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ORIGINAL ARTICLE

The causes, effects and challenges of Sahelian droughts: a critical review

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Abstract This paper is a critical synthesis of the causes, effects and challenges of the Sahelian droughts. The results show that the four main causes of the Sahelian droughts are as follows: sea surface temperature changes, vegetation and land degradation, dust feedbacks and human-induced climate change. However, human-induced climate change is seen as the major drought-determining factor because it controls sea surface temperatures, dust feedbacks and vegetation degradation. Increase rainfall and greening have been observed in the Sahel since the 1990s; yet, food yields remain low while tree mortality rates are high. The implication of this is that the rainfall is not available for agriculture since various human-induced climate change processes such as deforestation and the expansions of arable farms do not make the moisture available for agriculture. The increase in tree mortality has also been found to increase atmospheric CO_2 in the study area. However, this study hypothesizes that the increase in CO_2 might be responsible for the increase in greening and rainfall observed. This can be explained by an increased aerial fertilization effect of CO_2 that triggers plant productivity and water management efficiency through reduced transpiration. Also, the increase greening can be attributed to rural–urban migration which reduces the pressure of the population on the land. The remittances from migrant urban workers may make farming more sustainable in the rural areas, thus enhancing greening. The principal challenges in overcoming the effects of the droughts are HIV/AIDS and Malaria, political instability, data availability, proliferation of extensive non-mechanized farms and lack of adequate observations.

Keywords Droughts · Human-induced climate change · Tree mortality · CO_2 emissions · Food yields · HIV/AIDS · National security

Introduction

The Sahel is a semi-arid strip of land that is transitionally located between the tropical rainforest in the south and the arid north of Africa (Fig. 1) (Olsson and Mryka 2008). It covers an area of about 3,053 × 10^3 km^2 and has about 60 million inhabitants. The rainfall in the region is highly variable. At the 17° isohyet (northern boundary of the Sahel), less than 200 mm of rainfall is recorded annually while further south at the 15° isohyet (southern boundary of the Sahel), about 450–500 mm of rainfall is recorded annually (Wang et al. 2005; Zeng 2003). During the months of April to July, the temperatures are about 32–35 °C throughout the Sahel (Nicholson 1995). The most prominent droughts that have effected this region are those that began at the end of the 1960s and ended in the mid 1980s (Anyamba and Tucker 2005).

Climate change plays an important role in African development and cannot be left out of the debates on

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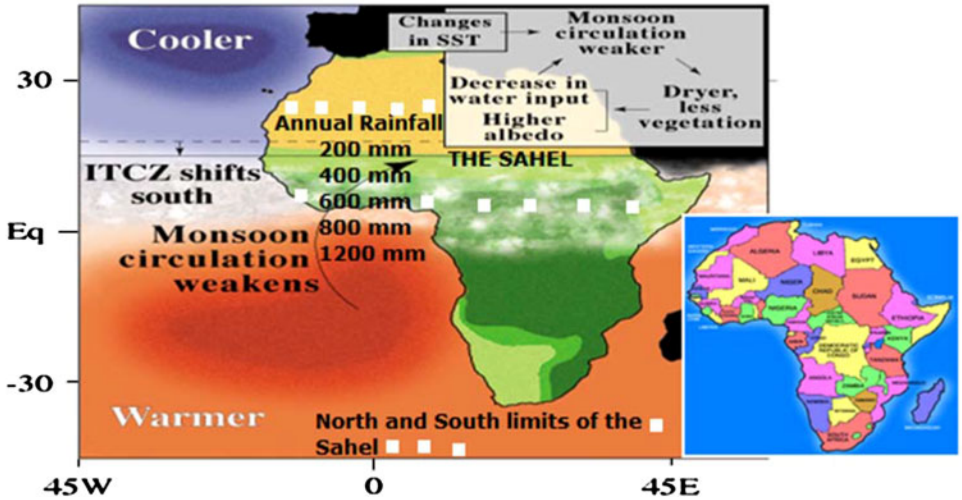


Fig. 1 Recent Sahel droughts caused by global sea surface temperature (SST) changes which reduced the strength of the West African Monsoon. Modified from Zeng (2003)

droughts and ecosystem responses in Africa (Giannini et al. 2003, 2008; Reynolds et al. 2007; Lu and Delworth 2005). The evidence that global climate has repercussions in the study site is based on remotely sensed observations of vegetation cover dynamics, models of land cover responses to changes in precipitation and land use models of African rainfall response to global sea surface temperature (SST) changes (Giannini et al. 2008; Anyamba and Eastman 1996; Prince et al. 1998; Nicholson et al. 1998; Eklundh and Olsson 2003; Herrmann et al. 2005).

On the other hand, the view that the Sahel is becoming increasingly green and wet should not only be based on remotely sensed data but be correlated by results of local surveys of population perceptions before a conclusion can be made because in less wealthy communities, there are reports of no such climatic adjustments as food yields remain persistently low (Giannini et al. 2008; Olsson and Mryka 2008; Herrmann et al. 2005). In wealthier communities, the ability to invest in water management has favored crop production (Giannini et al. 2008; Reij et al. 2005). It can be argued that the return of wetter and greener conditions in the Sahel is a product of land management efforts and not a return to pre-drought conditions of the years before the 1960s (Giannini et al. 2008). As such, this study aims at synthesizing the primary literature to uncover the key causes, effects and challenges imposed by the Sahelian droughts. To the best of our knowledge, this is the first comprehensive critical synthesis of the causes, effects and challenges of the Sahelian droughts in one study. Prior to this study, much of the information was found in diverse publications that dealt with different aspects of the droughts. The main gap that this study therefore fills is being able to synthesize the primary literature while vividly reviewing the causes, effects and challenges of the droughts. In another section on supplementary online information, the parameters, methods of drought quantification and simulation are also reviewed.

The causes of Sahelian droughts

The debates on the causes of the Sahelian droughts have been very intense and controversial (Lamb 1982; Hulme 2001). In the midst of a lot of research, a consensus on the mechanisms responsible has not been achieved (Thiaw and Mo 2005; Biasutti and Giannini 2006). Below is a critical synthesis of the causes.

Sea surface temperature (SST) changes

The West African Monsoon (WAM) is the main source of rainfall in the Sahel (Weldeab et al. 2007; Giannini et al. 2005; Hulme 2001; Zeng et al. 1999). Several studies have modeled the relationship between the pattern of SST and Sahelian rainfall using statistically based climatological analysis that reveals that with the onset of Sahelian droughts in the late 1960s, a particular configuration of global SST characterized by warm anomalies in the Southern Hemisphere and cool anomalies in the Northern Hemisphere Oceans was observed (Gleckler et al. 2008). Based on data spanning the period 1930–2000, it has been argued that the warming in the Atlantic Ocean has been weakening the moisture laden WAM, causing a southward shift in the Inter-tropical Convergence Zone (ITCZ). This decreases moisture input and reinforces the weakening of the WAM, creating drier conditions with less vegetation and higher albedo (Fig. 1) (Zeng 2003; Bader and Latif 2003; Zhang and Delworth 2006).

The trends in SST patterns above are plausible in explaining the droughts of the Sahel. However, they are not able to explain the patterns observed during the individual years (Hagos and Cook 2008). The repercussions of the El Nino (warm waters in the Pacific Ocean) in the Sahel are that they also result in a weakened WAM flow due to the northward shift of the mean sea level pressure (MSLP) along the coast of West Africa and hence creating dry conditions over the Sahel (Camberlin et al. 2001; Thiaw and Bells 2005; Chelliah and Bell 2004; Kang et al. 2008; Hoerling et al. 2006; Wolff et al. 2011; Held et al. 2005; Janicot et al. 2010; Hurrell 1995; Shanahan et al. 2009).

Effects of vegetation and land degradation

One of the earliest view points on the causes of the Sahelian droughts was based on the Charney hypothesis (Charney et al. 1977; Fuller and Ottke 2002). This hypothesis holds that the recent droughts in the Sahel were caused by a declining vegetation cover (Olsson and Mryka 2008). According to this model, declines in vegetation cover caused by overgrazing, the conversion of woodlands into agricultural lands have caused an increase in the reflectivity or albedo of the landscape (Zeng 2003; Clover 2010; Fuller and Ottke 2002). This results in a reduction in the heating of the earth as less sunlight is absorbed and less moisture is released to the atmosphere; resulting in less convection responsible for rainfall (Zeng 2003).

There is an inverse relationship between latitude or mean surface albedo (coefficient of reflectance) and mean annual rainfall and a direct relationship between latitude and albedo in the Sahel (Fig. 2). At 15°N (the south boundary of the Sahel), the surface albedo was 0.30 while mean rainfall between 1983–1988 was about 450 mm. However, at 17°N (the north boundary of the Sahel), the surface albedo was about 0.43 and the mean rainfall for the same period was about 200 mm. This is explained by the northward reduction in vegetation that reduces evapotranspiration (Fig. 2) (Nicholson et al. 1998; Wang et al. 2005). The question is, have such large anthropogenic offsets really taken place? A recent evaluation of population dynamics and the history of land use change in the Sahel holds that over the last 35–40 years there is evidence of just modest land use changes that is not nearly enough to explain the observed droughts (Zeng 2003). On the other hand, the idea that the Sahel witnessed a lot of land degradation and deforestation was supported by (Lamprey 1975) who asserted that the Sahara had advanced by 90–100 km in the north of Sudan between 1958 and 1975.

Dust feedbacks

The Sahara desert is the world's largest source of airborne dust (N'Tchayi et al. 1997). About one billion tones of mineral dust are transported from the Sahel-Sahara. Dust aerosols from the Sahara desert are said to contribute approximately half of the total atmospheric aerosols which are estimated at 1,500 Tg per year (Ramanathan et al. 2001).

The accumulation of Sahelian dust in the atmosphere further reduces rainfall by increasing the number of cloud condensation nuclei in warm clouds and thereby affecting the surface radiation budget's instability. This is because the dust particles suppress rainfall by promoting the formation of small cloud droplets which do not attain the size needed to form rain drops and possibly increase evaporation of clouds due to increase absorption of solar radiation (Lohmann and Feichter 2005). It has been argued further that, dust aerosols can contribute to surface heating by reflecting incoming solar radiation (Li et al. 1996); this enhances warming in the troposphere and thereby increasing atmospheric stability, reducing convection and reducing rainfall (Lintner and Chiang 2006). Atmospheric dust can also absorb long wave outgoing radiation, thus providing a green house effect (Fig. 3). (Hui et al. 2008; Kaufman et al. 2002). Reduced rainfall is said to result in drier soils, less vegetation and increase potential for the wind to blow off more dust minerals into the atmosphere (Rosenfeld et al. 2001; Lu and Delworth 2005). As observed on satellite images of dust outbreaks from the west coast of Africa, the dominant period of transport of Sahelian dust is usually in summer (Prospero and Lamb 2003).

A troubling issue on dust feedbacks is the fact that their impacts on the hydrological cycle in some Sahara desert margins such as the West African Sahel has not been quantified. Most studies have focused on the physical and microphysical mechanisms of rainfall reduction (Adhikari et al. 2005; Neelin and Su 2005). A few others have analyzed the correlation between aerosols and cloud cover over several rainy seasons and found that in West and East Africa, dust accumulation helped in reducing rainfall (Mahowald and Kiehl 2003; Hui et al. 2008).

Human-induced climate change

Human-induced climate change (CC) is mainly concerned with deforestation and land degradation through various unsustainable methods of cultivation and the spewing of green house gases (GHGs) such as carbon dioxide (CO_2) (Fig. 4), (Tippett 2006; Vecchi and Soden 2007; Epule et al. 2011). Between 2000 and 2010, it was reported that Africa had a net loss of forest of about 3.4 million hectares/year while the global rate was 13 million hectares/year during the same period (FAO 2010).

In terms of GHG emissions, the Sahel had a rate of 0.9 % per capita in 1980 and 0.8 % per capita in 2007 while Latin America and Asia had rates of 0.4 and 0.1 % per capita in 2007 (FAO 2010). This increase in GHG emissions is greatly associated with a 28 % increase in population recorded between 1960 and 2006 at a growth rate of about 2.2 percent and a rate of deforestation of about 0.5–0.7 % for the Sahel (Roncoli et al. 2002; Li et al. 1996). On a prognostic basis, it has also been argued that human-induced global warming will be associated with a

Fig. 2 The relationship between **a** latitude and rainfall, **b** albedo and rainfall, **c** latitude and albedo. *Source*: Inspired from Nicholson et al. (1998)

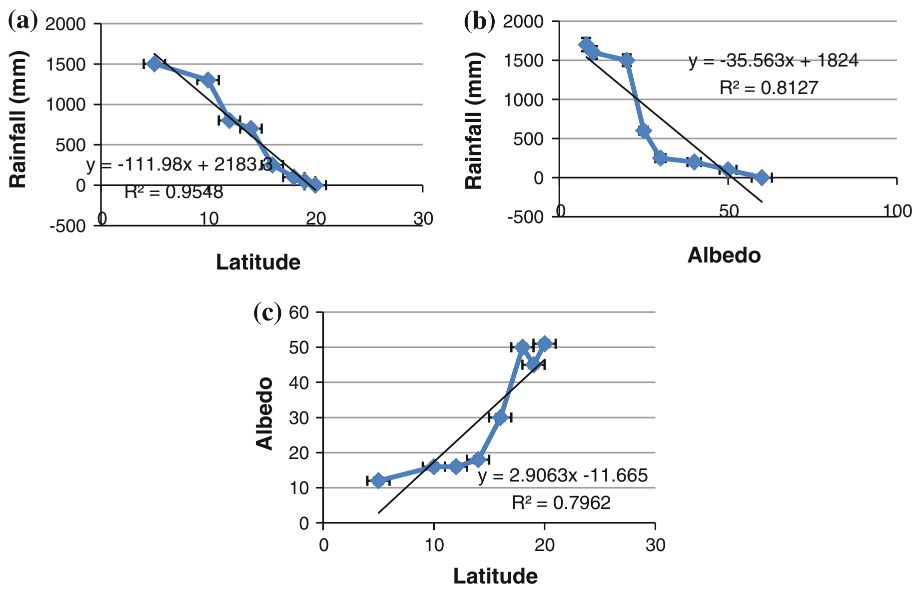


Fig. 3 Interactions between dust feedbacks and droughts. *Source*: Inspired from Prospero and Lamb (2003), N'Tchayi et al. (1997)

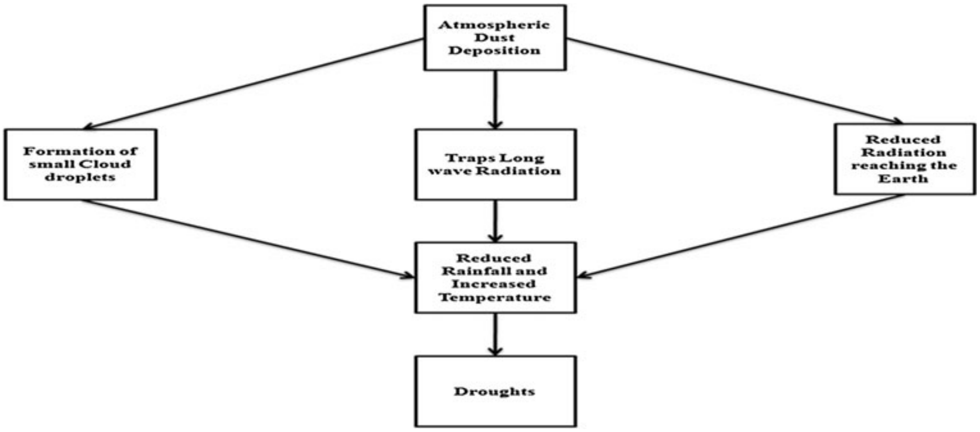
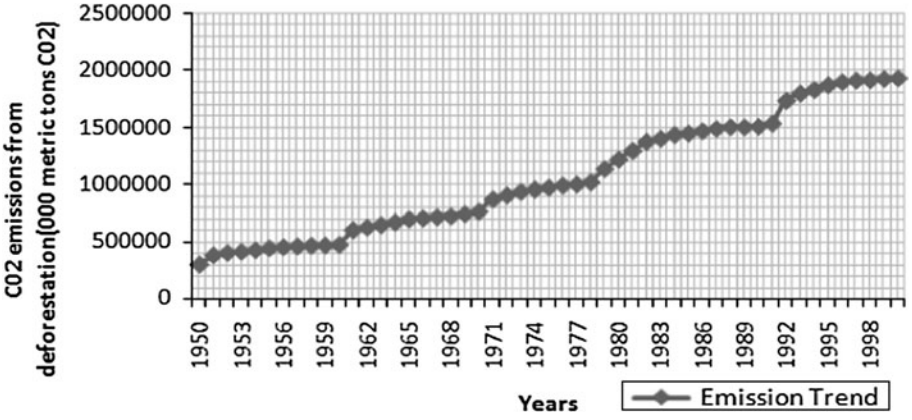


Fig. 4 CO_2 emissions from deforestation in sub-Saharan Africa, 1950–2000. *Source*: Inspired from data obtained from FAO (2010) and (http://www.wri.org) World Resource Institute (2011)



wetter regime in the Sahel and the southern Sahara. These finding is based on a simulation of 150 years that includes an ocean–atmosphere–sea ice model driven by fluctuations in CO_2. The results showed that an enhanced monsoon was responsible for increase precipitation over West Africa towards the end of the twentieth century (Maynard et al. 2002; Rotstayn and Lohmann 2002; Knutson et al. 2006).

Generally, it has been argued that global SST changes are more responsible for the droughts in the Sahel. Such evidence is based on a comprehensive modeling study by

Giannini et al. (2003). The authors used the results from a state of the art general circulation model (GCM) and principal component analysis (PCA) to argue that when SST changes observed between 1930 and 2000 are set in the model, the model reproduces much of the variability in the observed Sahelian rainfall. The importance of SST as a factor that causes droughts goes beyond the African continent. In a study on Canadian boreal forests, Peng et al. (2011) show that SST changes have been partly responsible for the droughts that are responsible for higher levels of tree mortality in the western part of Canada.

However, this current synthesis is of the view that human-induced CC through deforestation triggered by unsustainable methods of cattle rearing and farming are more significant. This is because, even when SSTs, albedo and dust feedbacks are considered, human-induced environmental and CC activities have a role to play. Therefore, this synthesis suggests that a better understanding of the causes of droughts in the Sahel can be achieved if researchers go beyond disciplinary boundaries and get involved in systemic or synergetic studies by bringing all the drivers on board.

The effects of droughts on ecosystem services

The observed droughts that have affected the Sahel have produced effects on trees and crop yields. This section of this paper reviews the possible effects of the Sahelian droughts on forests and food systems (FAO 2006). Examining the effects of these droughts on food and forest ecosystems is important for the following reasons: (1) Agriculture employs close to 80 % of the population in most African countries and (2) Forest mortality does not only create problems of CO_2 sequestration but also affects soil compactness, hampers agriculture, reduces environmental aesthetics, reduces the recreation and spiritual benefits of forests inter alia (Gonzalez et al. 2012; Epule et al. 2012a). For a synthesis of the key effects of droughts in the Sahel, see table S2 under supplementary information.

The effects of droughts on forests in the Sahel

Toward the end of the twentieth century, rainfall in the study area declined by approximately 20–40 % and average temperatures increased by 1.3 °C (Maranz 2009). This has been described as the most negative rainfall trend in the world in contemporary times (Nicholson 2001).

In the last half of the twentieth century, the persistence of droughts had been consistent with observed declines in tree density and tree species richness across the study area. A decrease in species richness for most of the study sites in Mauritania, Chad, Mali, Burkina Faso, Niger and Senegal was obtained between 1960 and 2000 (Gonzalez et al. 2012). A study on tree species richness for the Western Sahel in Senegal reports that between 1945 and 2002, the average species richness of an area 4 km^2 declined from 64 ± 2 to 43 ± 2 species (Fig. 5a). In terms of different species, the study holds that the species richness for the Guinea trees and shrubs (mesic species) fell by 54 ± 9 %, the Sudan tree species richness fell by 29 ± 4 % and Xeric species and Sahel species fell by 14 ± 4 % (Gonzalez 2001).

With the use of aerial photos and Ikonos images, declines in tree density in the midst of rising temperatures and declining rainfall have caused droughts in Senegal (Fig. 5b–e). A 29 % decrease in tree density between 1972 and 1976 was observed while between 1954 and 2002, a 20 % decrease was observed (Gonzalez et al. 2012; Wezel and Lykke 2006). A decrease in tree density per hectare was recorded at stations in Senegal such as in Njóobéen Mbataar and Fété Olé stations between 1954 and 2002. At both stations, tree density fell by one fifth between 1954 and 2002; tree mortality ranged from 0.11 ± 0.01 at Wolum per decade to 0.33 ± 0.04 per decade at Njóobéen Mbataar (Fig. 5c) (Gonzalez et al. 2012; Vincke et al. 2010). Furthermore, forest retractions in the Guinea and Sudan vegetation zones of Senegal are said to have tilted south-westward by 25–30 km with an average rate of 500–600 m/year between 1945 and 1993. These historic shifts took place through high mortality in mesic species leaving drought-resistant species to be the remaining vegetation cover (Gonzalez 2001).

Similarly, increased tree mortality that is linked to droughts has been reported in the moist forests of Uganda where the death of mesic species of trees has been observed (Allen et al. 2009; Lwanga 2003). In a related study, Maranz (2009) also discussed the view that rainfall declines of about 100 mm between the period 1930 and 1965 and 1966–2000 in the Sahel was responsible for the disappearance of several trees in the study area. In Burkina Faso, Mali and Sudan, arid trees have expanded due to reforestation by local farmers (Gonzalez et al. 2012; Wezel and Lykke 2006; Hiernaux et al. 2009). In parts of Senegal and Mauritania, human agricultural expansion and livestock grazing have been reported responsible for declines in tree density and not climate (Niang et al. 2008; Wezel and Lykke 2006). Whatever the case, this may be true locally when it comes to forests near urban areas and areas which serve as routes for the transportation of livestock and migration; for most tree species, a very close correlation with rainfall shifts has been established (Maranz 2009).

However, based on observations of increase rainfall in the Sahel from the 1990s, the trends in vegetation seem to be changing the debate. Using Normalized Difference Vegetation Index (NDVI), several recent studies have proven that both rainfall and vegetation have increase in

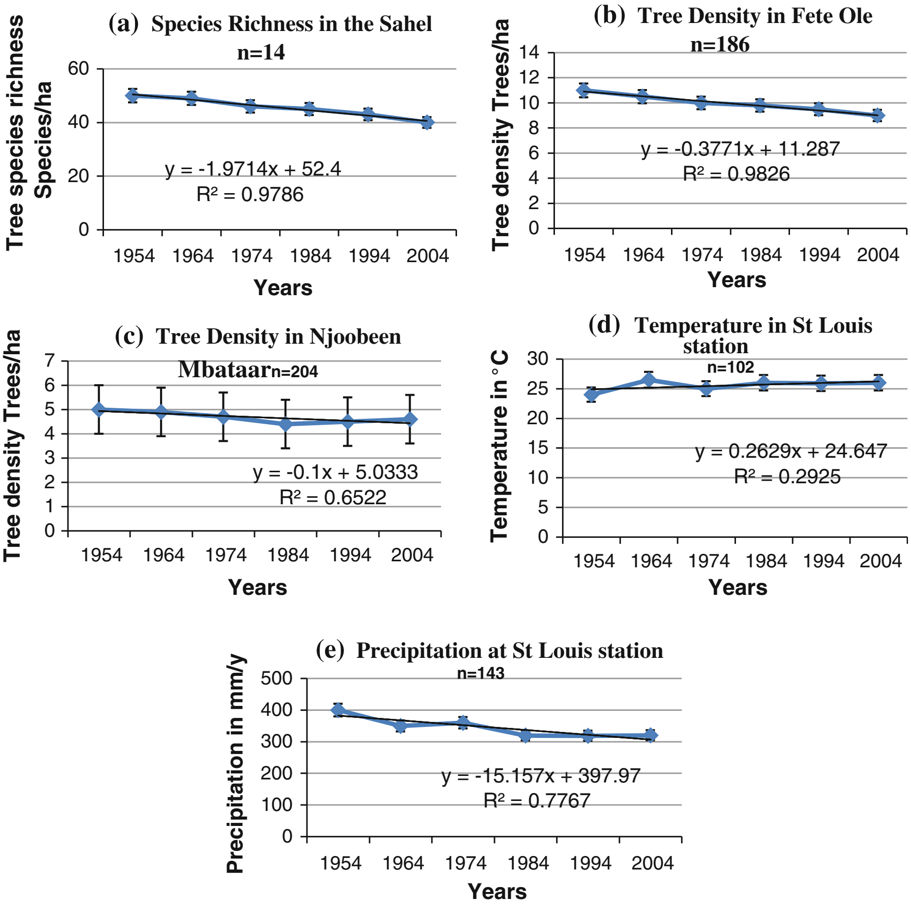


Fig. 5 Variations in **a** tree species richness for the Sahel, **b**, **c** tree density, **d** temperature and **e** precipitation for stations in the Sahel. *Source*: Inspired from Gonzalez et al. (2012)

the Sahel since the 1990s (Anyamba and Tucker 2005; Seaquist et al. 2006; Olsson and Mryka 2008; Olsson et al. 2005). It is now evident that rainfall and vegetation in the Sahel have increased and have bivariate correlations of about 85–90 % for the Sahel as seen on Fig. 6a. If downscaling is applied to verify the case of Cameroon, it is observed that the correlation between rainfall and tree growth is about 85 % for the Sahel of Cameroon (Fig. 6b) (Herrmann et al. 2005; Epule et al. 2012a). Giannini et al. (2008) argue that the recovery is not as a result of a recovery in rainfall but due to better land management in some affluent communities. Local studies on population perceptions of these changes are suggested to verify actually what obtains in the ground (Giannini et al. 2008).

The loss of trees in the Sahel has led to increase atmospheric carbon dioxide (CO_2). Even though uncertainties exist on the future of droughts in the study area, most climate projections show that most areas around the mid latitudes in Africa, Australia and Latin America will continue to be at the risk of droughts due to the fragility of their ecosystems (Molen et al. 2011). Such droughts are likely going to impact atmospheric CO_2 (Knorr et al. 2007). Droughts are known to affect the rate of CO_2 uptake by plants by affecting gross primary productivity (GPP), total ecosystem respiration (TER) (Molen et al. 2011; Meir et al. 2008). CO_2 flux measurements collected in a global network have shown that a majority of sites witnessed increase CO_2 accumulation and reduced GPP and TER due to droughts (Baldocchi 2008; Schwalm et al. 2010).

A recent study in Senegal shows that the proportion of carbon (C) residing in biomass decreased with time from 55 % in 1965 to 38 % in 2000. The study holds further that human land use disturbances only accounted for 22 % of biomass C loss in 1993, suggesting the dominant role of the long-term Sahelian extended droughts in the region (Woomer et al. 2004).

Generally, the reasons for the observations of increase greening in the Sahel have simply remained speculative or more commonly attributed to rising rainfall and land management in more affluent communities (Herrmann et al. 2005; Runnstrom 2003). However, while this current synthesis agrees with the role of rainfall and soil/water management as possible reasons for the observed greening, it can be argued that rising CO_2 content above the Sahelian atmosphere has an aerial fertilization repercussion as it triggers plant productivity and causes water management efficiency through reduced transpiration. Therefore, this study suggest that as the CO_2 continues to rise over the

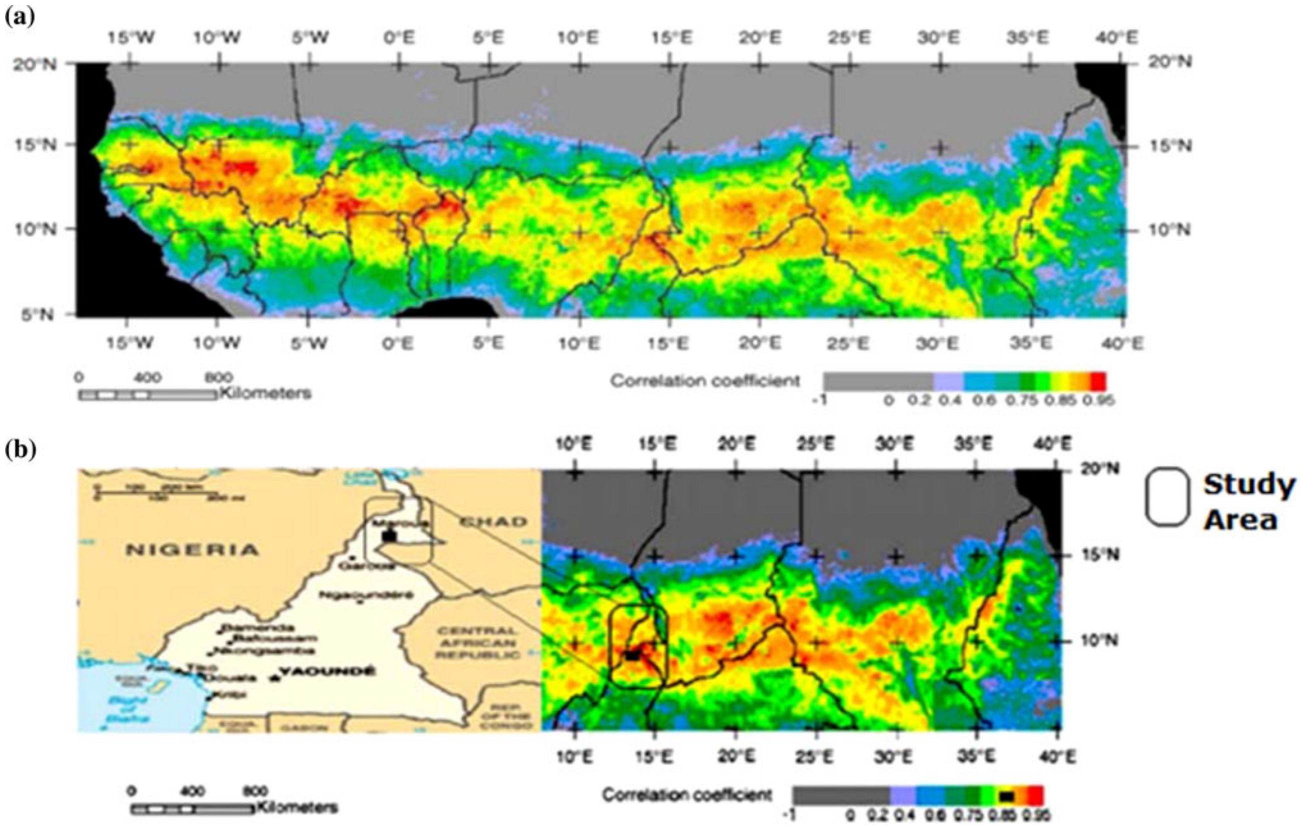


Fig. 6 **a** Correlation between rainfall and vegetation in most of the Sahel in general and the **b** Sahel of Cameroon in particular. *Source*: Modified from Herrmann et al. (2005), Epule et al. (2012a)

Sahel, we should expect further increases in greening, a view supported by (Prince et al. 1998). Also, the increase in greening could be explained by a surge in rural–urban migrations which reduced pressure from the agricultural population on land and the remittances from the migrant urban workers to their rural families have increased farm inputs and made farming more sustainable.

The effects of droughts on food yields in the Sahel

Per capita food production in the Sahel has declined in the past three decades due to droughts. The food self-sufficiency ratios have also dropped from 98 % in the 1960s to about 86 % in the mid 1980s. On average, every African had 12 % less grown food in the 1980s when the droughts were at a zenith than 30 years earlier (Nyariki and Wiggins 1997).

A huge number of people in developing countries suffer from hunger. More than 850 million people suffer from food shortages globally. About 700 million are from the developing countries while 100 million are from the African continent. Of the 60 million people living in the Sahel, 30 million are facing a food crisis (Nyariki and Wiggins 1997; Clover 2010). It was estimated that by the year 2000, the population in the Sahel of sub-Saharan (SSA) would grow by more than 3 % per year while food production would grow at 2 % per year leaving a majority of the people with insufficient food (Nyariki and Wiggins 1997). At the forecasted trend, the study area will experience food shortages of close to 250 million tons by the year 2020 (Nyariki and Wiggins 1997). It is argued that climate variability and extreme weather events such as droughts have for a long time recurrently stood as major factors affecting agricultural productivity and hence food security (Haile 2005). During the 1982 droughts in the Sahel, severe food shortages were recorded in over 27 Sahelian countries with notable famines in Chad, Ethiopia, Sudan and Angola (Dilley et al. 2005). However, Glantz (1994) and Lamb (1982) argued that things were made worse due to internal wars.

As a result of the resurgence of droughts between 1975 and 1985, per capita food production declined by 25 % in West Africa. During the onset of the 1984 droughts in Sudan, global attention was on Sudan due to reports of famine in areas like Darfur province, Kordofan province and the Eastern Sudan and Red Sea province (Olsson 1993). The resultant food shortages affected close to 20–25 million people in Sudan with a 3 %/month death rate, and millet and sorghum yields dropped to about 20 % of the normal. The observed or actual yields were below the predicted yields (Fig. 7a) throughout the period 1975–1985 while rainfall was equally declining (Fig. 7b) (Olsson 1986, 1993).

In Kenya, Makueni is an agro-ecological zone that is suitable for the growing of millet, maize, cowpeas, pigeon peas, beans and rearing of livestock. About 72 % of the households in this community are engaged in farming and livestock rearing (Dinku et al. 2007). In 1999/2000, 91 % of the households experienced food shortages for 3 months in 1999 and 5 months in 2000 due mainly to droughts. The resultant food shortages during the 1999/2000 droughts were reflected in a 31 % recourse of households to receive food relief; 6 % participated in food for work (FFW) activities; 17 % received relief food and participated in FFW (Ifejika Speranza 2006). With the aid of rainfall and crop yield data from 1971 to 2007, researchers found that Upper West and Upper East of Ghana had higher sensitivities to droughts as crop failures were rampant (Simelton et al. 2009; Antwi-Agyei et al. 2012). In Mbe, Ivory Coast, laboratory experiments that simulate drought conditions show that under water stress the crops reacted through reductions in height, leaf area, biomass production, tiller abortion, changes in root dry matter, rooting depth and a delay in reproductive development (Asch et al. 2005). With progressive droughts, there is a drop in the vertical distribution of root biomass within the soil as field capacity declines to 9 % moisture content (Fig. 8a–e) (Asch et al. 2005).

However, with indications of increase rainfall and vegetation in the Sahel since the 1990s, one is tempted to ask the question, why do we still have food problems in the Sahel? The answer to this lies in the fact that various human-oriented activities do not make the available moisture available for agriculture (De Rouw 2004). Some of these activities include deforestation, cattle grazing, unsustainable farming and fuel wood fetching inter alia. As such, these have had a negative reinforcing feedback effect on the drought cycle and have made the droughts recurrent in the region. Therefore, this study holds that since human activities are at the forefront of the droughts, it only suffices to synthesize that the trends in food production and tree mortality are principally caused by human activities which is also a key cause of the droughts.

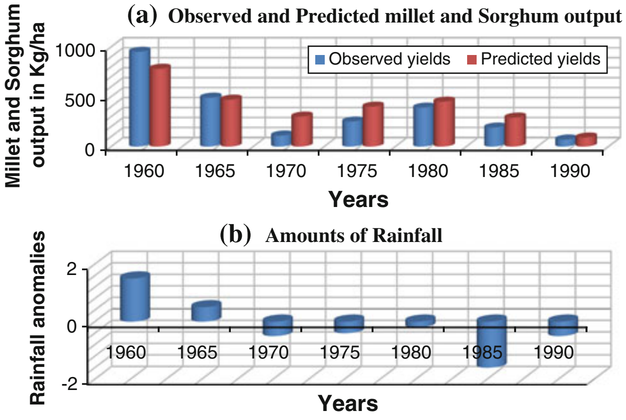


Fig. 7 **a** Variations in observed and predicted millet output in the Kordofan province of Sudan, **b** Rainfall anomalies. *Source*: Inspired from Olsson (1993)

Challenges, way forward and conclusion

1. Two major challenges that hamper the efforts at reducing food insecurity caused by droughts are internal political instability and public health concerns like HIV/AIDS and malaria. War and civil conflicts are common phenomenon in most of the Sahel as most countries in the region have been faced with civil conflicts (Antwi-Agyei et al. 2012; Olsson and Mryka 2008). The challenges of HIV/AIDS and malaria are ravaging a huge portion of human capital and placing the population at the mercy of the food crisis (Muller 2004; UNAIDS 2002). In the Sahel, health and national security problems linked to HIV/AIDS and Malaria (Muller 2004; UNAIDS 2002), and civil wars (resource wars) such as the rush for diamonds in Angola are making it difficult for the people to effectively handle the effects of droughts especially on food systems. Therefore, combating these diseases and providing peace for most Sahelian countries would be a major way forward. Most of the countries affected by droughts (Mali, Niger, Sudan, Somalia, Ethiopia, Central African Republic inter alia) have either had wars or are being seriously affected by HIV/AIDS and malaria.
2. Another problem is the absence of adequate observations. In the future, long-term observations will help fill in the gaps on inadequate climate, food production and ecosystem effects of tree mortality data. The available methods of simulation of climate, food production and tree mortality will make it possible to calibrate and validate models based on such long-term observations. Being that the droughts are recurrent, it is only through long-term observations of rainfall, temperatures, food yields, tree species densities and tree species richness that the overall ecosystem shifts and long-term adaptations can be applied.
3. Being that human activities are the main cause of the droughts, this study suggests the development of models that integrate both the natural and human-oriented variables. Currently, most of the models and drought quantification indices have dwelled on the physical- or climate-related variables such as rainfall, temperature, evapotranspiration, and transpiration at the expense of the human variables (see supplementary online section) (Palmer 1965; Vicente-Serrano et al.

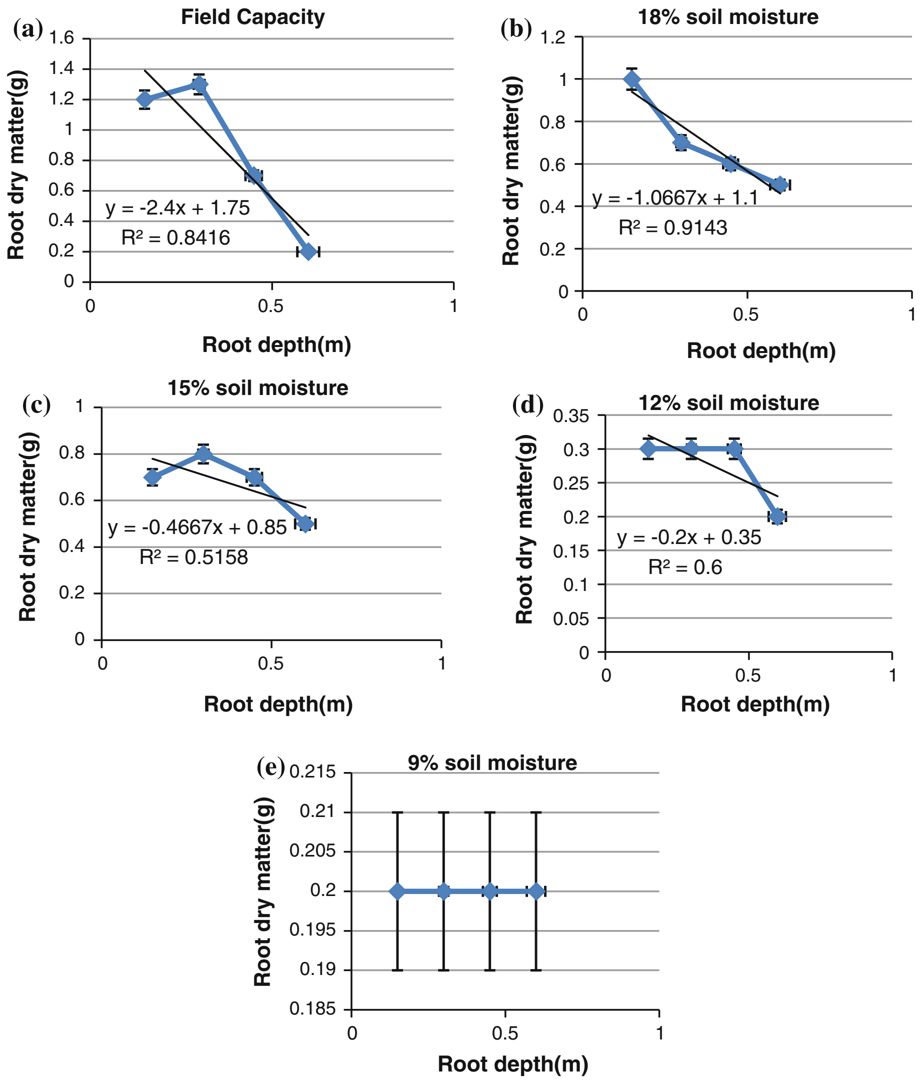


Fig. 8 Root depth and root dry matter distribution in the soil profile after 53 days of the experiment and at different soil moisture levels. *Source*: Inspired from Asch et al. (2005)

2010; McKee et al. 1993; Zhao et al. 2011). One way out of this is by carrying out grass root studies that will assess the perceptions of local farmers and integrate the results into cumulative models that will enhance understanding by analyzing both the human- and climate-related variables (Giannini et al. 2008). As such, future drought quantification efforts should aim at establishing indices that test both the climate- and human-oriented hypothesis against long-term experimental and observational data sets (Leuzinger and Quinn 2011; Zeppel et al. 2011).

4. More studies need to be carried out on the critical levels at which moisture deficits occur, what time span constitutes a drought's duration and what should a drought's threshold be? Ecological studies on the deficits, durations and threshold limits of trees and grains needs to be integrated into drought modeling/forecasting indices. This will help in establishing the thresholds above and below which the species can no longer survive (Frelich and Reich 2010). However, care must be taken to encompass regional disparities in environmental conditions and perceptions of what really droughts are to different people in different part of the world. In this situation, this study recommends the development of global models and subsequent testing of the latter against regional data to come out with regional models or indices that reflect the true drought deficits, durations and thresholds of the Sahel (Koepke et al. 2010).
5. Another way forward is to transform the entire system of farming in the region from extensive unproductive farms to intensive mechanized and organic fertilizer farms (Epule et al. 2012b). This approach is very important because this study has found out that the key problem is not with rainfall levels but the systems of farming and wide-scale forest loss. The question now is will these measures be feasible in the Sahel region where poverty is rife? The suggestion that African farmers should take up the use of fertilizers should be

treated with caution. This is because from the experience of the Asian agricultural revolution through which increase food production was attained from the application fertilizers; environmental repercussions such as degrading water quality in streams was the order of the day (Epule et al. 2012b; FAO and UNIDO 2008). Therefore, investments in organic fertilizers and machines would be appropriate. However, being that poverty is rife in this region, other stakeholder levels of collaboration and funding such as with governments, nongovernmental organizations (NGOs), cooperatives and reduction of emissions from deforestation and forest degradation (REDD+) should be reinforced (Lindell et al. 2010a, b). In Peru, for example, this has gained grounds and farmers involved in cooperatives are said to have a better understanding and potential of using organic fertilizers (Lindell et al. 2010a, b; Rosegrant and Cline 2003).

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