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**Syed Ashrafal ALAM**

**Carbon stocks, greenhouse gas emissions and water balance  
of Sudanese savannah woodlands in relation to climate change**

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# TROPICAL FORESTRY REPORTS

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# **Carbon stocks, greenhouse gas emissions and water balance of Sudanese savannah woodlands in relation to climate change**

**Syed Ashraful ALAM**

*Academic dissertation  
for the degree of Doctor of Science (DSc) in Agriculture and Forestry*

Department of Forest Sciences  
Faculty of Agriculture and Forestry  
University of Helsinki

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public discussion in Walter Hall, Viikki EE-Building, Agnes Sjöbergin katu 2, Helsinki on 22 February 2013, at 12 o'clock noon.

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## ABSTRACT

Understanding the carbon (C) sequestration potential of drylands requires knowledge of the stocks of C in soils and biomass and on the factors affecting them. The overall aim of the study was to determine and evaluate the variation in the C stocks and water balance of *Acacia* savannah woodlands across the dryland (arid and semi-arid) region (10–16 °N; 21–36 °E) of the former Sudan (now mainly in the Republic of the Sudan) and how they are related to climatic factors and may be affected by climate change. The role played by small but numerous brick making industries on woodland deforestation in the region and greenhouse gas production was also investigated. The study region is often referred to as the *gum belt* because it is the world's major source of gum Arabic, which is harvested from *Acacia* trees. The soils in the centre and west of the region are mainly Arenosols (sandy soils) and those in the eastern part are mainly Vertisols (clay soils). The soils are C poor and often in a degraded state.

This dissertation consists of a summary section and four articles (*Study I, II, III and IV*). *Study I* focuses on fuelwood consumption by the brick making industries (BMIs) and associated deforestation and greenhouse gas (GHG) emissions. In *Study II* the C densities ( $\text{g C m}^{-2}$ ) of the woodland tree biomass and soil (1 m) for 39 map sheets covering the study region were determined from national forest inventory data and global soil databases and the dependence on mean annual precipitation (MAP) and mean annual temperature (MAT) determined. The water balance of savannah woodlands for the same 39 map sheets was modelled in *Study III* and the variation in water balance components across the region evaluated. The potential impacts of climate change on woodland biomass C density and water-use (actual evapotranspiration, AET) was analysed for eight of the map sheets in *Study IV*.

Sudanese BMIs consume a considerable amount of fuelwood that mainly comes from unsustainably managed woodland and contributes to deforestation and GHG emissions (*Study I*). While GHG emissions from BMIs only account for a small part of Sudan's total GHG emissions, the associated deforestation and land degradation is of concern. Implementation of better regulation, use of biomass fuel from sustainable sources and technological improvement in BMIs kilns will reduce deforestation and GHG emissions.

Savannah woodland C densities, both biomass and soil, were low and clearly below potential C sequestration capacity (*Study II*). The loss of trees across the region was indicated by very low biomass C density values in comparison to modelled NPP (net primary production) values. The estimated SOC densities although low, were higher than reported in some recent soil C studies from the region. This was attributed to the use of old data in the global soil database and indicates the degree of land degradation and loss of SOC that has taken place over the last few decades. However, in spite of woodland and soil degradation, biomass C and SOC densities remained positively and significantly correlated with each other and both were significantly correlated to MAP. The results highlighted the need for improved land-use management and stewardship, which should involve increasing the cover of trees, and the need for up-to-date regional and integrated soils and forest (woodland) inventories to be made.

Water-use (AET) of savannah woodlands is strongly limited by rainfall. Rainfall exceeded AET only during some of the wet season months resulting in a small increase in soil moisture storage and production of surface runoff for some areas (*Study III*). Drainage (to groundwater) was negligible. Since AET was strongly limited by MAP, AET for both Arenosol and Vertisol

soil types increased southwards across the study region. Runoff also increased southwards across the study region for both soil types but were highest in south western and eastern areas. The restoration of woodlands may be expected to improve the soil-water conditions.

Compared to baseline (1961-1990) climate values, General Circulation Model (GCM) based results for 2080s indicated that MAT would increase across the study region but that MAP would either increase or decrease depending on climate change scenario (*Study IV*). Biomass C densities will be significantly affected by climate change. However, the impact varies with climate change scenario, with either increases or decreases in biomass C density being indicated for the same area. In general, water-use on Arenosols will increase while that on Vertisols will decrease. The largest relative changes in AET were associated with the areas receiving the lowest rainfall. Thus, even if MAP increases, the increase will have little impact on biomass levels in the driest areas of the region.

**Keywords:** Climate change, Carbon density, Carbon stock, Deforestation, Dryland, Fuelwood, General Circulation Model, Greenhouse gas emission, Savannah woodland, Sudanese gum belt, Water balance, Water-use.

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## PREFACE

Dryland areas, especially savannah woodlands of Sudan, have not been studied intensively and there is a huge gap between developed and developing countries in climatological research. Current research would not only facilitate the know-how transfer to the tropical drylands but also help to develop expertise on the mitigation aspect of climate change research. The author of this study came from the south (Bangladesh) and using the excellent research facilities in the north (Finland), the author attempted to transfer the know-how on climatological research to another country in the south (Sudan). However, the study was mainly funded by the Doctoral Programme in Forest Sciences (GSForest, former Graduate School in Forest Sciences), the Research Foundation of the University of Helsinki, and the Finnish Cultural Foundation. The study, at later stage, also received financial support from the CASFAD (Carbon sequestration and Soil Fertility on African Drylands) project financed by the Academy of Finland, The Centre of Excellence in Physics, Chemistry, Biology and Meteorology of Atmospheric Composition and Climate Change WP4 and the Finnish Society of Forest Science.

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Syed Ashraful Alam  
February 2013, Helsinki



## LIST OF ORIGINAL ARTICLES

This doctoral dissertation consists of a summary and the four following articles, which are referred to by roman numerals I-IV. Articles (I, II and IV) are reprinted with the kind permission of the publishers, and the article III is the author version of the submitted manuscript.

- I. Alam, S.A. & Starr, M. 2009. Deforestation and greenhouse gas emissions associated with fuelwood consumption of the brick making industry in Sudan. *Science of the Total Environment* 407: 847-852. DOI:10.1016/j.scitotenv.2008.09.040.
- II. Alam, S.A., Starr, M. & Clark, B.J.F. 2013. Tree biomass and soil organic carbon densities across the Sudanese woodland savannah: a regional carbon sequestration study. *Journal of Arid Environments* 89: 67-76. DOI:10.1016/j.jaridenv.2012.10.002.
- III. Starr, M. & Alam, S.A. 2013. Water balance of savannah woodlands: a modelling study of the Sudanese *Acacia* gum belt region (Submitted).
- IV. Alam, S.A. & Starr, M. 2012. Impacts of climate change on savannah woodland biomass carbon density and water-use: a modelling study of the Sudanese gum belt region. *Mitigation and Adaptation Strategies for Global Change*. DOI:10.1007/s11027-012-9403-5.

## AUTHOR'S CONTRIBUTION

- I. Syed A. Alam planned the study, carried out the field work, analysed the dataset and wrote the first version of the manuscript. Mike Starr modified the methodologies, commented and helped to finalize the manuscript.
- II. Syed A. Alam and Mike Starr jointly planned the study but original idea came from Mike Starr. Syed A. Alam retrieved the datasets with the help of Barnaby J. F. Clark, especially the soil dataset. Syed A. Alam and Mike Starr together analysed data and results. Syed A. Alam produced all results and wrote the first version of manuscript in consultation with Mike Starr. Barnaby J.F. Clark commented on the first version of the manuscript. Mike Starr commented, revised and helped to finalize the manuscript.
- III. Mike Starr introduced the research plan for the study. Syed A. Alam retrieved all the datasets and made the model runs with the help of Mike Starr. Syed A. Alam and Mike Starr together analysed data and results. Syed A. Alam produced all model results and wrote the first version of manuscript in consultation with Mike Starr. Mike Starr commented, revised and finalized the manuscript.
- IV. Syed A. Alam and Mike Starr jointly planned the study but original idea came from Mike Starr. Syed A. Alam retrieved all the datasets, made the model run and analysed the datasets with the help of Mike Starr. Syed A. Alam produced all results and wrote the first version of manuscript in consultation with Mike Starr. Mike Starr commented, revised and updated the manuscript.

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# 1. Introduction

## 1.1 Drylands and savannah woodlands

Drylands cover arid, semi-arid and dry sub-humid climatic zones where the ratio of mean annual precipitation (MAP) to mean annual potential evapotranspiration (PET) ranges from 0.05 to 0.65, and are characterized by scarcity of water, low and erratic rainfall and often with high temperatures (UNEP 1992, Lal 2002, FAO 2004). The vegetation of drylands forms a continuum, from barren or sparsely vegetated desert to grasslands through shrublands to woodland savannahs, the productivity and distribution of which are largely related to rainfall (Halwagy 1961, FAO 2004). At least 40% of the global land area (ca. 54 million km<sup>2</sup>) are classified as drylands and are inhabited by more than two billion people (UNEP 1992, FAO 2004). About 29.7% of this area falls in the arid region, 44.3% in the semi-arid region and 26% in the dry sub-humid region (Sivakumar 2007). Drylands occur on all continents (between 63 °N and 55 °S) but Australia is described as the driest continent with 75% covered by drylands, followed by Africa (66%) and Asia (46%) (Kadomura 1997, Safriel et al. 2005). In the Sudan<sup>1</sup>, drylands cover an estimated area of 1.7 million km<sup>2</sup> equivalent to 67% of the total land area, forming a zone across much of north Sudan (MEPD/HCENR 2003, White and Nackoney 2003, UNEP 2007).

The word *savanna(h)* has been known in English since 1555 and has been derived from the sixteenth century Spanish word *zavana* or *sabana*, which applied to *a treeless plain or the land without trees, but with much grass, short and tall* (Bourlière and Hadley 1992). Though there is no commonly agreed definition of the word savannah, African botanists defined savannah as *'formation of grasses at least 80 cm high, which form a continuous layer with dominating a lower stratum and usually burnt annually; woody plants are usually present and leaves of grasses are flat, basal and cauline'* (CSA 1956). Within this physiognomic category, savannah woodlands are recognized with trees and shrubs forming a light canopy where trees occur throughout, but the stocking density and cover are low (CSA 1956, Bourlière and Hadley 1992), and generally do not meet the criteria to be defined as forest (FAO 2010a, DAFE 2011). Savannahs occupy one-fifth of the earth's land surface and support a large proportion of the world's human population and most of its rangeland, livestock and wild herbivore biomass (Scholes and Archer 1997, Sankaran et al. 2005). Tropical savannahs and savannah woodlands cover large areas of the southern continents (65% of Africa, 60% of Australia and 45% of South America), and contain almost one-fifth of the world's population (Huntley and Walker 1982). In the Sudan, woodland savannah follows south of the semi-desert, which is south of 14 °N latitude, to cover rest of the country except small portions of the equatorial zone (FAO 2006). According to annual rainfall, Sudanese woodland savannah is divided into low rainfall woodland savannah (covering 27.6% of the country area, rainfall 200-800 mm) and high rainfall woodland savannah (covering 13.8% of the country area, rainfall 800-1400 mm) (Griffith 1961, Gorashi 2001, MEPD/HCENR 2003, FAO 2006, UNEP 2007). In low rainfall woodland savannah, the vegetation is composed of mixed grass types with bushes and trees while that of in high rainfall woodland savannah is composed of gigantic broadleaved timber trees with tall grasses (FAO 2006, UNEP 2007).

Tropical savannahs can be remarkably productive, with a net primary productivity of 1-12 t C ha<sup>-1</sup> yr<sup>-1</sup> where the lower values came from arid and semi-arid savannah regions of Africa.

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<sup>1</sup> Throughout the study, the Sudan (former) includes both the Republic of the Sudan and the Republic of South Sudan

The carbon (C) sequestration rate (net ecosystem productivity) in this region averages  $0.14 \text{ t C ha}^{-1} \text{ yr}^{-1}$  (Grace et al. 2006). The productivity of savannahs is, however, attributed to water and nutrient availability, rainfall distribution, prolonged dry season, soil texture and, disturbance regimes (e.g. fire and herbivory) (Frost et al. 1986, Sankaran et al. 2005 & 2008, Grace et al. 2006). In arid and semi-arid savannahs within the rainfall range of 150-650 mm, Sankaran et al. (2005) found that woody cover increases linearly with MAP but shows no relationship with soil nutrients, fire frequency and herbivory. Whereas Frost et al. (1986), Higgins et al. (2000), Bond et al. (2005) and Sankaran et al. (2008) clearly depicted that these latter variables are also dominant drivers for reducing woody cover in the savannahs.

Savannah woodlands are globally important ecosystems of great significance to human economies (Bourlière and Hadley 1992, Sankaran et al. 2005). The millennium ecosystem assessment recognized ecosystem services into supporting (soil formation and conservation, nutrient cycling and primary production), regulating (water and climate regulation and pollination and seed dispersal), provisioning (food and fibre, fuelwood, freshwater and biochemicals) and cultural (spiritual, aesthetic and inspirational) services (Safriel et al. 2005). In Africa, ecosystem services that come from dry forests and woodlands include biodiversity conservation, regulation of fresh water and river flows, desertification control and soil amelioration, and stabilization of climate through C sequestration (Pagiola et al. 2002, Nair and Tieguhong 2004, Wunder 2007, Marunda and Bouda 2010). Among other provisioning ecosystem services, most woodfuel (the collective term for fuelwood, charcoal and other wood derived fuels) is provided by trees or bushes inhabiting natural dryland ecosystems (Safriel et al. 2005). Africa is the most intensive user of fuelwood with an average annual per-capita consumption of  $0.89 \text{ m}^3$  and the fuelwood is used predominantly at the household level for cooking and heating (Amous 1999). Nevertheless, the Sudan has lower per-capita annual fuelwood consumption ( $0.68 \text{ m}^3$ ) than African average (UNEP 2007).

Some 10-20% of drylands are already degraded (UNEP 1992, UNDP/UNSO 1997, Dregne 2002, MEA 2005, Niemeijer et al. 2005). Based on these rough estimates, about 1-6% of the dryland people live in desertified areas, while a much larger number is under threat from further desertification (MEA 2005). Land degradation, in drylands, is usually termed as 'desertification' and considered as an indication of a persistent decline in the ability of an ecosystem to provide goods and services associated with primary production (Safriel et al. 2005). UNEP (1990) and UNCCD (2004) defined desertification as the land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climate change and adverse human activities. Desertification is characterised by the (i) reduction or loss of biological or economic productivity and complexity of cropland, range, pasture, forest, and woodlands, (ii) loss of vegetation cover and soil organic matter (SOM), (iii) reduction in soil fertility and structure, (iv) loss of soil resilience and natural regeneration, and (v) reduction in infiltration capacity and water storage of soil, and lowering the water table (Dregne 2002, FAO 2004, UNCCD 2004, Sivakumar 2007). Annual rate of desertification is about  $5.8 \text{ thousand km}^2$  (Lal 2001) and estimates of the extent of desertification vary widely, ranging from 11.4 to 32.5 million  $\text{km}^2$  (Dregne 1983, Oldeman and van Lynden 1998). However, the consequences of desertification include undermining of food production, famines, increased social costs, decline in the quantity and quality of fresh water supplies, increased poverty and political instability, and decreased soil productivity (UNCCD 2004).

Countries of the Sahel region, such as Sudan, have been particularly affected by degradation (Ayoub 1998 & 1999). Most of the Sudanese dryland area, including that of savannah woodlands, is classified as moderate to very severely degraded (FAO/AGL 2005), and 81% of

Sudan's degraded soils (64 million ha) being in drylands (Ayoub 1998). This level of land degradation has major implications for the livelihood and well-being of people living in the region (Mustafa 1997, Ayoub 1999, Ringius et al. 2002, Raddad et al. 2006). The most degraded regions were the arid and semi-arid regions where 76% (ca. 21 million) of the Sudan's population used to live (Ayoub 1998). The same study also reported that the overgrazing, improper agricultural practices, cutting of trees for firewood and charcoal production and over exploitation of vegetation for domestic use were to be the main causes of the degradation. Therefore, land-use practices, including protection and planting of trees and reintroduction of traditional agroforestry systems with lengthened fallow-period, that increase litterfall production and supply of organic matter to the soil can be expected to increase SOM contents and so improve the soil fertility of degraded drylands (Ardö and Olsson 2004, Vågen et al. 2005, El Tahir et al. 2009).

## 1.2 C pools, emissions and sequestration in drylands

Removal of atmospheric C and storing it in the terrestrial biosphere is one of the main options that have been proposed to compensate for greenhouse gas (GHG) emissions. The Kyoto Protocol recognized that some terrestrial ecosystems have the potential to sequester large amounts of C and thus further slow down the increase of atmospheric CO<sub>2</sub> concentrations (Ardö and Olsson 2004).

Total (biomass and soil) C storage in drylands has been estimated to be about 743 Gt, which is more than one third of the global total terrestrial C stock, 2053 Gt (Trumper et al. 2008). Using the global dryland area of 6.15 billion ha (Lal 2004), it can be estimated that the C density of dryland ecosystems averages about 121 t ha<sup>-1</sup> (12 081 g m<sup>-2</sup>). However, savannahs account for approximately 58.7 Gt of biomass, approximately 30% of the global C store of terrestrial ecosystem (Chen et al. 2003). Above-ground biomass C stocks of world-wide savannahs vary widely from 1.8 t ha<sup>-1</sup> where trees are absent to 30 t ha<sup>-1</sup> where there is substantial tree cover. The soil organic carbon (SOC) pool of the savannah biome has been estimated at 200-300 Gt C, which is equivalent to 10-30% of the world's SOC pool (Grace et al. 2006). Grace et al. (2006) also estimated that the total C pool (vegetation plus SOC) of tropical savannah and grasslands is 326 Gt C, which is about 15% of total C pool (2137 Gt C) of all types of biome. Jobbágy and Jackson (2000) reported soil C densities (0-1 m) for the tropical grassland/savannah biome of 13.2 kg m<sup>-2</sup> (13 200 g m<sup>-2</sup>).

Globally, C emissions from dryland ecosystems contribute 0.23-0.29 Gt C yr<sup>-1</sup> to the atmosphere as a result of desertification and related soil erosion and vegetation destruction, which is about 4% of global emissions from all sources combined (Lal 2001, MEA 2005). Land use change and degradation are important sources of GHGs and are responsible for about 20% global emissions (IPCC 2007a). Africa plays a global role in C emissions through land use and fire, and during the period of 2000-2005, emission from land use change contributed 48% (0.24 Gt C yr<sup>-1</sup>) of its total (0.5 Gt C yr<sup>-1</sup>) anthropogenic C emissions (Houghton 2003, Williams et al. 2007, Canadell et al. 2009). Within the emission from land use change, 89% emissions came from deforestation for agriculture (permanent croplands and shifting cultivation) and 11% from industrial wood harvesting. DeFries et al. (2002) reported that due to tropical deforestation, Africa contributed 0.6 Gt C yr<sup>-1</sup> in 1980s and 0.9 Gt C yr<sup>-1</sup> in 1990s to the atmosphere and these C losses through deforestation tend to be permanent as current afforestation and reforestation rates are less than 5% of annual deforestation.

Forest cover in Sudan in the late 1950s was estimated at between 36% and 43%, and by 1990, forest cover had shrunk to 19% (MEPD/HCENR 2003). This loss in forest cover has been mainly due to the expansion of agriculture, fuelwood harvesting and grazing, and there is little sustainable forest management. The last forest inventory, published in 1995, estimated the annual forest harvest (allowable cut) at 11 million m<sup>3</sup>. Biomass is the main source of energy production in Sudan. In 1995, 79% of Sudan's total energy supply came from biomass (MEPD/HCENR 2003). Wood fuel provides about 69% of the total energy consumption in traditional industries, including brick making, bakeries and oil mills. The industrial sector of Sudan only consumes 6.8% of its total wood consumption, of which 51.5% (ca. 183 000 t of fuelwood) goes to the rural brick making industry (BMI) for brick production (FNC/FAO 1995, BENS 1996).

Most of the Sudanese BMIs are of the intermittent scove type, having low combustion efficiencies, and use fuelwood that mainly comes from unsustainably managed forests (Hamid 1994, BENS 1996). WB (1998) reported that biomass burning is responsible for the emission of trace and non-trace greenhouse gases, such as CO<sub>2</sub>, CH<sub>4</sub>, CO, N<sub>2</sub>O, NO<sub>x</sub> and NO. Therefore, the BMIs in Sudan can be expected to be both a significant cause of deforestation and source of GHG emissions. Sudan's national inventory indicated that the total GHG emission for 1995 was 0.026 Gt, in which CO<sub>2</sub> alone contributed about 75% (0.020 Gt) of the total emission (MEPD/HCENR 2003). Land use change and forestry, where biomass is accounted for, was found to be the main emitter of CO<sub>2</sub> and contributed more than 75% (0.016 Gt) of the total CO<sub>2</sub> emission. While the overall GHG emissions from fuelwood burning in Sudan and other African countries have been documented (Amous 1999, MEPD/HCENR 2003) and the biomass energy production in Sudan reviewed (Omer 2005), the contribution of the BMIs to deforestation and GHG emissions has not specifically been addressed.

Although drylands have climatic constraints, their C sequestration potential has been estimated to be huge. This is not only due to the extent of drylands but also because they are under stocked with trees and soil is far from C saturation (Glenn et al. 1993, Squires 1998, FAO 2004, Lal 2004 & 2009). Attainable sink of C in drylands would be 1.0-1.9 Gt yr<sup>-1</sup> over the next 25-50 yrs (Squires 1998), and that of tropical savannah and grasslands would be 0.39 Gt yr<sup>-1</sup> (Grace et al. 2006). Batjes (1996) estimated that 0.6-2.0 Gt C yr<sup>-1</sup> could be sequestered in the world's degraded lands by the large-scale application of appropriate land management which accounts for 18-60% of the annual increase of CO<sub>2</sub> in the atmosphere. Sequestering C in dryland soils would be a 'win-win situation' by offering benefits of improved food security and agricultural sustainability at the national scale, and enhanced biodiversity, increased C offsets and climate change mitigation at the global level (FAO 2004).

However, there is a general lack of data and measurement on the C cycle and C sequestration of savannah and dry tropical forest (Tiessen et al. 1998), particularly at the regional scale. In the Sudan, C sequestration studies have been confined to a few sites in North Kordofan (Jakubaschk 2002, Olsson and Ardö 2002, Ardö and Olsson 2003 & 2004, Poussart et al. 2004). Using empirical data and modelling, these studies indicated that a considerable loss in SOC has already been taken place in the Sudan, particularly since the 1960s, and this decline is related to changes in cultivation practice (replacement of traditional *Acacia* tree-based agroforestry systems with continuous cultivation, shortening of fallow-period, and removal of trees).



### 1.3 Water balance and water-use of drylands

In arid and semi-arid regions (drylands), soil water availability is the main factor limiting plant growth, productivity and distribution (Zahner 1968, Fischer and Turner 1978, Webb et al. 1978, Stephenson 1990) and is strongly related to the amount of rainfall and evapotranspiration. Zahner (1968) reported that about 90% of the diameter growth in woody plants in dry regions is attributed to water availability. The availability of water in drylands is determined by both the amount of rainfall and evapotranspiration (Cooper et al. 1983, Wallace 1991). Rainfall in dryland regions is not only low but shows distinct seasonality and high spatial and temporal variation. In contrast to rainfall, PET is conservative, showing little interannual variation. PET in arid and semi-arid regions, by definition, is greater than rainfall and therefore dryland regions are subject to a state of permanent evapotranspiration deficiency, a state to which plants have adopted various strategies to allow them to cope (Fischer and Turner, 1978). However, the amount of actual evapotranspiration (AET) – or water-use – that takes place and determining plant productivity is variable as it depends on rainfall, soil water storage capacity, and vegetation cover. The relationship between plant productivity and water-use is critical to understand how dryland ecosystems function and how they may respond to climate change (Loik et al. 2004, Emmerich 2007). AET is an important term of the water balance (Droogers 2000) and in water limited environments, understanding of water-use is essential for evaluating the potential of new crops (Johnson and Henderson 2002).

Water quantity is a prime attribute of the water services provided by ecosystems and is best described by using a water balance. The water balance, in which rainfall is balanced against evapotranspiration, runoff, drainage and changes in soil water storage, is a useful way to assess and evaluate how water is used in relation to soil type and vegetation. While much is known about the water balance of forest ecosystems in humid environments, less is known about those in dryland regions. Furthermore, input data (meteorological, site, soil and vegetation) and data for calibration (e.g. time series of soil moisture contents) are often unavailable, especially for Africa. However, few studies have been carried out in Sudan on crop water requirements, soil water availability, vulnerability of water resources and irrigation effects on a reference crop (Saeed and El-Nadi 1997, Abdelhadi et al. 2000, MEPD/HCENR 2003, Möllerström 2004) but none of them on ecosystem water balance of savannah woodlands.

As mentioned, evapotranspiration represents the major loss of water from dryland regions, and often is equal to rainfall. AET consists of interception, evaporation from the soil, and transpiration, but these components are difficult to separate (Wallace 1991). Interception losses in dryland environments may be relatively more important than in humid environments, but it is highly variable, depending on rainfall intensity, duration and canopy cover (Dunkerley 2000). Wilcox et al. (2003) reported interception losses from rangeland (dryland) ecosystems in North America of between 1% and 80% of annual water budget, but generally were between 20% and 40%. Evaporation from bare soil can account for a significant proportion of AET in arid and semi-arid regions according to Wilcox et al. (2003), depending on the extent of bare soil. However, other studies suggest that bare soil evaporation in dryland environments soon becomes negligible after rainfall (Williams and Albertson, 2005).

Runoff in dryland regions is usually small; a few percent of the annual water budget, but it occurs as overland flow associated with storm events, even on sandy soils. The development

of water repellence and surface crusting that occurs on sandy soils in dryland regions is widespread, significantly reducing infiltration and recharge of the soil water store while promoting runoff (Abu-Awwad 1997, Francis et al. 2007). Drainage to groundwater in arid and semi-arid regions is also characteristically small, often negligible, as water infiltrating the soil is used to meet the evapotranspiration demand. The soil water storage component of the water balance represents the integrated effects of the other water balance components. The capacity of the soil to store water depends on soil texture, which determines field capacity and permanent wilting point of the soil, and depth. The presence of trees is generally promotes infiltration and increases water retention in the soil because of the relatively higher production of SOC compared to other vegetation types (Weltzin and Coughenour 1990, Githae et al. 2011).

#### **1.4 Climate change in drylands**

Dryland-specific climate change information and predictions for the drylands systems are not readily available, but it can be inferred that many drylands have already been affected by the climate change (Safriel et al. 2005). IPCC (2001) reported that 0.3% decrease of rainfall per decade during the 20<sup>th</sup> century between 10 and 30 °N, 2-4% increase in the frequency of heavy precipitation events over latter half of the last century in mid-latitudes of the Northern Hemisphere, and increase in frequency and intensity of droughts in parts of Asia and Africa in recent decades. During the period of 1982-1997, global annual evapotranspiration increased on average by 7.1±1.0 mm per year per decade, and since then the rising trend seems to have declined probably because of soil-moisture limitation in the southern hemisphere, particularly in Africa and Australia (Jung et al. 2010). Studies have indicated an increase in drought events may push dryland systems across a biophysical (e.g. soil, water, temperature) threshold of biomass productivity, causing a long-term decline in productivity and is expected to exacerbate desertification (Schlesinger et al. 1990, Boko et al. 2007, Fraser et al. 2010). These trends are, however, expected to continue in future, whereas precipitation will either increase or decrease in different regions (IPCC 2001, UNCCD/UNDP/UNEP 2009). By 2050, temperatures over drylands are expected to increase by 1-3 °C and PET to increase by 72 mm yr<sup>-1</sup> per degree increase in mean annual temperature (MAT) (Le Houérou 1996). However, while there is good agreement between the various Global Circulation Models (GCMs) in predicting temperature change for drylands, the effect of climate change on rainfall remains unclear and both increases and decreases are reported (Hulme et al. 1995 & 2001, Boko et al. 2007).

The continent of Africa is considered to be at the highest risk from climate change, and significant areas of African drylands are likely to experience a high temperature rise and changing rainfall patterns with more frequent and more intense extreme events such as droughts and floods (IPCC 2007b). Ruosteenoja et al. (2003) indicated higher levels of warming for North Africa for the period of 2070-2099 with increases up to 9 °C between June and August. However, studies on the impacts of climate change on water availability and vegetation in African drylands are few (Hulme et al. 1995 & 2001). Climate change studies in the Sudan have dealt with changing patterns in rainfall and temperature (Hulme 1990, Elagib and Mansell 2000a & 2000b) and the impacts of rainfall change on hydrology and water supply (Walsh et al. 1988), particularly that of the Blue Nile (Elshamy 2009). Sudan's First National Communications (SFNC) generated climate change scenarios for two mile-stone years, 2030 and 2060, using three GCMs (HadCM2, GFDL, BMRC) and IPCC (Intergovernmental Panel on Climate Change) IS92 emission scenarios (MEPD/HCENR 2003) and looked at the impacts on agricultural crop production, water resources and malaria



outbreaks. GCM based temperature changes for the Sudan has indicated that the country average increase in MAT for 2080s could reach a maximum of 6 °C (Mitchell and Hulme 2000). However, the impact of climate change on Sudanese savannah woodlands, particularly in relation to biomass production and water-use, remains unknown. Such studies are needed in the context of reversing land degradation, adaptation to and mitigation of climate change, sustaining water resources and reducing conflict.

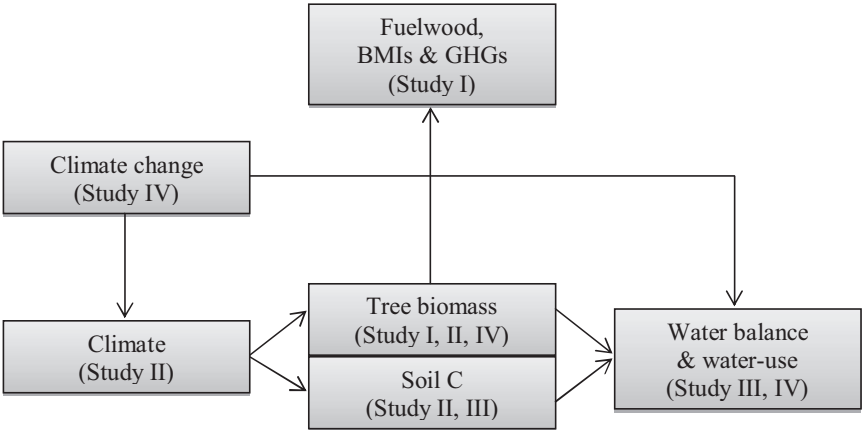
**1.5 Aims of the study**

Understanding the C sequestration potential of drylands requires knowledge of the stocks of C in soils and biomass and on the factors affecting them. The overall aim of the study was to determine and evaluate the variation in the C stocks and water balance of *Acacia* savannah woodlands across the dryland (arid and semi-arid) region (10–16 °N; 21–36 °E) of the former Sudan (now mainly in the Republic of the Sudan) and how they are related to climatic factors and may be affected by climate change. The role played by small but numerous BMIs on woodland deforestation in the region and GHG production was also investigated.

The specific objectives of this study were to:

- i. Estimate the fuelwood consumption and associated deforestation and GHG emissions of the Sudanese BMIs (I),
- ii. Estimate tree biomass C and SOC densities for the Sudanese woodland savannah region and evaluate how the C densities relate to each other and vary with MAP and MAT across the region (II),
- iii. Determine the long-term mean annual and monthly water balances of Sudanese savannah woodlands and how the components of water balance (AET, runoff, drainage and changes in soil water storage) vary across the region (III),
- iv. Analyse the impact of various climate change scenarios for the 2080s on biomass C density and water-use of Sudanese savannah woodlands (IV).

The specific objectives were set based on the articles (I-IV) that included in this doctoral dissertation and the linkages among the articles were shown in the following schematic diagram:



## 2. Material and Methods

### 2.1 Study region

This study covered the savannah woodland region of Sudan (10–16 °N; 21–36 °E) (Fig. 1). In this study, savannah ecoregion was considered instead of the political boundary between Sudan and South Sudan and literature reviews include both countries. The study region embraces arid and semi-arid areas and is often referred to as the *gum belt* because it is the world's major source of gum arabic, which is harvested mainly from *Acacia senegal* (Griffith 1961, Kananji 1994). *Acacia* trees occur throughout as scattered individuals, but the stocking density increases southwards (UNEP 2007). The vegetation cover is savannah, mostly composed of grasses with scattered shrubs and trees, where biomass productivity and SOC contents are low (Dregne 2002, FAO 2004, Lal 2004). Typical tree species include *Acacia senegal*, *A. raddiana*, *A. seyal* and *A. laeta*, but other tree species such as *Commiphora africana* occur and woody shrubs, including *Salvadora*, *Leptadenia* and several species of *Grewia*, are common (Griffith 1961). MAP ranges from 300 mm in the north to 800 mm in the south (Jamal and Huntsinger 1993). The soils in the centre and west of the region are mainly sandy soils, Arenosols (AR, locally named “Qoz”), and those in the eastern part are mainly clay soils, Vertisols (VR, locally named “Gradud”) (Ayoub 1998, FAO/IASA/ISRIC/ISS-CAS/JRC 2009).

For *Study I*, three administrative states (Khartoum, Kassala and Gezira; red circled in Fig. 1) from the gum belt region were chosen. Khartoum state was chosen because most of Sudan's BMI units are located there and it is the only state in which animal dung is used for brick burning. Kassala state was chosen because the BMI units in this state have a distinctly higher fuelwood consumption rate and Gezira state was chosen because only one species of wood from plantations is used as fuel in the BMI. For *Study II and III*, 39 map sheet grids (1:250 000; 1.0° latitude x 1.5° longitude; Haberalah 2005; Fig. 1) covering the gum belt region (80.4 M ha) were selected. For *Study IV*, eight map sheet grids (shaded in Fig. 1) with same scale and resolution were selected from the gum belt region. The five of the eight map sheet grids were selected from the Kordofan region and the remaining three were from Khartoum, Eastern and Darfur regions. The Kordofan region covers desert and semi-desert in the north and moist, sub-humid and rich savannah types in the south (MEPD/HCENR 2003). Together the eight grids cover the range of climatic conditions and dominant soil types (AR and VR) over the Sudanese gum belt region.

### 2.2 Methods

#### 2.2.1 Estimation of deforestation and GHG emissions associated with BMIs' fuelwood consumption (I)

Fuelwood and dung cake consumption data from 25 BMIs were collected from Khartoum, Kassala and Gezira states using semi-structured questionnaire survey and interviews of owners and employees. Fifteen of these BMI units were in Khartoum state and five BMI units each were in each of the other two states, Kassala and Gezira. As the interviewees were not willing to state whether the unit was registered or not it is difficult to determine if there is a difference in fuelwood consumption between registered and unregistered units. However, both bigger ( $>750 \times 10^3$  bricks production  $\text{yr}^{-1}$ ; 13 units) and smaller ( $<750 \times 10^3$  bricks production  $\text{yr}^{-1}$ ; 12 units) were included in the sample. There is little data available about the

BMIs of northernmost Sudan, but brick making is limited because of the Sahara desert. Data about the BMIs in southern and western Sudan is unavailable due to the conflict in these regions. According to official statistics, there were some 1700 BMI units in Sudan in 1995 (Hamid 1994, FNC 1995). However, the number of BMI units has increased and there are many more unregistered units scattered in rural areas. The current number of BMI units in Sudan and their distribution among the states were derived from the personal communication with Mr. Ali Ahmed Ibrahim, secretary of Brick Making Owner's Association in Khartoum State. According to him, the total number of BMIs in Sudan is probably nearer to 3450, of which 2000 are in Khartoum state, 800 in Gezira state and 70 in Kassala state.

Harvesting statistics are usually given in units of cubic meter ( $m^3$ ) and usually only for the round-wood portion. The fuelwood biomass data (t dm) were converted into  $m^3$  by dividing by a default wood density value for deciduous trees of  $0.65 \text{ t dm m}^{-3}$  (Dixon et al. 1991). To account for the non-commercial biomass (i.e. branches and small trees), which is also used as fuel in the BMIs, an expansion ratio of 1.90 for logged forests was applied (UNEP/OECD/IEA/IPCC 1997). To estimate GHG emissions from the BMIs, the methodological approach outlined by the IPCC (IPCC 1994, WB 1998) was adopted and modified. Total carbon released from BMI fuelwood and dung cake burning was calculated from total biomass burnt, fraction of biomass oxidized and biomass carbon content:

$$TC_r = TB_b \times B_{ox} \times B_c$$

where  $TC_r$  = total carbon released (t C),  $TB_b$  = total biomass burnt (t dm),  $B_{ox}$  = fraction of biomass oxidized, and  $B_c$  = biomass carbon content (t C/t dm). A default value of 0.9 was used for the fraction of biomass oxidized in the kilns and a carbon content of 50% (0.5 t C/t dm) was used for woody biomass and 45% (0.45 t C/t dm) for dung biomass components.

Non- $CO_2$  GHGs ( $CH_4$ ,  $CO$ ,  $N_2O$ ,  $NO$ , and  $NO_x$ ) were calculated from total carbon released using a gas specific emission ratio, the gas/C molecular ratio and, in the case of  $N_2O$ ,  $NO$ , and  $NO_x$ , also the N/C ratio:

$$\begin{aligned} CH_4 &= TC_r \times ER \times 16/12 \\ CO &= TC_r \times ER \times 28/12 \\ N_2O &= TC_r \times ER \times N/C \times 44/28 \\ NO_x &= TC_r \times ER \times N/C \times 46/14 \\ NO &= TC_r \times ER \times N/C \times 30/14 \end{aligned}$$

where ER = emission ratio ( $CH_4 = 0.012$ ,  $CO = 0.060$ ,  $N_2O = 0.007$ ,  $NO_x = 0.121$ , and  $NO = 0.121$ ) and N/C = N/C ratio in biomass (0.01).

$CO_2$  emissions were calculated from the total carbon released minus the carbon released as  $CH_4$  and  $CO$ , and the  $CO_2/C$  molecular ratio:

$$CO_2 = TC_r - (CH_4-C + CO-C) \times 44/12$$

The deforestation and GHG emissions for Khartoum state, Kassala state and the rest of Sudan were estimated separately and then summed to obtain values for the entire country. For upscaling, the mean deforestation and GHG emissions values for Khartoum state were used to represent all BMIs in Khartoum state, mean values for Kassala state to represent all BMIs in

Kassala state, and the mean of Khartoum and Gezira values were used as representative of BMIs in the rest of Sudan.

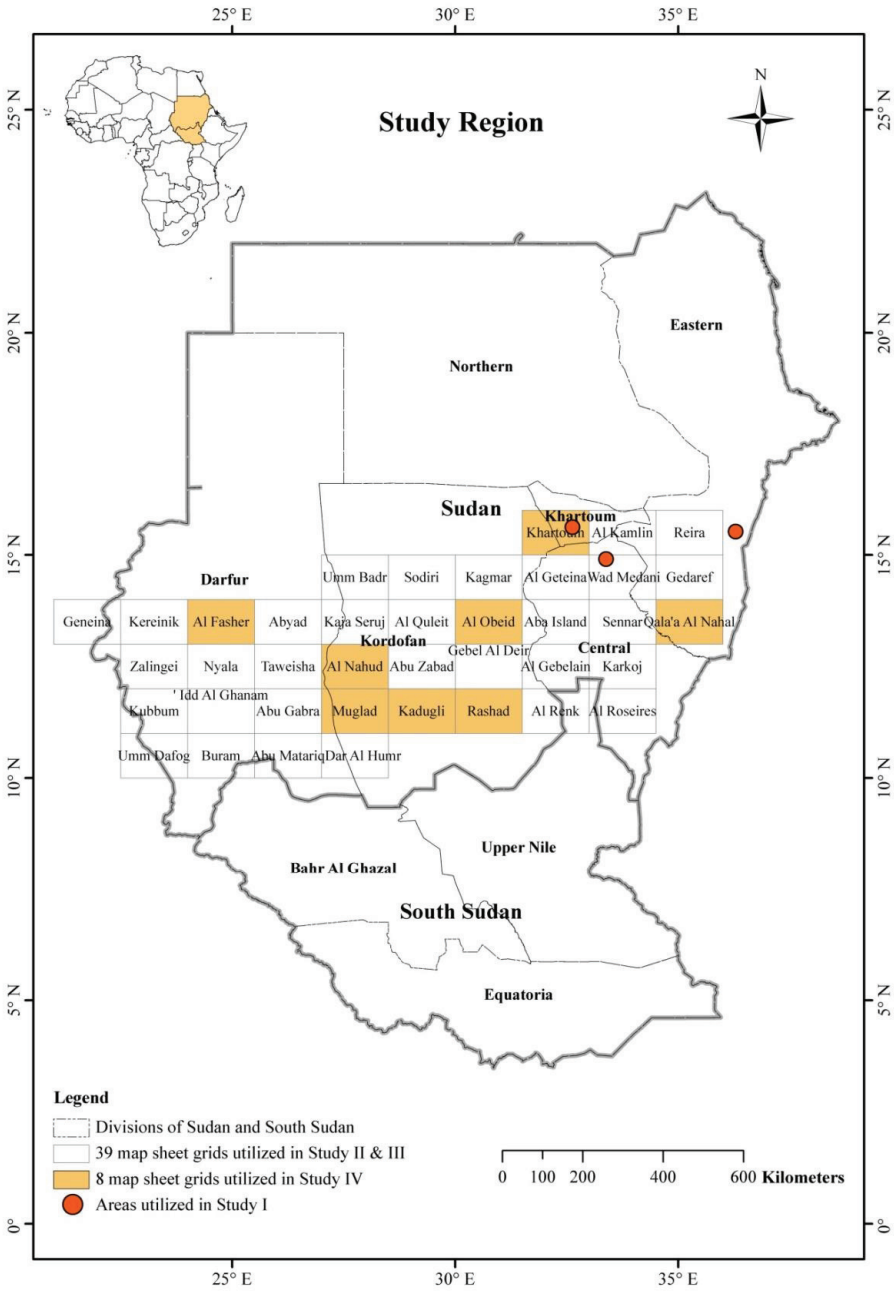


Figure 1. Map shows areas (red circled) utilized in *Study I*, 39 map sheet grids (1.0° latitude x 1.5° longitude) utilized in *Study II and III*, and 8 map sheet grids (shaded) utilized in *Study IV*.

### 2.2.2 Calculation of tree biomass and soil C densities (II, IV)

Tree biomass C densities for 39 map sheet grids were derived from the spatially distributed aggregated forest inventory data collected by Forests National Corporation (FNC) of Sudan. Between 1995 and 1997, the FNC carried out a national forest inventory (NFI) of 6160 plots (20 x 100 m in size) based on a 10 x 10 km grid covering 62.3 M ha south of latitude 16° N and calculated the mean volume ( $\text{m}^3 \text{ha}^{-1}$ ) of the above-ground biomass, excluding the foliage, for each grid (Glen 1996, FNC/MAF/FAO 1998). This published grid above-ground biomass mean volume values were converted into C densities ( $\text{g C m}^{-2}$ ) using a wood (dry matter) density value for deciduous trees of  $0.65 \text{ g cm}^{-3}$  and assuming a dry matter C content of 50% (Dixon et al. 1991, Fang et al. 2001). Below-ground C densities were calculated using an estimate of below-ground biomass and assuming a dry matter C content of 50%. The estimated below-ground biomass was calculated as the mean of three separate estimates: the below-ground biomass model for forests presented by Cairns et al. (1997; equation 3 parameterized for tropics), an estimate calculated using an assumed root shoot ratio of 0.38 (Woomer et al. 2004), and an estimate calculated using an assumed root shoot ratio of 0.2 (Toky and Bisht 1992, Deans et al. 1999).

SOC densities ( $\text{g C m}^{-2}$ ) for the same 39 map sheet grids were derived from the Harmonized World Soil Database (HWSD; FAO/IIASA/ISRIC/ISS-CAS/JRC 2009) soil data. The HWSD soil map and associated soil mapping unit (SMU) attribute database, covering the study region, were imported into ArcGIS (version 9.2) and cut into polygons corresponding to the 39 grids to determine the area (ha) of each SMU in each grid and access the corresponding soil data from the database. The mean SOC (0-1 m) density value for each grid was calculated according to the following three-stage procedure. First, the SOC density of the 0-30 and 30-100 cm layers for all non-Leptosol soil units ( $n = 503$ ) from across all the grids (regardless of whether it was the dominant, an association or an inclusion) was calculated as the product of organic C content ( $\text{g g}^{-1}$ ), bulk density ( $\text{g cm}^{-3}$ ) and layer thickness (cm), and corrected for the volume of coarse fragment (gravel) content. The SOC density value was calculated as the sum of the two layers. Leptosols (very shallow soils over hard rock, gravel or stony material) were excluded considering their incapability of supporting trees. Second, the mean SOC density for all non-Leptosol SMUs across the region ( $n = 203$ ) was calculated, weighting by the share of each soil unit present. Finally, the weighted SMU SOC density values were used to calculate the mean SOC density value for each grid, but this time the weighting was by the area of SMU present in each grid. In this way SOC density values were derived and considered to be the average of the area of woodland savannah in each grid and that can be compared to the biomass C density values.

### 2.2.3 Calculation of water balance and water-use (III, IV)

A simple water balance model, WATBAL (Starr 1999), used to calculate the long-term annual and monthly water balances for each map sheet grid and soil type:

$$P = \text{AET} + R + D + \Delta\text{SM}$$

where P = rainfall, AET = actual evapotranspiration, R = surface runoff, D = drainage and  $\Delta\text{SM}$  = change in soil moisture storage (0-1 m). WATBAL is a single layer capacity type model for deriving the components of the water balance at the plot or stand scale. The input meteorological data (monthly temperature, precipitation and cloud cover) and the site, stand and soil parameters data are required to enable modest and widespread application. In the

model, AET is calculated using the Jensen-Haise alfalfa-reference crop radiation (global) equation, a crop coefficient (Kc) to convert the alfalfa values to values for the savannah woodland, and a soil water function approach to take into account the effect of soil water availability on transpiration (Allen et al. 1998). Monthly global radiation was calculated from solar radiation and cloud cover using the equation developed by Black (1956). Cloud cover in tenths was calculated from LocClim sunshine fraction as  $((100 - \text{sunshine fraction, \%}) / 10)$ .

Kc values are mainly dependent on the characteristics of the vegetation type and integrate the effects of height, albedo, canopy resistance and evaporation from soil (Allen et al. 1998). While Kc values are widely available for food crops they are rarely available for trees and forest. Since trees tend to exhibit higher evapotranspiration rates than low crops because of interception, Kc values for trees can be expected to be  $>1$ , at least for forests with high stocking density and canopy cover. However, because of the open nature of savannah woodlands, Kc values can be expected to be relatively low, particularly on sandy soils where tree densities are less than on clay soils (Gaafar et al. 2006, Raddad et al. 2006). Kc values for the map sheet grids were derived using a linear regression model and biomass C density values of 39 map sheet grids. The regression model for each soil type was derived by pairing the minimum and maximum grid biomass C density values with minimum and maximum Kc values. The map sheet grid tree biomass C densities were calculated from data collected during a national forest inventory (Glen 1996, FNC/MAF/FAO 1998) as described in previous section. Initial minimum and maximum Kc values were given on the basis of the above discussion of Kc and subsequently modified by comparing WATBAL annual AET values with a map of AET for Africa produced using the evapoclimatology model by Nicholson et al. (1997). Accordingly, the minimum and maximum Kc values used in the regression models were 0.6 and 1.0 for VR soils and 0.4 and 0.8 for AR soils, and the equations were  $0.5936 + 0.0011X$  and  $0.3936 + 0.0011X$  for VR and AR soil types, respectively, where X is the grid mean tree biomass C density value.

Soil water availability in WATBAL is taken into account using field capacity (FC) and permanent wilting point (PWP) parameters to define the plant available water storage capacity of the soil. The pedotransfer function developed by Saxton et al. (1986) was used to compute FC and PWP for each grid from soil texture data. The soil texture data for VR and AR soil types in each grid was taken from the HWSO (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009) for the 0-30 cm and 30-100 cm layers. The depth of water (mm) in the two soil layers when at FC and PWP, which are parameters needed in WATBAL, were calculated from the FC and PWP moisture contents and layer thickness and summed to give values for the 0-1 m soil layer, i.e. the layer from which we have assumed water is extracted to meet the transpiration demand.

In WATBAL if the evapotranspiration demand cannot be met by rainfall, the unsatisfied part of the demand is transferred to the soil water store. Water is withdrawn from the soil at the PET rate until a critical moisture content is reached (SMcrit), below which any further evapotranspiration demand is met at a reduced rate (SMrate) until the PWP limit is reached. The SMcrit and SMrate parameters depend on soil texture (Zahner 1968). The AET therefore equals rainfall plus the amount of water extracted from the 1 m soil layer. The threshold value of rainfall (Pcrit) at which surface runoff (R) is generated was set at 140 mm in the case of AR soils and 130 mm in the case of VR soils. The general level of Pcrit to use was established by trial-and-error and comparing WATBAL annual runoff values with Budyko model values provided as additional information by New LocClim and a high resolution map of annual runoff for Africa produced using a water balance model, evapoclimatology, by Nicholson et al. (1997). The different Pcrit values decided upon for AR and VR soils was because of the



difference in infiltration rates between sand and clay soils, a difference accentuated when clays swell upon wetting. Drainage represents percolation from the layer of soil defining the soil water store and only occurs when the soil water store is at FC. If the soil water store is not at FC, then the water entering the soil recharges the soil water store. Surface runoff is calculated as the amount of rainfall in excess of Pcrit.

For the assessment of the effects of interannual variation in climate on the water balance in *Study III*, the monthly water balance for one randomly chosen map sheet, Rashad, was determined for the 30-year period 1961-1990. In the study of interannual variation, the same values for the Pcrit, Kc, SMfc (soil moisture content at field capacity), SMPwp (soil moisture at permanent wilting point), SMcrit and SMrate parameters as used in the long-term mean study of the Rashad map sheet water balance were used for the entire 30-year period. While it can be assumed that the soil hydraulic parameters will not have changed over this period, forest cover, and therefore Kc, may have. However, there is no relevant data available to enable changes in forest cover to be taken into account and, in any case, the intention was to assess the effects of variation in climate on the water balance.

Validating the model against soil moisture data is considered particularly suitable because changes in soil moisture integrate the effects of the other components of the water balance, and surface runoff and drainage (percolation) are rarely, if ever, measured. As empirical data for validating WATBAL at the map sheet scale is not available, the *Study III* sought to demonstrate the conceptual and operational validity of model by comparing daily WATBAL soil moisture simulations with empirical measurements of soil moisture data from Demokeya (13.3 °N, 30.5 °E), which falls within the Al Obeid map sheet (Fig. 1), in Northern Kordofan. Soil moisture and meteorological data has been collected by Ardö (2013) at the Demokeya site during the period of 2002-2012 as part of a long-term savannah woodland ecosystem study. The data available includes daily rainfall (mm), air temperature (°C), incoming global radiation ( $W m^{-2}$ ), and volumetric soil moisture content (v/v) measured at 5, 15, 30, 60, 100 cm depths using time-domain reflectometry. Because of gaps and errors in the original datasets, daily data for the two periods, 1 February 2005 – 20 April 2007 and 6 July 2007- 19 January 2010, were used for validating WATBAL.

#### **2.2.4 Baseline climate and climate change scenario data (II, III, IV)**

For *Study II and III*, long-term (1961-1990) MAP and MAT values for each of the 39 grids were generated using New LocClim, a local climate estimator software tool that estimates long-term monthly climate data for any global location using various interpolation methods and the FAO agroclimatic database of observations from nearly 30,000 stations worldwide (FAO 2005, Grieser et al. 2006). New LocClim was used in the single point mode (centre of grid) and interpolation was done using Shepard's inverse distance weighting method (Shepard 1968). MAP and MAT values for each grid were calculated from the New LocClim monthly values; MAP by summing the monthly rainfall values and MAT by averaging the monthly temperature values.

The climate data (monthly temperature, precipitation and cloud cover % for 1961-1990) were used from the University of East Anglia (UEA) Climate Research Unit (CRU TS 2.1; Mitchell and Jones 2005) to assess the effects of interannual variation in climate on the water balance in *Study III*. For *Study IV*, monthly baseline (1961-1990) and climate change scenario data (2070-2099) for the study region were taken from the UEA Climate Research Unit (CRU TS 2.1; Mitchell and Jones 2005) and UEA Tyndall Centre for Climate Change Research

(TYN SC 2.03; Mitchell et al. 2004), respectively. The climate data were available in  $0.5^\circ \times 0.5^\circ$  grids for the entire globe. Ten climate change scenarios were constructed from five GCMs (CGCM2, CSIRO2, ECHam4, HadCM3, PCM) and the effects of two IPCC Special Report on Emission Scenarios (SRES; A1FI and B1) (IPCC 2000 & 2001). The five GCMs are those available in the TYN SC 2.03 dataset and among the set of state-of-the-art GCMs used by the IPCC in the Third Assessment Working Group 1 Report (IPCC 2001). Among the SRES emission scenarios, the A1FI and B1 scenarios respectively have the greatest and least effect on climate change (IPCC 2000, Arnell 2004).

After downloading the global monthly baseline (1901-2002) and climate change scenario data (2001-2100), the data (temperature, precipitation and cloud cover) for the 48 ( $0.5^\circ \times 0.5^\circ$ ) grids corresponding to eight ( $1^\circ \times 1.5^\circ$ ) study grids were extracted using the TETYN software (Solymosi et al. 2008). Ten climate change scenario datasets were formed, corresponding to the combination of the five GCMs and two SRES emission scenarios. The CRU/TYN data for the six grids corresponding to each of the eight study grids were then averaged. The monthly data for the 30 year period 1961-1990 were then averaged to form the monthly baseline climate data set and for the climate change scenario monthly data for the 30 year period 2070-2099 averaged to form the climate change scenario data sets for the period of 2080s. Biomass C density values for the baseline period and under each climate change scenario were estimated using an exponential relationship, developed in *Study II*, between above-ground biomass C density and current long-term MAP ( $y = 6.798.e^{0.0054x}$ ,  $R^2 = 70\%$ ) for the 39 grids that cover the entire gum belt region of Sudan. Monthly water-use (AET) values of AR and VR soil types for the baseline period and under each climate change scenario were estimated using a water balance model, WATBAL (Starr 1999), which described in section 2.2.3.



### 3. Results

#### 3.1 BMIs' fuelwood consumption, associated deforestation and GHG emissions (I)

The mean annual fuelwood consumption and associated deforestation caused by the surveyed BMIs in each of the three states and that estimated for the rest of Sudan were presented in Table 1. It is seen that the annual consumption of fuelwood varies widely (from 27 to 300 t dry matter) among the enterprises, but the consumption by enterprises in the Kassala state was 10-fold that of enterprises in the other states.

Table 1. Annual brick production, fuelwood consumption and associated deforestation by the surveyed BMI enterprises for regions in Sudan.

| State                   | n  | Total brick production, $10^3 \text{ yr}^{-1}$ | Fuelwood consumption         |                       | Deforested roundwood, $\text{m}^3$ | Deforested branches + small trees, $\text{m}^3$ | Total deforested wood, $\text{m}^3$ |
|-------------------------|----|--|------------------------------|-----------------------|------------------------------------|---|-------------------------------------|
|                         |    |  | kg /1000 bricks <sup>a</sup> | t dm $\text{yr}^{-1}$ |                                    |   |                                     |
| Khartoum                | 15 | 987 $\pm$ 287                                  | 51 $\pm$ 0                   | 50 $\pm$ 15           | 77 $\pm$ 22                        | 69 $\pm$ 20                                     | 146 $\pm$ 42                        |
| Kassala                 | 5  | 562 $\pm$ 120                                  | 533 $\pm$ 0                  | 300 $\pm$ 64          | 461 $\pm$ 98                       | 415 $\pm$ 89                                    | 876 $\pm$ 187                       |
| Gezira                  | 5  | 683 $\pm$ 195                                  | 39 $\pm$ 0                   | 27 $\pm$ 0            | 41 $\pm$ 12                        | 37 $\pm$ 11                                     | 78 $\pm$ 22                         |
| Rest Sudan <sup>b</sup> | 20 | 835 $\pm$ 295                                  | 45 $\pm$ 5                   | 38 $\pm$ 17           | 59 $\pm$ 26                        | 53 $\pm$ 23                                     | 112 $\pm$ 49                        |

Values are mean  $\pm$  standard deviation

<sup>a</sup>Hamid (1994)

<sup>b</sup>Mean and standard deviation based on Khartoum and Gezira's data

The upscaled deforestation values for Khartoum, Kassala, the rest of Sudan and for the whole of Sudan were given in Fig. 2. Deforestation is clearly dominated by the Khartoum state ( $292.5 \times 10^3 \text{ m}^3$ ), accounting for 58% of the total deforestation ( $508.4 \times 10^3 \text{ m}^3$ ) associated with the BMI in the whole country. Kassala accounts for 12% ( $61.3 \times 10^3 \text{ m}^3$ ) and the rest of Sudan 30% ( $154.6 \times 10^3 \text{ m}^3$ ) of the total deforestation.

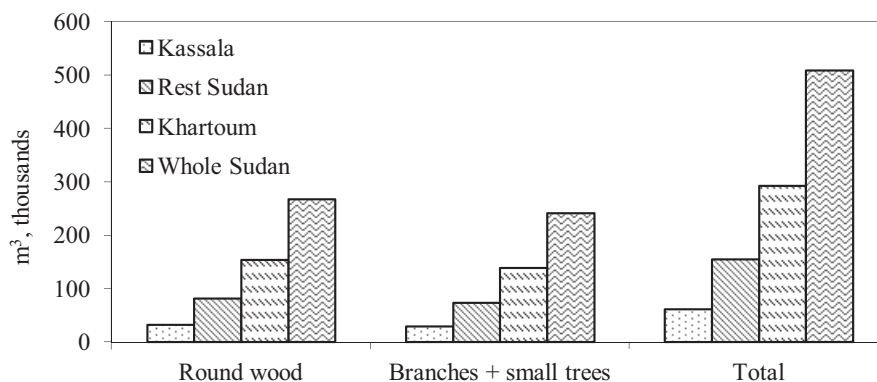


Figure 2. Upscaled estimates of annual deforestation associated with the BMI for regions and the whole of Sudan.

Table 2. Annual GHG emissions (t yr<sup>-1</sup>) by the surveyed BMI enterprises for regions in Sudan.

| Region                  | n  | CO <sub>2</sub> | CO         | CH <sub>4</sub> | NO <sub>x</sub> | NO             | N <sub>2</sub> O |
|-------------------------|----|-----------------|------------|-----------------|-----------------|----------------|------------------|
| Khartoum                | 15 | 76.6 ±22.2      | 3.2 ±0.9   | 0.36 ±0.10      | 0.090 ±0.026    | 0.058 ±0.017   | 0.002 ±0.001     |
|                         |    | (55.9 ±12.5)    | (2.3 ±0.5) | (0.26 ±0.06)    | (0.065 ±0.015)  | (0.043 ±0.010) | (0.002 ±0.000)   |
| Kassala                 | 5  | 458.7 ±98.0     | 18.9 ± 4.0 | 2.16 ±0.46      | 0.536 ±0.115    | 0.350 ±0.075   | 0.015 ±0.003     |
| Gezira                  | 5  | 40.8 ±11.7      | 1.7 ±0.5   | 0.19 ±0.05      | 0.048 ±0.014    | 0.031 ±0.009   | 0.001 ±0.000     |
| Rest Sudan <sup>a</sup> | 20 | 58.7 ±25.4      | 2.4 ±1.1   | 0.28 ±0.12      | 0.069 ±0.030    | 0.045 ±0.019   | 0.002 ±0.001     |

Values are mean ± standard deviation; values in parentheses are for dung cake (used only in Khartoum state)

<sup>a</sup>Based on Khartoum and Gezira's data

The mean annual GHG emissions from the surveyed BMIs in each of the three states and that estimated for the rest of the Sudan were presented in Table 2. GHG emissions from enterprises in Kassala are much higher than those in other regions of Sudan, as could be expected from their higher fuelwood consumption (Table 1). For Khartoum, nearly as much GHG emissions are associated with the burning of dung cake as with the burning of fuelwood. The population of livestock is much greater in the Khartoum area and therefore dung is readily available. Dung is not used outside the Khartoum state. The upscaled annual GHG emission values for Khartoum, Kassala, the rest of Sudan and for the whole of Sudan were given in Table 3. The emissions are clearly dominated by CO<sub>2</sub> that total some 378 028 t yr<sup>-1</sup> for the whole of Sudan. Khartoum state accounts for 70% of all GHG emissions from the Sudanese BMI. However, GHG emissions from Khartoum state include those from burning dung cake (42%) and fuelwood (58%).

Table 3. Upscaled estimates of total annual GHG emissions (t yr<sup>-1</sup>) and CO<sub>2</sub>-equivalent (global warming potential for 100-year time horizon) from all BMI enterprises by region and for the whole of Sudan.

| Region                  | CO <sub>2</sub> | CO     | CH <sub>4</sub> | NO <sub>x</sub> | NO  | N <sub>2</sub> O | CO <sub>2</sub> -equivalent <sup>a</sup> |
|-------------------------|-----------------|--------|-----------------|-----------------|-----|------------------|--|
| Khartoum                | 264 923         | 10 900 | 1 246           | 310             | 202 | 8.6              | 319 346                                  |
| Kassala                 | 32 107          | 1 321  | 151             | 38              | 24  | 1.0              | 38 690                                   |
| Rest Sudan <sup>b</sup> | 80 999          | 3 333  | 381             | 95              | 62  | 2.6              | 97 632                                   |
| Whole Sudan             | 378 028         | 15 554 | 1 778           | 442             | 288 | 12.2             | 455 666                                  |

<sup>a</sup> Factors for converting non-CO<sub>2</sub> GHG gases into CO<sub>2</sub>-equivalent were taken from IPCC (2007); NO<sub>x</sub> and NO are not included due to unavailability of conversion factors for these gases

<sup>b</sup>Based on Khartoum and Gezira's data

### 3.2 C densities, their regional variation and relation with MAP and MAT (II)

The mean climate, tree biomass, soil and ecosystem C densities for each of the 39 map sheet grids in the study region were presented in Table 4. New LocClim generated grid MAT values ranged from 24.2 to 29.2 °C and MAP from 147 to 732 mm across the study region. Grid mean above- and below-ground biomass C density values were 112 (ranged from 6 to 380) g C m<sup>-2</sup> and 33 (ranged from 2 to 108) g C m<sup>-2</sup>, respectively. Mean total biomass C density, which is the sum of above- and below-ground biomass C density, was 146 (ranged from 8 to 488) g C m<sup>-2</sup>. The mean root-shoot ratio was 0.31 (ranged from 0.28 to 0.38). Grid mean SOC density values for the top- (0-30 cm) and sub-soil (30-100 cm) were 2558 (ranged from 1323 to 3758) g C m<sup>-2</sup> and 2895 (ranged from 1417 to 4534) g C m<sup>-2</sup>, respectively and that of to a depth of 1 m was 5453 (ranged from 2757 to 8292) g C m<sup>-2</sup>. Ecosystem (biomass plus soil) C density values ranged between 2788 and 8507 g C m<sup>-2</sup> with a mean of 5598 g C m<sup>-2</sup>.

MAT were highest in the north east and central southern area of the study region and MAP increased southwards across the study region (Fig. 3). Maps of biomass C densities show that densities were highest in the south-western part of the region while SOC and ecosystem C densities were highest in the south-eastern part of the region (Fig. 4). Both above-ground biomass C and SOC densities were positively and significantly ( $p < 0.05$ ) correlated with MAP ( $r_s = 0.84$  and  $r_s = 0.34$ , respectively). The relationship between above-ground biomass C density ( $y$ ) and MAP ( $x$ ) was best fitted with an exponential function ( $y = 6.798.e^{0.0054.x}$ ;  $R^2 = 0.70$ ) while that between SOC density and MAP was linear ( $y = 3.3968.x + 3996.1$ ;  $R^2 = 0.11$ ) (Fig. 5).

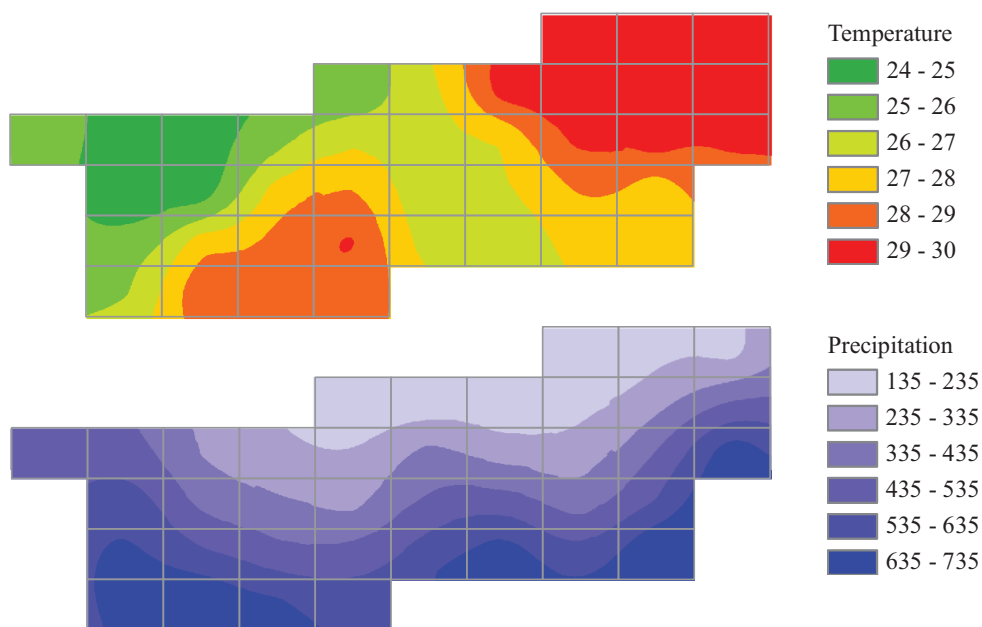


Figure 3. Maps showing distribution of MAT (°C) and MAP (mm) across the study region (see Fig. 1).

Table 4. Mean climate (based on FAO Local Climate Estimator), tree biomass, soil and ecosystem (total biomass plus soil, 1 m) C densities ( $\text{g C m}^{-2}$ ) of the study region by grid.

| Map sheet grid  | MAT<br>°C | MAP,<br>mm | Biomass C                     |                               |       | SOC <sup>c</sup> |              |      | Ecosystem<br>C, total |
|-----------------|-----------|------------|-------------------------------|-------------------------------|-------|------------------|--------------|------|-----------------------|
|                 |           |            | Above-<br>ground <sup>a</sup> | Below-<br>ground <sup>b</sup> | Total | 0-30<br>cm       | 30-100<br>cm | 1 m  |                       |
| Aba Island      | 28.6      | 289        | 55                            | 17                            | 72    | 2338             | 2758         | 5096 | 5168                  |
| Abu Gabra       | 28.0      | 466        | 91                            | 27                            | 118   | 1664             | 1850         | 3514 | 3632                  |
| Abu Matariq     | 28.0      | 644        | 312                           | 89                            | 401   | 2724             | 2894         | 5618 | 6019                  |
| Abu Zabad       | 26.6      | 452        | 52                            | 16                            | 68    | 1970             | 2128         | 4097 | 4166                  |
| Abyad           | 26.0      | 273        | 39                            | 12                            | 52    | 1355             | 1462         | 2817 | 2869                  |
| Al Fasher       | 24.6      | 334        | 143                           | 42                            | 185   | 2537             | 2625         | 5162 | 5347                  |
| Al Gebelain     | 27.9      | 384        | 47                            | 15                            | 61    | 3379             | 4068         | 7447 | 7508                  |
| Al Geteina      | 29.0      | 209        | 63                            | 19                            | 83    | 2872             | 3424         | 6296 | 6379                  |
| Al Kamlin       | 28.6      | 215        | 18                            | 6                             | 24    | 3186             | 3905         | 7091 | 7115                  |
| Al Nahud        | 27.8      | 315        | 23                            | 7                             | 30    | 1323             | 1434         | 2757 | 2788                  |
| Al Obeid        | 27.2      | 301        | 11                            | 4                             | 15    | 1358             | 1448         | 2807 | 2822                  |
| Al Quleit       | 26.7      | 373        | 23                            | 7                             | 31    | 1367             | 1468         | 2835 | 2866                  |
| Al Renk         | 27.4      | 567        | 68                            | 21                            | 89    | 3609             | 4235         | 7844 | 7933                  |
| Al Roseires     | 27.6      | 732        | 190                           | 55                            | 245   | 3708             | 4432         | 8139 | 8385                  |
| Buram           | 28.2      | 718        | 376                           | 107                           | 484   | 1973             | 2240         | 4213 | 4697                  |
| Dar Al Humr     | 28.3      | 583        | 221                           | 64                            | 285   | 2280             | 2510         | 4790 | 5075                  |
| Gebel Al Deir   | 27.0      | 482        | 60                            | 19                            | 79    | 2702             | 3118         | 5820 | 5899                  |
| Gedaref         | 28.7      | 440        | 65                            | 20                            | 85    | 3542             | 4327         | 7868 | 7953                  |
| Geneina         | 26.1      | 456        | 77                            | 23                            | 100   | 3269             | 2968         | 6237 | 6338                  |
| Idd Al Ghanam   | 27.5      | 550        | 151                           | 45                            | 196   | 1943             | 2296         | 4238 | 4434                  |
| Kadugli         | 26.8      | 587        | 105                           | 31                            | 136   | 3283             | 3927         | 7210 | 7347                  |
| Kagmar          | 28.8      | 162        | 7                             | 2                             | 9     | 1647             | 1869         | 3516 | 3524                  |
| Kaja Seruj      | 27.0      | 250        | 28                            | 9                             | 37    | 1910             | 2077         | 3987 | 4025                  |
| Karkoj          | 27.4      | 542        | 321                           | 92                            | 413   | 3653             | 4441         | 8094 | 8507                  |
| Kereinik        | 24.5      | 475        | 143                           | 42                            | 186   | 2521             | 2329         | 4850 | 5036                  |
| Khartoum        | 29.2      | 147        | 19                            | 6                             | 25    | 2653             | 2875         | 5528 | 5554                  |
| Kubbum          | 25.6      | 636        | 306                           | 88                            | 394   | 3116             | 3214         | 6330 | 6723                  |
| Muglad          | 28.5      | 471        | 116                           | 35                            | 150   | 1824             | 2087         | 3911 | 4061                  |
| Nyala           | 24.4      | 414        | 67                            | 21                            | 88    | 2001             | 2323         | 4323 | 4411                  |
| Qala'a Al Nahal | 28.6      | 683        | 70                            | 21                            | 91    | 3758             | 4534         | 8292 | 8382                  |
| Rashad          | 26.5      | 676        | 212                           | 62                            | 274   | 3400             | 4069         | 7468 | 7742                  |
| Reira           | 29.0      | 211        | 15                            | 5                             | 20    | 2978             | 3677         | 6655 | 6675                  |
| Sennar          | 28.8      | 440        | 135                           | 40                            | 175   | 3630             | 4416         | 8046 | 8221                  |
| Sodiri          | 26.9      | 185        | 6                             | 2                             | 8     | 1556             | 1832         | 3388 | 3396                  |
| Taweisha        | 27.4      | 356        | 47                            | 15                            | 62    | 1368             | 1417         | 2785 | 2847                  |
| Umm Badr        | 25.5      | 165        | 19                            | 6                             | 25    | 2654             | 2730         | 5383 | 5409                  |
| Umm Dafog       | 26.2      | 642        | 380                           | 108                           | 488   | 2285             | 2322         | 4607 | 5094                  |
| Wad Medani      | 28.5      | 302        | 77                            | 23                            | 100   | 3621             | 4438         | 8059 | 8159                  |
| Zalingei        | 24.2      | 595        | 226                           | 66                            | 291   | 2788             | 2740         | 5528 | 5820                  |
| Mean            | 27.3      | 429        | 112                           | 33                            | 146   | 2558             | 2895         | 5453 | 5598                  |
| Minimum         | 24.2      | 147        | 6                             | 2                             | 8     | 1323             | 1417         | 2757 | 2788                  |
| Maximum         | 29.2      | 732        | 380                           | 108                           | 488   | 3758             | 4534         | 8292 | 8507                  |
| Std. Deviation  | 1.4       | 172        | 107                           | 30                            | 137   | 799              | 1021         | 1808 | 1840                  |

<sup>a</sup> Based on Sudanese NFI data (FNC/MAF/FAO, 1998)

<sup>b</sup> Modeled values, calculated using a root shoot ratio (see materials and methods for details)

<sup>c</sup> Based on HWSD data (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009)

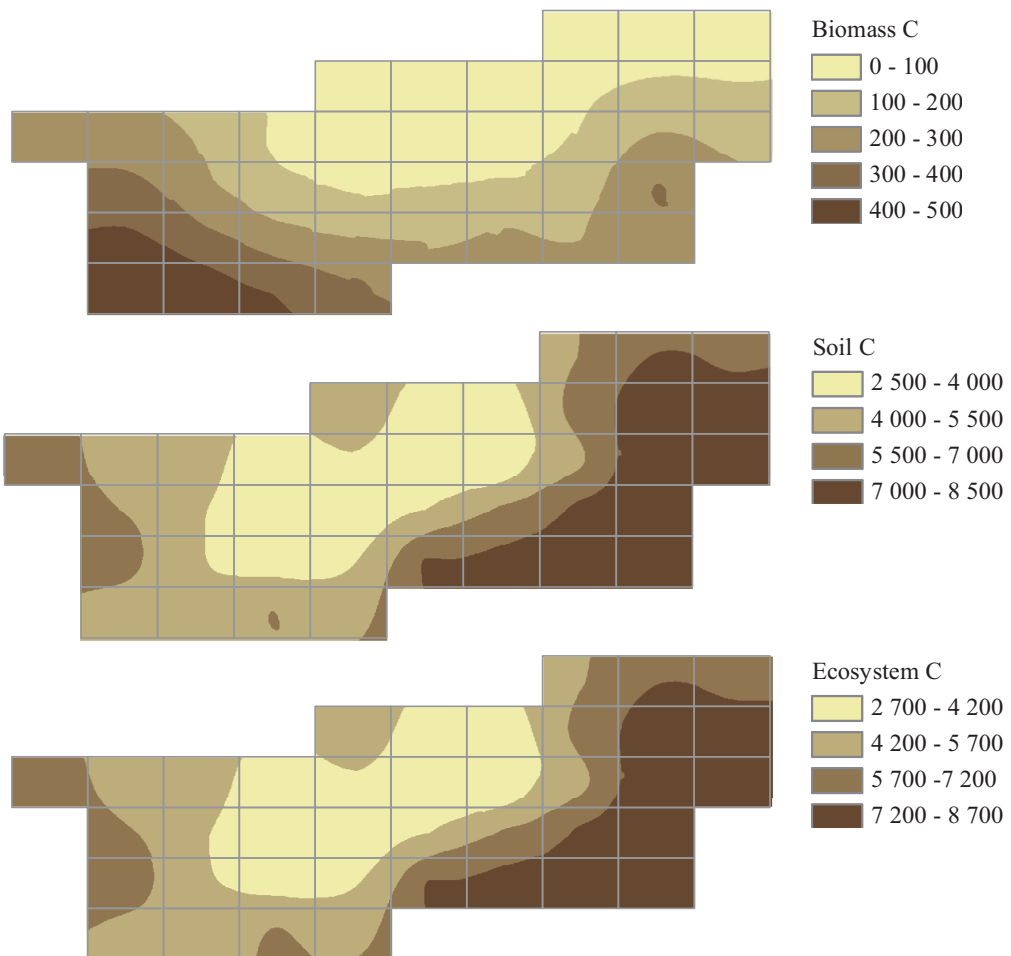


Figure 4. Maps showing distribution of total biomass (above- plus below-ground, upper), soil (to 1 m, middle) and ecosystem (biomass plus soil, lower) C densities ( $\text{g C m}^{-2}$ ) across the study region (see Fig. 1).

Both above-ground biomass C and SOC densities showed non-significant correlations with MAT ( $r_s = -0.22$  and  $r_s = 0.24$ , respectively; Fig. 6). SOC densities in this study were much greater than biomass C density values for some grids and, although weak, the correlation between SOC and biomass C densities was significant ( $r_s = 0.34$ ; Fig. 7).

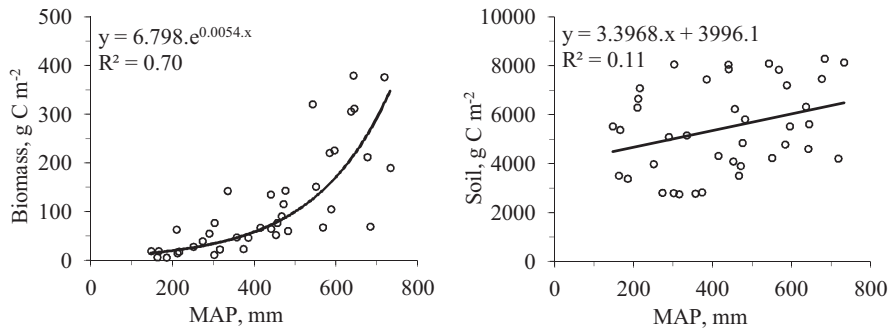


Figure 5. Relationship between grid mean (n = 39) above-ground biomass C density and long-term MAP (left), and between SOC density to 1 m depth and long-term MAP (right).

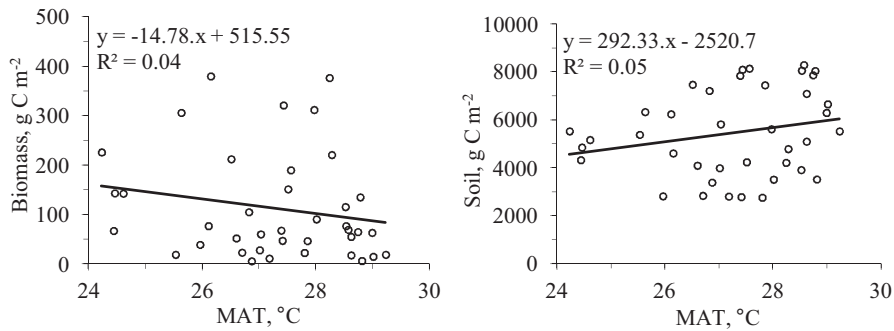


Figure 6. Relationship between grid mean (n = 39) above-ground biomass C density and long-term MAT (left), and between SOC density to 1 m depth and long-term MAT (right).

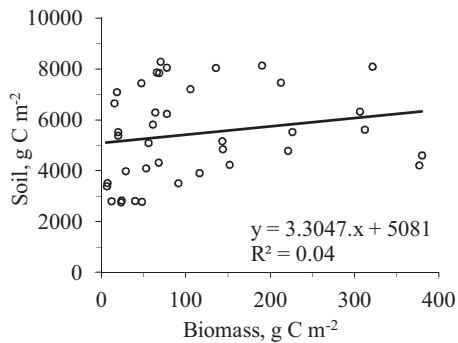


Figure 7. Dependence of grid mean (n = 39) SOC density on above-ground biomass C density.

### 3.3 Water balance of savannah woodlands and variation across the region (III)

The modelled and measured values of daily soil moisture content of the 1 m soil layer at the Demokeya site for the two time periods are displayed as time series plots in Fig. 8. The results show that WATBAL captured well the dynamics and level of soil moisture during the two study periods. The measured and modelled values are plotted against each other in Fig. 9. The fitted linear regression line has a coefficient of determination ( $R^2$ ) value of 0.84 and index of agreement (D) value of 0.87 (Legates and McCabe 1999). Lower plant available soil moisture contents are underestimated and higher soil moisture contents are overestimated. The standard deviation of the residuals was 10.2 mm.

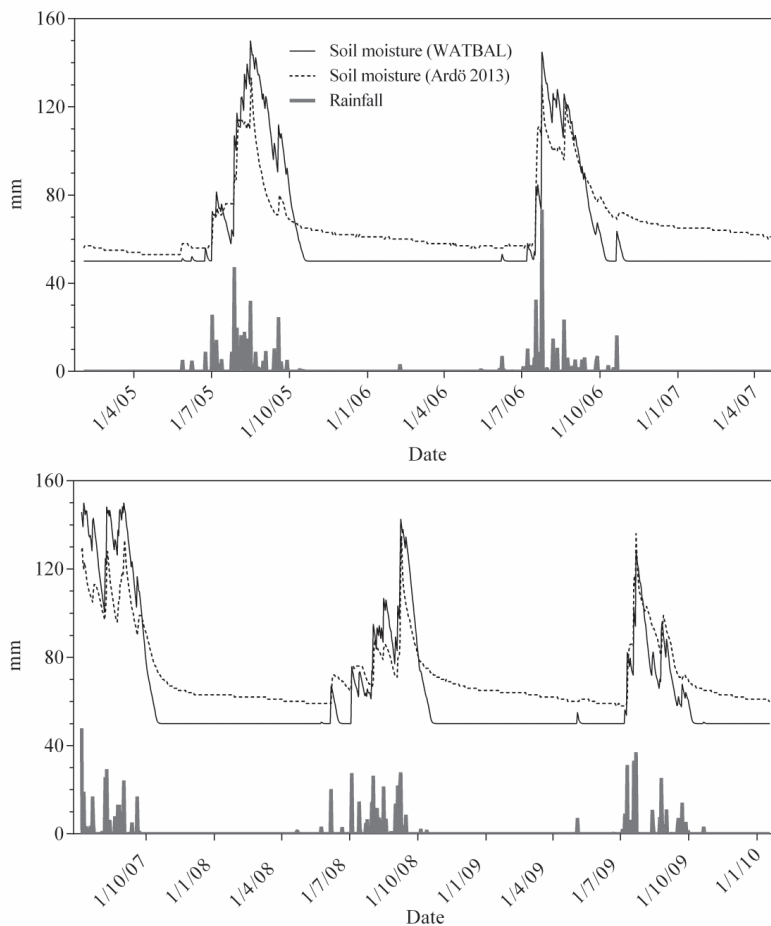


Figure 8. Daily rainfall and measured (Ardö 2013) and modelled (WATBAL) soil moisture contents during two periods, 1/2/05–20/4/07 and 6/7/07–19/1/10, for the Demokeya site, in northern Kordofan (Al Obeid map sheet).

Map sheet grid specific MAT and MAP values were given in Table 4, and annual values for the water-balance components of AR and VR soil types were presented in Table 5. Grid MAP values varied from 147 to 732 mm and MAT from 24.2 to 29.2 °C. MAT were highest in the north east and central southern area of the study region and MAP increased southwards across

the study region (cf. Fig. 3). Map sheet mean annual AET for AR soils averaged 408 mm (95% of MAP) and varied from 147 to 652 mm. For VR soils, map sheet annual AET averaged 403 mm (94% of MAP) and ranged from 147 to 669 mm. Since AET is strongly limited by MAP in arid and semi-arid environments, the maps of AET for AR and VR soil types strongly resembled each other and the map of MAP, with values increasing southwards across the study region (Fig. 10).

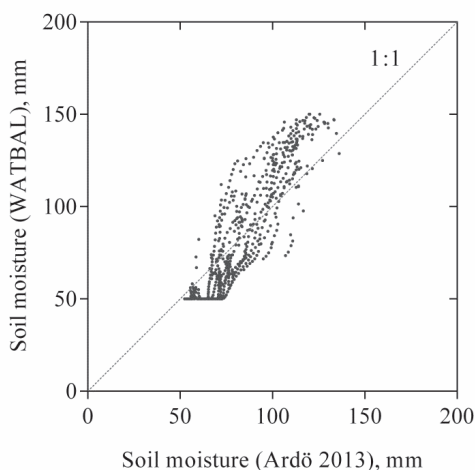


Figure 9. Scatter plot of the measured (Ardö 2013) and modelled (WATBAL) soil moisture contents for 1/2/05–20/4/07 and 6/7/07–19/1/10 for the Demokeya site, in northern Kordofan (Al Obeid map sheet). Dotted line is the 1:1 line.

Map sheet mean annual runoff values varied from 0 to 89 mm for AR soils and from 0 to 109 mm for VR soils. Annual runoff averaged across the region was 17 mm for AR soils and 26 mm for VR soils, corresponding to 4% and 6% of MAP, respectively. For AR soil types, runoff was produced on 17 of the map sheets but 23 of the map sheets in the case of VR soils. Though runoff increased southwards across the study region, it was clearly greater in the south western and eastern areas of the study region (Fig. 11). No drainage was produced from VR soils for any of the map sheets and drainage from AR soils only occurred for four of the map sheets grids. The highest annual drainage value was 68 mm in Kubbum map sheet, corresponding to 1% of MAP. The grids that produced drainage values for AR soil types were located in the south eastern and western areas of the study region (Fig. 12).

The annual water balance components for the Rashad map sheet for the period 1961-1990 are presented in Fig. 13 and Table 6. Annual rainfall ranged from 339 (1984) to 970 mm (1963) and generally declined over the 30-year period. The coefficient of variation (cv) was 20%. The annual mean temperature showed an increasing trend over the period, ranging from 26.2 (1961) to 28.8 °C (1987) and the cv was 2.8%. Of the water balance components, AET showed the least interannual variation (cv = 13%) and surface runoff showed the most (cv = 92% for arenosols, 81% for vertisols), being zero in very dry years for both soil types. The interannual variation in drainage (percolation from below 1 m) was relatively small for AR soils but large for VR soils, and was also zero in very dry years for both soil types. The mean end-of-month plant available moisture content of the soil was generally higher for VR soils but the interannual variation was similar for both soil types.



Table 5. Map sheet grid specific annual values for the water balance components of AR and VR soil types.

| Map sheet grid  | AET, mm |     | Runoff, mm |     | Drainage, mm |    |
|-----------------|---------|-----|------------|-----|--------------|----|
|                 | AR      | VR  | AR         | VR  | AR           | VR |
| Aba Island      | 289     | 289 | 0          | 0   | 0            | 0  |
| Abu Gabra       | 466     | 458 | 0          | 8   | 0            | 0  |
| Abu Matariq     | 608     | 588 | 36         | 56  | 0            | 0  |
| Abu Zabad       | 452     | 448 | 0          | 4   | 0            | 0  |
| Abyad           | 273     | 273 | 0          | 0   | 0            | 0  |
| Al Fasher       | 334     | 329 | 0          | 5   | 0            | 0  |
| Al Gebelain     | 384     | 383 | 0          | 1   | 0            | 0  |
| Al Geteina      | 209     | 209 | 0          | 0   | 0            | 0  |
| Al Kamlin       | 215     | 215 | 0          | 0   | 0            | 0  |
| Al Nahud        | 315     | 315 | 0          | 0   | 0            | 0  |
| Al Obeid        | 301     | 301 | 0          | 0   | 0            | 0  |
| Al Quleit       | 373     | 373 | 0          | 0   | 0            | 0  |
| Al Renk         | 555     | 561 | 0          | 6   | 12           | 0  |
| Al Roseires     | 652     | 669 | 33         | 63  | 47           | 0  |
| Buram           | 633     | 613 | 85         | 105 | 0            | 0  |
| Dar Al Humr     | 583     | 567 | 0          | 16  | 0            | 0  |
| Gebel Al Deir   | 475     | 455 | 7          | 27  | 0            | 0  |
| Gedaref         | 423     | 409 | 17         | 31  | 0            | 0  |
| Geneina         | 414     | 400 | 42         | 56  | 0            | 0  |
| Idd Al Ghanam   | 518     | 498 | 32         | 52  | 0            | 0  |
| Kadugli         | 557     | 543 | 30         | 44  | 0            | 0  |
| Kagmar          | 162     | 162 | 0          | 0   | 0            | 0  |
| Kaja Seruj      | 250     | 250 | 0          | 0   | 0            | 0  |
| Karkoj          | 536     | 524 | 6          | 18  | 0            | 0  |
| Kereinik        | 446     | 426 | 29         | 49  | 0            | 0  |
| Khartoum        | 147     | 147 | 0          | 0   | 0            | 0  |
| Kubbum          | 479     | 527 | 89         | 109 | 68           | 0  |
| Muglad          | 471     | 471 | 0          | 0   | 0            | 0  |
| Nyala           | 402     | 392 | 12         | 22  | 0            | 0  |
| Qala'a Al Nahal | 598     | 578 | 85         | 105 | 0            | 0  |
| Rashad          | 640     | 620 | 36         | 56  | 0            | 0  |
| Reira           | 211     | 211 | 0          | 0   | 0            | 0  |
| Sennar          | 434     | 424 | 6          | 16  | 0            | 0  |
| Sodiri          | 185     | 185 | 0          | 0   | 0            | 0  |
| Taweisha        | 356     | 356 | 0          | 0   | 0            | 0  |
| Umm Badr        | 165     | 165 | 0          | 0   | 0            | 0  |
| Umm Dafog       | 591     | 571 | 51         | 71  | 0            | 0  |
| Wad Medani      | 302     | 302 | 0          | 0   | 0            | 0  |
| Zalingei        | 515     | 499 | 76         | 96  | 4            | 0  |
| Mean            | 408     | 403 | 17         | 26  | 3            | 0  |
| Minimum         | 147     | 147 | 0          | 0   | 0            | 0  |
| Maximum         | 652     | 669 | 89         | 109 | 68           | 0  |
| Std. Deviation  | 151     | 147 | 27         | 35  | 13           | 0  |

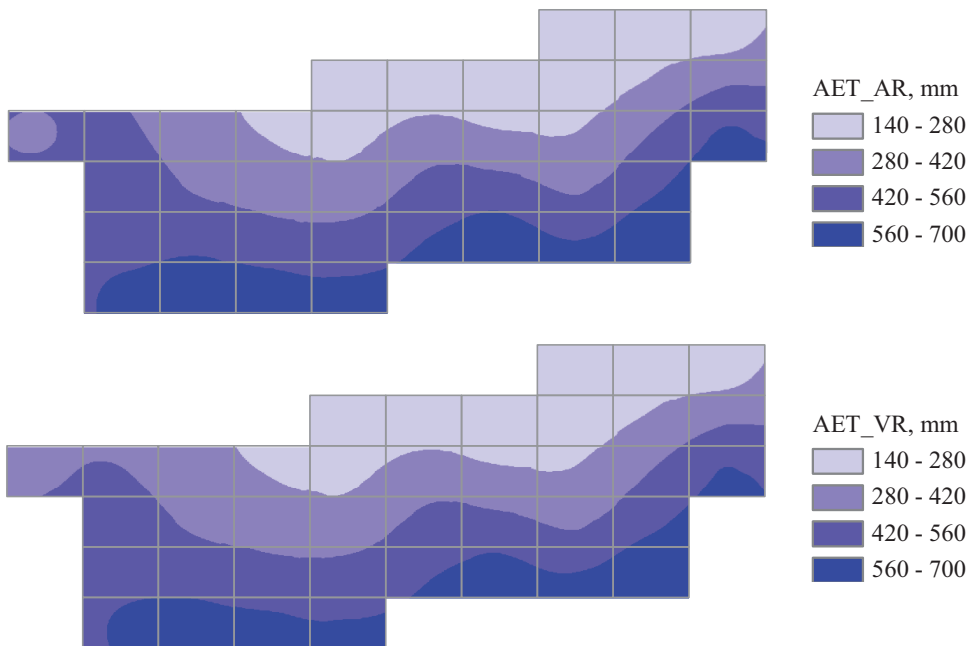


Figure 10. Map showing distribution of annual AET for AR and VR soil types across the study region (see Fig. 1).

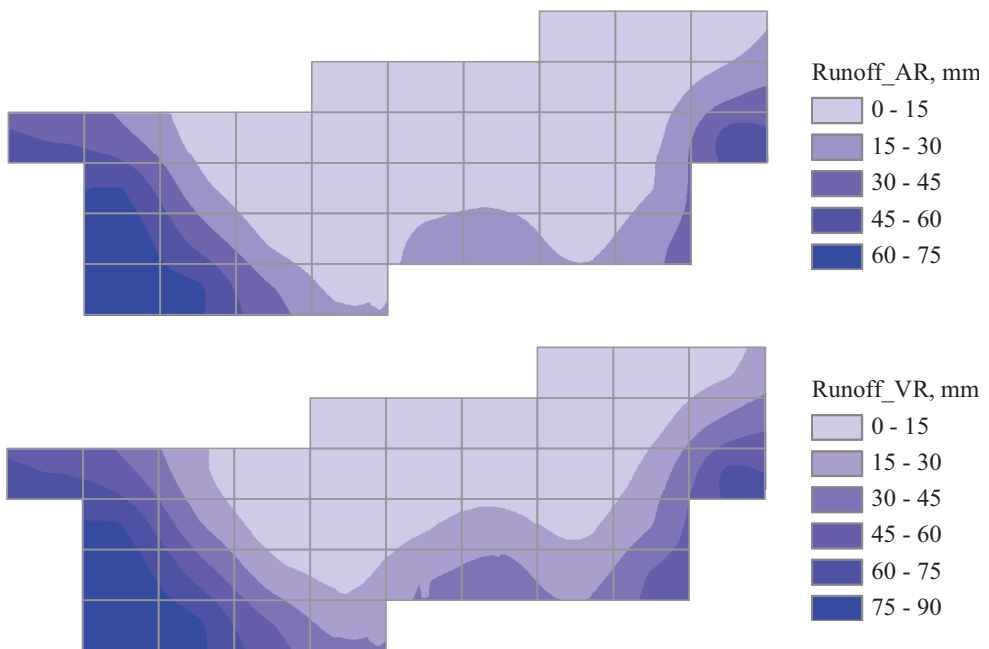


Figure 11. Map showing distribution of annual runoff for AR and VR soil types across the study region (see Fig. 1).

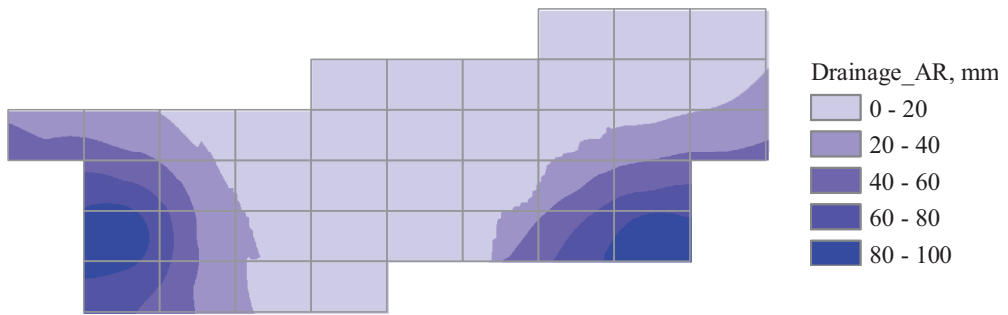


Figure 12. Map showing distribution of annual drainage for AR soil type across the study region (see Fig. 1).

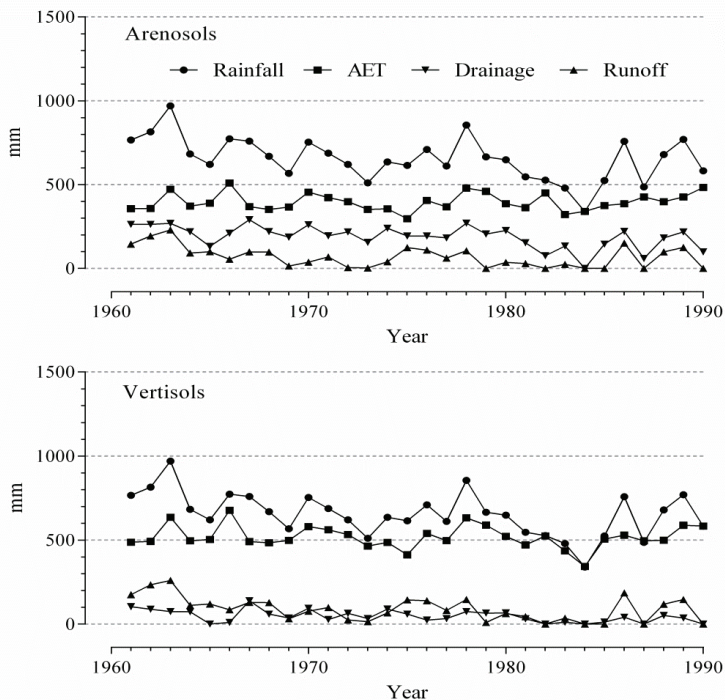


Figure 13. Annual rainfall and WATBAL modelled water balance components for AR and VR soil types for the Rashad map sheet (11.5 °N, 30.75 °E) during 1961-1990.

The seasonal water balance averaged over the 39 grids for AR and VR soil types were presented in Fig. 14. The rainy season occurred between May and October; outside this period, rainfall was negligible. The rainfall was high enough for the soil to be recharged during the period July to January for AR soils (totalling 63 mm) but for a shorter period (July to October) for VR soils (totalling 6 mm), otherwise soil water contents at the end of the month were reduced to the PWP. However, there was a soil water deficit (SMfc minus available soil water content at the end of the month) for each month. This monthly deficit averaged 69 mm for AR soils and 133 mm for VR soils, reflecting a monthly

evapotranspiration deficit (PET minus AET) averaging 217 mm for both soil types. The surface runoff that was generated during July and August for both soil types, and drainage, which was generated from AR soils only, occurred during August and September.

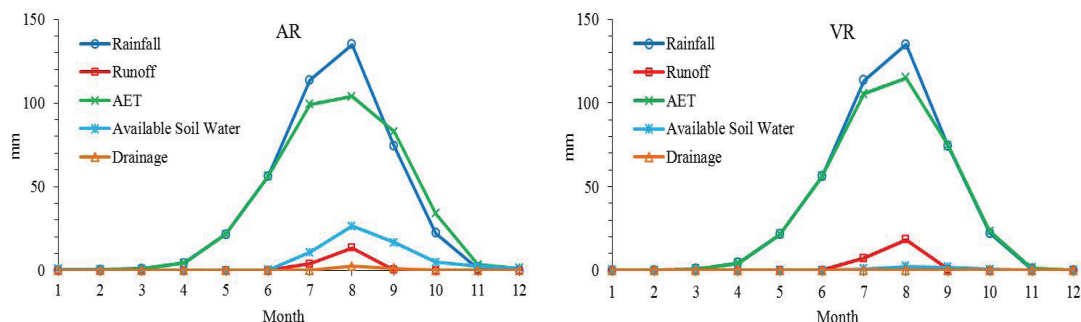


Figure 14. Map sheet mean (n = 39) seasonal (monthly) water balances for AR and VR soil types.

Table 6. Descriptive statistics of annual rainfall, temperature and WATBAL modelled water balance components for AR and VR soil types for the Rashad map sheet (11.5 °N, 30.75 °E) during 1961-1990.

|                                | Rainfall<br>(mm) | Temp.<br>(°C) | AR (mm) |         |         |                 | VR (mm) |         |         |    |
|--------------------------------|------------------|---------------|---------|---------|---------|-----------------|---------|---------|---------|----|
|                                |                  |               | AET     | R       | D       | SM <sup>a</sup> | AET     | R       | D       | SM |
| Minimum                        | 339              | 26.2          | 297     | 0       | 0       | 1               | 343     | 0       | 0       | 0  |
| Maximum                        | 970              | 28.8          | 509     | 22<br>9 | 29<br>1 | 34              | 677     | 26<br>0 | 13<br>9 | 49 |
| Mean                           | 654              | 27.3          | 396     | 68      | 18<br>9 | 26              | 519     | 89      | 47      | 37 |
| Coefficient of<br>variation, % | 20               | 3             | 13      | 92      | 36      | 23              | 13      | 81      | 77      | 29 |

<sup>a</sup> SM = end-of-month mean available soil moisture content of upper 1 m soil

### 3.4 Climate change impacts on biomass C density and water-use (IV)

Baseline (1961-1990) MAP for the eight study grids ranged from 140 to 654 mm and MAT from 23.3 to 29.1 °C (Table 7). Depending on climate change scenario, MAP showed both increases and decreases for 2080s compared to baseline values but MAT only showed increases. Compared to baseline, the increases in MAP ranged from +112 (Al Nahud; ECHam4\_A1FI) to +221 (Muglad; ECHam4\_A1FI) mm and in case of decreases, the change in MAP varied from -13 (Khartoum; CGCM2\_A1FI) to -188 (Rashad; CGCM2\_A1FI) mm (Fig. 15). The increases in MAT compared to baseline varied from +1.2 (Qala'a Al Nahal and Rashad; PCM\_B1) to +8.3 (Qala'a Al Nahal; ECHam4\_A1FI) °C. The A1FI scenarios resulted in the highest MAT values compared to B1 scenarios (2.4 °C higher when averaged across GCMs and grids; Table 8). However, values for MAP were lower with the A1FI scenarios than with the B1 scenarios (34 mm lower when averaged across GCMs and grids; Table 8).

Table 7. Map sheet grid baseline (1961-90) MAT (°C), MAP (mm), annual AET (mm), plant available water capacity (PAWC, mm) of soil, Kc and above-ground woody biomass C density (g C m<sup>-2</sup>) values for AR and VR soil types.

| Map sheet grid               | MAT  | MAP | AET |     | PAWC <sup>a</sup> |     | Kc   |      | Biomass C |
|------------------------------|------|-----|-----|-----|-------------------|-----|------|------|-----------|
|                              |      |     | AR  | VR  | AR                | VR  | AR   | VR   |           |
| Al Fasher                    | 23.3 | 386 | 346 | 385 | 74                | 134 | 0.45 | 0.65 | 55        |
| Al Nahud <sup>b</sup>        | 27.2 | 368 | 332 | -   | 74                | -   | 0.45 | -    | 49        |
| Al Obeid                     | 28.1 | 264 | 256 | 263 | 74                | 134 | 0.42 | 0.62 | 28        |
| Kadugli                      | 27.1 | 598 | 420 | 555 | 75                | 134 | 0.58 | 0.78 | 171       |
| Khartoum                     | 29.1 | 140 | 140 | 140 | 74                | 134 | 0.41 | 0.61 | 14        |
| Muglad                       | 27.6 | 506 | 394 | 503 | 74                | 134 | 0.51 | 0.71 | 105       |
| Qala'a Al Nahal <sup>c</sup> | 28.8 | 603 | -   | 496 | -                 | 134 | -    | 0.79 | 177       |
| Rashad                       | 27.3 | 654 | 443 | 579 | 74                | 134 | 0.65 | 0.85 | 232       |
| Mean                         | 27.3 | 440 | 333 | 417 | 74                | 134 | 0.50 | 0.72 | 104       |

<sup>a</sup> Difference between water content of soil (1 m) when at FC and PWP

<sup>b</sup> Al Nahud grid only has AR soil type

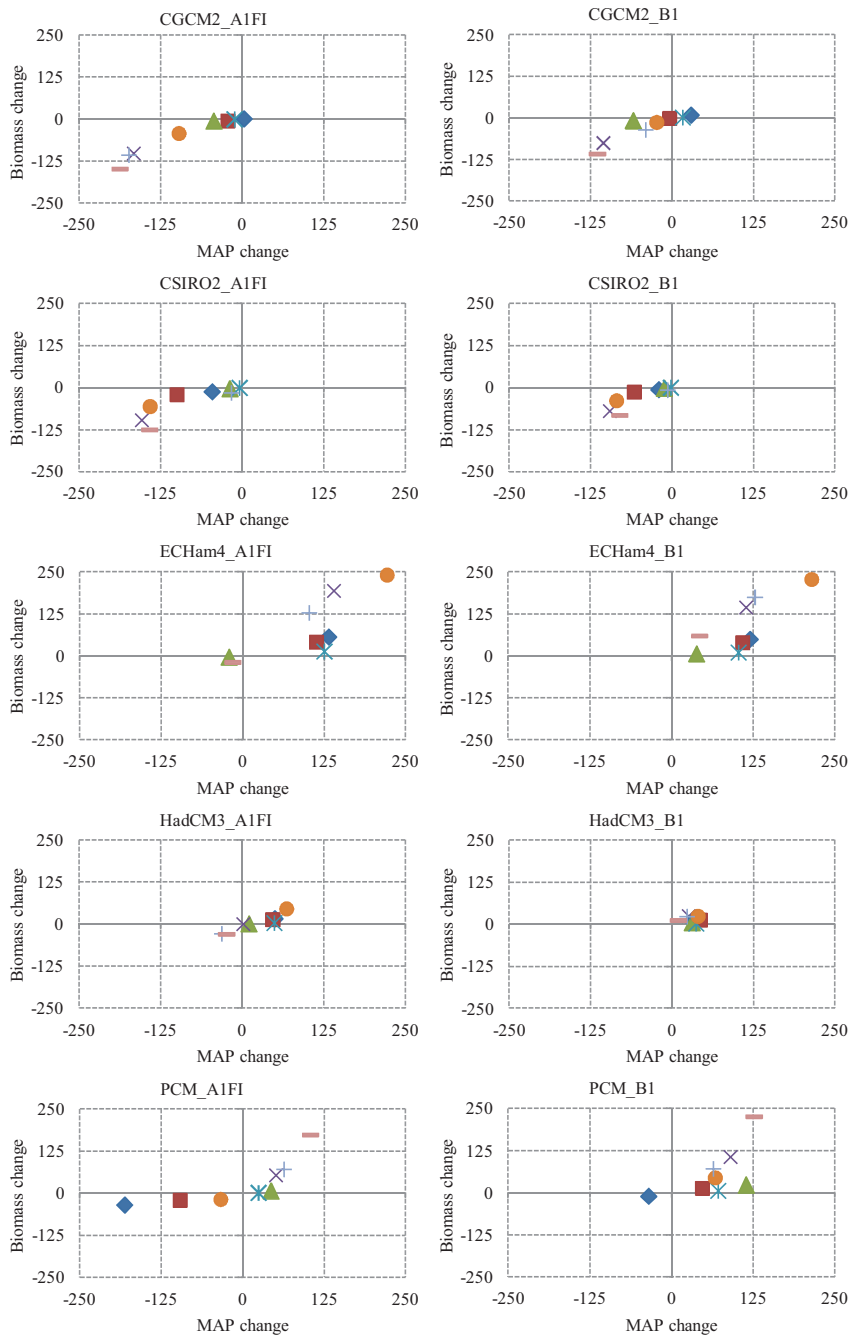
<sup>c</sup> Qala'a Al Nahal grid only has VR soil type

Table 8. Map sheet grid MAT (°C), MAP (mm), annual AET (mm) and above-ground woody biomass C density (g C m<sup>-2</sup>) for AR and VR soil types during the 2080s for the A1FI and B1 emission scenarios (averaged across the five GCMs).

| Map sheet grid               | A1FI |     |          |          |           | B1   |     |          |          |           |
|------------------------------|------|-----|----------|----------|-----------|------|-----|----------|----------|-----------|
|                              | MAT  | MAP | AET (AR) | AET (VR) | Biomass C | MAT  | MAP | AET (AR) | AET (VR) | Biomass C |
| Al Fasher                    | 28.4 | 377 | 353      | 360      | 60        | 26.0 | 411 | 387      | 400      | 65        |
| Al Nahud <sup>a</sup>        | 32.2 | 355 | 332      | -        | 51        | 29.8 | 395 | 372      | -        | 60        |
| Al Obeid                     | 33.1 | 258 | 258      | 257      | 28        | 30.7 | 286 | 287      | 287      | 34        |
| Kadugli                      | 31.9 | 572 | 468      | 529      | 181       | 29.6 | 603 | 477      | 574      | 198       |
| Khartoum                     | 34.2 | 176 | 176      | 175      | 18        | 31.8 | 184 | 184      | 184      | 19        |
| Muglad                       | 32.4 | 509 | 453      | 478      | 139       | 30.1 | 548 | 478      | 520      | 154       |
| Qala'a Al Nahal <sup>b</sup> | 33.8 | 591 | -        | 480      | 186       | 31.3 | 636 | -        | 517      | 222       |
| Rashad                       | 32.1 | 601 | 478      | 559      | 203       | 29.8 | 650 | 504      | 603      | 254       |
| Mean                         | 32.3 | 430 | 360      | 406      | 108       | 29.9 | 464 | 384      | 441      | 126       |

<sup>a</sup> Al Nahud grid only has AR soil type

<sup>b</sup> Qala'a Al Nahal grid only has VR soil type



◆ Al Fasher   ■ Al Nahud   ▲ Al Obeid   ✕ Kadugli   \* Khartoum   ● Muglad   + Qala'a Al Nahal   - Rashad

Figure 15. Map sheet grid biomass C density ( $\text{g C m}^{-2}$ ) and MAP (mm) changes in 2080s relative to baseline (1961-90) values for each climate change scenario.

Baseline (1961-1990) biomass C density values for the eight study grids estimated using MAP (*Study II*) varied from 14 to 232 g C m<sup>-2</sup> (Table 7). Biomass C densities, estimated from MAP, under the various climate change scenarios for 2080s either increased or decreased depending on grid and climate change scenario (Fig. 15). The increases in biomass C density varied from +14 (Khartoum; ECHam4\_A1FI) to +241 (Muglad; ECHam4\_A1FI) g C m<sup>-2</sup> and the decreases from -1 (Khartoum; CGCM2\_A1FI) to -148 (Rashad; CGCM2\_A1FI) g C m<sup>-2</sup>. Biomass C density values were lower with the A1FI scenarios than with the B1 scenarios (18 g C m<sup>-2</sup> lower when averaged across GCMs and grids; Table 8).

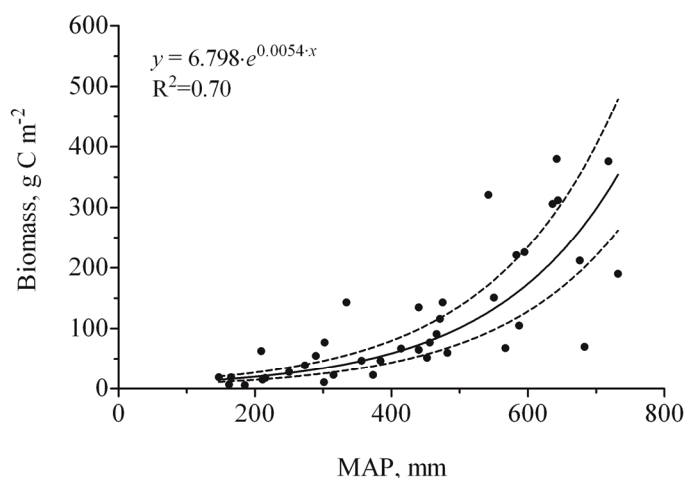


Figure 16. Relationship between map sheet grid mean above-ground biomass C density and long-term MAP. *Dotted lines* show upper and lower limit of 95% confidence limits (n = 39).

The confidence interval of the biomass C density estimate increases with MAP and estimates of biomass C density, which are based on the relationship between current biomass C density and MAP, are subject to considerable uncertainty (Fig. 16). The 95% confidence limits of the predicted biomass C density for the eight grids under baseline and each climate change scenario are presented in Fig. 17. The results show that the effect of climate change on biomass C density is only significant ( $p < 0.05$ ) when the MAP is greater than 250-260 mm and for certain climate change scenarios. Under the A1FI emissions scenario a significant impact of climate change on biomass C density is associated with the CGCM2, CSIRO2 (each 4 grids), ECHam4 (3 grids) and PCM (2 grids) climate change models. Under the B1 emission scenarios the number of climate change scenarios having a significant impact on biomass C density were fewer; ECHam4 (3 grids) and CGCM2 (1 grid) climate change models.

Baseline (1961-1990) mean annual AET values for the eight study grids varied from 140 to 579 mm for VR soils and from 140 to 443 mm for AR soils (Table 7). Relative to baseline values, AET for 2080s also either increased or decreased depending on grid and climate change scenario (Figs. 18a and 18b). Considering minimum and maximum scenarios within each grid and relative to baseline values, AET for VR soils among the grids, increases from +100 (Qala'a Al Nahal; PCM\_A1FI) to +145 (Muglad; ECHam4\_A1FI) mm and decreases from -12 (Khartoum; CGCM2\_A1FI) to -178 (Al Fasher; PCM\_A1FI) mm. Whereas the increases of AET for AR soils among the grids varied from +82 (Al Nahud; PCM\_B1) to

+197 (Rashad; PCM\_B1) mm and the decreases from -12 (Khartoum; CGCM2\_A1FI) to -132 (Al Fasher; PCM\_A1FI) mm. As with MAP, AET values were lower with the A1FI scenarios than with the B1 scenarios (35 and 24 mm lower, respectively for VR and AR soils when averaged across GCMs and grids; Table 8).

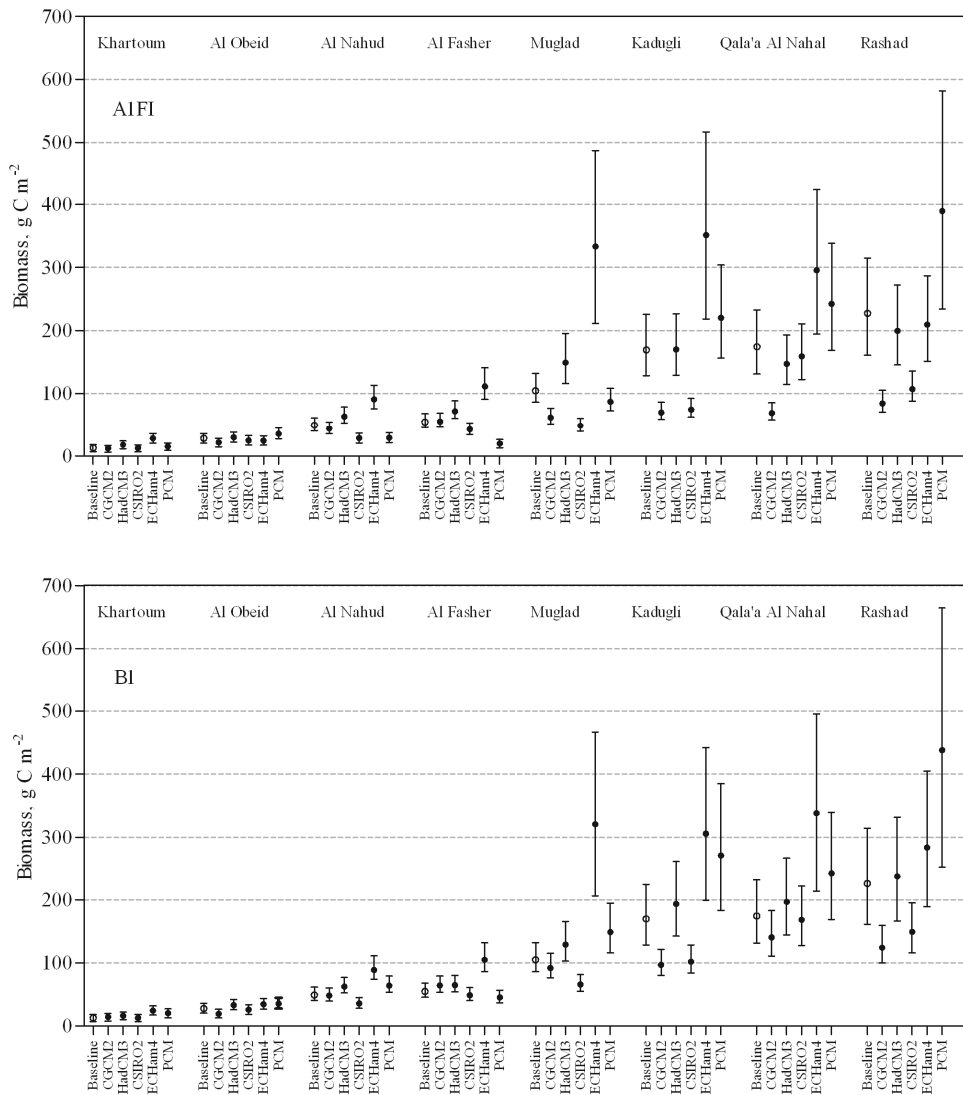


Figure 17. Estimated biomass C density values under baseline (1961-90) and climate change scenarios for 2080s calculated using the exponential model ( $y = 6.798.e^{0.0054.x}$ ,  $R^2 = 70\%$ ). Error bars are the 95% confidence limits. Map sheet grids ordered from lowest to highest according to baseline MAP values.



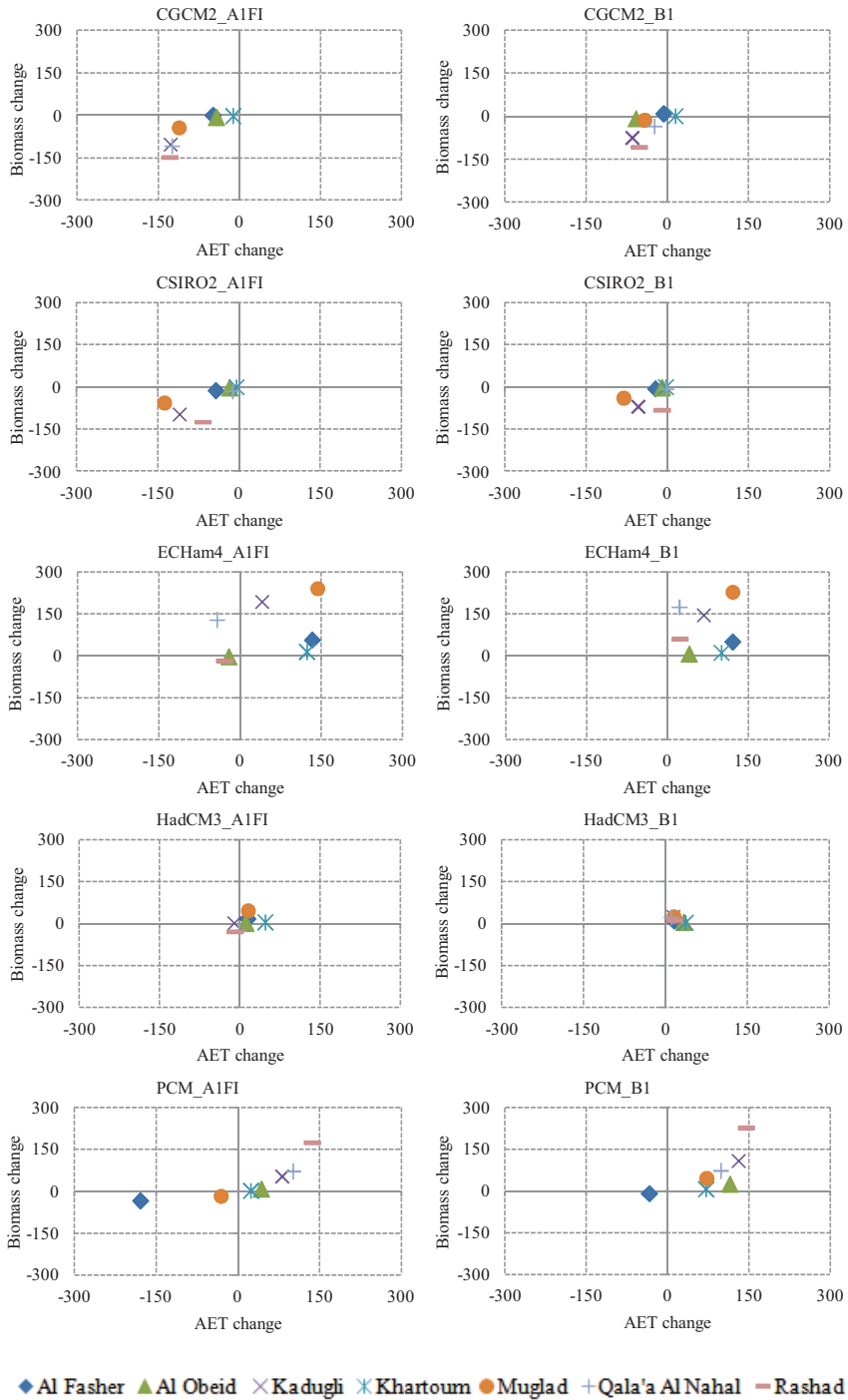


Figure 18a. Map sheet grid biomass C density ( $g\ C\ m^{-2}$ ) and AET (mm) changes in 2080s relative to baseline (1961-90) values for VR soil type and for each climate change scenario.

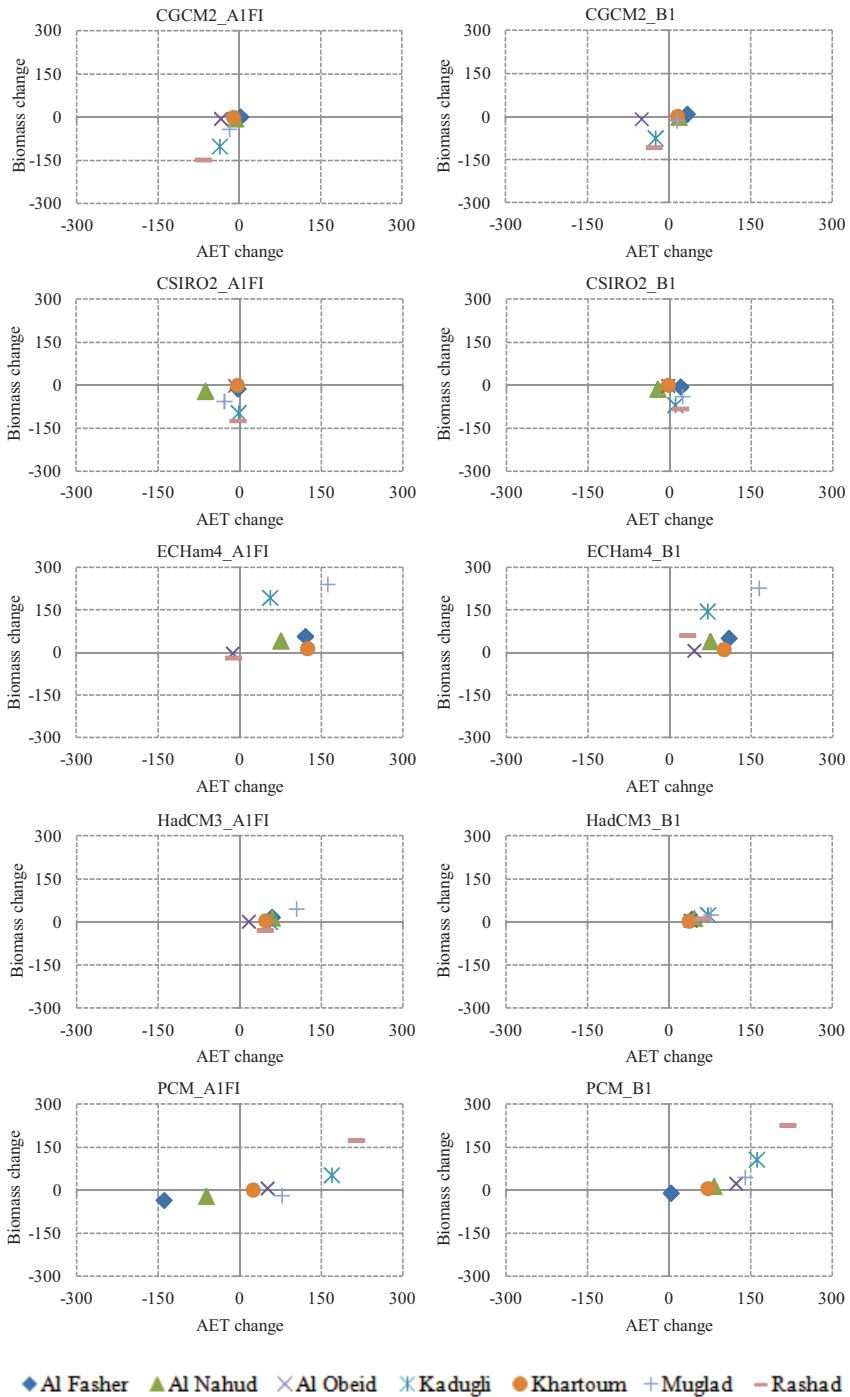


Figure 18b. Map sheet grid biomass C density ( $\text{g C m}^{-2}$ ) and AET (mm) changes in 2080s relative to baseline (1961-90) values for AR soil type and for each climate change scenario.

## 4. Discussion

### 4.1 Deforestation and GHG emissions (I)

The term ‘deforestation’ is often unclear and partly related to more than 90 definitions of forest in use around the world (Lepers et al. 2005). However, because of the need for GHG emissions and C accounting related to climate change impacts issues, attempts to define ‘forest’, ‘deforestation’ and ‘forest degradation’ have been made. An area is considered as ‘forest’ if it has a canopy cover of at least 10% (FAO 2010a) and ‘deforestation’ refers to the long-term or permanent loss of forest cover and implies the conversion of forest to another land cover or the reduction in tree canopy cover to below 10% (Ramankutty et al. 2006, FAO 2010a, UNEP 2012). An area is not considered deforested if there is a guarantee that the forest cover will be maintained through regeneration of the forest. Forest ‘degradation’ refers to the loss of quality of the forest, rather than coverage (UNEP 2012). The quality of a forest can be observed through monitoring the survival rates of ecosystem components, e.g. vegetation layers, soil, flora and fauna. The gathering of wood for fuel, and damage from insects and pests are some of the causes of forest degradation. Remote sensed estimates of tree canopy cover for Sudan (Wu 2011) indicate that the canopy cover for the study region in summer increases from <5% in the north to up to 60% in the central and western southern areas of the study region, while values in the autumn are lower (<5 to 40%). Therefore, not all the area of savannah woodlands included in this study would be classified as ‘forest’.

The fuelwood consumed by the Sudanese BMIs mainly comes from the cutting down trees, and there is no replanting or regeneration carried out. Therefore the fuelwood consumption of the BMIs can be considered to result in deforestation rather than forest degradation; the exception being Gezira state, where plantations are used, and Kassala, where fruit trees are used. While the use of fruit trees is not considered as forest loss, it does however represent a loss of biomass and therefore C storage. The mean annual fuelwood consumption and associated deforestation by the surveyed BMIs for study regions in Sudan were presented in Table 1. In Khartoum state and in the rest of Sudan, 13 tree species (*Acacia nilotica*, *Acacia seyal*, *Acacia mellifera*, *Acacia tortilis*, *Acacia nubica*, *Faidherbia albida*, *Azadirachta indica*, *Eucalyptus* spp., *Prosopis juliflora*, *Capparis decidua*, *Mangifera indica*, *Citrus paradisi*, and *Psidium guajava*) are reported to be used. In the Gezira state, only *Acacia nilotica* is used and the wood comes from plantations managed by the FNC of Sudan. In *Study I* it was observed that the mean annual fuelwood consumption by BMIs in the Kassala state was 10-fold that of BMIs in the other states. The higher fuelwood consumption value of the Kassala is related to low fuelwood consumption efficiency (fuelwood consumption per 1000 bricks) and is due to a number of factors, including the type of clay used, the clay to dung or bagasse (cane residues) mix ratio, size of brick produced, and the species used for fuelwood (Hamid 1994, FNC/FAO 1995). In Kassala state, fruit trees (in particular mango, grapefruit and guava) and mesquite (*Prosopis juliflora*) were used by the BMIs as fuel, which have low calorific values.

The upscaled fuelwood consumption values of BMIs’ for the study regions and whole of Sudan (3450 BMIs) were given in Fig. 2. Fuelwood consumption is clearly dominated by the Khartoum state (ca. 0.3 million m<sup>3</sup>), accounting for 58% of the total fuelwood consumption (0.5 million m<sup>3</sup> of roundwood annually). The FNC/FAO (1995) estimated that the total annual consumption of wood by the BMIs was about 0.55 million stacked m<sup>3</sup>, which would correspond to 0.3 million m<sup>3</sup> of roundwood volume (assuming 1 m<sup>3</sup> roundwood = 1.795 m<sup>3</sup> stacked roundwood), and Hamid (1994) reported that the Khartoum state accounted for 46%

of BMI fuelwood consumption and 42% by the central states. However, both these studies were based on 1700 BMI units. Using the Sudan's mean volume ( $3.5 \text{ m}^3 \text{ ha}^{-1}$ ) of above-ground tree biomass (*Study II*), the total forest area (70 220 000 ha) of Sudan in 2005 (FAO 2010a) and the total annual amount of fuelwood ( $508\,392 \text{ m}^3$ ) consumed by BMIs in Sudan (*Study I*), it can be calculated that 0.2% of Sudan's total wood volume ( $245\,770\,000 \text{ m}^3$ ) is consumed annually by the BMIs. However, because neither the source of the fuelwood used by BMIs nor the area of forest in the study region are precisely known, the amount of deforestation (ha) due to the BMIs cannot be calculated. The Global Forest Resources Assessment reports the annual loss of forest cover in the Sudan of  $54\,000 \text{ ha yr}^{-1}$  (0.08% of forest land) during the period 2000-2005 (FAO 2010a).

Total  $\text{CO}_2$  emissions from fuelwood burning in Africa for the year of 1996 was estimated at 597 553 000 t, of which Sudan's contribution was 8 814 000 t (Amous 1999). The upscaled BMIs annual GHG emission values for study regions and for whole of Sudan were given in Table 3. The emissions are clearly dominated by  $\text{CO}_2$ , which total some 378 028 t for the whole of Sudan and that accounts for 4.3% of the total fuelwood  $\text{CO}_2$  emissions from Sudan. According to Sudan's national GHG inventory, emissions from all sources totalled 25 800 000 t in 1995, of which 75% ( $19\,350\,000 \text{ t}$ ) was  $\text{CO}_2$  (MEPD/HCENR 2003). Using the value of  $19\,350\,000 \text{ t}$  for  $\text{CO}_2$  emissions from Sudan, it can be estimated that the BMI accounts for only 2% of Sudan's total  $\text{CO}_2$  emissions. For comparison, the total global amount of C emitted in 1995 from all energy activities was estimated at 6 billion t. Thus, Sudan's contribution to global GHG emissions is very modest, even in comparison to other developing countries. However, because of the uncertainty about the number and size of BMIs, the estimates of GHG emissions associated with the BMI as reported in *Study I* should be considered with some caution.

#### 4.2 Biomass and soil C densities (II)

Grid mean above-ground biomass C density value of this study was  $112 \text{ g C m}^{-2}$  (Table 4). There are few published values for woodland savannah with which to compare biomass C density values of this study. Tiessen et al. (1998) reported above-ground biomass C density values for degraded savannah in Senegal of between 100 and  $200 \text{ g C m}^{-2}$  and that of non-degraded savannah were  $175 \text{ g C m}^{-2}$  in Senegal and  $120 \text{ g C m}^{-2}$  in Burkina-Faso (biomass density values were converted into biomass C densities assuming a dry weight biomass C content of 50%). These values are within the range calculated in this study (cf. Table 4). However, the highest savannah woodland tree biomass C density values of this study only overlap with lower above-ground biomass C density values ( $180\text{-}3400 \text{ g C m}^{-2}$ ) reported for savannah ecosystems globally by Grace et al. (2006). Using the Miami model, which predicts plant community NPP from MAP, modified for the tropics (Friedlingstein et al. 1992), the mean NPP for the grids was 273 (ranged from 105 to 433)  $\text{g C m}^{-2} \text{ yr}^{-1}$ , which is similar to biomass C densities of this study. Since NPP is typically one or two orders of magnitude lower than the standing biomass (e.g. O'Neill and DeAngelis 1981, Jiang et al. 1999), the biomass C densities of this study would indicate that the Sudanese savannah woodlands are considerably depleted and below potential stocking.

Grid mean below-ground biomass C density and mean root-shoot ratio of this study were  $33 \text{ g C m}^{-2}$  (Table 4) and 0.31, respectively. Tiessen et al. (1998), using an above- to below-ground biomass ratio of 0.38, reported below-ground biomass C density values of between 250 and  $500 \text{ g C m}^{-2}$  for degraded savannah in Senegal, while Grace et al. (2006) reported that of between 490 and  $5000 \text{ g C m}^{-2}$  for savannah ecosystems from around the world. Below-

ground biomass C densities of this study are clearly lower than these values. This may be partly explained by the lower root shoot ratios used in the study, but also may be an indication of the degree of land degradation that has taken place across the study region. Mean total biomass C density value ( $146 \text{ g C m}^{-2}$ ; Table 4) of this study is, however, comparable with the values reported in studies (Woomer et al. 2004, Takimoto et al. 2008) that have been carried out in similar climatic and vegetation conditions of this study. Takimoto et al. (2008) reported a total biomass C density value of  $70 \text{ g C m}^{-2}$  for degraded land with bushes and grasses in Mali. Woomer et al. (2004) reported an average total biomass C density of  $258 \text{ g C m}^{-2}$  for the Sahel transition zone in Senegal covering degraded grassland, scattered shrubs and trees. In such a regional study that carried out across the whole Sudanese gum belt region, uncertainties in the data may exist, much of it difficult, if not impossible, to quantify. However, since biomass C density values of this study are based on forest inventories, they are considered reliable and reflecting the current situation.

Grid mean SOC density values of this study for the top- (0-30 cm) and sub-soil (30-100 cm) were  $2558$  and  $2895 \text{ g C m}^{-2}$ , respectively and that of to a depth of 1 m was  $5453 \text{ g C m}^{-2}$  (Table 4). Studies (Post et al. 1982, Jobbágy and Jackson 2000, Henry et al. 2009) those used soils data from the FAO/UNESCO Soil Map of the World (FAO/UNESCO 1971-1981), which is incorporated into the HWSO are essentially the same as used in this study and provided similar SOC density values. Henry et al. (2009) reported SOC density values of  $1530 \text{ g C m}^{-2}$  for the 0-30 cm layer in African desert and xeric shrubland ecoregion and Jobbágy and Jackson (2000) reported mean SOC densities to 1 m depth for deserts of  $6200 \text{ g C m}^{-2}$ . Post et al. (1982) reported global SOC densities to 1 m depth for tropical woodland and savannah of  $5400 \text{ g C m}^{-2}$  and for tropical very dry forest of  $6100 \text{ g C m}^{-2}$ . Studies (Neary et al. 2002, Woomer et al. 2004) that used independent data also reported similar SOC density values as in this study. Using the database of the US Soil Survey Laboratory, Neary et al. (2002) reported average SOC density values (1 m) of  $2500 \text{ g C m}^{-2}$  for hot desert scrubland forest ecosystems and of  $7800 \text{ g C m}^{-2}$  for sparse woodland or scrubland forest ecosystems in western US. Woomer et al. (2004) reported mean SOC densities of  $1725 \text{ g C m}^{-2}$  to 40 cm depth in Senegal's Sahel transition zone.

Studies that have been carried out in Sudan by Jakubaschk (2002) and El Tahir et al. (2009) give considerably lower SOC density values than this study. The SOC densities reported by Jakubaschk (2002) averaged  $416 \text{ g C m}^{-2}$  (ranging from 315 to 510) for the 0-20 cm layer and  $490 \text{ g C m}^{-2}$  (ranging from 436 to 621) for the 20-50 cm layer in sandy soils (Arenosols) supporting undisturbed *Acacia senegal* in Northern Kordofan. However, the SOC density values reported by Jakubaschk (2002) are based on only a few soil samples (6 for 0-20 cm and 5 for 20-50 cm soil layer) and were taken in the open between tree canopies. Other studies have shown that SOC contents in *Acacia* sites are considerably lower in the open than under the canopy (Weltzin and Coughenour 1990; Githae et al. 2011). The study by El Tahir et al. (2009) was based on 144 soil samples taken 1 m from the trunks and in the open (mid-way between the trees) of a pure 6-year-old *A. senegal* plantation growing on cambic Arenosols in North Kordofan. They reported a mean SOC density value of  $738 \text{ g C m}^{-2}$  for the 0-30 cm layer. Besides differences in sampling, the higher SOC density values in *Study II* compared to the results of the studies cited above may also be related to that fact that the C contents reported in the HWSO for the Sudan are based on a general soils map made in the 1950s (Worral 1961). Extensive degradation and losses in SOC has taken place over the last few decades (FAO/UNESCO 1971-1981, Selvaradjou et al. 2005). Modelling studies carried out by Olsson and Ardö (2002), Ardö and Olsson (2003) and Poussart et al. (2004) indicate a considerable reduction in SOC has taken place during recent decades. Ardö and Olsson

(2004) estimated that SOC densities (0-20 cm) have declined from 851 g C m<sup>-2</sup> in 1963 to 227 g C m<sup>-2</sup> in 2000 for cultivated Arenosol soils in North Kordofan.

Both above-ground biomass C and SOC densities of this study were positively and significantly ( $p < 0.05$ ) correlated with MAP ( $r_s = 0.84$  and  $r_s = 0.34$ , respectively; Fig. 5) but non-significantly correlated with MAT ( $r_s = -0.22$  and  $r_s = 0.24$ , respectively; Fig. 6). In a global scale study, Jobbágy and Jackson (2000) reported SOC contents to be positively correlated with MAP ( $r = 0.25$ ,  $p < 0.001$ ) but negatively correlated with MAT ( $r = -0.16$ ,  $p < 0.001$ ). Since above-ground (and total) biomass C densities of this study were found to be directly and significantly correlated to MAP but only weakly and non-significantly correlated to MAT, the relationships would reflect the dependence of biomass productivity on the availability of soil water in drylands (Halwagy 1961). The significant correlation ( $r_s = 0.34$ ; Fig. 7) between SOC densities and above-ground (and total) biomass C densities would indicate a broad dependence of SOC contents on plant and root litter production. However, due to the large variation in C densities among the grids, particularly in the biomass C densities (cf. Table 4), the correlation was weak. While the degree of degradation in both woodland biomass and soil is likely vary among the grids due to differences in fire frequency, fuel wood collection, grazing pressure and population density, for example, the ratio of above-ground biomass C to SOC densities was strongly correlated to MAP. This indicates that the proportion of ecosystem C that is sequestered in the biomass and in the soil is strongly controlled by climate rather than being the result of degradation.

### 4.3 Water balance of savannah woodlands (III)

Existing water scarcity in drylands is projected to increase over time due to high population pressure, and changes in climate, land use and land cover (Hassan et al. 2005). Looking at the long-term water balance at the regional scale is particularly useful when assessing how these factors are related and interact, and for planning the mitigation of water scarcity. The use of simple water balances models, such as the one used in this study and *Study IV*, is therefore appropriate and indeed the only means for making regional assessments of the water balance. Unfortunately, appropriate climate data, particularly global radiation and evapotranspiration, and data on runoff and soil moisture for validating and calibrating water balance models are rarely available for African countries (Williams and Albertson 2005). There is clearly a great need for appropriate data to be collected and made available and for in-depth studies in the region to be carried out.

The meteorological and soil data for the Demokeya site (Ardö 2013) used to validate the model is very much the exception. The study considers the goodness-of-fit to the Demokeya daily data to confirm the conceptual and operational validity of WATBAL and its suitability for making the regional long-term water balances. Calibration of soil hydraulic parameters using the soil moisture data could be expected to have improved the goodness-of-fit. Estimates of SM<sub>fc</sub> and SM<sub>pwp</sub> using the reported soil texture data and the Saxton pedotransfer function (Saxton et al. 1986) were respectively 8.3% and 2.5%, which are different from the values used in this study as reported by Ardö (2013).

As a result of high evaporation demand (PET) in drylands that varies little from year-to-year and consistently higher than rainfall (Nicholson et al. 1997, Ayoub 1999), most of the annual rainfall is lost through evapotranspiration, soil moisture contents brought close to PWP, and runoff and drainage made minimal and highly variable components of the water balance. This pattern in the distribution of water among the components of the water balance was borne out



by the long-term water balances for the entire study region and by the interannual variation exemplified by the Rashad map sheet. Interannual variation in the water balance is likely to increase with climate change (Huntington 2006), which may make water security in drylands particularly challenging in the future.

Map sheet annual AET for AR soils averaged 408 (ranged from 147 to 652) mm and that of for VR soils averaged 403 (ranged from 147 to 669) mm (Table 5). There were no published values for Sudanese woodland savannah with which to compare AET values of this study. But at continental level of study in Africa, Ateawung (2010) reported that annual AET values range from 0 to 2162 mm with the mean value of 588 mm. This study also reported that the annual AET value for arid region in Africa ranges from 100 to 250 mm and that of for semi-arid region varies from 200 to 700 mm. Both Ateawung (2010) and Nicholson et al. (1997) mentioned that in the central part of the Sahel (about 15 °N), the annual AET value is 500 mm. Shahin (2002) summarized previously computed water balance studies for Africa and reported that annual AET values ranges between 492 and 587 mm. Apparently, annual AET values of this study are within the range of previously computed values.

AET characteristically accounts for most of the rainfall in dryland regions. In this study, AET accounted for 75% to 100% of map sheet MAP for AR soils and from 83% to 100% of map sheet MAP for VR soils. There was little difference in AET values between AR and VR soils in spite of large differences in the plant available moisture storage capacity (PAWC; AR soils:  $\bar{x} = 74 \pm 0.4$  mm; VR soils:  $\bar{x} = 134 \pm 0.5$  mm). Map of annual AET values of this study showed good agreement with that produced by Nicholson et al. (1997) for the same region and map sheet AET values were strongly correlated with Bodyko ET values produced by New LocClim ( $R^2 = 0.83$  for AR soils and 0.84 for VR soils). The monthly water balances showed that AET parallels the seasonal distribution of rainfall.

The WATBAL model used a single  $K_c$  value, based on the tree biomass C density present, to convert reference crop evapotranspiration  $PET$  values into  $PET$  values appropriate for the cover and evaporative ability of the trees present. While some savannah woodland species are evergreen others shed their leaves during the dry season so that canopy cover varies during the year (Murphy and Lugo 1986, Sarmiento and Monasterio 1992, Timberlake et al. 2010). Changes in canopy cover may be expected to affect AET and therefore using  $K_c$  values that change during the season in order to reflect the changes in canopy cover and development may be expected to produce more reliable AET estimates.

The study tried using a seasonal  $K_c$  (lower monthly  $K_c$  values during the dry season months) but found it had little effect on the annual AET values. The content of plant available water in the soil was calculated for a 1 m layer; this being the depth to which soil data was available for. While the maximum depth of the tree roots may exceed 1 m (Canadell et al. 1996) and so expected to increase the amount of available water for evapotranspiration (Zhang et al. 2001), studies have found that different types of drylands vegetation cover (varying combinations grass and wood) have little or no significant effect on water-use (Kabatawala et al. 1997, Williams and Albertson 2005). This is further confirmation that AET in dryland regions is limited by rainfall rather than the characteristics of the vegetation and availability of soil water.

The study was unable to separate AET into its three components (interception, bare soil evaporation and transpiration). Savannah woodlands have canopies that are sparse and of mixed species and a heterogeneous ground cover (grass and bare soil), all of which make modelling AET difficult (Wallace 1991). This complexity is made even more complex when

one considers the effects of stripped vegetation typical of African drylands on runoff-runon (Cornet et al. 1992, Dunkerley 2000) and the effects of soil crusting and sealing on infiltration (Abu-Awwad 1997, Francis et al. 2007).

Map sheet annual runoff values for VR soils averaged 26 (ranged from 0 to 109) mm and that of for AR soils averaged 17 (ranged from 0 to 89) mm (Table 5). Map sheet annual runoff accounted for up to 17% of MAP on VR soils and for up to 14% on AR soils and were strongly correlated with Bodyko runoff values produced by New LocClim ( $R^2 = 0.59$  for AR and 0.68 for VR soils). Furthermore, map of annual runoff of this study was in good agreement with the high resolution map of annual runoff for the region presented by Nicholson et al. (1997). Drainage from below 1 m depth (to groundwater) was negligible for VR soils across the study region and for AR soils only accounted for a maximum of 11% of MAP in the case of the four map sheets at which drainage occurred. Although the SMfc of AR soils was 29% of the value for VR soils for all map sheets, the PET demand was so high that soil moisture contents were rarely able to exceed FC even on sandy soils. Though there is no study available that reported annual drainage values for the Sudan, Nicholson et al. (1997) and Ateawun (2010) showed very little or no surface runoff for the Sahel region. For the south of the Sahel (12–15 °N) region, their reported annual drainage values ranges between 10 and 50 mm, and that of in the horn of Africa ranges between 0 and 10 mm.

#### **4.4 Climate change impacts on savannah woodlands (IV)**

The *Study IV* focused on the impacts of a number of climate change scenarios for 2080s on savannah woodland biomass C density and water-use in the Sudanese gum belt region. This study indicates that compared to baseline (1961-1990) values and depending on scenario, MAT in the 2080s would increase by between 1.2 and 8.3 °C but that MAP would either decrease (by up to -188 mm) or increase (by up to +221 mm). Mitchell and Hulme (2000) indicated MAT increases in Sudan for 2080s could reach a maximum of 6 °C. The SFNC have carried out climate change studies for the Kordofan region of Sudan and reported that by 2060 MAT may increase by 2.6 °C (Al Obeid and Al Nahud; HadCM2) and MAP may increase by 47 mm (Al Nahud; BMRC) or decrease by 31 mm (Babanusa; BMRC) (MEPD/HCENR 2003). Results for the Kordofan region according to this study indicate that MAT in the 2080s may rise by 7.1 °C (Al Obeid and Rashad; ECHam4\_A1FI), and the MAP either increase by 221 mm (Muglad; ECHam4\_A1FI) or decrease by 188 mm (Rashad; CGCM2\_A1FI). Presumably the larger MAT and MAP changes indicated in this study are due to longer time projection and to the use of different GCMs and climate change scenarios. However, it should be remembered that GCMs have been developed for global and continental scales, and climate change scenario data extracted for regional studies are less reliable, particularly concerning rainfall, and considerable uncertainty exists (Hewitson and Crane 1996, Elshamy et al. 2009). Regional Climate Models for much of Africa are scarce (Kamga et al. 2005, Nkomo et al. 2006, Christensen et al. 2007).

Water-use and water availability are important climatic controls on the distribution and density of forests (Stephenson 1990, Frank and Inouye 1994). In arid and semi-arid regions, PET typically exceeds rainfall and therefore water availability, and water-use and biomass production is largely determined by the amount of rainfall rather than temperature (Williams and Albertson 2004). Thus in *Study II*, biomass C density was found to be significantly and positively correlated with MAP but not correlated with MAT. Photosynthesis under increasing MAT is likely to be increasingly non-optimal while autotrophic respiration increased. It is therefore surprising that Scheiter and Higgins (2009), using adaptive



vegetation modelling and IPCC SRES scenario A1B with changes in CO<sub>2</sub>, temperature and rainfall, found that tree biomass in the savannah woodland region of Africa would increase. This increase is apparently due to the fertilization effect of elevated CO<sub>2</sub> concentrations. The SFNC has modelled a decrease in the forest area of the Sudan and a decline in gum production by between 25% and 30% by 2060 (MEPD/HCENR 2003). The results of this study indicate that, depending on climate change scenario, savannah woodland biomass C densities for the 2080s may either increase or decrease. The climate change to baseline biomass C density ratio varied from 0.36 (Rashad; CGCM2\_A1FI) to 3.30 (Muglad; ECHam4\_A1FI) (Fig. 15 and Table 7). This variation is a direct reflection of the changes in MAP as discussed earlier.

Mean annual baseline AET values (Table 7) of this study for AR soils as a percentage of MAP ranged from 71% for the wettest grid (Rashad) to 100% for the driest grid (Khartoum) and similarly for VR soils from 82% (Qala'a Al Nahal) to 100% (Khartoum) thus showing that AET is strongly limited by MAP in arid and semi-arid environments. A strong increase in biomass C density values occurs when AET is greater than 350-400 mm. The greater AET values for VR soils than for AR soils reflect the greater PAWC of VR soils (Table 7). The climate change to baseline annual AET ratio varied from 0.54 (Al Fasher) to 1.88 (Khartoum) for VR soils and from 0.61 (Al Fasher) to 1.89 (Khartoum) for AR soils. Irrespective of soil type, the largest relative changes in AET were associated with the grids having the lowest MAP values. For both VR and AR soil types, the PCM\_A1FI scenario generated the lowest relative change in AET and the ECHam4\_A1FI scenario generated the highest relative change in AET (Figs. 18a and 18b).

There is a general lack of climate, forest inventory, biomass and soil data for much of Africa, particularly dryland Africa (Tiessen et al. 1998, Jenkins et al. 2002, Poussart et al. 2004). According to the available information, this is the first study to use forest inventory data to determine the biomass C densities for the savannah woodland region of Sudan. Estimates of annual mean NPP for the eight grids using baseline MAP values and the global Miami NPP model modified for tropics (Friedlingstein et al. 1992), which gives more accurate estimates for the tropics, were more than double (grid mean NPP = 280 g C m<sup>-2</sup> yr<sup>-1</sup>) than our standing biomass values (Table 7). This discrepancy not only gives an indication of the degree of degradation and under stocking of the savannah woodlands but also an indication of their potential C sequestration possible role in climate change mitigation (Dixon et al. 1994, Canadell and Raupach 2008). However, biomass C density estimates of this study are based on the relationship between current biomass C density and MAP, and are subject to considerable uncertainty (Fig. 16) and only some of the climate change scenarios were shown to have a significant impact on future biomass C density (Fig. 17).

## 5. Conclusions and Recommendations

The present study is the first such regional scale study that deals with the C stocks (densities, both biomass and soil), water balance and water-use of dryland savannah woodlands and the impacts of climate change. Both the C and water cycles are important provisioning and regulating ecosystem services for the region, benefitting and supporting the livelihoods of millions of people, but under severe pressure from poor land-use management, growing population and climate change. This is also the first study that has dealt with the impact of fuelwood consumption on deforestation and GHG emissions in relation to an important local industry in a dryland environment.

*Study I* indicated that BMIs consume a considerable amount of fuelwood and contribute to ongoing deforestation and elevated GHG emissions. The main limitation of this study is the lack of information on the sources of fuelwood and so that the area deforested by the BMIs could not be calculated. Nevertheless, better regulation, use of biomass fuel from sustainable sources and technological improvements in BMIs kilns would reduce deforestation and GHG emissions.

*Study II* revealed that savannah woodland C densities, both biomass and soil, were low and below potential levels as a result of land degradation; that is, not in equilibrium with current climatic conditions. However, in spite of this lack of equilibrium, biomass C and SOC densities were positively and significantly correlated with each other and both significantly correlated to MAP but not to MAT. The biomass C density values in this study were based on Sudanese NFI data from the mid 1990s, which is the most reliable data available, and SOC density values on HWSO soil data, which pre-dates the recent land degradation and loss of SOC.

The water balance of drylands is characterized by low rainfall and high evaporation demand (PET). In *Study III*, a simple water balance model was found to reliably predict the annual and monthly water balance of the savannah woodlands in Sudan. The modelling showed that the annual AET largely corresponds to the annual amount of rainfall, but for some areas and some months, rainfall exceeded AET resulting in soil water contents being above PWP at the end of the month and the generation of surface runoff. The use of seasonal Kc to reflect leaf shedding during the dry season was found not to have a significant effect on AET and due to the permanently high PET values. The water balance was found to provide useful insights into the spatial variability of AET, runoff, drainage and changes in soil moisture for the region.

In *Study IV*, the uncertainty in the relationship between biomass C density and MAP indicated that a significant increase in biomass C densities could only be detected for areas receiving 250-260 mm rainfall per year. Under climate change scenarios for 2080s, biomass C densities and AET were found to either increase or decrease depending on scenario, the biggest increases being associated with the ECHam4\_A1FI scenario and biggest decreases with the CGCM2\_A1FI scenario. The largest relative changes (compared to baseline values) in AET were associated with the areas receiving the lowest rainfall, and AET on arenosols will increase while that on vertisols will decrease. Future levels of savannah woodland biomass and water-use in the study region will depend on which climate change scenario develops and on how the woodlands will be utilized and managed.

There is a clear need for up-to-date and integrated biomass and soil inventories to be carried out and for climate data to be collected in order to improve the accuracy and precision of C

and water cycle modelling. Better knowledge and models about the C and water cycles in savannah woodlands are needed for policy formulation to reverse land degradation and help to mitigate the adverse impacts of climate change for this large and important region of the world.

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