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Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security

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Abstract Sub-Saharan Africa has been portrayed as the most vulnerable region to the impacts of global climate change because of its reliance on agriculture which is highly sensitive to weather and climate variables such as temperature, precipitation, and light and extreme events and low capacity for adaptation. This article reviews evidence on the scope and nature of the climate change challenge; and assesses the impact of climate change on agriculture and food security in Sub-Saharan Africa. From the review, it is apparent that the climate in Africa is already exhibiting significant changes, evident by changes in average temperature, change in amount of rainfall and patterns and the prevalence of frequency and intensity of weather extremes. The review also revealed that although uncertainties exist with regards to the magnitude of impacts, climate will negatively affect agricultural production in Sub-Saharan Africa. Specifically, as result of current and expected climate change, the area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease. These impacts will affect all components of food security: *food availability*, *food accessibility*, *food utilisation and food stability* and hence increase the risk of hunger in the region. The review thus confirms the general consensus that Sub-Saharan Africa is the most vulnerable region to climate change. It suggests that, policymakers and development agencies should focus on formulating and implementing policies and programmes that promote farm level adaptation strategies currently being practiced by farmers across the region.

Keywords Climate change · Agriculture · Food security · Sub-Saharan

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1 Introduction

There is no serious doubt about the fact that our climate is changing. The world's climate has been changing for several thousand years. Seven thousand years ago, for example, the Sahara was a landscape of lakes and forests (Brown and Crawford 2009). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report confirms and reinforces the evidence that climate change is real and poses serious environmental, social and economic threats. According to the IPCC, recent "warming of the climate system is unequivocal" as it is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC 2007, p. 5). The impacts of climate change such as rising global average temperature and changes in precipitation are undeniably clear with impacts already affecting ecosystems, biodiversity and human systems throughout the world. Future impacts are projected to worsen as the temperature continues to rise and as precipitation becomes more unpredictable. Among the many adverse impacts of climate change, the risk to agriculture is considered most significant (Cline 2007; Dinar et al. 2008; Kurukulasuriya and Mendelsohn 2008a, b; Seo et al. 2009), as majority of the world's population; especially those in the developing countries highly depend on agriculture for their livelihoods (World Bank 2007). Agriculture is very much sensitive to weather and climate variables, including temperature, precipitation, light and weather extremes, such as droughts, floods and severe storms (Molua 2002).

Many studies have concluded that the impacts of climate change will not be equally shared among the population of the world (Kurukulasuriya and Mendelsohn 2007; Thornton et al. 2008; Smith et al. 2001). The distribution of impacts will vary as both the ability to respond to impacts and resources with which to do so vary across nations (Kurukulasuriya and Rosenthal 2003). There is high confidence that developing countries will be more vulnerable to climate change than developed countries, and there is medium confidence that climate change would exacerbate income inequalities between and within countries (Smith et al. 2001). There also is medium confidence that a small temperature increase would have net negative impacts on market sectors in many developing countries and net positive impacts on market sectors in many developed countries (Smith et al. 2001).

Sub-Saharan Africa (henceforth, 'SSA') is considered most vulnerable to the impacts of climate change because of its high dependence on agriculture and natural resources, warmer baseline climates, low precipitation, and limited ability to adapt (Kurukulasuriya and Mendelsohn 2007, 2008a; Hassan and Nhemachena 2008; Thornton et al. 2008). This vulnerability is also due to the fact that current climate is already severe, present information is poorest, and technological change has been slowest in SSA (Dinar et al. 2008). Climate change is expected to affect rains, increase the frequency of droughts, and raise average temperatures, threatening the availability of fresh water for agricultural production (IFAD 2009). In its fourth assessment report, the IPCC (2007) concluded that by 2100, parts of the Sahara are likely to emerge as the most vulnerable, showing likely agricultural losses of between 2 and 7% GDP. These impacts will occur along with high population growth in the region currently projected to grow from 0.9 billion people in 2005 to about 2 billion by 2050 (UNDP 2007). As studies on agricultural vulnerability continue to emerge or be updated, it is essential to review and assess these results on a regular basis, with the aim of identifying common findings and trends. Lessons learned from current and future impacts assessments and vulnerability will provide essential understanding of processes and actions on climate change and enhance human society's understanding of the links between climate change and agricultural production and food security in SSA. According to Lobell et al. (2008) while the relationships between crop production and climate remain most unclear in West, Central, and East Africa, in contrast, that of the Sahel, South Asia, Southern Africa, and Brazil are relatively better understood.

This article therefore takes stock of the burgeoning literature on climate change and reviews evidence on the extent and nature of the climate change challenge; and assesses how the changing trends affect agricultural production and food security in SSA. It attempts to highlight the areas of agreement among researchers, and note where opinions differ. The aspects of climate change considered are: changes in temperature, altered patterns of precipitation, and extreme weather events, including droughts and floods. Temperature and precipitation are the climate factors that directly connect agricultural production-"not because the significance of the range between high and low values, and also the frequency at which these extremes occur and the intensity of the events" (Ziervogel et al. 2006, p. 3). Also, an increase in average temperature can lengthen the growing season in many locations; adversely affect crops in Africa where heat already limits production; increase soil evaporation rates, and increase the likelihood of severe droughts. Changes in rainfall amount and patterns can affect soil erosion rates and soil moisture, both of which are significant for crop yields.

2 State of agriculture in Sub-Saharan Africa

Agriculture plays a central role in supporting rural livelihoods and economic growth over most of Africa. The sector contributes between 20 and 30% of GDP and 55% of the total value of African exports (World Bank 2007). More than 70% of the population lives in rural areas, and the livelihoods of about 85% depend on rain-fed agriculture and agriculture-based rural activities (Shah et al. 2008). Rain-fed farming dominates agricultural production in SSA, covering around 97% of total crop land, and exposes agricultural production to high seasonal rainfall variability (Calzadilla et al. 2008). Irrigation systems are few. Just 4 percent of the area in production is under irrigation in SSA, compared with 39% in South Asia and 29% in East Asia (World Bank 2007).

Despite the high dependence, agricultural productivity has been steadily declining in SSA over the last 50 years (Ward et al. 2010). Indeed, SSA's agriculture has seen the slowest record of productivity increase in the world (Dinar et al. 2008). While Asia saw a rapid increase in food production and yields during the green revolution in the late 1970s and early 1980s, in SSA per capita food production and yields have declined (Calzadilla et al. 2008). The dismal performance of the agricultural sector is due to long standing issues such as a lack of demand for irrigated products; poor market access and supporting institutions; low population densities; low incentives to agricultural intensification; unfavourable topography; low quality soils and inadequate policy environments; agroecological complexities and heterogeneity of the region (FAO 2008a; World Bank 2007). This situation will be significantly exacerbated by climate change, as well as by the increase of extreme events. The impacts of climate change on agriculture could severely worsen the livelihood conditions for the rural poor and increase food insecurity in the region.

3 Climate, climate variability and climate change in Sub-Saharan Africa

The climate of Africa is distinguished by seven climate zones: tropical rainforest, tropical wet and dry, tropical dry, mountain, Mediterranean, middle latitude dry, and humid sub-tropical. Within the various zones, altitude and other localised variables generate different regional climates (Eriksen et al. 2008). Hulme et al. (2005) therefore describe the climates of Africa as both *varied* and *varying*. *Varied*, because they range from humid equatorial regimes, through seasonally-arid tropical regimes, to sub-tropical Mediterranean-type climates; and *varying* because all these climates exhibit differing degrees of temporal variability, particularly with regard to rainfall. Instrumental and observational records have shown that climate and environmental conditions in Africa continue to exhibit significant changes. Alteration in temperature, rainfall, extreme weather events have been documented across SSA (e.g. Baker 2000; Hulme 1996a, b; Hulme et al. 2001, 2005; L'Hôte et al. 2002; Nicholson et al. 2000, Nicholson 2001). These studies have shown that changes in climatic variables such as temperature, precipitation and extreme weather events such as floods and droughts and their distributions have been dramatic across SSA. The situation is expected to persist in the coming decades.

3.1 Temperature changes

The global mean surface temperature has increased in a linear trend of 0.74°C over the last 100 years (IPCC 2007). The continent of Africa is generally noted to be hot and dry with current trends showing warmer spells than it was 100 years ago (Hulme et al. 2005; Kurukulasuriya et al. 2006; van de Steeg et al. 2009). Observed temperatures have shown a greater warming trend since the 1960s (IPCC 2007). Warming through the twentieth century has been at the rate of about 0.5°C/century with slightly larger warming in the June–August and September–November seasons than in December–February and March–May (Hulme et al. 2005). Hulme et al. (2005) recorded the late 1980s and 1990s to be the warmest years with 1987 and 1998 being the warmest years. These warmings are anticipated because most of SSA lies in tropical and subtropical latitudes, where temperatures are high throughout the year and vary more from daytime to night time than during the course of the year (Nicholson 2001).

Although these trends appear to be widespread over the continent, the temperature changes are not always uniform. They vary considerably between and within regions and countries. For example, countries lying around the Nile Basin witnessed an elevated temperature of between 0.2 and 0.3°C per decade in the second half of the century, while in Rwanda, temperature increased by 0.7 to 0.9°C (Eriksen et al. 2008). Mean annual Diurnal Temperature Range (DTR) decreased by between 0.5 and 1°C since the 1950s in Sudan and Ethiopia, and a similar amount rise in temperature is experienced in Zimbabwe. In South Africa, DTR decreased during the 1950s and 1960s, but has remained quite stable since then (Hulme et al. 2001). According to New et al. (2006), between 1961 and 2000, there was an increase in the number of warm spells over Southern and Western Africa, and a decrease in the number of exceedingly cold days. For the whole of the Southern Africa region, Hulme (1996b) observed that the six warmest years in this century have all occurred since 1980 with the warmest decade being 1986–1995.

The rate of warming does not differ from that experienced globally and the periods of most rapid warming—the 1910–1930s and the post—1970s which occur simultaneously in Africa and the world (Hulme et al. 2005; IPCC 2001). According to the Third Assessment Report (TAR) of the IPCC, the Earth's average surface temperature increased 0.6 ± 0.2°C in the twentieth century. This trend is expected to persist, with a rise of 1.4 to 5.8°C by 2100 (IPCC 2001).

With respect to future changes, the whole of Africa is expected to warm across all seasons throughout this century (Boko et al. 2007). Model-based predictions of future greenhouse gas-induced climate change for the continent clearly suggest that this warming will continue and, in most scenarios, accelerate (van de Steeg et al. 2009). Projected results showed that for all seasons, the average temperature will increase by the end of this century to between 0.3 and 4°C, by 2099, around 1.5 times the mean global temperatures (a land masses warm more than water bodies) (Boko et al. 2007), with warming likely to be severe over the interior of semi-arid margins of the Sahara and Central Southern Africa (Eriksen et al. 2008). In SSA, there will be roughly +2.0 to +4.5°C of temperature rise by 2100, and this expected to be stronger than the global average (Müller 2009). Under the IPCC Special Report on Emission Scenarios (SRES), an average surface warming of 3.8°C in summer and 4.1°C in winter is expected by 2080s (Met Office Hadley Centre 2006). Again, these projections are not uniform across the region. For example, Hernes et al. (1995, cited in Hulme et al. 2001) and Ringius et al. (1996) observed climate change scenarios for the African continent that indicate that land areas over the Sahara and semi-arid parts of southern Africa warming will be as much as 1.6°C by 2050s and the equatorial African countries warming at a slightly slower rate of about 1.4°C. Model results by Meadows (2006) revealed positive mean annual temperature anomalies in the future, in the range of 2–3°C for Southern Africa. The Equatorial countries of Cameroon, Uganda and Kenya, for example, will be about 1.4°C warmer. This represents a rate of warming to 2050 of about 0.2°C per decade.

3.2 Changing pattern of rainfall

Temperature plays a significant role in driving year-to-year production changes, but compared to rainfall, it is less important in determining agricultural production in the tropics (Lobell and Burke 2008). Rainfall plays a significant role in determining agricultural production and thus the economic and social well being of rural communities (Lobell and Burke 2008; Haile 2005). Both seasonal and annual high variability characterised the patterns of rainfall in SSA (Eriksen et al. 2008). The rainfall pattern in SSA is influenced by large-scale intra-seasonal and inter-annual climate variability including occasional El Niño-Southern Oscillation (ENSO) events in the tropical Pacific resulting in frequent extreme weather event such as droughts and floods that reduce agricultural outputs leading to severe food shortages (Conway et al. 2007; Dore 2005; Haile 2005). The ENSO phenomenon is the climatic engine influencing rainfall on an inter-annual time-scale and is often described as one of the important determinants of year-to-year climatic variability and severe impacts around the globe (Cane 2000, cited in Vogel and O'Brien 2003). Two regions in Africa with the most dominant ENSO influences are in Eastern equatorial Africa during the short October–November rainy season and in South-eastern Africa during the main November–February wet season (Hulme et al. 2001; Nicholson et al. 2000; Vogel and O'Brien 2003).

As already noted, current records indicate that rainfall pattern across Africa varies extremely and exhibits different scales of temporal and spatial variability (Boko et al. 2007; Hulme 1996a). Hulme et al. (2005) illustrated the nature of rainfall variability for the three regions of Africa—the Sahel, East Africa and Southeast. Their observation showed that these three regions exhibit contrasting rainfall variability characteristics: the Sahel exhibits large multi-decadal variability with recent drying; East Africa shows a relatively steady regime with some evidence of long-term wetting; while South-East Africa displays a stable regime, but with noticeable inter-decadal variability. In East Africa, 1997 was a very wet year and, like in 1961 and 1963, led to a surge in the level of Lake Victoria (Birkett et al. 1999, cited in Hulme et al. 2001). Southern Africa has seen an increase in inter-annual variability over the past 40 years, but with intermittent droughts, although some countries such as Angola, Namibia, Mozambique, Malawi and Zambia recorded heavy rainfall events along with changes in seasonality and extreme weather events (Boko et al. 2007; Brown and Crawford 2009). West Africa on the other hand has seen an increase in rainfall during the past 10 years when contrasted from the extended droughts years from the 1960s to the 1990s, during which annual average rainfall decreased by as much as 30% (Hulme et al. 2001).

Although some parts of SSA have seen some increases in rainfall, it is the drop in rainfall that is often more pronounced. In general, several studies showed that the most significant climatic change that has occurred in the region is a long-term reduction in precipitation in the semi-arid regions of West Africa, particularly in the Sahel (Baker 2000; Dore 2005; Hulme 1996b, 2001, 2005; Nicholson 2001). The Western Sahel saw a pattern of decreasing rainfall since the late 1960s (20 to 40% between the periods 1931–1960 and 1968–1997) (Baker 2000; Hulme et al. 2001). Specifically, average rainfall in the Sahel is observed to have declined by 20–49% in the late 1960s and 1990s compared with 5–49% across the rest of Africa (IPCC 2001). The last 25 years have seen a trend towards reduced rainfall and in Southern Africa and, during the early 1990s, two or three serious droughts occurred (Vogel and O'Brien 2003). Under the same annual amounts, seasonal, length and intensity of wet/dry seasons is, however, a more cryptic parameter (Meadows 2006).

Projected model results in SSA indicate clearly a relatively wetting East Africa, drying in Southeast Africa, and poorly specified outcome for the Sahel (Met Office Hadley Centre 2006). The Met Office Hardley Centre projected a reduction in rainfall over much of the western and subtropical areas. Conversely, wetter conditions will occur over Eastern Equatorial and tropical Southern Africa during summer. Winter rains will however diminish by up to 40% in Southern Africa (Brown and Crawford 2009). Annual rainfall fluctuation is also projected to increase in Western Africa and decrease in Southern Africa during the century (Hendrix and Glaser 2007). According to Hulme et al. (2001) while these predictions of future 'warming' may be relatively strong, there remain fundamental reasons why we are much less confident about the magnitude, and even direction, of regional 'rainfall' changes in the region. They attributed these uncertainties to two main reasons. The first involves the uncertainties in relation to most global climate models, especially of ENSO-type climate variability in the tropics (a key determinant of African rainfall variability). The second relates to the omission in all current global climate models of any representation of dynamic land cover-atmosphere interactions and dust and biomass aerosols.

3.3 Extreme weather events

In many parts of SSA, natural disasters involve too much or too little rain (Brown and Crawford 2009). Elevated temperature and the unpredictability of the rainfall (both temporally and spatially) are projected to increase both frequency and intensity of extreme weather events for SSA, including droughts, heavy rain storms, flooding, forest fires and ENSO events (Case 2006). Droughts and floods for instance have been common in most parts of SSA, particularly in the Horn of Africa and the Sahel. Drought has been defined as the "phenomenon that exists when precipitation is significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resources and production systems" (IPCC 2007, p. 986). Droughts thus come about due to too little rainfall or too much evaporation, for example, if temperature increases (Met Office Hadley Centre 2006) leading to dryness/aridity.

One-third of the people in Africa resides in drought-prone areas and is vulnerable to its consequences (World Water Forum 2000, cited in UNDP 2007). Since the 1960s, droughts have mainly persisted in the Sahel, the Horn of Africa and southern Africa and this has captured the attention of several researchers (e.g. Usman and Reason 2004; Mortimore 1989, Mortimore and Adams 2001; Brooks 2004; Orindi et al. 2007; Zeng 2003). The drought in the Sahel started in earnest in 1968 and reached its highest point in 1972. It then declined, only to return in the late 1970s and exacerbated during the 1980s before easing off in the 1990s (Buroughs 2001). In 1990s and 2000s, a number of East African countries, including Ethiopia, Kenya and Somaliland, suffered severe droughts as a result of failed annual rains. With crops unable to grow, many people have been left without enough food to eat. For example, the 2000/2001 and 2006 droughts were the worst in at least 60 years in Kenya affecting more than 3.5 million people (Orindi et al. 2007). On the flip side, some countries in SSA have had too much rainfall. For example, Burkina Faso (2007 and 2009), Mozambique (2000 and 2001), Ethiopia (2006) and Ghana (2007 and 2010) have experienced severe flooding with harsh livelihood consequences.

Future projections using the Palmer Drought Severity Index (PDSI) based on the IPCC SRES A2 indicate a mix and uncertain picture throughout Africa. The Palmer Drought Index (PDI) is used as an indicator of drought severity, and a particular index value is often the signal to begin or discontinue elements of a drought contingency plan, and have used as a measure of drought for both agriculture and water resources management (Guttman 1998). The projections indicate that much of SSA will experience an expanding droughts condition in the coming decades. In particular, Arid and Semi-arid areas are projected to increase by 60–90 million hectares (UNDP 2007). The Mediterranean coast and southern Africa are both expected to witness increased severity of droughts (Boko et al. 2007).

4 Current and future impacts of climate change on agriculture

A number of scientific approaches have been used to predict the impacts of the contemporary and future climate change on agricultural land and cereal production throughout the world including SSA. Traditionally, three methods have been used to assess the impacts of climate change on African agriculture: crop simulation models, agro-ecological zone (AEZ) models, and cross-sectional Ricardian models. The crop simulation method uses the direct effect of climate change on individual crops (e.g. Conway et al. 2007; Jones and Thornton 2003; Parry et al. 1999; Thornton et al. 2009). These studies reveal that the yields of the major cereals grown in SSA would fall precipitously with warming.

The AEZ model is a promising new method for valuing the long-term impacts of climate change on agriculture (Kurukulasuriya and Mendelsohn 2008a). Originally developed by the Food and Agricultural Organisation of the United Nations (FAO) in collaboration with the International Institute for Applied Systems Analysis (IIASA) in the late 1970s, the AEZ method follows an environmental approach and includes an identification of areas with specific climate, soil, and terrain constraints to crop production; estimation of the extent and productivity of rain-fed and irrigated cultivable land and potential for expansion; quantification of cultivation potential of land currently in forest ecosystems; and impacts of climate change on food production, geographical shifts of cultivable land (cited in Fischer et al. 2002). The zones were intended to capture the Length of the Growing Period (LGP) defined as the number of days in a year with temperature and soil moisture conditions favorable to crop cultivation (Fischer et al. 2005). The LGP is often chosen as a proxy for agricultural impacts as it is crop-independent and a useful integrator of changes in rainfall amounts and patterns and temperatures (Thornton et al. 2008). Although longer growing seasons are not always better, a key advantage of the

AEZ method is 'dividing a variety of landscape into a set of homogeneous zones' (Kurukulasuriya and Mendelsohn 2008a).

The Ricardian method measures the relationship between net revenues from crops and climate using cross sectional evidence (Kurukulasuriya et al. 2006; Kurukulasuriya and Mendelsohn 2008a). With the Ricardian method, land values or net revenues are regressed on climate, soils, geographic variables and economic variables that are independent of the farmer (not choices) (Mendelsohn 2009). It also assumes that prices are constant (Kurukulasuriya and Mendelsohn 2008b) and that farmers adjust their inputs, outputs and farming practices to best take advantage of where the farm is located, including the climate (Mendelsohn 2009; Seo and Mandelsohn 2008).

Regardless of the approach used, most studies show a negative impact of climate change on arable land and changes in crop productivity patterns in all regions of the world including SSA. For example, based on Atmosphere–Ocean General Circulation Models (AOGCMs) on the impact of future climate, Lotsch (2007) analysis suggests that cropland area in Africa is likely to decrease significantly in response to transient changes in climate. Specifically, the continent is expected to have lost on average 4.1% of its cropland by 2039, and 18.4% is likely to have disappeared by the end of the century. In some regions of Africa the losses in cropland area are likely to occur at a much faster rate, with northern and eastern Africa losing up to 15% of their current cropland area within the next 30 years or so. Although western and southern Africa will experience some gains as a result of anticipated increases in rainfall during the earlier period of the century, these benefits will be negated by some losses as the years go by (Lotsch 2007).

Using the AEZ model, Shah et al. (2008) projected that by 2080s, two-thirds of the global land surface will suffer severe constraints for rain-fed crop cultivation due to unfavourable temperatures, precipitations, topography or soil quality. In SSA, their assessment revealed that arable land will suffer severe environmental constraints, preventing crop production in Eastern Africa (by up to 2.4%); Central Africa (by up to 1.2%) and Western Africa (by up to 1.7%). Southern Africa will be the most severely affected region with about 11% of its total land area (265 million hectares) at risk of being lost for crop production due to environmental constraints induced by climate change (Fischer et al. 2005; Shah et al. 2008). Furthermore, they projected that 1.1 billion hectares of arid and dry semi-arid land in Africa will develop under current climate conditions, i.e., the temperature growing period will be less than 120 days forcing large regions of marginal agricultural lands out of production (Boko et al. 2007; Fischer et al. 2005; Shah et al. 2008). Under the climate change scenarios considered, AEZ estimates an increase of arid and dry semi-arid areas in Africa by 5–8%, or 60–90 million hectares in the 2080s (Shah et al. 2008). The changes in the growing period are also significant, particularly when contrasted with potential changes in seasonality of precipitation, onset of rain days and intensity of rainfall (Boko et al. 2007).

Shah et al. (2008) estimation is consistent with Fischer et al. (2002, 2005) simulations with AEZ which portrayed the following overall picture for SSA: decrease of constraint free prime land with highest suitability for crop cultivation; increase in land with moisture stress; and expansion of land with severe climate, soil or terrain constraints, by 30–60 million hectares, in addition to the 1.5 billion hectares already unfit for rainfed agriculture under current climate (Fischer et al. 2002, 2005). According to this projection, dry conditions will occur in 43.5% of land in Africa, a figure well above the world total of 29% (Fischer et al. 2002). When this happens, Eastern Africa, Central Africa and West Africa are expected to be severely affected. For example, a loss of more than 20% in length of growing seasons is expected in Eritrea, Ethiopia, Kenya and Sudan. Also, increased rainfall could lead to nutrient leaching, loss of topsoil and water logging, all of which will seriously affect agricultural production in East Africa (Orindi and Murray 2005).

The negative effect of future climate change on arable land will result in adverse impacts on cereal crop production and net revenue of these crops. Cereals (wheat, rice, barley, maize, millet, sorghum, groundnuts, cassava, rye and oats,) play an important role in the diets of people in SAA (Schlenker and Lobell 2010; Ward et al. 2010). Overall, cereals constitute 47% of total caloric food consumption (Kcal/capita/day) for households in SSA and 50% of protein consumption (FAO 2008b). These grains also represent a significant source of expenditure, calories and earnings for many of the poor in developing countries, including those in SSA (Cranfield et al. 2003; Thurlow and Wobst 2003; Ulimengu et al. 2009).

Yet, a synthesis of results from various global circulation and Ricardian models, by Cline (2007) predicts a general significant reduction in overall yields across SSA. Also under global climate models (GCMs), Parry et al. (1999) found that by 2080 Africa generally is expected to experience marked reductions in yield, decreases in production, and increases in the risk of hunger as a result of climate change. Generally, crop yields in Africa may fall by 10–20% to 2050 because of warming and drying, but there are places where yield losses may be much more severe, as well as areas where crop yields may increase, for example, some parts of Ethiopian highlands around Addis Ababa where maize production is expected to benefit from potential climate change (Jones and Thornton 2003). Projected reductions in yield in some regions could be as much as 50% by 2020, and crop net revenues could fall by as much as 90% by 2100 in South Africa, with small-scale farmers being the most affected (Boko et al. 2007). A model results by the International Food Policy Research Institute (IFPRI) indicates that in 2050, average rice, wheat, and maize yields will decline by up to 14, 22, and 5%, respectively, as a result of climate change (IFPRI 2009). A combination of historical crop production and weather data into a panel analysis, estimated that by mid-century, the mean estimates of aggregate production changes will be −22, −17, −17, −18, and −8% for maize, sorghum, millet, groundnut, and cassava, respectively (Schlenker and Lobell 2010). According to this estimation, there is a 95% likelihood that damages will surpass 7, and a 5% probability that they will exceed 27% for all crops except cassava.

On net crop revenues, several analysis have shown that hot and dry climate scenarios would reduce crop net revenues in parts of SSA. For example, using the AEZ model, Kurukulasuriya and Mendelsohn (2008a) find that total cropland in Africa may not change much as climate change alters agroecological zones and the productivity of farms within them. Cropping area in middle to high elevations is supposed to increase due to the shifting of agro-ecological zones. The dry desert and lowland semiarid agro-ecological zones are expected to lose cropland. The AEZs by Seo et al. (2009) also shows that the effects of climate change will be quite different across Africa. For example, currently productive areas such as dry/moist savannah are more vulnerable to climate change while currently less productive agricultural zones such as humid forest or sub-humid AEZs become more productive in the future. With the Ricardian method and farm-level data from over 9,000 farmers in 11 countries in SSA, Kurukulasuriya and Mendelsohn (2007) found that net revenues will fall as precipitation falls or as temperatures warm across all the surveyed farms. Specifically, a 10% increase in temperature would lead to a 13% decline in net revenue. The elasticity of net revenue with respect to precipitation is 0.4. With over 9,500 farmers and by 2100, Kurukulasuriya and Mendelsohn, 2008b) revealed that dryland crop net revenues could rise by 51% if future warming is mild and wet but fall by 43% if future climates are hot and dry. In all studies, warming is expected to be harmful to rain-fed farming but beneficial to presently irrigated farms.

At the individual country level, a Ricardian analysis by Molua (2009) projected that in Cameroon, a 7% decrease in precipitation would cause net revenues from crops to fall by US$2.86 billion and a 14% decrease in precipitation would cause net revenue from crops to fall by US$3.48 billion. Increases in precipitation would have the opposite effect on net revenues. For a 2.5°C warming, net revenues would fall by US$0.79 billion, and a 5°C warming would cause net revenues to fall US$1.94 billion. His earlier study also showed that climate change will adversely affect agricultural production at the national level (Molua 2008). Similarly in Nigeria, Adejuwon (2006) modelled the worst case climate change scenarios for maize, sorghum, rice, millet and cassava and projected that, in general, there will be increases in crop yield across all low land ecological zones as the climate changes during the early parts of the twenty-first century, but the rate of increase will be slow towards the end of the century. In South Africa, Gbetibouo and Hassan (2005) found that temperature rise will positively affect net revenue of certain field crops (including maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybean) whereas the effect of reduction in rainfall on these crops is negative. Other projections also showed that maize is expected to be heavily impacted in Southern Africa under anticipated ENSO conditions (Lobell et al. 2008; Stige et al. 2006). Specifically, by 2030, rain-fed maize yields will decline by as much as 30%, relative to production in 1990 (Lobell et al. 2008). In Ethiopia, Deressa and Hassan (2009) seasonal marginal impact analysis indicates that a marginal elevated temperature during summer and winter would significantly reduce crop net revenue per hectare while a marginal increasing rainfall during spring would considerably increase net crop revenue per hectare.

In spite of these gains and losses, it is the negative impacts that are more pronounced. For example, as Shah et al. (2008) AEZ estimation concluded "the net balance of changes in the cereal production potential of SSA is projected to be negative, with net losses of up to 12%. Overall, approximately 40% of SSA countries will be at risk of significant declines in crop and pasture production due to climate change. The cereal production potential of 16 SSA countries, with a projected population of 780 million in 2080, will drop 7.9% due to climate change, while the cereal production potential of 14 countries with a projected population of 580 million in 2080 will increase by 5.3%".

Despite the growing knowledge of climate change and its impacts on agriculture, many uncertainties remain. Of particular concern are some of the limitations of the general circulation models used to simulate climate changes, and the way those limitations may affect the predicted impacts of climate change on agriculture (Lobell and Burke 2008; Lobell et al. 2008; Parry et al. 1999; Thornton et al. 2008). In their assessment of the potential effects of climate change on crop yields, world food supply, and risk of hunger Parry et al. (1999, p. 25) concluded that their results was "not a forecast of the future" due to large uncertainties including: "the uncertainties about climate change at the regional level; the effects of future technological change on agricultural productivity; the potential realisation of any benefits from the CO_2 *fertilisation effects*; uncertainties about water availability for irrigation in the future and; trends in demand (including population growth), and the wide range adaptation options" (p. 65). Kurukulasuriya and Mendelsohn (2007, 2008b) also noted similar concerns.

Uncertainties associated with temperature represented a greater contribution to climate change impact uncertainty than those related to precipitation for most crops and regions, and in particular the sensitivity of crop yields to temperature is a critical source of uncertainty, especially in relation to predominantly rainfed systems, such as most cases with maize, cassava, sorghum or millet (Lobell and Burke 2008). In addition, lack of information or disagreement about what is known or even knowable about climate change (van de Steeg et al. 2009) or the lack of sufficient, consistent and geographically coherent local economic data on cropping systems make it difficult accurately to measure the direct impact of climate change on agriculture for the entire Africa region (Lotsch 2007; Morton 2007; Mendelsohn 2009).

5 Implications for food security

At the World Food Summit (WFS) in November 1996 the Food and Agriculture Organisation (FAO), defined food security as a situation which "exists when all people at all times have physical or economic access to sufficient safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996). From this definition, food security consists of four key dimensions: *food availability* (production, distribution, trade and exchange), *food accessibility* (affordability, allocation and preference), *food utilisation* (nutritional and societal values and safety) and *food stability* (FAO 2008a; Ericksen 2008; Schmidhuber and Tubiello 2007).

It is however imperative to note that food insecurity is a more complex problem. In addition to climate change, food security is influence by an array of factors including wider issues of poverty, natural resource disparities, poor or corrupt governance, poor infrastructure, conflict, lack of markets, finance, high disease burden such as HIV/AIDS and malaria, unequal global trading arrangements and inequity within countries, and so on (Brown and Crawford 2009; Brown et al. 2009; FAO 2008a; Ericksen 2008; Devereux and Maxwell 2001; Misselhorn 2005). Nevertheless, "climate change will act as a multiplier of existing threats to food security, according to the Inter-Agency Standing Committee (IASC)[1] group's report (IASC 2009). Globally, food system performance currently depends more on climate than it did 200 years ago (FAO 2008a). The risks climate change poses on food security are particularly pressing at a time of high oil prices, at levels surpassing $130 a barrel in May 2008 (von Braun 2008). High fuel prices make agricultural production more expensive by raising the cost of fertilizers, irrigation, and transportation. In SSA climate variability and extreme weather events such as droughts, excessive rains and floods are among the main risks affecting agricultural productivity and hence rural household food security (Haile 2005). A failure of the rainy season is directly linked to agricultural failure reducing food availability at household level as well as limiting rural employment possibilities (Haile 2005).

Climate change and extreme weather events will affect all dimensions of food security in several ways ranging from direct effects on crop production (for example, altered rainfall pattern leading to drought or flooding, or warmer or cooler temperatures leading to changes in the length of growing season), to changes in markets, food prices and supply chain infrastructure (FAO 2008a; Gregory et al. 2005). Specifically, climate change will reduce food availability, because it will negatively affect the basic elements of food production—soil, water and biodiversity (IASC 2009). It will indirectly affect food availability through its impacts on economic growth, income distribution, and agricultural demand (Schmidhuber and Tubiello 2007). Without climate change, calorie availability is

[1] The Inter-Agency Standing Committee (IASC) is the primary mechanism for inter-agency coordination of humanitarian assistance. It is a unique forum involving the key UN and non-UN humanitarian partners, including Caritas; CARE; Food and Agriculture Organization of the United Nations (FAO); International Federation of Red Cross And Red Crescent Societies (IFRC); Oxfam; Save the Children Alliance; United Nations World Food Programme (WFP); World Health Organization (WHO); World Vision.

expected to increase in Africa between 2000 and 2050. With climate change, however, food availability in the region will average 500 calories less per person in 2050, a 21% decline (IFPRI 2009). Also, the continent can expect to have between 55 and 65 million extra people at risk of hunger by the 2080s under the HadCM2 climate scenario. Under the HadCM3 climate scenario the effect is even more severe, producing an estimated additional 70+ million people at risk of hunger in Africa (Parry et al. 1999).

Access to food will be affected by climate change events in terms of direct impacts on agricultural zones affecting incomes, employment opportunities, macro economy and GDP which shape livelihoods in many ways, including forms of social protection (African Union 2005, cited in Boko et al. 2007). SSA currently has the highest prevalence of undernourishment, with some 32% of the total population deprived of access to food (Shah et al. 2008). The strongest impact of climate change on the economic output of agriculture in SSA is that the poorest and already most food-insecure region will suffer the largest reduction of agricultural incomes (Schmidhuber and Tubiello 2007). While by 2080, climate change will reduce Asia's agricultural GDP by 4% that of SSA will decline by up to 8% (Shah et al. 2008). If projected increases in weather variability occur, they are likely to lead to increases in the frequency and magnitude of food emergencies for which neither the global food system nor affected local food systems are adequately prepared (FAO 2008a). In addition, physical, economic, and social access to food will be severely compromise by climate change and variability because as agricultural production declines, food prices rise, and purchasing power decreases (von Braun 2008). In many developing countries, between 10 and 40% of cereal consumption will have to be covered by imports. Many of these countries, however, lack the foreign exchange to finance food imports, thus putting them at risk of increased food insecurity (Shah et al. 2008). Currently, the SSA region's net cereal imports amount to approximately 7 million tons, but the impact of climate change may result in a net import of roughly 143 million tons of cereal by 2080 (Shah et al. 2008).

Food stability is viewed in relations to stability of crop yields and food supplies which will be negatively affected by variable weather conditions and influenced by the temporal availability of, and access to, food (FAO 2008a). Recent studies suggest that while the world food supply does not appear to be seriously threatened by the projected global changes in climate, food insecurity in Africa will worsen and the population at the risk of hunger will increase both in terms of percentage and absolute numbers during the coming century (Brown et al. 2009; Boko et al. 2007). Finally, climate change poses threats to food utilization through its impacts on human, including the spread of diseases such as malaria, HIV/AIDS, and undermines livelihood capability and food security at various scales (Piot and Pinstrup-Anderson 2002, cited in Boko et al. 2007).

The above picture is however far from conclusive. According to the IPCC fourth assessment report the causal contribution of climate to food insecurity in Africa is still not fully understood, particularly the role of other multiple stresses that enhance the impacts of droughts and floods and possible future climate change (IPCC 2007). All the same, the broad consensus is that unabated climate change could, by 2080, result in an additional 30–170 million people suffering from malnutrition or under-nutrition globally, of whom three-quarters will live in Africa.

6 Farm-level adaptations

The strong trends in climate change is already evident, the potential of further changes occurring, and the increasing scale of potential climate impacts give urgency to addressing adaptation more coherently (Howden et al. 2007). Generally, adaptation is defined as "changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change" (Smit et al. 2001, p. 879). According to Olesen (2005) it is useful to differentiate between adaptation at farm level and adaptation that requires changes at regional to national levels in infrastructure, planning and support schemes. Farm-level adaptation involves changes in agricultural management practices in response to changes in climate conditions. It usually entails a combination of individual responses at the farm-level and presumes that farmers have access to alternative practices and technology available in the region (Nhemachena and Hassan 2007). Most farm level adaptation measures are autonomous in the sense that no other sectors are needed in their development and implementation (Olesen 2005). The concept and practice of adaptation is not new to human society. They have existed since the beginning of human presence on Earth (Smithers and Smit 1997) but increased risk from climate change will severely affect farmers ability to adapt and cope.

It is well established that farmers in African are accustomed to managing and adapting to unpredictable climates to meet their farming needs. Several researchers have documented some of the wider range of farm-level adaptation practices current being practiced by farmers in SSA (e.g. Benhin 2006; Bryan et al. 2009; Deressa et al. 2009; Kurukulasuriya and Mendelsohn 2006, 2008c; O'Farrell et al. 2009; Nhemachena and Hassan 2007; Orindi et al. 2007; Osman-Elasha et al. 2006; Paavola 2004; Seo et al. 2008; Siedenburg 2008; Thomas et al. 2007; Ziervogel 2004). These adaptation strategies include: livelihood diversification, migration, agricultural intensification with mineral fertilizers and green manures, agricultural extensification (i.e. bringing new units of land under cultivation), crop rotation, crop switching and selection, changes in planting dates and varieties, soil conservation and tillage practices, improvement on fallow trees, planting tress, among others. There are some adaptation options such changes in land use, farming systems, plant breeding usually undertaken at higher a level (Olesen 2005). While the evidence of these suites of adaptive practices is a welcome development, it must be emphasised that they are not sufficient to offset the current and anticipated impacts of uncertainties in climate, including variability and weather extremes (Eriksen et al. 2008; Smit et al. 2001). This is because current farming technology is basic, incomes low, suggesting that farmers will have few options to adapt (Dinar et al. 2008). Also, not every country, community or individual farmer has access to these options or the capacity to employ them (Smit et al. 2001; Klein et al. 2005) coupled with the fact that many practices largely operate without any formal government support (Eriksen et al. 2008).

Thus, the focus of policymakers and development agencies should be on formulating and implementing policies that can significantly enhance farm-level adaptation. For example, more systemic changes in resource allocation need to be considered, such as targeted diversification of production systems and livelihoods (Howden et al. 2007); In addition, incentives that promote adaptation need to be formulated and incorporated into existing and prospective development programmes in a way that contributes to poverty reduction across scale. Specifically, a suite of measures can help reduce vulnerability. These should include: improved access to markets (input and output), credit facilities, information (climatic and agronomic), extension services, farm assets (labour, land and capital); adopting and utilizing new technologies; awareness creation; capacity building for resourced poor farmers; institutional strengthening; and removing barriers to adaptation via the improvement of rural transportation infrastructure, investments in public healthcare and public welfare programmes, and policies that improve local governance and coordinate donor activities. These practical activities will greatly enhance adaptive capacity and in the long run reduce vulnerability and climate change impacts at the macro, meso and more importantly at the micro levels.

7 Conclusions

This paper reviewed the existing literature on the current variability and future changes in climate and the possible impacts of climate change on agricultural production in SSA and the adaptation issues arising. The aspects of climate change considered were: changes in temperature, altered patterns of rainfall, and extreme weather events such as droughts and floods. From the review, there are some conclusions common to all studies. Specifically, the climate in SSA is already exhibiting significant changes, evident by changes in average temperature, changes in amount of rainfall and patterns and the prevalence of frequency and intensity of weather extremes such as droughts and floods. In addition, climate change will negatively affect crop production potential, reduce yields considerably and increase risk of hunger. For example, the area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease. These changes will affect all components of food security*: food availability*, *food accessibility*, *food utilisation and food stability*, exacerbating long standing development challenges of reducing poverty, ensuring food security and achieving the Millennium Development Goals (MDGs).

The review also revealed that the degree of projected impacts of climate change on agriculture in SSA varies widely among different studies. The magnitude of the impacts of climate change is not going to be the same for every region or country in SSA. Hot and dry parts of Africa are likely to be severely affected. The distributions of impacts arise from the variety of climate scenario and crop models used, and the different analytical methods used to assess current and projected impacts. The extent of climate change and spatial patterns of impacts are, however, highly uncertain. In spite of all the uncertainties in climate change and impact projections, the review confirms the general consensus that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Also, while there is uncertainty in the projections with regard to the exact magnitude, rate, and regional patterns of climate change, its consequences will change the destiny of many generations to come and particularly impact on the poor if no appropriate measures are taken. There is some evidence of farm-level adaption strategies current being practiced by farmers but these are not sufficient to reduce the negative impacts of climate change. Thus, incentives that promote adaptation need to be formulated and incorporated into existing and prospective development programmes in a way that contributes to poverty reduction across scale.

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