, various resources and social constraints may limit the capacity of the smallholders to adopt irrigation as an adaptation measure. With the rapid growth of population, there will be an increase in competition for water resources among various sectors such as municipal, industrial and agricultural. In addition, affordability remains a key issue in developing irrigation systems or water harvesting structures since more than 60% of the population in the region lives on less than $2 a day (World Bank 2015). In some places, geographic location necessitates the use of mechanical power to draw irrigation water and the lack of available power sources and associated costs may limit irrigation development (ADF 2006). Migration of the male population to urban areas in the region has increased the number of female-headed households, who lack financial resources and social support to adopt climate change adaptation measures (Olson et al. 2010; Hazell 2013). Furthermore, the migration of the population also disrupts the existing farming system and raises land ownership issues (Messina et al. 2014), thereby increasing the risk in investing in irrigation infrastructure.

Despite the fact that irrigation remains the key to cope with the climate change, several farm level adaptation measures can be implemented to minimize the risk of future conditions. These adaptation measures can be incremental, systems or transformational and are based on the severity of the climate impacts (Rickards and Howden 2012). Incremental adaptation is the fine tuning of the existing system to minimize impacts, which includes changing planting dates, crop varieties, plant density, and nutrient and water management practices (Rickards and Howden 2012). These changes can greatly reduce the adverse impact of climate change on crop yields, thereby minimizing the vulnerability (Easterling et al. 2007). In East Africa, farmers have already implemented marginal adaptation measures by changing their planting date and crop varieties, however, soil, water and land management practices have not been widely adopted (Kristjanson et al. 2012). Soil and water conservation are particularly important since these practices can enhance the effectiveness of irrigation, fertilizer and improved seeds (Kato et al. 2011). When the incremental adaptations become inadequate, farmers may have to implement systems adaptation (switching to resilient crops, crop diversification, or precision agriculture) or even to transformational adaptations (seek alternative income generation methods) (Rickards and Howden 2012).

Conclusions

This paper synthesizes more than 160 studies on the impacts of climate change on most of the economically viable crops in selected eastern African countries. A review of literature reveals that most of the impact studies have focused on cereal crops, while a number of noncereal crops (e.g., banana, sweet potato, cassava, potato), which serve as staple foods, are also important and should be considered in future research.

Current literature on the impacts of climate change on crops in East Africa suggested that wheat is likely to be the most negatively impacted crop. It is projected that wheat yield will decrease by up to 72% by the 2080s. Other grain crops such as maize, rice, millet and beans are projected to be moderately impacted, with yield changes ranging from −45% to +18%, −15% to +3%, −17% to +27% and −12% to +17%, respectively. Among the grain crops, sorghum is projected to be least impacted, where the projected impact is within 5% of the current yield. Root crops are projected to be less impacted by the climate change. For example, projected future change on the yields of cassava, sweet potato, and potato range from −8% to +10%, −15% to +1%, and −17% to −15%, respectively. Moderate temperature rise is beneficial for highland bananas, but higher increase in temperature would negatively impact its yield. Optimum production zones for tea and coffee are projected to decrease by as much as 40% due to rise in temperature. Cotton and sugarcane are less sensitive to temperature rise, but more prone to drought stress under climate change.

As most of the cropped area is rainfed, development of small-scale irrigation would be the most crucial step in ensuring future food security, but farmers' affordability remains a key problem. Soil and water conservation measure are important in maintaining crop productivity and building resilience against climate change. Development and adoption of drought tolerant varieties is one of the options to cope with the changing climate. Transitioning to heat tolerant and drought-resistant crops is would be necessary if the climate change renders current crops unsuitable in the future.

To better assist in formulating potential coping measures, further research is needed to quantify the impacts of climate change on regionally important staple food crops such as cassava, potatoes, sweet potatoes, and banana as well as cash crops such as tea, coffee, cotton, and sugarcane. As food production is also impacted by other factors such as landuse changes, disease incidence, and market demand, future research studies should take these factors into consideration when studying the effects of climate change on crop production. In addition, there is a need to incorporate uncertainty of climate models into consideration. This will provide better information in regard to the impacts of climate change in the region. In addition, the level of uncertainty can be reduced by repeating this type of analysis with the new set of climate change information, such as IPCC AR5 and future versions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Table S1. Projected change in yield (kg/ha) under three (B1, A1B and A2) climate change scenarios by 2090s (2080s for Rwanda) (Muchow et al. 1990; Baker and Allen 1993; Boote et al. 1998; Hatfield et al. 2008; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011, HarvestChoice 2015a,b,c,d,e).

Figure S1. Current (a) and projected wheat yield by the end of 21st century under B1 (b), A1B (c) and A2 (d) scenarios (Hatfield et al. 2008; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011; HarvestChoice 2015e).

Figure S2. Current (a) and projected rice yield by the end of 21st century under B1 (b), A1B (c) and A2 (d) scenarios (Baker and Allen 1993; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011; HarvestChoice 2015b).

Figure S3. Current (a) and projected sorghum yield by the end of 21st century under B1 (b), A1B (c) and A2 (d) scenarios (Hatfield et al. 2008; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011; HarvestChoice 2015c).

Figure S4. Current (a) and projected soybean yield by the end of 21st century under B1 (b), A1B (c) and A2 (d) scenarios (Boote et al. 1998; McSweeney et al. 2010a,b,c,d,e,f,g,h; Cole 2011; HarvestChoice 2015d).

