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Soil Carbon Sequestration and Climate Change in Semi-arid Sudan

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Abstract

Climate change poses risk for natural and human systems in Africa. Increasing temperatures and changes in precipitation patterns is likely to affect agriculture, pastoralism and forestry. Mitigation of increasing atmospheric concentration of CO_2 through soil carbon sequestration in semi-arid ecosystems may be beneficial to soil properties and cultivation. This paper describes and discusses soil carbon sequestration in relation to climate change in semi-arid regions, with special attention to the Sudan. It is anticipated that adaptation to climate changes is a more reasonable way to cope with future climate change than mitigation through soil carbon sequestration, especially for low emitting countries in Africa such as the Sudan.

Keywords: Adaptation, GHGs, Climate Change, Mitigation

Introduction

The increase of CO_2 and other greenhouse gases (GHGs) in the atmosphere are very likely to impact future climate through increasing temperatures and changes in precipitation patterns and magnitudes. This will alter the general conditions for agriculture, forestry and similar activities directly depending on ‘weather’ or climate. Marginal areas such as semi-arid regions are expected to be strongly affected by climate change as they are already affected by strong natural climatic fluctuations (mainly precipitation) that impact prosperity of self-supporting populations.

The term climate change has different meanings in different contexts. According to IPCC, climate change refer to *“any change in climate over time, whether due to natural variability or as a result of human activity*” (IPCC, 2014). United Nations Framework Convention on Climate Change (UNFCCC), on the other hand, defines climate change as “*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*” (UNFCCC, 2014). The recent IPCC fifth assessment report (AR5) describes and summarizes the state of the art of the current knowledge on the physical science basis of climate change (IPCC, 2013a), as well as the probabilities for various phenomena. The report combines a qualitative level of confidence for evaluation of the underlying scientific understanding and uses quantified probabilistic likelihoods when possible, to describe the degree of evidence for key findings (IPCC, 2013b).

Two major strategies to cope with climate changes are often considered, adaptation and mitigation (a third option, to deny or ignore that climate change occur at all, exists, but this is not based on scientific principles (Dunlap and

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McCright, 2011; Wikipedia, 2014)). Climate change mitigation includes actions taken to reduce the sources or enhance the sinks of GHGs. Climate change adaptation includes actions taken to decrease the effects or vulnerability of anthropogenic and biological systems to climate change effects. It is defined by UNFCCC as "*Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*".

Carbon sequestration is the process of removing carbon (C) from the atmosphere and depositing it in a reservoir (UNFCCC, 2014) such as soil or biomass. It is hence mainly, but not only, a mitigating action. Carbon sequestered in soils or in vegetation is only temporarily removed from the carbon cycle. Residence times vary among carbon pools (soil, vegetation, atmosphere, oceans) and, hence will the sequestered carbon continue its flow as part of the carbon cycle after some time. This time is dependent on the abiotic and biotic environments, management, as well as other factors. The magnitude of these fluxes is also strongly influenced by the climate and can provide feedbacks on the climate system (IPCC, 2014; Arneth *et al.*, 2010).

This paper briefly describes, discusses and exemplifies experiences gained from studies of soil carbon sequestration and carbon cycle studies in semi-arid Africa with focus on the Sudan. The presented material is a combination of results from finished and current research projects as well as from selected scientific literature within the field.

1. Climate change

IPCC states that "*Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased*" (IPCC, 2013a). The global average temperature have increased 0.78 °C when comparing the 1850–1900 period with the 2003–2012 period and almost the entire globe has experienced surface warming (IPCC, 2013a). Due to natural variability, trends calculated on short time series describing surface temperature are very sensitive to start and end time of these time series and robust multi-decadal data sets are needed. Most reports agree on the global warming, however a recent report mentions that the warming has taken "a pause" since 1998, and the increase in the global surface temperature from 1998 until 2013 is only 0.04 °C per decade from observations, but 0.21 °C per decade from recent simulations (Tollefson, 2014). This temporary reduction in temperature increase (Santer *et al.,* 2014) should not be interpreted as a reduction of the changes in the climate. Out of the 14 warmest years since 1850 have 12 that occurred during the 21th century and for the north hemisphere is the latest 30 year period probably the hottest since the 15^{th} century (IPCC, 2013a). Changes in precipitation are less confident and both positive and negative changes occur.

Extreme weather and climate events have been observed since about 1950. On the global scale, it is very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased (IPCC, 2013a).

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There are likely more land regions where the number of heavy precipitation events has increased than where it has decreased.

The main cause of the observed climatic changes is attributed to the increase of GHGs in the atmosphere. The atmospheric concentrations of CO_2, CH_4 and N_2O are higher today than they had been during the last 800,000 years (IPCC, 2013a). The mean rates of increase are the highest in 22,000 years. The major sources of CO_2 include emissions from fossil fuel burning and cement production yielding a source of 9.5 Gt C yr^{-1} in 2011. The annual net increase of CO_2 due to anthropogenic land use change was estimated at 0.9 Gt C yr^{-1} (average for 2002-2011). The increase of CO_2 makes the total radiative forcing positive and cause an uptake of energy in the climate system. The total radiative forcing has increased with a factor of 2.29 as compared to the 1750 level (IPCC, 2013a).

A waste majority of the scientific community agree that there is a casual relationship between the release of GHGs and increasing temperatures (IPCC, 2013b; Anderegg, 2010; Doran and Zimmerman, 2009; Oreskes, 2004; NASA, 2014). A recent investigation concludes that "*the number of papers rejecting the consensus on anthropogenic global warming is a vanishingly small proportion of the published research*" (John *et al.*, 2013) and the AR5 also states that "*human influence on the climate system is clear*" (IPCC, 2013b).

The large amount of scientific literature concerning climate change is demanding to survey but an up to date summary is given in the fifth IPCC assessment report whereof the working group 1 (The Physical Basis) report (IPCC, 2013a) is already available and the reports of working group 2 (Impacts, Adaptation and Vulnerability) and 3 (Mitigation of Climate Change) will be released during the spring of 2014 and will be available at http://www.ipcc.ch/.

We find support for anthropogenic climate changes, mainly attributed to emissions of GHGs originating from the developed world and with a tendency to affect the developing world, not at least Africa (Toulmin, 2009).

Africa

IPCC fourth assessment report states that "*Africa is one of the most vulnerable continents to climate change and climate variability, a situation aggravated by the interaction of 'multiple stresses occurring at various levels and low adaptive capacity"* (Boko *et al.*, 2007), and it points out the high vulnerability of Africa's major economic sectors to current climate change. This vulnerability is due to the already limited water supply, poverty, ecosystem degradation, complex disasters and conflicts, among other causes. The adaptive capacity is considered weak, further increasing the vulnerability to climate change. Water stress may increase due to changes in precipitation, rainfall intensity and increased evaporation in combination with an increased demand for water. The proportion of arid and semi-arid regions is likely to increase by 5-8% (Boko *et al.*, 2007).

Minimum temperatures have been observed to increase slightly faster than maximum and mean temperatures (Boko *et al.*, 2007). The number of warm spells over western and southern Africa has increased and a decrease in the number of very cold days has been reported (New *et al.*, 2006). The recent IPCC fifth assessment report shows significant temperature increases for all of Africa (1901-2012) whereas some areas are uncertain due to incomplete or missing data (IPCC,

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2013b).The density of the network of climate stations in Africa is low, averaging one station per 26000 km^2, eight times lower than the WMO's (World Meteorological Organization) recommendation (Osman Elasha *et al.*, 2006). The number of climate monitoring stations in Africa has also decreased since the 1970's (Hulme, 1992), which may result in less reliable observations and forecasts, especially in areas with strong environmental gradients such as the Sahel region (Sjöström *et al.*, 2013). Estimates for Africa indicate, with high likelihood, higher future temperatures, warmer and more frequent hot days and nights or most land areas (IPCC, 2013b).

African precipitation shows a less clear pattern, both in terms of observations, as well as for predicted future precipitation patterns (Giannini *et al.*, 2008; Boko *et al.*, 2007). Interannual variability is large over most of Africa and some areas also show strong multi-decadal variability (Boko *et al.*, 2007). During the last 50 years, declines in precipitation have been observed in West Africa, whereas a recent increase has been observed along the Guinean coast (Boko *et al.*, 2007). Some areas, such as southern Africa show no clear trend but some areas have experienced extreme precipitation events causing severe flooding (Usman and Reason, 2004). The recent greening observed in the Sahel (Olsson *et al.*, 2005; Dardel *et al.*, 2014) is mainly explained by increased precipitation (Hickler *et al.*, 2005). Predictions for the 21st century state that the Sahara region which is already very dry is very likely to remain very dry. The confidence in projection statements about drying or wetting of western Africa is low (IPCC, 2013b). A minor positive change in precipitation, with medium confidence is predicted for East Africa and changes in precipitation seasonality may occur in several regions. The importance of sea surface temperatures and the monsoon are highlighted for the Sahel region whereas ENSO (El Niño–Southern Oscillation) may play an important role in southern Africa (IPCC, 2013b).

Effects of climate change

Direct effects of increased temperatures include higher levels of plant and water stress, larger evaporative losses of water from soil and surface waters. This will decrease water availability for agriculture and water power and may further limit access to drinking water. Higher air temperatures increase the amount of water and energy that the atmosphere can hold which in turn may increase severity of extreme events (Field *et al.*, 2012). Extreme precipitation events increase the risk of flooding and severe erosion causing damage to cultivation and infrastructure. Even in areas where precipitation are predicted to increase, higher temperatures may cause an increased evaporative demand counteracting the precipitation increase and result in a no change or net decrease in water availability and an increase in aridity (Sherwood and Fu, 2014). Recent observational studies have shown that the P/PET (precipitation/potential evapotranspiration) ratio is decreasing on average as the global temperature increases, resulting in a drier future (Sherwood and Fu, 2014). Water demand will increase due to increase in population and increases in per capita consumption. This increased water demand (agricultural, domestic and industrial) in combination with increased evaporation due to higher temperature and unreliable predictions of future precipitation will very likely cause increased water stress in large regions of Africa (Toulmin, 2009;

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Schlosser *et al.*, 2014). The strong spatial and temporal variability of precipitation (Hulme *et al.*,2005) can strongly affect local resource availability, sometimes with adverse effects to populations directly depending on agriculture (Olsson, 1993; Zarocostas, 2011). Even if nomadic groups may suffer from marginalisation when land resources decrease and the area under cultivation increase, one may say that the mobility flexibility that nomadic pastoralism represents can provide a type of security and adaptation of strong temporal and spatial resource variability (Sulieman and Elagib, 2012).

Additional effects of climate changes in Africa include inundation of coastal agricultural land due to rising sea level (Frihy and El-Sayed, 2013), coastal erosion, changes in malaria transmission (Ermert *et al.*, 2013), changes to other vector borne diseases, and effects on plant pests and pathogens (Gregory *et al.*, 2009) and much more not included here. Some studies even point to an increased risk of civil conflicts due to warming and a general resource decrease (Burke *et al.*, 2009).

Sudan

Studies on climate change in Sudan include the national reports to UNFCCC, the first one in 2003 (Anon., 2003b; 2003a) and the second in 2013 (Anon.; 2013). These reports constitute the official national communications including information on emissions and removals of GHGs and details of the activities undertaken to implement the climate convention. Sudan's second national communication to UNFCCC (Anon.; 2013) gives an overview of adaptation activities, coastal zone and water resource vulnerability, mitigation possibilities and carbon sequestration opportunities. Forestry is considered as the only carbon sequestration measure currently appropriate for Sudan (Anon.; 2013). The report does not treat soil carbon sequestration, but points out that large area of agricultural land and rangeland could be utilized for carbon sequestration in the form of biomass.

A large proportion of Sudan's agriculture is rainfed and it is, hence vulnerable to decreased rainfall and/or increase rates of evapotranspiration, resulting in a decrease in water availability. The large numbers of grazing animals (cattle, sheep, goat and camel) in the semi-arid areas rely on grazing and crop residues, almost entirely of non-irrigated sources. Some areas have experiences of lower stocking rates and climatic changes have been reported to make pastoral production more uncertain than ever before (Sulieman and Siddig, 2014). Adaptation strategies such as in situ rain water harvesting, adjusted sowing dates and the use of suitable cultivars are crucial issues for traditional rural farmers (Ahmed, 2010). Potential effects on biodiversity have been reported (El Tahir *et al.*, 2010; Bashir, 2001), stressing the importance of "*involvement of local communities in natural resource conservation, forest rehabilitation and protection; use of indigenous knowledge and local experience in forest management".*

2. Soil carbon sequestration

Sequestration, i.e. depositing carbon originating from the atmosphere in some reservoir such as soil or biomass, decreases the atmospheric concentration of CO_2 and is, hence considered to mitigate climate change. Other techniques such as

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deliberate CO_2 removal through geoengineering, is often called CO_2 removal, and refers to a number of technologies (also including non-biotic technologies such as direct air capture) which reduce the levels of atmospheric CO_2. Activities such as REDD (Reducing Emissions from Deforestation and forest Degradation) is not directly carbon sequestration but aims to reduce emission originating from land use conversion and forestry activities. REDD target developing countries (Nations, 2014), and as deforestation and forest degradation is estimated to contribute to approximately 17% of all GHGs emissions globally (Solomon *et al.*, 2007), such activities are of great importance. REDD focus more on not losing already stored CO_2, whereas carbon sequestration has emphasis on transfer of CO_2 from the atmosphere to soil and biomass.

A wide range of studies of carbon sequestration (Andrén and Kättterer, 2001; Batjes and Sombroek, 1997), the carbon cycle (Schimel, 1995; Schlesinger and Andrews, 2000) and drivers of important processes such as photosynthetic assimilation of CO_2 by terrestrial vegetation (Monson and Baldocchi, 2014; Merbold *et al.*, 2009) and autotrophic and heterotrophic respiration (Reichstein *et al.*, 2005) have been performed. This type of studies promotes understanding of ecosystem function and properties relevant as background information for more applied carbon sequestration studies and projects. Numerous studies have aimed to quantify the potential for carbon sequestration in various ecosystems (Farage *et al.*, 2007; Ingram and Fernandes, 2001), both in soils and in biomass. This potential is often seen as a “gap” which could be closed or decreased by different types of soil and land management actions varying with climate, vegetation type, soil, cropping system and other factors. Utilisation of this potential may have positive environmental effects as well as allowing participation in various payments for ecosystem services (PES) schemes, for example within the Kyoto Protocol. Such payment schemes may promote transfer of funds from larger emitters of CO_2 to projects sequestering carbon (Balgis *et al.*, 2006).

The concept of carbon sequestration potential was recently scrutinized and a separation into biophysical, technical, economic and practical potential was suggested in order to increase comparability among studies (Luedeling *et al.*, 2011). In short is the biophysical potential a function of the geographical / climatological and soil setting of a region, the technical potential are dependent on management options available and feasible, the economic potential considers economic constraints such as profitability and marginal abatements costs. Finally the practical potential considers additional constraints such as socioeconomic factors, institutional and governance constraints and market access (Luedeling *et al.*, 2011). Hence, we may have cases where one type of potential is low and as such decrease the overall potential for a successful sequestration project.

Several semi-arid areas of the world are vulnerable to environmental changes (Warren *et al.*, 1996; Lal, 2001a) and to some extent degraded (UNEP, 1992), partly due to reduction in the permanent plant cover (Le Houérou, 1995) and low soil carbon content (Ringius, 1999). Such areas including degraded agro-ecosystems in Africa, have been identified as suitable targets for carbon sequestration due to their below natural carbon stock (both soil and biomass), as well as due to the potential benefits originating from an increase in carbon content

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(Olsson and Ardö, 2002). Soils have been suggested as preferable to storage in biomass/vegetation due to their longer residence times for C and less risk of a rapid release (Lal *et al.*, 1999). Hence, is the focus below on soil C sequestration in semi-arid environments including some examples from Kordofan.

Soils

Soil organic matter (SOM) influences the physical, chemical and biological properties of the soils and contributes to their functioning (Ontl and Schulte, 2012). We often consider storage of soil carbon as a vital ecosystem service and a function of several interacting ecological processes. These processes are affected by human activities which can reduce or enhance the storage of soil carbon (FAO, 2001; Lai *et al.*, 2013).

Soil quality is improved by increased SOM content through better water holding capacity which would imply less need for irrigation, improved micro-aggregate structure, preventing erosion (decrease soil erodibility) and a stabilizing effect on the soil structure (Jewitt and Manton, 1954; Gerakis and Tsangarakis, 1970; Warren, 1970; Batjes and Sombroek, 1997; Lal *et al.*, 1999). Soil organic carbon (SOC) is also an important determinant of the cation exchange capacity of soils (Batjes, 1999) and there is commonly a clear correlation between SOC in the topsoil and crop yields (Sombroek *et al.*, 1993). Large pools of SOM with low decomposition rates also permit a long-lasting mineralization of N and other nutrients. Both the net primary production (NPP) and the decomposition rate of plant residues in semi-arid areas increase with water availability (Parton *et al.*, 1996). Higher temperatures in tropical ecosystems are likely to reduce carbon uptake (Xia *et al.*, 2014; Schneising *et al.*, 2014). Soil carbon can have a very long residence time, hundreds and even thousands of years (Lal *et al.*, 1998), compared with carbon stored in aboveground vegetation which may rapidly disappear through clear cutting of fire.

When soils under natural vegetation are being transformed to agricultural soils, carbon is usually being lost to the atmosphere (Burke *et al.*, 1989; Pieri, 1992; Scholes *et al.*, 1997; DOE, 1999; Schlesinger, 2000; Lal *et al.*, 1999). During intense cultivation, without fertilization or add-on of organic matter, this decrease may be fast (Buyanovsky and Wagner, 1998). Several agro-ecological ecosystems in semi-arid areas are today considered to be poor in SOM due to deforestation, high intensity cropping and cultivation, intense tilling and overgrazing. In the Sahel region, continuous millet cultivation on sandy soils in Burkina Faso has been reported to slowly deplete soil N and P (Krogh, 1997) and decreased fallow periods have been reported to deplete soils in Niger (Wezel and Haigis, 2002). Conversion of forest land to cropland in Senegal has been reported to significantly decrease soil carbon (Loum *et al.*, 2014) and low soil nutrient levels have been associated with low African agricultural yields in general (Sanchez, 2010).

For the Kordofan region of Sudan, it is evident that the land use practices have changed markedly from a rotation system with long fallow periods (15–20 years) interspersed with short periods of cultivation (4–5 years) (Haaland, 1991) to shorter fallow periods or even continuous cultivation over the last four to five decades (Davies, 1985; Jewitt and Manton, 1954; Craig, 1991; Khogali, 1991; Olsson and Rapp, 1991; Ardö and Olsson, 2004; Olsson and Ardö, 2002). When

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continuous millet (*Pennisetum glaucum*) cultivation, as in Kordofan, is combined with annual burning prior to planting, no or little addition of manure or artificial fertilizers and removal of most crop residues after harvest, we may expect a decrease of SOM as well as a decrease in soil nutrients such as P and N. Similar trends are found elsewhere in the Sahel region and continuous millet cultivation in a similar environment on a sandy soil in Burkina Faso has been reported to slowly deplete soil N and P (Krogh, 1997). In Niger, significant increases of C and N with fallow age on sandy soils (<4.5% clay) were found (Wezel and Böcker, 1999). This reduced time for soil revitalization may be caused by an increased demand for food; reduced crop yield (Olsson, 1993) due to decreasing precipitation, soil degradation, crop diseases and parasites (Khogali, 1991) and an increased desire to grow cash crops (e.g., groundnuts). During the same period, crop yields have decreased (Olsson, 1985; Olsson and Ardö, 2002).

The use of fallow periods is the dominating measure taken to improve soil fertility in the Kordofan region. Fallow periods increase not only soil carbon content but also soil nutrients and potentially the clay fraction of the soil can be increased when trees capture wind transported fine material (El Tahir, 2006). Herbaceous and arboreal improved fallows have been suggested as key components of many sustainable tropical farming systems (Sanchez, 1999).

Several studies have pointed out the potential (many of them not considering the different types of potentials mentioned above) to sequester carbon in both soils and biomass in semi-arid environments and degraded agro-ecosystems. Restoration of soil fertility and improvement of soil properties through increased soil carbon sequestration in agro-ecosystems (by means of no-till, agroforestry options, fallowing, special cover crops, return of crop residues, mulching, reduced grazing intensity, green fallow periods, conservation tillage, etc. (Lal *et al.*, 1998), may, apart from removing CO_2 from the atmosphere, also improve our chances of meeting future food production demands (Ringius, 1999; Olsson and Ardö, 2002; Sanchez, 2002).

Batjes (1999) estimated that between 0.6 and 2 Pg C yr^{-1} could be sequestered by large-scale application of appropriate land management in degraded lands of the world. Squires (1998) estimated the potential sink of dry lands to be 10 Pg C yr^{-1} over the next 50 years, whereas global desertification control could have been estimated to sequester 0.9-1.9 Pg C yr^{-1} for 25-50 years (Lal, 2001b). Such general numbers may be interesting from a global carbon budget point of view but are less useful when investigating the possibilities for sequestration on regional or local level.

Local examples from Kordofan, Sudan

Studies were conducted in North Kordofan to investigate the potential for soil carbon sequestration in areas intensely utilized for agriculture and pastoralism (Ardö and Olsson, 2004; 2003; 2001; Poussart *et al.*, 2003; Farage *et al.*, 2007; Olsson and Ardö, 2002). The basis in these studies is that the large proportion of the ecosystems in North Kordofan are depleted of SOM due to intense land use and low inputs of both organic and inorganic fertilizers. Traditional, non-mechanized, rain-fed agriculture, without the use of any type of fertilizers or addition of organic matter, is common in central and western Sudan (Craig, 1991).

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Fig. 1 illustrates a potential general scenario of SOC changes for an area with sandy soil and a mean annual precipitation of about 300 mm in North Kordofan from year 1850 to year 2100 (Olsson and Ardö, 2002). Prior to significant human intervention, we assume an equilibrium level of about 300 g C m^{-2} (for the upper 20 cm of the soil profile) in a natural grassland/sparse savanna without cultivation (1850). This equilibrium level was determined by a l000 year simulation under stable climate and management conditions. From 1891 to 1973, we assumed rotational millet cultivation with an increasing crop: fallow ratio where cultivation periods correspond to a decrease in SOC and fallow periods to an increase in SOC (Fig. 1).

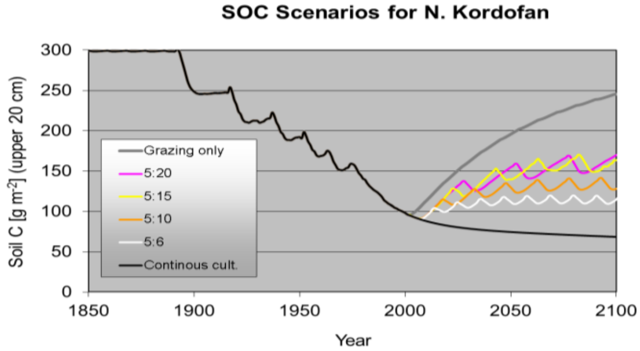

Fig. 1. Simulated changes of soil organic carbon from 1850 to 2100 for a site in N Kordofan (Sudan) characterized by sandy soils, 300 mm of mean annual precipitation and rotational millet cultivation with increasing intensity from 1891 to year 2000. From year 2000 and onward are various recovery options (decreased cropping intensity) simulated. Modified from (Olsson and Ardö, 2002).

From 1974 to 2000, we assumed a continuous cultivation of millet. From year 2000 and forward, the effects on SOC from land use simulated, showing a further decline in SOC during continuous cultivation, and increase in SOC if grazing only are applied. The impact of the crop: fallow ratio implies roughly that a fallow period should be longer than the interspersed cropping periods in order to increase SOC.

The historical SOC development as well as the future scenarios was simulated with the CENTURY model (Metherell *et al.*, 1993; Parton *et al.*, 1987; Parton *et al.*, 1988). The CENTURY model is a general model of plant-soil nutrient cycling which is being used to simulate carbon and nutrient dynamics for different types of ecosystems including grassland, agricultural, forest and savanna (NREL, 2014). The model is useful for testing effects on SOC and soil nutrients from management options such as crop rotations, addition of manure, addition of organic matter, fire, harvest, grazing and cultivation practices.

Longer fallow periods have been suggested as suitable for recovery of SOC after periods of cultivation (Ardö and Olsson, 2001; Deans *et al.*, 1999; Sanchez, 1999; Wezel and Haigis, 2002). An empirical data from soil sampling in combination with interviews on land use history show a weak but significant positive relationship indicating increase of SOC with longer fallow periods/shorter cultivation (Fig. 2).

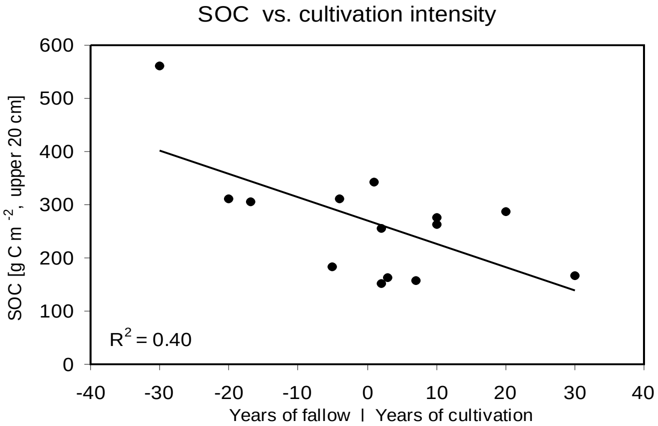

Fig. 2. Impact of cultivation intensity on SOC in agricultural land on sandy soils in North Kordofan, Sudan. ***Negative numbers (on x-axis) denote years of consecutive fallow and positive numbers denote years of consecutive cropping. Modified from (Ardö and Olsson, 2004).***

Fallow periods with trees such as *Acacia senegal*, potentially a N-fixing species, also increase the amount of SOC when compared to cultivation (Fig. 3) (Ardö *et al.*, 2008). However, there are some doubts on the N-fixing potential of Acacia Senegal (Deans *et al.*, 1999) even if it has been reported to fix N (Barbier, 2000). Tree cover and tree cover duration tend to increase SOC for *Acacia senegal* plantations in Demokeya experimental site in Kordofan, Sudan. Comparing SOC of the cultivated site clearly illustrates the positive effect on SOC from trees (Ardö *et al.*, 2008) (Fig. 3).

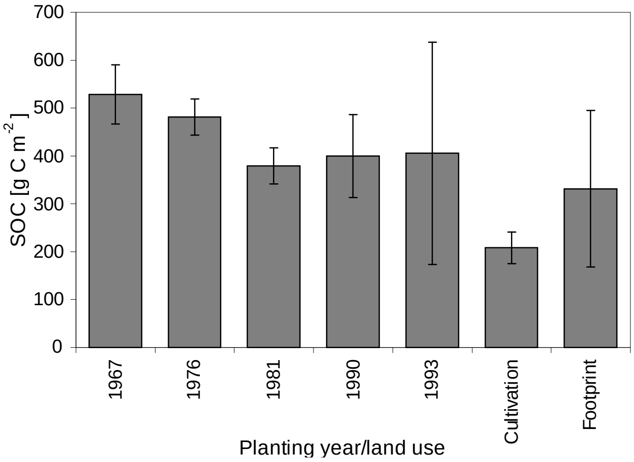

Fig. 3. Soil organic carbon in the upper 20 cm of the soil profile in *Acacia senegal* plantations with different age, at a cultivated site and in the close vicinity of the flux tower in Demokeya (foot print). Error bars denote ± one standard deviation, four samples taken at each site. Modified from (Ardö *et al.*, 2008).

Intercropping of sorghum (*Sorghum bicolor*), sesame (*Sesamum indicum*) and roselle (*Hibiscus sabdariffa*) with *A. senegal* have been shown to give higher net return than monocropping of the same crops (Fadl and El Sheikh, 2010; Fadl, 2013). Additional environmental benefits of fallow periods with trees include lower soil temperatures, higher soil moisture, higher SOC (Abril and Bucher, 2001), greater fuel production, and the possibilities of tapping gum (Haaland, 1991; Khogali, 1991) and shade for grazing animals. Litter produced by woody plants is beneficial due to its higher content of polyphenols (lignins and tannins) in the litter, which decreases the decomposition rate (Abril and Bucher, 2001), when compared to grasses and annual herbs.

Spatial variability - GIS

As environmental factor such as soil, precipitation and land cover varies significantly over space (in addition to time), integration of tools that handle spatially distributed data with SOC simulations models, for instance the CENTURY model, can be beneficial. A simple such integration is exemplified in Fig. (4).

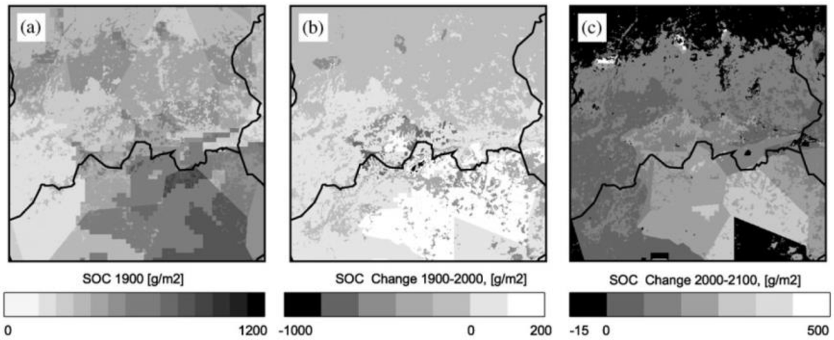

Fig. 4. Estimated soil organic carbon (SOC) (g C m^{-2}) in 1900 (a), SOC changes from 1900 to 2000 (b) and potential SOC changes from 2000 to 2100 (c). The area is approximately 500 x 500 km in central Sudan, covering parts of both Northern and Southern Kordofan. CENTURY simulations were performed for each km^2, modified from (Ardö and Olsson, 2003).

Through linking a Geographical Information System (GIS) with the CENTURY model spatially explicit simulations were performed (Ardö and Olsson, 2003) for each km^2 in a 500 x 500 km area. Verification of simulation results from SOC models and ecosystem models may indicate their usefulness through quantitative comparison with measured data (Fig. 5) (Ardö and Olsson, 2004).

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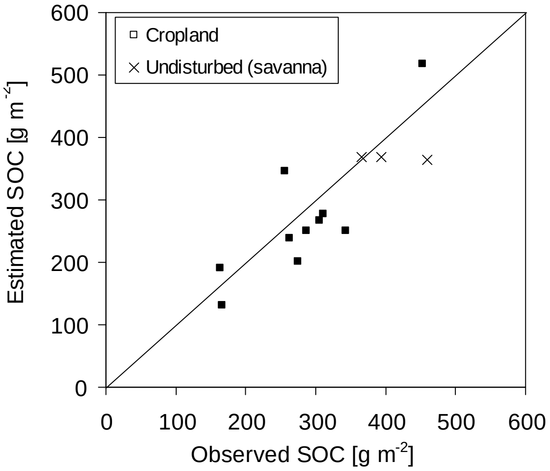

Fig. 5. Comparison of soil organic carbon (SOC) observations based on soil samples and estimates of (SOC) from the CENTURY model. N =13, r^2 = 0.70. Modified from (Ardö and Olsson, 2004).

Uncertainties

Uncertainties must be considered when using modelling to estimate current and future ecosystem processes, such as assimilation of CO_2 and ecosystem properties such as carbon stocks. We have uncertainties in data, affecting calibration and validation, model uncertainties indicating that our representation of the process may differ between the model and reality (Barkman, 1998). One example is the climatic data (most often including temperature, precipitation and incoming radiation, as well as other model specific data needs) needed as drivers for most ecosystem models. These data are often a result of an interpolation based on observations from a limited number of loci, most often climate stations. A low number of climate stations (see above) will decrease the quality of the interpolated result (Dardel *et al.*, 2014). Interpolated data will, hence, not fully agree with reality and in areas with high spatial and temporal variability, such as the Sahel region, may differences be substantial (Sjöström *et al.*, 2013). Satellite derived estimates of precipitation may of course improve these estimates. Another example is shown in Fig. 6, which is similar to Fig.1, but with uncertainty originating from the data on soil texture included.

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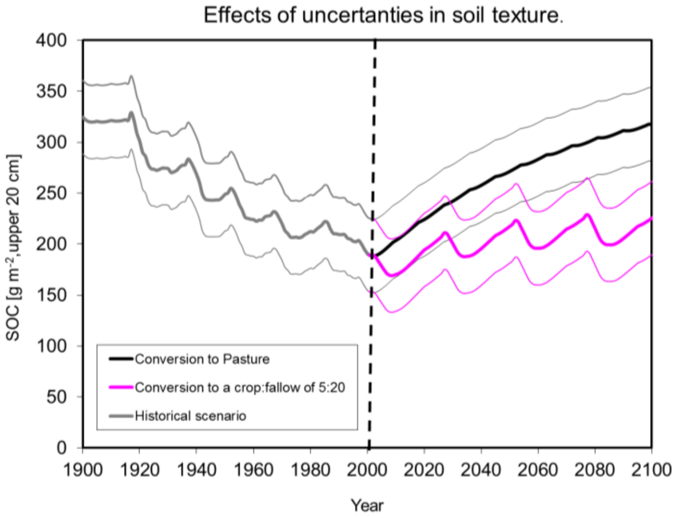

Fig. 6. Effects of data uncertainty during modelling of the potential impact on soil organic carbon from land use management. Result from a Monte Carlo simulation (n=500) assuming a data uncertainty in the soil clay content (mean = 5% and σ= 2.5%). Thick lines describe simulation without data uncertainty and the thin lines describe the output distribution (95%) from the Monte Carlo simulation (calculated as the output standard deviation from the Monte Carlo simulation (18) x 1.96 = 36). The black line describes effects on SOC assuming grazing only and the blue line describe effects on SOC assuming a traditional Millet cropping system with 5 year of cultivation and then 20 years of fallow.

In this case, we assume a clay content in the soil of 5%, with an uncertainty quantified as a standard deviation (σ) of 2.5% (i.e. we assume that 68% of the observations are within 2.5% of the mean value). We executed 500 simulations with the soil clay content randomly taken from a normal distribution (mean = 5% and σ = 2.5%) in a Monte Carlo approach, remaining variables and parameter being unchanged. The output variability/uncertainty in SOC is represented by a σ of 18 g C m^{-2} (in the upper 20 cm of the soil profile). The uncertainty is illustrated (Fig. 6) by calculating a 95% distribution (σ * 1.96 ≈ 36), showing a clear influence on simulated SOC from uncertainty of input data.

Rate of sequestration

There are several factors that influence the rate of soil carbon (SOC) sequestration, which is a balance of the input (litter-fall, fine root dieback, atmospheric input of organic matter) and the heterotrophic soil respiration, (Rh). Rh differs for different pools of soil carbon and, hence will the long-livety of the soil carbon sequestration be of importance. This is partly dependent on chemistry of the organic matter (lignin content and other components), as well as the clay binding of soil organic matter (SOM). Still, sequestration rates in semi-arid areas

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are often low and have been estimated to 1-2 g C m^{-2} yr^{-1} on sandy soils in Kordofan (Olsson and Ardö, 2002; Ardö and Olsson, 2003),

3. Sudan in perspective

From a global perspective, the Sudanese emission of GHGs is low. According to the Global Carbon Project (NREL, 2014), Sudan is ranked as country number 87 on the list of emitters, with an annual emission of 14 Mt CO_2 in 2012 as compared with China (9621 Mt CO_2) and USA (5118 Mt CO_2) for the same year.

Quantifying this emission per capita, Qatar is ranked as country #1 (44 t CO_2 per capita), while Sudan is ranked as country #183 (0.3 t CO_2 per capita) in the year 2012. USA and China are ranked as #14 and #53, with 16 and 7 t CO_2 per capita, respectively. The global emission of CO_2 was 35418 Mt CO_2 in 2012. Sudan was emitting 0.04% of this amount, a very small fraction. Corresponding percentages of global emissions for USA are 14.5% and for China 27.2% (NREL, 2014). In this perspective, the job to reduce the atmospheric concentration of CO_2 belongs to other nations than Sudan.

4. Future studies

A wide range of different approaches are available when studying and quantifying environmental drivers, climatic change and anthropogenic and management impact on agro-ecosystems, including attempts to estimate carbon sequestration and plant productivity. A common approach is field experiments, but modelling and simulation, and various measurements are also utilized, either as separate activities or in combination.

Field experiments constitute empirical testing of effects on crop/forest productivity and effects on soil properties due to environmental drivers and management options such as optimal fertilizer use or improved crop varieties. Environmental variability such as temperature, radiation, water availability etc. directly affects output. For many branches of agriculture are small-plot field experiments a fundamental tool for progress of plant science. In addition to tests of crop varieties and yield optimization, test of new technology and equipment can demonstrate new knowledge to growers. They promote development of basic understanding of the factors that control the production of crops and how these factors interact (Petersen, 1994). In addition, they can provide significant data and information on carbon fluxes and carbon pools, and hence, be a valuable contribution to carbon sequestration research (Liu *et al.*, 2014).

Modelling and simulation provide a strong and often suitable tool for assessing impacts of climatic conditions and management options on plant productivity and soil properties. Process based models, with an effort to represent key processes such as hydrology, photosynthesis and respiration allow prediction of future behaviour of vegetation to be performed. This can bring information on future effects of, for example altered water use efficiency in semi-arid areas due to increased atmospheric CO_2 concentration or potentially changed conditions for common pathogens and plant diseases. Field experiments and measurements provide vital data for development, calibration and validation of tools for modelling and simulation.

The plethora of available models include, among other, crop models (EPIC, PEGASUS) (Folberth *et al.*, 2012; Webber *et al.*, 2009; Liu *et al.*, 2013),

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dynamic vegetation models (LPJ-GUESS (Lindeskog *et al.*, 2013; Weber *et al.*, 2009) and models focusing on carbon turnover (CENTURY (Parton *et al.*, 1988), Roth-C (Jenkinson *et al.*, 1999). These and other models all have different properties, data requirements, use different time steps in their calculation etc., but they all provide an effort to integrate existing knowledge into a framework for understanding properties and performance of ecosystems, today and tomorrow.

Measurement is a wide but basic scientific concept. In the context discussed here, we can utilize direct measurement of carbon pools in soils or in biomass in combination with measurements of meteorological drivers (radiation, temperature, precipitation and available soil water etc.) and environmental properties (e.g. soil). Key processes such as plant assimilation and autotroph and heterotroph respiration are strongly influenced by both meteorology and environmental properties that is why their quantifications are crucial both in order to directly infer relationships, as well as to be used as input data for modelling and simulation.

Direct measurements of fluxes of CO_2, H_2O, energy and momentum between the atmosphere and biosphere can be performed using the eddy covariance method, providing data with high temporal resolution (Ardö *et al.*, 2008; Merbold *et al.*, 2009; Monson and Baldocchi, 2014). This method measures the net flux, i.e. the net ecosystem exchange (NEE) to which two opposing fluxes contribute: CO_2 uptake during photosynthesis and CO_2 release during respiration. Partitioning of NEE into these component fluxes increase ecosystem understanding and is, hence a required post processing of the flux data (Reichstein *et al.*, 2005). In combination with measurements of radiation, soil moisture, vapour pressure deficit and air temperature (i.e. important environmental drivers) can eddy covariance measurements provide good insight to ecosystem fluxes of carbon on diurnal, seasonal and annual time scales. Drawbacks with the methodology include high costs and that it is relatively technology intense, both when compared to standard meteorological measurements and especially when compared to field experiments. The measurements most often represent a small source area (about 1 km^2) and hence do not provide much information on spatial variability. Post processing can be demanding, uncertainty of output variables can be substantial (Richardson *et al.*, 2012) and the time from installation to scientific results may be long.

5. Concluding remarks

Many studies have pointed out the possibility to move CO_2 from the atmosphere to the soil and the biosphere in order to mitigate climate change. As this mitigation may have numerous beneficial effects on soil properties and cropping systems have this often been denoted as a 'win-win' situation (Ponce-Hernandez *et al.*, 2004). For drier areas, the amount of carbon possible to sequester is often rather low, both in soils and in biomass and costs for monitoring and verification may exceed the payment received for provision of ecosystem services through increased carbon storage.

The understanding of the carbon cycle and the processes that govern assimilation and respiration of carbon naturally requires a combination of the methodologies mentioned above, as well as other complementary methods not mentioned here. A

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resource efficient strategy could be a combination of small plot field experiments in combination with a modelling effort. This could provide practical, hands on data from the experiments, increase skills and process understanding through model simulations. If local measurements exist (Ardö *et al*., 2015), these could be used as environmental drivers as well as for calibration and validation of model results.

Given the low GHGs emission of Sudan, it may be considered less important to focus on carbon sequestration as a mitigation activity aiming to decrease the global atmospheric concentration of CO_2. It is considered more important to promote research and education on strategies to reduce vulnerability to adverse climate events and to increase the capacity to adapt to short-term/seasonal weather conditions and climatic variability (Hulme *et al.*, 2001).

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References

Abril, A. and Bucher, E. H. 2001. Overgrazing and soil carbon dynamics in the western Chaco of Argentina. Applied Soil Ecology, Vol. (16): 243 - 249.

Ahmed, S. M. 2010. Impacts of climate change on rainfed agroculture in a semi arid zone - a case study from Sudan. In The global dimensions of changes in river basins. Threats linkages and adpatation., 14-22. Berlin: GWSP.

Anderegg, W. R. L. 2010. Expert credibility in climate change. Proceedings of the National Academy of Sciences, 107: 12107-12109.

Andrén, O. and Kättterer, T. 2001. Basic principles for soil carbon sequestration and calculating dynamic country-level balances including future scenarios. In Assessment methods for soil carbon(R. Lal, B. A. Stewart, J. M. Kimble, and R. F. Follet, eds.). 495-511 pp.: Lewish Publishers.

Anon. 2003a. Sudan's First National Communications under the United Nations Framework Convention on Climate Change Volume II: Appendix. Ministry of Environment & Physical Development Higher Council for Environment and Natural Resources Report, Khartoum, 236 pp.

Anon., 2003b. Sudan's First National Communications under the United Nations Framework Convention on Climate Change, Volume I: Main Communications. Ministry of Environment & Physical Development, Higher Council for Environment and Natural Resources Report, Khartoum, 111 pp.

Anon., 2013. Sudan's Second National Communication under the United Nations Framework Convention on Climate Change. Ministry of Environment,

Copyright © 2015 SAPDH
ISSN 1816-8272

Forestry & Physical Development, Higher Council for Environment and Natural Resources Report, Khartoum, 104 pp.

Ardö, J., Mölder, M., El-Tahir, B. and Elkhidir, H. 2008. Seasonal variation of carbon fluxes in a sparse savanna in semi arid Sudan. Carbon Balance and Management, 3: 7.

Ardö, J., ElKhidir, A, M., Khatir, A. and Cropley, F. 2015. Meteorological Measurements in Demokeya, North Kordofan: A Contribution to Climate Change Research. Sudan Academy of Sciences Journal-Special Issue (Climate Change) Vol. 11, 2015, 118-127.

Ardö, J. and Olsson, L. 2001. Soil Carbon Sequestration by Extended Fallow Periods in Semiarid Agro-ecosystems in Kordofan, Sudan? In Global Change Open Science Conference - Challenges of a Changing Earth. Amsterdam: IGBP.

Ardö, J. and Olsson, L. 2003. Assessment of soil organic carbon in semi-arid Sudan using GIS and the CENTURY model. Journal of Arid Environments, 54: 633-651.

Ardö, J. and Olsson, L. 2004. Soil carbon sequestration in traditional farming in Sudanese dry lands. Environmental Management, 33: S318 –S332.

Arneth, A., Harrison, S. P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P. J., Feichter, J., and Korhola. 2010. Terrestrial biogeochemical feedbacks in the climate system. Nature Geoscience, 3: 525-532.

Balgis, O.-E., N. Goutbi, E. Spanger-Siegfried, B. Dougherty, A. Hanafi, S. Zakieldeen, A. Sanjak, H. Atti, et al., 2006. Adaptation strategies to increase human resilience against climate variability and change: Lessons from the arid regions of Sudan. AIACC Working Paper Report 1-42 pp.

Barbier, E. B. 2000. The economic linkages between rural poverty and land degradation: some evidence from Africa. Agriculture Ecosystems & Environment, 82: 355-370.

Barkman, A. 1998. Critical loads - assessment of uncertainty. Ph. D Thesis, Lund University Lund, Sweden:

Bashir, M., 2001. Sudan country study on biodiversity. NBSAP Report, Khartom, 272 pp.

Batjes, N. H. 1999. Management options for reducing CO2-concentrations in the atmosphere by increasing carbon sequestration in the soil., International Soil Reference and Information Centre. Report 410-200-031, Wageningen, 114 pp.

Batjes, N. H. and Sombroek, W. G. 1997. Possibilities for carbon sequestration in tropical and subtropical soils. Global Change Biology, 3: 161-173.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. 2007. Africa In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. v. d. Linden, and C. E. Hanson, 433-467 pp. Cambridge UK: Cambridge University Press.

Burke, I. C., Yonker, C. M., Parton, W. J., Cole, C. V., Flach, K. and Schimel, D. S. 1989. Texture, climate, and cultivation effects on soil organic matter

Copyright © 2015 SAPDH

ISSN 1816-8272

context in U.S. grassland soils. Soil Science Society of America Journal, 53: 800-805.

Burke, M. B., Miguel, E., Satyanath, S., Dykema, J. A. and Lobell, D. B. 2009. Warming increases the risk of civil war in Africa. Proceedings of the National Academy of Sciences of the United States of America, 106: 20670-20674.

Buyanovsky, G. A. and Wagner, G. H. 1998. Carbon cycling in cultivated land and its global significance. Global Change Biology, 4: 131-141.

Craig, G. M. 1991. The Agriculture of the Sudan. In Centre for Agricultural Strategy Series, eds. C. R. W. Spedding, and L. J. Peel, 450. Oxford: Oxford University Press.

Dardel, C., Kergoat, L., Hiernaux, P., Mougin, E., Grippa, M. and Tucker, C. J. 2014. Re-greening Sahel: 30 years of remote sensing data and field observations (Mali, Niger). Remote Sensing of Environment, 140: 350-364.

Davies, H. R. J. 1985. Natural resources and rural development in arid lands: Case studies from Sudan. 94. Tokyo: United Nations University Press.

Deans, J. D., Diagne, O., Lindley, D. K., Dione, M. and Parkinson, J. A. 1999. Nutrient and organic-matter accumulation in Acacia senegal fallows over 18 years. Forest Ecology and Management, 124: 153-167.

DOE. 1999. Carbon Seqestration, State of the Science. U.S. Department of Energy Office of Science Office of Fossile Energy Report, Washington D.C., 150 pp.

Doran, P. T. and Zimmerman, M. K. 2009. Examining the Scientific Consensus on Climate Change. Eos Transactions American Geophysical Union, 90.

Dunlap, R. E. and McCright, A. M. 2011. Climate Change Denial: Sources, actors, and strategies. In Routledge Handbook of Climate Change and Society, ed. C. Lever-Tracy. Taylor & Francis.

El Tahir, B. A. 2006. Nutrien balances in traditional farming systems involving Acacia senegal (L.) Willd. in semi-arid sandy soils of northern Kordofan, Sudan. Ph. D Thesis, University of Khartoum, Khartoum, Sudan:

El Tahir, B. A., Fadl, K. E. M. and Fadlalmula, A. G. D. 2010. Forest biodiversity in Kordofan Region, Sudan: Effects of climate change, pests, disease and human activity. Biodiversity, 11: 34-44.

Ermert, V., Fink, A. H. and Paeth, H. 2013. The potential effects of climate change on malaria transmission in Africa using bias-corrected regionalised climate projections and a simple malaria seasonality model. Climatic Change, 120: 741-754.

Fadl, K. E. M. 2013. Influence of Acacia senegal agroforestry system on growth and yield of sorghum, sesame, roselle and gum in north Kordofan State, Sudan. Journal of Forestry Research, 24: 173-177.

Fadl, K. E. M. and El Sheikh, S. E. 2010. Effect of Acacia senegal on growth and yield of groundnut, sesame and roselle in an agroforestry system in North Kordofan state, Sudan. Agroforestry Systems, 78: 243-252.

FAO. 2001. Soil carbon sequestration for improved land management. Food and Agriculture Organization of the United Nations Report 96, Rome, 75 pp.

Farage, P. K., Ardö, J., Olsson, L., Rienzi, E. A., Ball, A. S.and. Pretty, J. N 2007. The potential for soil carbon sequestration in three tropical dryland farming

Copyright © 2015 SAPDH
ISSN 1816-8272

systems of Africa and Latin America: A modelling approach. Soil & Tillage Research, 94: 457-472.

Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. 582. Cambridge, UK and New York, NY, USA: Cambridge University Press.

Folberth, C., Gaiser, T., Abbaspour, K. C., Schulin, R. and Yang, H. 2012. Regionalization of a large-scale crop growth model for sub-Saharan Africa: Model setup, evaluation, and estimation of maize yields. Agriculture, Ecosystems & Environment, 151: 21-33.

Frihy, O. E. and El-Sayed, M. K. 2013. Vulnerability risk assessment and adaptation to climate change induced sea level rise along the Mediterranean coast of Egypt. Mitigation and Adaptation Strategies for Global Change, 18: 1215-1237.

Gerakis, P. A. and Tsangarakis, C. Z. 1970. The influence of Acacia sengal on the fertility of a sand sheet (GOZ) soil in the central Sudan. Plant and Soil, 33: 81-86.

Giannini, A., Biasutti, M., Held, I. M., and Sobel, A. H. 2008. A global perspective on African climate. Climatic Change, 90: 359-383.

Gregory, P. J., Johnson, S. N., Newton, A. C. and Ingram, J. S. I. 2009. Integrating pests and pathogens into the climate change/food security debate. Journal of Experimental Botany, 60: 2827-2838.

Haaland, G. 1991. Production systems in Western Sudan. In The Agriculture of the Sudan, ed. G. M. Craig, 230-251 pp. Oxford: Oxford University Press.

Hickler, T., Eklundh, L., Seaquist, J. W., Smith, B., Ardö, J., Olsson, L., Sykes, M. T. and Sjöström, M. 2005. Precipitation controls Sahel greening trend. Geophysical Research Letters, 32: L21415.

Hulme, M. 1992. The recent Sahel drought is real. International Journal of Climatology, 12: 685-699.

Hulme, M., Doherty, R., Ngara, T. and New, M. 2005. Global warming and African climate change. In Climate Change and Africa, ed. P. S. Low, 29-40 pp. Cambridge: Cambridge University Press.

Hulme, M., Doherty, R., Ngara, T., New, M. and Lister, D. 2001. African Climate Change: 1900-2100. Climate Research, 17.

Ingram, J. S. I. and Fernandes, E. C. M. 2001. Managing carbon sequestration in soils: concepts and terminology. Agriculture, Ecosystems and Environment, 87: 111-117.

IPCC. 2013a. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovern mental Panel on Climate Change. IPCC Report, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC. 2013b. Summary for Policymakers. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, V. B.

Copyright © 2015 SAPDH

Y. Xia, and P. M. Midgley, 27 pp. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

IPCC. 2014. IPCC Fourth Assessment Report: Climate Change 2007. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. Glossary A-D. Retrieved February 10 2014, from. http: // www.ipcc.ch /publications_and_data/ar4/wg2/en/ annexessglossary -a-d.html.

Jenkinson, D. S., Harris, H. C., Ryan, J., McNeill, A. M., Pilbeam, C. J. and Coleman, K. 1999. Organic matter turnover in a calcareous clay soil from Syria under a two-course cereal rotation. Soil Biology & Biochemistry, 31: 687-693.

Jewitt, T. N. and Manton, J. S. 1954. Soil exhaustion in the Goz sands of the Sudan. In Congres international de la science du sol, 413-416. Leopodville.

John, C., Dana, N., Sarah, A. G., Mark, R., Bärbel, W., Rob, P., Robert, W. and Peter, J. 2013. Quantifying the consensus on anthropogenic global warming in the scientific literature. Environmental Research Letters, 8: 024024.

Khogali, M. M. 1991. Famine, Desertification and Vulnerable Populations: the Case of Umm Ruwaba District, Kordofan Region, Sudan. AMBIO, 20: 204-206.

Krogh, L. 1997. Field and village nutrient balances in millet cultivation in northern Burkina Faso: a village case study. Journal of Arid Environments, 35: 147-159.

Lai, L. M., Li, Y. F., Tian, Y., Jiang, L. H., Zhao, X. C., Zhu, L. H., Chen, X. and Gao, Y. 2013. Effects of Added Organic Matter and Water on Soil Carbon Sequestration in an Arid Region. Plos One, 8.

Lal, R. 2001a. Desertification control to sequester carbon and reduce net emissions in the United States. Arid Lands Newsletter, 49.

Lal, R. 2001b. Potential of Desertification Control to Sequester Carbon and Mitigate the Greenhouse Effect. Climatic Change, 51: 35-72.

Lal, R., Hassan, H. M., and Dumanski, J. 1999. Desertification control to sequester C and mitigate the greenhouse effect. In St. Michaels workshop on carbon sequestration and desertification, Pacific Northwest National Lab., eds. N. J. Rosenberg, R. C. Izaurralde, and E. L. Malone, 83-149. St. Michaels: Batelle Press.

Lal, R., Kimble, J. , Follet, R. F. and Stewart, B. A. 1998. Management of Carbon Sequestration in Soil. Boca Raton, FA, USA: CRC.

Le Houérou, H. N. 1995. Climate change, drought and desertification. Journal of Arid Environments, 33: 133-185.

Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S. and Smith, B. 2013. Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa. Earth System Dynamics, 4: 385-407.

Liu, C., Lu, M., Cui, J., Li, B. and Fang, C. 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Global Change Biology.

Copyright © 2015 SAPDH
ISSN 1816-8272

Liu, J. G., Folberth, C., Yang, H., Rockstrom, J., Abbaspour, K. and Zehnder, A. J. B. 2013. A Global and Spatially Explicit Assessment of Climate Change Impacts on Crop Production and Consumptive Water Use. Plos One, 8.

Loum, M., Viaud, V., Fouad, Y., Nicolas, H. and Walter, C. 2014. Retrospective and prospective dynamics of soil carbon sequestration in Sahelian agrosystems in Senegal. Journal of Arid Environments, 100: 100-105.

Luedeling, E., Sileshi, G., Beedy, T. and Dietz, J. 2011. Carbon Sequestration Potential of Agroforestry Systems in Africa. In Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges, eds. B. M. Kumar, and P. K. R. Nai, 61-83 pp. Dordrecht: Springer Science.

Merbold, L., Ardö, J., Arneth, A., Scholes, R. J., Nouvellon, Y., de Grandcourt, A., Archibald, S. and Bonnefond, J. M. 2009. Precipitation as driver of carbon fluxes in 11 African ecosystems. Biogeosciences, 6: 1027-1041.

Metherell, A. K., Harding, L. A., Cole, C. V. and Parton, W. J. 1993. CENTURY Soil Organic Matter Model Environment, Technical Documentation, Agroecosystem Version 4.0. United States Department of Agriculture, Agricultiral Research Service, Great Plains System Research Unit Report Technical Report No. 4250 pp.

Monson, R. K. and D. D. Baldocchi. 2014. Terrestrial biosphere-atmosphere fluxes. Cambridge: Cambridge University Press.

NASA. 2014. Consensus. Retrieved February 10 2014, from. http://climate.nasa.gov/scientific-consensus.

Nations, U. 2014. UN-REDD programme. Retrieved February 24 2014, from. http://www.un-redd.org/ Home/ tabid/565/ Default.aspx.

New, M., Hewitson, B., Stephenson, D. B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B. and Coelho, C. A. S. 2006. Evidence of trends in daily climate extremes over southern and west Africa. Journal of Geophysical Research: Atmospheres, 111: D14102.

NREL. 2014. CENTURY 4. Retrieved February 26 2014, from. http://www.nrel.colostate.edu/projects/century/

Olsson, K. and Rapp, A. 1991. Dryland degradation in central Sudan and conservation for survival. AMBIO, 20: 192-195.

Olsson, L. 1985. An integrated study of desertification. Ph. D Thesis. Lund: Lund University.

Olsson, L. 1993. On the causes of famine - drought, desertification and market failure in the Sudan. AMBIO, 22: 395-403.

Olsson, L. and Ardö, J. 2002. Soil carbon sequestration in degraded semiarid agro-ecosystems - perils and potentials. AMBIO, 31: 471-477.

Olsson, L., Eklundh, L. and Ardö, J. 2005. A recent greening of the Sahel - Trends, patterns and potential causes. Journal of Arid Environments, 63: 556-566.

Ontl, T. A. and Schulte, L. A. 2012. Soil Carbon Storage. Nature Education Knowledge, 3.

Oreskes, N. 2004. Beyond the Ivory Tower: The Scientific Consensus on Climate Change. Science, 306: 1686.

Copyright © 2015 SAPDH

ISSN 1816-8272

Osman Elasha, B., Niang-Diop, M. M. I., Nyong, T., Tabo, R. and Vogel, C. 2006. Background paper on Impacts, vulnerability and adaptation to climate change in Africa for the African Workshop on Adaptation Implementation of Decision 1/CP.10 of the UNFCCC Convention, Accra, Ghana, 21 – 23 September. UNFCCC Report, Accra, Ghana, 54 pp.

Parton, W. J., Coughenour, M. B., Scurlock, J. M. O., Ojima, D. S., Gilmanov, T. G., Scholes, R. J., Schimel, D. S. and Kirchner, T. B. 1996. Global Grassland Ecosystem Modelling: Development and Test of Ecosystem Models for Grassland Systems. In Global Change: Effects on Coniferous Forests and Grasslands, eds. A. I. Breymeyer, D. O. Hall, J. M. Mellilio, and G. I. Ågren, 229-279 pp. New York: John Wiley & Sons.

Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S. 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. Soil Science Society of America Journal, 51: 1173-1179.

Parton, W. J., Stewart, J. W. B. and Cole, C. V. 1988. Dynamics of C, N, P and S in grasslands soils: a model. Biogeochemistry, 5: 109-131.

Petersen, R. G. 1994. Agricultural Field experiments: design and analysis.New York: Marcel Dekker Inc.

Pieri, C. J. M. G. 1992. Fertility of Soils: A future for farming in the West African Savannah. 348. Berlin: Springer-Verlag.

Ponce-Hernandez, R., Koohafkan, P. and Antoine, J. 2004. Assessing carbon stocks and modelling win–win scenarios of carbon sequestration throughland-use changes. FAO Report, Rome, 156 pp.

Poussart, J. N., Ardö, J. and Olsson, L. 2003. Effects of Data Uncertainties on Soil Organic Carbon in the Sahel Simulated with the CENTURY Model. Environmental Management, in press.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, P. and Buchmann, N. 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology, 11: 1424-1439.

Richardson, A. D., Aubinet, M., Barr, A. G., Hollinger, D. Y., Ibrom, A., Lasslop, G. and Reichstein, M. 2012. Uncertainty quantification. In Eddy covariance: A practical guide to measurement and data analysis, eds. M. Aubinet, T. Vesala, and D. Papale, 173–209 pp. Netherlands: Springer.

Ringius, L., 1999. Soil carbon sequestration and the CDM. Opportunities and challanges for Africa. Center for International Climate and Environmental Research Report 1999:7, Oslo, 33 pp.

Sanchez, P. A. 1999. Improved fallows come of age in the tropics. Agroforestry Systems, 47: 3-12.

Sanchez, P. A. 2002. Soil fertility and hunger in Africa. Science, 295: 2019-2020.

Sanchez, P. A. 2010. Tripling crop yields in tropical africa. Nature Geoscience, 3: 299-300.

Santer, B. D., Bonfils, C., Painter, J. F., Zelinka, M. D., Mears, C., Solomon, S., Schmidt, G. A. and Fyfe, J. C. 2014. Volcanic contribution to decadal changes in tropospheric temperature. Nature Geoscience, 7: 185-189.

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ISSN 1816-8272

Schimel, D. S. 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biology, 1: 77-91.

Schlesinger, W. H. 2000. Carbon sequestration in soils: some cautions amidst optimism. Agriculture, Ecosystems & Environment, 82: 121-127.

Schlesinger, W. H. and Andrews, J. A. 2000. Soil respiration and the global carbon cycle. Biogeochemistry, 48: 7-20.

Schlosser, C. A., Strzepek, K., Gao, X., Gueneau, A., Fant, C., Paltsev, S., Rasheed, B. and Smith-Greico, T. 2014. The Future of Global Water Stress: An Integrated Assessment. Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology Report, Cambridge, MA, USA., 31 pp.

Schneising, O., Reuter, M., Buchwitz, M., Heymann, J., Bovensmann, H. and Burrows. J. P. 2014. Terrestrial carbon sink observed from space: variation of growth rates and seasonal cycle amplitudes in response to interannual surface temperature variability. Atmospheric Chemistry and Physics, 14: 133-141.

Scholes, M. C., Powlson, D. S. and Guanglong, T. 1997. Input control of organic matter dynamics. Geoderma, 79: 25-47.

Sherwood, S. and Fu, Q. 2014. A Drier Future? Science, 343: 737-739.

Sjöström, M., Zhao, M., Archibald, S., Arneth, A., Cappelaere, B., Falk, U., de Grandcourt, A. and Hanan, N. 2013. Evaluation of MODIS gross primary productivity for Africa using eddy covariance data. Remote Sensing of Environment, 131: 275-286.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L. 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Report, Cambridge, United Kingdom and New York, NY, USA.

Sombroek, W. G., Nachtergaele, F. O. and Hebel, A. 1993. Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. AMBIO, 22: 417-426.

Squires, V. R. 1998. Dryland soils: their potential as a sink for carbon and as an agent to mitigate climate change. Advances in GeoEcology, 31: 209-215.

Sulieman, H. M. and Elagib, N. A. 2012. Implications of climate, land-use and land-cover changes for pastoralism in eastern Sudan. Journal of Arid Environments, 85: 132-141.

Sulieman, H. M. and Siddig, K. H. A. 2014. Climate Change and Rangeland Degradation in Eastern Sudan: Which Adaptation Strategy Works Well? In Nile river basin. Ecohydrological cghallanges, climate change and hydropolitics, eds. A. M. Melesse, W. Abtew, and S. G. Setegn. Heidelberg: Springer.

Tollefson, J. 2014. The case of the missing heat. Nature, 505: 276–278.

Toulmin, C. 2009. Climate change in Africa.London, New York: Zed Books.

UNEP. 1992. World Atlas of Desertification.Nairobi, Kenya.

UNFCCC. 2014. United Nations Framework Convention on Climate Change. Retrieved 10 February 2014, from.http://unfccc.int/essential_ background /convention/background/items/2536.php.

Copyright © 2015 SAPDH
ISSN 1816-8272

Usman, M. T. and Reason, C. J. C. 2004. Dry spell frequencies and their variability over southern Africa. Climate Research, 26: 199-211.

Warren, A. 1970. Dune trends and their implications in the central Sudan. Zeitshrift fur Geomorphologie, Supplementband 10: 154-180.

Warren, A., Sud, Y. C. and Rozanov, B. 1996. The future of deserts. Journal of Arid Environments, 32: 75-89.

Weber, U., Jung, M., Reichstein, M., Beer, C., Braakhekke, M. C., Lehsten, V., Ghent, D. Kaduk, J. 2009. The interannual variability of Africa's ecosystem productivity: a multi-model analysis. Biogeosciences, 6: 285-295.

Wezel, A. and Böcker, R. 1999. Mulching with branches of an indigenous shrub (Guiera senegalensis) and yield of millet in semi-arid Niger. Soil and Tillage Research, 50: 341-344.

Wezel, A. and Haigis, J. 2002. Fallow cultivation system and farmers' resource management in Niger, West Africa. Land Degradation & Development, 13: 221-231.

Wikipedia. 2014. Climate change denial. Retrieved March 24 2014, from. http:// en.wikipedia.org /wiki/ Climate_ change _denial.

Xia, J., Chen, J., Piao, S., Ciais, P., Luo, Y. and Wan, S. 2014. Terrestrial carbon cycle affected by non-uniform climate warming. Nature Geoscience, 7: 173-180.

Zarocostas, J. 2011. Famine and disease threaten millions in drought hit Horn of Africa. British Medical Journal, 343.

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