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Crop Waterstress Management in the Tropics and Subtropics (380c)

RELATIONSHIP BETWEEN VEGETATION TYPE, SOIL TYPE, SOIL MOISTURE AND CARBON STOCKS IN SEMIARID ETHIOPIAN SAVANNAHS

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M.Sc. Thesis

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Dedication

This work is dedicated to my parents Gerhard and Hilary Glatzle.

Abstract

Almost 65% of all pastoral lands in the tropics are in Africa and approximately half of them are dominated by a semi-arid climate. In Ethiopia, 62% of the surface area is pastoral lands. The Borana rangelands cover around 95000 km² in southern Ethiopia. Livestock-based pastoral and agro-pastoral livelihoods are no longer sufficient to sustain food security and living standards for pastoral people, due to rapid population growth, extreme weather events and structural changes. Payment for Environmental Services (PES), based on carbon sequestration under improved livestock and rangeland management could be one way to diversify livelihoods and generate income to the vulnerable pastoralist communities in southern Ethiopia.

To assess the potential of such PES systems, more knowledge about the biophysical potential for carbon sequestration and the environment are required. The main aim of this pilot study was to characterize the study area, located in the southern part of the Oromia region (south Ethiopia), and provide basic data on vegetation types, soil types, soil properties, precipitation pattern, soil moisture content and carbon stocks.

For each of the vegetation types (Grassland, Tree savannah and Bush-Tree savannah), five plots were selected in the 10 x 10 km study area. For each plot the soil type was identified with the help of auger samples. Furthermore, total aboveground biomass and C-stock [t ha^{-1}], total SOC stock [t ha^{-1}] for 1 m depth, SOC concentration [%] and carbonate content [%] in four depths (0-10, 10-30, 30-60, 60-100 cm), and bulk density [g cm^{-3}] were examined. At 10 of the 15 plots precipitation measurements [mm] and soil moisture [Vol%] measurements in two depths (0-6 and 30-36 cm) were carried out.

An analysis of variance (ANOVA) was used to describe differences in aboveground C-stocks, SOC stocks, SOC concentrations and soil moisture content depending on vegetation or soil type. It was shown, that except for total aboveground C-stock, the SOC stock for 1 m, SOC concentration and soil moisture content were significantly different ($P<0.05$) for the soil types but not for the vegetation types. This indicates that soil type has a stronger impact on these parameters than the vegetation type.

The result on C-stocks for the different vegetation types and soil types can help to give some indication on the carbon sequestration potential of this region.

Key words: vegetation type, soil type, soil moisture, C-stock

Declaration

I, Sarah Glatzle, (Matriculation number 401418) born on the 19th of October 1983 hereby declare on my honour that the attached Master thesis entitled "RELATIONSHIP BETWEEN VEGETATION TYPE, SOIL TYPE, SOIL MOISTURE AND CARBON STOCKS IN SEMIARID ETHIOPIAN SAVANNAHS" has been independently prepared, solely with the support of the listed literature references, and that no information has been presented that has not been officially acknowledged.

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Semester: 6

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Last but not least to my parents I would like to say: “Thank you so very much for always been there for me. For supporting me not just financially throughout my entire studies but also emotionally. For always picking up the pieces when I thought I couldn’t cope anymore. Love you.”

Table of Content

List of Figures

List of Tables

List of Abbreviations

AB	Aboveground
B	Bush land
BG	Belowground
BM	Biomass
BT	Bush and Tree savannah
C	Carbon
calVER	calcic Vertisol
CAMcal	Cambisol calcaric
CAMch	Cambisol chromic
CO_2	Carbon dioxide
G	Grassland
LOI	Loss-on-ignition
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
ST	Soil type
T	Tree savannah
TDR	Time Domain Reflectometry
VT	Vegetation type

1 Introduction

All tropical pastoral lands (grassland, rangeland, shrub land and savannah) cover with an area of 32 million km² more than a quarter of the earth's land surface. This is twice the land area that cropland covers (Reid et al., 2004). Savannahs alone cover 16 million km² of the earth's land surface (Chen et al., 2003). Because pastoral lands are so broad, pastoralism is the most widespread human land use system on earth (FAO, 1993). According to Tennigkeit et al. (2008) there are more than 120 million pastoralists on earth.

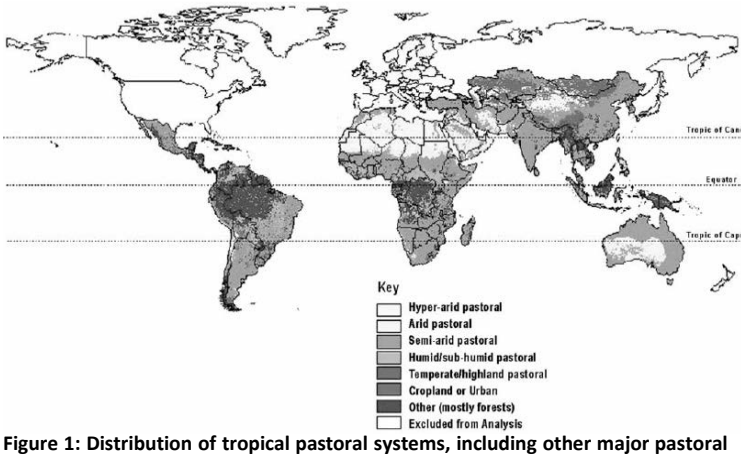

Figure 1: Distribution of tropical pastoral systems, including other major pastoral areas that touch the tropics for completeness, adapted from Reid et al., 2004.

With a land area of 13 million km² approximately 65 % of all pastoral lands in the tropics are in Africa. In Ethiopia alone 62 % of the surface area is pastoral lands. About half of the pastoral lands in Africa (6.03 million km²) are dominated by a semi-arid climate. These semi-arid lands are very widespread trough all areas of the African continent (Reid et al., 2004).

In grasslands carbon is stored or sequestered in living biomass and litter aboveground and in dead and alive biomass in the soil. Aboveground biomass in grassland includes annual and perennial grasses and if present shrubs/bushes and trees. The aboveground carbon stocks in tropical grasslands range between 0.15 and 33 t C ha^{-1} (Ordóñez et al., 2008). The global soil carbon pool, consisting of soil organic carbon (SOC) and soil inorganic carbon (SIC), was estimated by Lal (2004a) to be more than four times as much carbon as in the biotic pool and about three times as much as in the atmospheric pool. SOC is made up of living fine roots, soil microbial biomass and dead organic residues and in tropical grassland the stock ranges in the first 30 cm of the soil from 38 to 148 t C ha^{-1} (Steinbeiss et al., 2007).

This master thesis was carried out within the framework of the project "Livelihood diversifying potential of livestock based carbon sequestration options in pastoral and agro-pastoral systems in Africa" funded by the BMZ (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung), coordinated by ILRI (International Livestock Research Institute) and a cooperation between the DITSL in Kassel (German Institute for Agriculture in the Tropics and Subtropics), the University of Hawassa, Ethiopia and the University of

Hohenheim, Germany. One of the research sites is located in the Borana pastoral area, southern Ethiopia.

The Borana rangelands cover approximately 95000 km² in southern Ethiopia, bordering to Kenya and Somalia in the south. Pastoral and agro-pastoral communities in these rangelands are poor, vulnerable and marginalized. Population pressure, increased occurrence of extreme weather events (floods and droughts), a general change towards less rain amounts and a raising competition for converting grassland into cropland have negative impact on the pastoral production systems in this region. This makes traditional livestock-based pastoral and agro-pastoral livelihoods no longer a sustainable source for food and income. Diversification of income plays an essential role in defeating poverty and vulnerability of these communities.

Rangelands provide various environmental services linked to the water household, carbon sequestration and biodiversity. Carbon sequestration is of special interest because of its contribution to climate change mitigation (Lal, 2001) and options of Payment for Environmental Services (PES). Carbon sequestration involves the removal of atmospheric CO_2 through photosynthesis and the transfer of carbon into vegetation and soil pools for "secure" long-term storage (Nair, 2011). It has been suggested that dry rangelands hold great potential for carbon sequestration (Conant and Paustian, 2002). PES based on carbon sequestration under improved livestock and rangeland management could be one way to diversify livelihoods and generate income to the vulnerable pastoral people. To assess the potential of such PES systems, more knowledge about the biophysical potential for carbon sequestration is required. This study will contribute information by characterization of vegetation and soil related biomass and carbon stocks in relation to soil moisture content within different vegetation and soil types. Furthermore, data on vegetation characteristics, soil parameter and water balance will help to describe the environment and landscape of the Borana rangelands and can be used to describe bigger areas concerning potential carbon stocks.

2 Objectives & Hypotheses

The main objective of this pilot study was to characterize the study area and provide basic data on vegetation types, soil types and properties, precipitation pattern, soil moisture content and carbon stocks. Soil characteristics (e.g. SOC content, soil texture) affect the distribution and retention of soil moisture (originated from rainfall) stored in the soil. This, in turn, affects vegetation distribution, structure and productivity and this again affects SOC levels in the soil. To accomplish this, the specific objectives were to:

(i) Identify the different vegetation types (VT) in the study area using on–site survey and a "Google Earth" satellite image.

(ii) Identify and characterize the soil types (ST) within each vegetation type.

(iii) Measure precipitation.

(iv) Estimate soil moisture content in two depths (depth 1: 0–6 cm and depth 2: 30–36 cm); determine seasonal differences within each VT and ST and response to rain events.

(v) Estimate aboveground (AB) biomass and determine AB C-stocks

(vi) Estimate soil organic carbon (SOC) content in the dry and rainy season and determine soil carbon concentrations and soil carbon stocks.

In this context, following hypotheses were adopted:

(i) Aboveground carbon stocks [t ha^{-1}] differ between the VT and ST.

(ii) Soil organic carbon (SOC) stocks [t ha^{-1}] differ between the VT and ST.

(iii) Due to the fact that in the upper 30 cm of the soil the organic material is concentrated and the microorganisms are more active, the assumption is that SOC concentrations [%] decrease with increasing soil depths.

(iv) Regarding the relationship between precipitation [mm], soil moisture [Vol%], VT and ST:

- Soil moisture contents differ among the VT and ST and soil depths.
- The relationship was assumed to be stronger in depth 1 (0-6 cm) than in depth 2 (30-36 cm).

(v) Soil organic carbon can retain and store up to four times its own weight in water. Based on this fact, it was assumed that the soil moisture content [Vol%] is higher in soils with higher SOC concentrations [%].

(vi) Increasing soil moisture level in the rainy season leads to an increase in vegetation productivity and increase in microbial activity, assuming a change in SOC concentration [%] from dry to rainy season.

3 Literature Review

3.1 Carbon

3.1.1 Carbon Cycle

The global carbon (C) cycle can be divided into five main pools: Hydrosphere, lithosphere, pedosphere, atmosphere and biosphere store about 38.000 Pg C, 5.000 Pg C, 2.300 Pg C, 720 Pg C and 560 Pg C, respectively (Figure 2). The C cycling processes between the pools are complex. The complexity is caused by following problems: (i) C has different chemical forms within the different pools, (ii) fluxes between the pools are regulated by numerous processes and (iii) the atmospheric concentration of CO_2 varies as a result of climatic changes on a time scale from days to millennia (Lal, 2001).

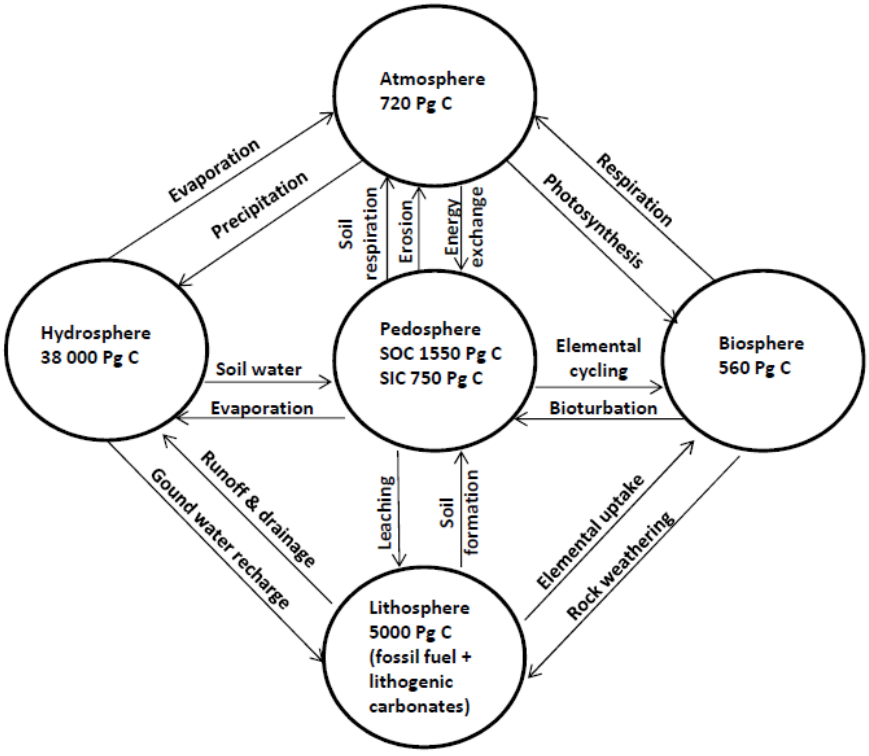

Figure 2: Principal global C pools and the C fluxes between them, adapted from Lal, 2001 and Lal et al., 1998.

The pedosphere plays a central role in this cycle and interacts with the other four pools. These interactions have an impact on the biogeochemical cycle of main nutrients like N, P, K and S and water. Interactive processes lead to gaseous (e.g. CO_2 through soil respiration) and energy exchange between pedosphere and atmosphere. Interaction among the lithosphere and soil imply leaching of nutrients and new soil formation as a result of

weathering. Interactive processes between the pedosphere and the biosphere are elemental cycling and bioturbation. Water exchange among pedosphere and atmosphere plays a primary role in the local, regional and global hydrological cycle. Additionally to the interactive connections with the pedosphere, there are a number of important processes connecting all five pools (Figure 2). The interactive processes between the pedosphere, atmosphere and biosphere are of capital importance in the global carbon cycle (Lal et al., 1998). Even in sum, the pedosphere and biosphere pools are much smaller than the carbon pool of the hydrosphere. But potentially they are much more labile in the short term. The direct impact of human activities (e.g. land use change, deforestation and biomass burning) can markedly change the carbon balance of the pedosphere and biosphere pools. These changes result in an increased release of CO_2 to the atmosphere (Batjes, 1996). The atmospheric concentrations of CO_2 and other greenhouse gases e.g. N_2O and CH_4, have incresed steadily with the beginning of the Industrial Revolution around 1850. The concentration of CO_2 in the atmosphere was about 260 to 280 ppmv (part per million by volume) from 4000 BC to 1750 AD. Ever since the concentration has gradually increased to around 370 ppmv in 2000. At the moment it is increasing at a rate of 0,5 % per year. If the concentrations of greenhouse gases continue to increase at the current rate, significant climate changes are projected to happen during the 21st century (Lal, 2001).

3.1.2 Soil organic matter

Soil organic matter (SOM) is defined as the sum of all organic carbon containing substances in the soil. SOM consists of a mix of plant and animal residues in different stages of decomposition. Additionally of substances synthesized microbiologically and/or chemically from the breakdown products of the residues and of living or dead microorganisms. SOM is typically subdivided into nonhumic and humic substances. Nonhumic substances include those substances where the chemical characteristics (e.g. carbohydrates, proteins, peptides etc.) are still recognizable. Generally, these compounds are relatively easily decomposed in soils and have short life spans. Nevertheless, the main part of SOM consists of humic substances. These are amorphous, dark-coloured, partly aromatic, mostly hydrophilic and chemically complex materials. They no longer show specific chemical and physical characteristics and they are more resistant to chemical or biological decomposition. Humic substances are partitioned into the following three main fractions: humic acid, fulvic acid and humin (Schnitzer, 1991). SOM has favourable effects on physical, chemical and thermal

properties and on the biological activity of the soil. One important effect is the stabilizing effect on soil structure and protection against soil erosion (Batjes and Sombroek, 1997). Furthermore, the colloidal property of SOM (particularly the humic substances) improves the soil moisture retention (water-holding capacity) – a very important property in sandy soils. However, some of the water retained by SOM is unavailable to plants and microorganisms. SOM can retain up to four times its own weight in water, however only about half of this is available to plants (Vaughan and Malcolm, 1985). The decomposition and mineralisation of SOM provides a C source for heterotrophic microorganisms and releases nutrients like N, P, S and K that are essential for plant and microbial growth. SOM is additionally an important determinant of the cation exchange capacity of soils, especially for coarse textured soils. SOM has the ability to interact with metals, metal oxides and hydroxides and clay minerals to build metal-organic complexes (Batjes and Sombroek, 1997).

3.1.3 Soil organic carbon

Carbon in soil occurs in at least two forms, as SOC and as SIC (1.550 Pg and 750 Pg respectively in the upper 1 m depth of soil solum). SOC consists of highly active humus and relatively inert charcoal carbon. Soil organic matter contains about 58 % SOC and includes a wide range of organic substances (see “soil organic matter” section above). That means: all properties and functions of SOM apply for SOC. The SIC pool, mainly composed of carbonates (e.g. $CaCO_3$), can be large in soils of the arid and semiarid regions. 29 % of the global SIC pool is contributed by the soils of the tropics. The SIC pool is divided into two different pools: the lithogenic inorganic carbon and the pedogenic inorganic carbon. Pedogenic inorganic carbon consists of secondary carbonates which are formed through the dissolution of lithogenic inorganic carbon or carbonate containing minerals and re-precipitation of weathering products (Lal, 2001).

Soil organic carbon is heterogeneous in nature and can be roughly grouped into three pools based on their turnover rates in the soil (Table 1). The active pool contains soluble fresh plant residues including fine roots (< 2 mm in diameter), microbial biomass, particulate organic C and/or light fraction (Allen et al., 2010). It is of special importance because it controls ecosystem productivity in the short term (Hu et al., 1997) and reacts more sensitive to climate change and disturbance. For example, microbial

Table 1: Soil C Pools

Soil C Pools	Turnover period
active or labile C	< 10 years
slow C	10 – 200 years
resistant or passive	> 100 years

biomass is considered as a sensitive indicator of SOC changes due to land-use and or management.

The slow pool consists of humus or C that is absorbed to clay minerals. The size of this pool depends on soil types, clay content, clay mineralogy and Fe- and Al-oxides. Following reasons have been suggested for the slow turnover rate for the slow pools: (i) the chemical structure of SOM (meaning, that an increase in aromaticity leads to an increase in spatial inaccessibility for microorganisms and extracellular enzymes owed to microaggregation and physical separation), (ii) sorption of C on mineral surfaces and/or (iii) interactions with mineral particles. The resistant C pool consists of charcoal carbon, phytolith C and carbonates (Allen et al., 2010).

Soil organic carbon contents are influenced by various abiotic and biotic factors, such as climate, vegetation, soil properties, topography and land use change (Sombroek et al., 1993). Some of these factors will be discussed in the following.

3.1.3.1 Climatic factors

Climatic factors are primary factors that regulate SOC levels in soils. Soil moisture (that originates from precipitation) and soil temperature affect plant productivity and microbial activity as well as their decomposition rates. An increase in soil moisture increases detritivore abundance and activity. This may lead to higher rates of litter decomposition and incorporation of litter into the soil and therefore increasing SOC concentration and reduced bulk density. As long as soils are well drained and there is no lack of oxygen, high temperatures and high soil moisture increase decomposition rates (Allen et al., 2010; Sombroek et al., 1993). Variations in temperature across arid and semiarid lands create significant difference in water use efficiency, strongly influencing the biomass production, the length of growing season and SOC concentrations. The amount and kind of biomass that is produced depends on the length of the growing season and has significant impact on the SOC concentration in soils (Lal, 2004b). In general SOC stocks globally increase with precipitation and decrease with temperature (Hiederer, 2009).

3.1.3.2 Vegetation

The amount of SOC in soils depends on the supply of organic matter in situ in the form of biomass production and their decomposition rate (Sombroek et al., 1993). The majority of carbon additions to soils are from the vegetation. Carbon from vegetation can be added to

the soil by deposition of litter on the soil surface and though the root system. About 50 % of the C fixed in net photosynthesis is transferred belowground. Here it is partitioned between root growth, rhizosphere respiration and addition to SOM. Between 5 – 10 % of net fixed C can be recovered in the soil (Rees, 2005). The quantity of SOC, therefore, depends on the amount of plant material entering the soil, the decomposition rate of those residues and the soil chemistry and mineralogy. The spatial variability of SOC is controlled by vegetative patterns and plant community dynamics, plant size and morphology (e.g. trees, bushes and grass). Spatial distributions of plants affect the areas where carbon enters the soil and also the locations of other sources of SOC like soil microbial biomass (Allen et al., 2010).

3.1.3.3 Soil properties

Soil physical and chemical properties like texture, pH, soil moisture and mineralogy influence the SOC content. Soil texture plays an important role, because with increasing clay concentration carbon outputs decease. Clay minerals physically protect SOM from decomposition by forming a coating around it or absorb SOC to their surface. Furthermore SOC is trapped in small pores in aggregates inaccessible to microbes (Hassink et al., 1993). Hassink et al. (1992) confirmed the assumption that in clay soils more SOC was protected in small pores than in sandy soils. According to Hinderer (2009) the effect of clay concentration on SOC is a more dominant factor in deeper soil layers than in upper layers where climate plays an important role in determining SOC levels.

3.1.4 Above- and belowground C Stock

Carbon stocks refer to the absolute quantity of C (t C ha^{-1}) measured at the time of the research. There are two major sections of carbon stocks: the aboveground and belowground section. Aboveground C is stored in specific plant parts e.g. stem and leaves of trees/bushes and herbaceous parts. Belowground into living biomass such as roots and in SOC pools. Aboveground measurements of carbon stocks are derived from aboveground biomass measurements/estimates, assuming that the biomass consists of 50 % carbon. The aboveground biomass is the sum of harvested and standing biomass. An old approach of estimating tree/bush biomass was to harvest the whole tree/bush. The procedure is to cut down sample trees/bushes and to separate various parts (stem, leaves, branches etc.) from each other. Next step is to dig out the roots and wash them. Followed by determining the dry weight from samples of each part and adding them up to get the total biomass.

Furthermore, the C content of every separated part (stem, leaves, branches etc.), roots and fine roots are measured. Using all these data, allometric equations are developed as regression models with the measured variable like diameter at breast height (DBH), total tree/bush and/or both crown widths as the independent variables and the total dry weight as the dependent variable. The destructive method of determining aboveground biomass is very time and labour intensive. There are also the less invasive and costly non-destructive in-situ measurements to estimate aboveground C stocks. With this method, only the measurements of e.g. diameter at breast height (DBH), total tree/bush and/or both crown widths are needed and entered into already existing species fitting allometric equation. Such allometric equations, developed based on biophysical properties of trees/bushes and validated by occasional measurements of destructive sampling, are widely used.

The determination of belowground organic C is more difficult. Organic C occurs in soils in form of living roots (belowground biomass) and soil organic matter (including fine roots) in labile and more recalcitrant forms. The most widespread method of estimating the soil carbon stocks is based on soil analysis, whereby the C content in a sample of soil is determined (as C concentration [%]). Carbon stocks expressed as tons per hectare are calculated for a specific soil depth by using the bulk density as a factor.

In addition to SOM, belowground biomass (living roots) is a major C pool. However, it is difficult to measure. Because data on belowground biomass are rare, many researchers assume that the belowground biomass constitutes a defined portion of the aboveground biomass. The values are assumed to be in the range of 25 – 40 % depending on the nature of the plant, its root system and ecological conditions (Nair, 2011). This master thesis is concentrated on the determination of aboveground carbon stocks and soil organic carbon stock (without belowground biomass made up out of living roots).

3.2 Water

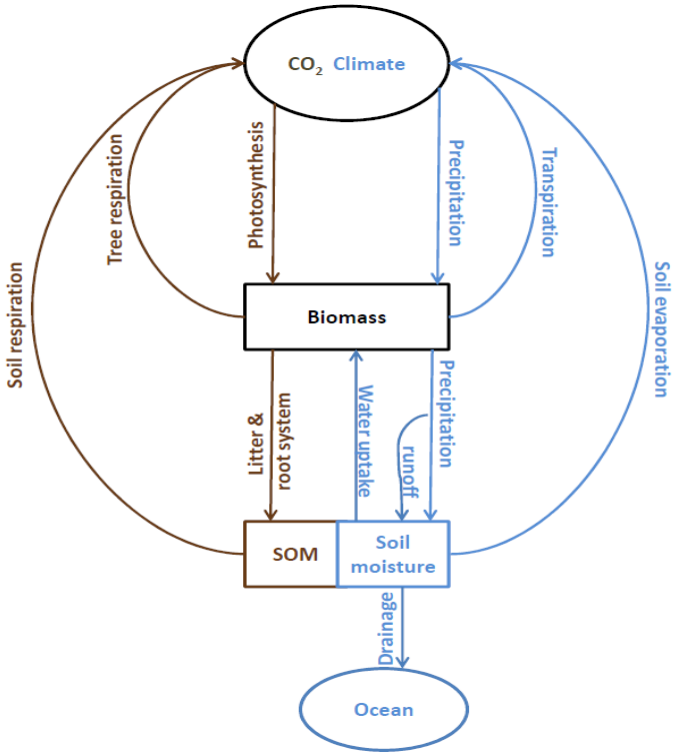

Figure 3: Carbon balance (on the left) and water balance (on the right) are closely linked. Pools are represented by boxes, processes by arrows and sinks/sources by circles, adapted from Gärdenäs, 1998.

3.2.1 Water balance

The water balance, key for ecosystem processes, is determined by multiple factors, including precipitation, vegetation, temperature and slope. Ecosystem water balance (Figure 4) is determined by inputs in the form of precipitation and by outputs in the form of surface runoff, evaporation, transpiration and drainage. Local inputs and outputs differ considerably temporally and spatially, among other things, because of vegetation cover, vegetation phenology and soil type. The effect of vegetation on ecosystem water balance is complex. On the one hand, vegetation can increase soil drying through transpiration. On the other hand, it can bring water up from deeper soil layers via hydraulic lift, decrease runoff on steep slopes and reduce soil evaporation due to shading (Liancourt, 2012).

$$P = I + R + E + T + \Delta S + D$$

Figure 4: Components of the water balance. P = precipitation, I = canopy interception, R = runoff, E = evaporation from soil surface, T = transpiration from vegetation, ΔS = change in soil moisture, D = drainage, adapted from Asner et al., 2004.

The soil plays a very important role in the hydrological cycle. Especially crucial to this role is the soil surface zone, where the interaction of atmospheric water with the pedosphere

occurs. In this zone the complex partitioning between rainfall, infiltration, runoff, evaporation, transpiration and drainage is initiated and sustained. The water added through rainfall can either infiltrate into the soil or from surface runoff. The water available for runoff is evidently determined by the process of infiltration (Hadas et al., 1973). The balance between infiltration and runoff depends on the hydrologic conductivity and spatial heterogeneity of the soil and vegetation surface (Fiedler et al., 2002). The infiltrated water, known as the soil moisture, is then partitioned into evaporation, transpiration and drainage. Some of the drainage water appears as streamflow and the rest reaches the water table as groundwater recharge. Infiltration is defined as the process whereby water enters into the soil through the surface (Hadas et al., 1973). Infiltration is influenced by soil texture, land use type and vegetation factors including plant cover and type, litter cover and organic carbon content of the soil (Abdelkadir and Yimer, 2011).

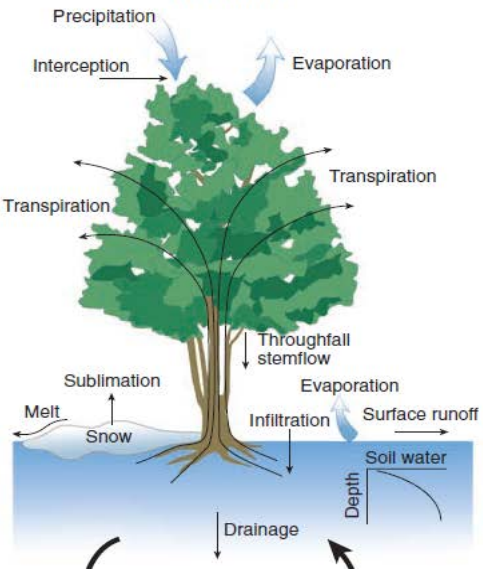

Figure 5: Hydrological cycle, adapted from Bonan, 2008.

3.2.2 Soil moisture

In water limited arid und semiarid ecosystems, soil moisture and vegetation have a coupled relationship that is fundamental for ecosystem dynamics. Soil moisture plays a primary role in the dynamic interaction between climate, soil and vegetation. There is a coupled dependence of water balance and water stress processes on soil moisture (Figure 6). Through transpiration, vegetation influences the soil moisture use that strongly conditions the water balance. The water balance on the other hand influences plant growth, reproduction and germination through the start of water stress (Fernandez-Illescas et al., 2001).

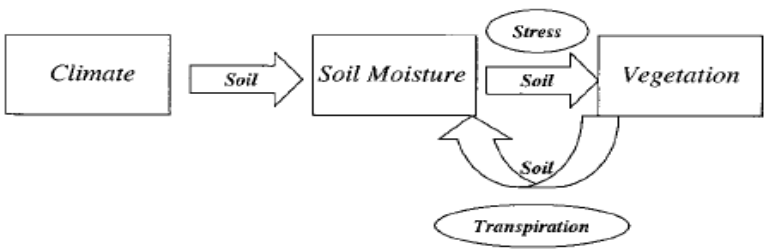

Figure 6: Schematic representation of the vegetation–soil moisture relationship, adapted from Fernandez-Illescas et al., 2001

Soil moisture is very important for predicting the development of soil carbon stocks and fluxes, because it strongly controls organic matter decomposition. Soil moisture is one of the major environmental factors controlling productivity and carbon cycling in terrestrial ecosystems. It is, besides temperature, a main determinant of the rate at which microorganisms mineralize soil carbon to CO_2. Soil moisture usually originates from precipitation of seasonal rainfall events. It is predicted to change significantly at global scales due to climate change in the following decades. This will potentially lead to large scale changes in soil carbon stocks in various regions (Moyano et al., 2012).

Soil respiration is a main process through which organic carbon is released as CO_2 into the atmosphere, due to the heterotrophic microbial activity. Heterotrophic microorganisms use organic carbon as an energy source for growth. It is influenced by several abiotic and biotic factors, such as soil moisture, soil temperature, substrate quality and availability and vegetation and microbial community structure. Even though soil temperature is usually considered the most important factor controlling this flux, the factor soil moisture is of greater importance in water limited ecosystems (Shen et al., 2008). The semiarid Borana Rangeland is a water limited ecosystem and is a part of the arid and semiarid lands that occupy 41 % of the global land surface. These lands store about 15.5 % of the world's total soil organic carbon in the first meter and a large amount of inorganic carbon. With the large area and the large amount of soil carbon stored, arid and semiarid ecosystems may play an important role in terrestrial carbon balance and feedback to climate change (Lal, 2004c). Global and regional precipitation regimes are expected to change due to warming-induced alterations in global air circulation and hydrological cycling patterns. In arid and semiarid ecosystems, processes like soil respiration and primary production are controlled by sporadic rainfall events. Therefore, these ecosystems are predicted to be very responsive to predicted changes in future precipitation regimes. The response of arid and semiarid ecosystems is uncertain as drying of soils might reduce soil respiration, whereas wetting soils might increase it. The components of soil respiration are root and microbial respiration. These components could be differently effected by precipitation amount and timing. Microbial respiration might respond to very small or moderate rainfall events, whereas the photosynthetic activity of plants that is linked to root respiration generally increases following relatively large rain events or a series of small ones. This implies that soil

respiration might be influenced not only by the amount of precipitation, but also by the seasonality and intensity (Shen et al., 2008).

3.2.3 Soil moisture and SOC

Soils are able to build water holding capacity. This is due to their potential to store organic carbon and to protect it against complete microbial breakdown. This protection is supported by a range of chemical and physical bonds with the inorganic soil fraction (e.g. clay minerals and iron oxides). SOC impregnates the surface of micro and macro pores in the soil matrix and the outside of mineral particles creating an exponential increase in the number of sites for water absorption and storage. Therefore it has a positive effect on soil structure and water holding capacity. SOC can absorb and store up to four times its own weight in water. Sombroek et al. (1993) concluded that in most tropical and subtropical soils SOC is essential for the maintenance and improvement of water infiltration and water-holding capacity. The formation of good soil structure is not just attributed to SOC but also to clay minerals and their interactions, ionic bridging and carbonates. SOC and clay minerals form metal-organic complexes. These are formed by a bridging process, whereby negatively charged SOC is bonded to the negatively charged clay mineral, either via a positively charged hydrogen atom in a water bridge or via metal bridging with an Al^{3+} or Ca^{2+} cation. The metal-organic complexes protect SOC from further microbial attack and in the same time sequester organic carbon. Metal ions form bridges between mineral and organo-mineral particles and formation of secondary carbonates in arid and semi-arid regions is also linked to soil structure dynamics (Scheffer and Schachtschabel, 1992; Kay et al., 1998; Morris, 2004; Bronick and Lal, 2005).

3.3 Vegetation

Savannahs are a main part of the world's vegetation. They cover approximately 20 % of the land surface and account for about 30 % of the primary production of all terrestrial vegetation. Savannahs are characterized by a dynamic mixture of woody and grassy species and are primarily composed of C4 grasses and C3 bushes and trees. There are dense tree and bush savannahs as well as grasslands and grassy areas with scattered or more regularly distributed trees (Bond and Midgley, 2000; Grace et al., 2006; De Deyn et al., 2008). After Scholes, 1997 (cited in Rodriguez-Iturbe et al., 1999) water availability is the key factor influencing the function, spatial pattern and individual structure of the vegetation in

Savannahs. Savannahs, as mentioned above, are a stable coexistence of woody plants and grasses. At present the most common explanation for this coexistence is based on the so-called Walter hypothesis (Walter 1971 cited in Rodriguez-Iturbe et al., 1999). The hypothesis is based on rooting depth separation with respect to competition for water by trees and grasses. Assuming, that woody vegetation have roots in surface and subsurface layer and grasses only in the surface layer (Rodriguez-Iturbe et al., 1999). According to Jackson et al. (1997) grasses have a relatively high specific root length (118 m g^{-1}) compared to trees (12 m g^{-1}), so that one gram of grass roots explore more soil than one gram of tree roots. That means, grasses have a dense fibrous root system exploring soils more intensively for nutrients and water than woody vegetation (trees and bushes) (Pärtel and Wilson, 2002). Then again, woody vegetation has a deeper and wider spread rooting system, which takes advantage of soil moisture that lays deeper in the soil and that extensively, finds high resource patches in the soil (Asner et al., 2004; Bond, 2008).

The plant allocation above- and belowground and the vertical root distribution (shallow or deep roots) of different vegetation types might have a great influence on the relative distribution of soil carbon with depth (Jobbágy and Jackson, 2000). In a global review of root distribution by Jackson et al. (1996) grasses had the shallowest root profile; bushes the deepest and trees were in the middle. Grasses can store comparably or partly more carbon in soils than trees. This is due to their high productivity and turnover rates. Also, compared to trees and bushes they allocate more biomass belowground as aboveground.

According to Dong et al. (2003) vegetation cover can change surface runoff, infiltration and evaporation. The vegetation cover modifies infiltration in arid and semiarid regions by buffering the kinetic energy of the rainfall before the water reaches the soil and thereby reducing ponding, sealing and crusting. Additionally, by bringing the precipitation to the soil surface in a redistributed pattern, different drop size and different energy level and altering the drying rate of the soil surface (Saxton 1979 cited in Dong et al., 2003). Vegetation can increase infiltration by forming macropores caused by the root system (Bellot et al., 1999). Macropores form preferential flow pathways for the infiltrating water. However, in general bare soils have higher soil moisture content than soils that are vegetated (Dong et al., 2003).

4 Materials & Methods

4.1 Environmental settings

4.1.1 Study site

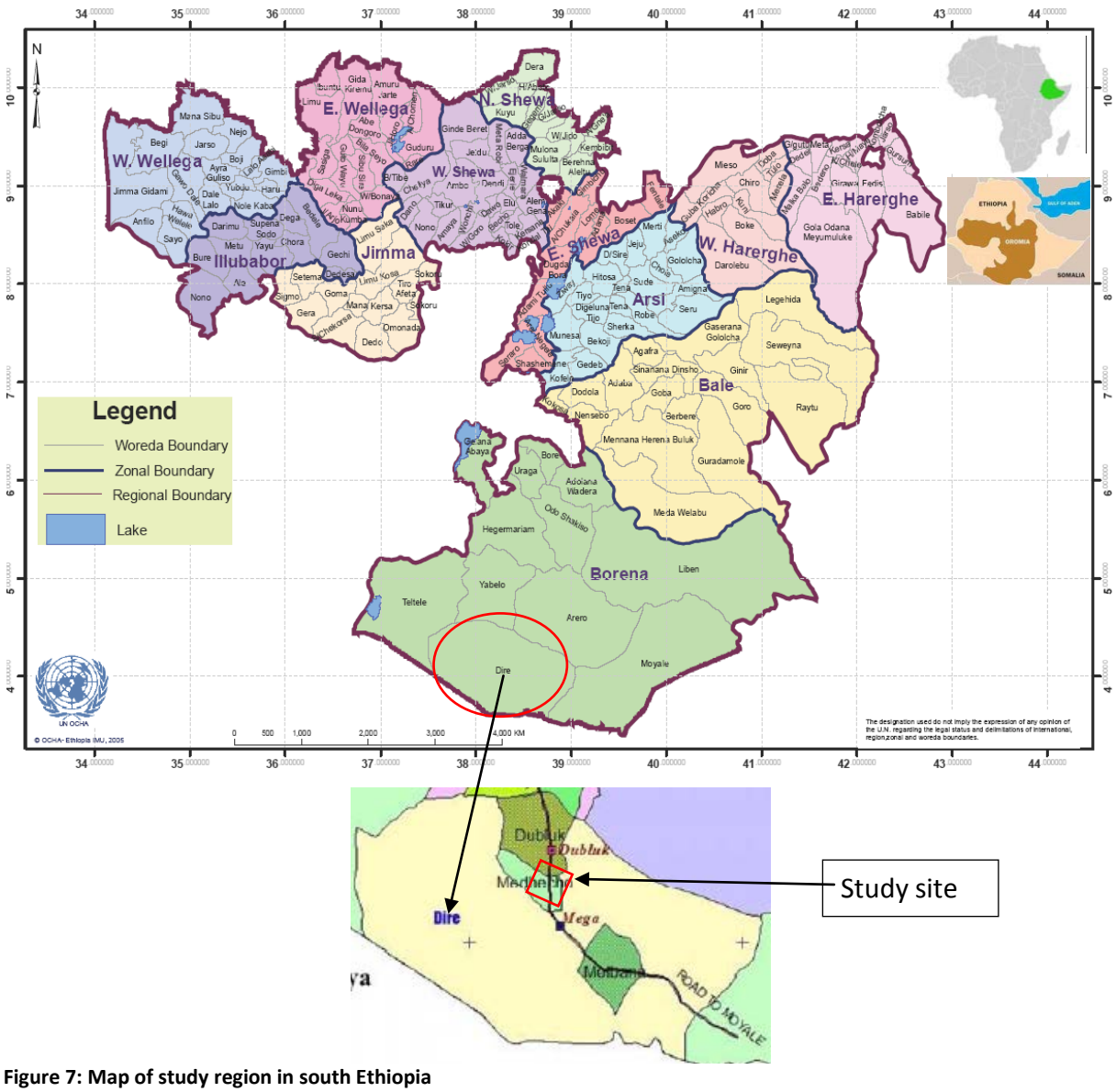

Figure 7: Map of study region in south Ethiopia

The study site is located in the Dire district, Borana zone, Oromia region, south Ethiopia. In a 10 x 10 km grid (NW: N4°16.682/E38°15.634; NE: N4°15.028/E38°20.853; SW: N4°11.491/E38°14.058; SE: N4°9.868/E38°19.220) around the village Madhecho (Figure 7). The Borana zone (also known as Borana rangeland or Borana plateau) lies in the southern part of the Oromia region. The Borana rangeland occupies a total land area of approximately 95000 km² and extends from 4° to 6°N latitude and 36°to 42°E longitude (Kamara et al.,

2001). The Borana people are the predominant ethnic group in this area. The majority of the Borana people are with 89% pastoralists, the remaining 11% are crop farmers (Coppock, 1994).

4.1.2 Climate

The area is dominated by a semiarid climate with annual average rainfall ranging from 110 mm in the south to 600 mm in the north. The rainfall in general is bimodal with 59 % of the total rainfall occurring in the long rainy season (March to May) and 27 % in the short rainy season (September to October). Droughts happen regularly once every five to ten years. The average annual temperature varies between 19 to 24°C and shows little variation across the season (Coppock, 1994).

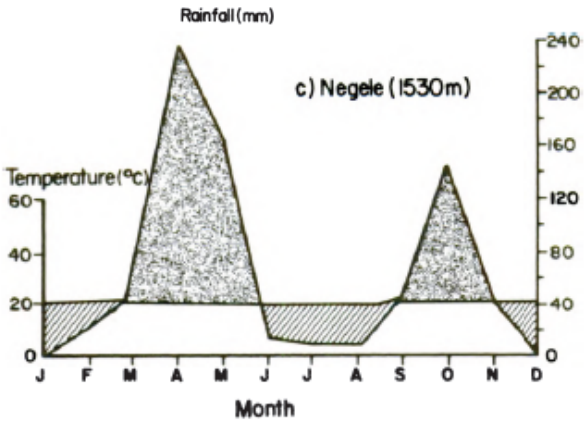

Figure 8: Climate chart

4.1.3 Geology, geomorphology and soils

Precambrian basement complex, sedimentary deposit, tertiary and quaternary Volcanic and quaternary deposit are the four basic geological formations the Borana rangeland is composed of. The Precambrian basement complex formation is part of the Mozambican Belt of East Africa and the age varies between 600 and 950 million years. It consists of granites, gneisses and migmatites. The sedimentary deposits were deposited 180 million years ago throughout the Jurassic period. These materials are mainly a result from oceanic activity and consist of shales, sandstone and lime stones. The Volcanics (basalt and tuff) were deposited during the tertiary and quaternary periods, starting about 70 million years ago up until 3 million years ago. The quaternary deposits were deposited at least three million years ago and are the outcome from alluvial (river, lake or swamp deposition) or eluvial (in situ weathering of rock) processes (Coppock, 1994).

The landscape of the area is, except for a central mountain range and scattered volcanic cones and craters, slightly undulating and ranges in elevation from 1000 to 1500 m a.s.l., with peaks up to 2000 m a.s.l. (Coppock, 1994).

The soils in the study area were identified and classified according to the World Reference Base for Soil Resources (WRB) (IUSS Working Group, 2006). The soil forming factors in the study area are: climate, parent material, relief/topography, flora/fauna and man. The interactions of these factors determine the diversity of soil characteristics and the nature of the soils (Oromiya Pastoral Area Development Commission, unpublished). After Coppock (1994) the soil types of the region comprise 53 % sand, 30 % clay and 17 % silt, which is sandy clay loam in texture. Two major soil types cover the present study area: Cambisols and Vertisols, while Vertisols were found in the depressions and Cambisols rather in higher located areas. Cambisols are rather young soils and are typical for the temperate zones, but can be found in the tropical region (IUSS Working Group WRB, 2006). They were identified as Cambisol chromic and Cambisol calcaric. There colours varied from reddish-brown to brown to white-brown and sandy loam, sandy clay, sandy clay loam and loam textured. Vertisols are typically found in seasonal tropics and subtropics, above all in regions with irregular rainfalls and changing rainfall amounts. Most Vertisols occur in the semiarid tropics. They are churning, heavy clay soils with a high amount of swelling clays. The change in swelling and shrinking of expanding clays (peloturbation) results in forming deep wide cracks from the surface downward in the dry season (IUSS Working Group WRB, 2006). The Vertisols of the study area were identified as calcic Vertisols, varied in colours from dark brown to dark gray and were clay textured (clay content >50 %).

4.1.4 Vegetation and land use

The dominant vegetation in the Borana rangeland is the savannah vegetation containing mixtures of perennial herbaceous and woody plants (Coppock, 1994). Main tree species in the present study area were *Acacia tortillis, A. nilotica, Commiphora africana, A. bussei and A. seyal*. In Bush land were mainly found *A. nubica, A. mellifera*, *A. drepanolobium* and sometimes *Solanum ssp.* and *Ossimum ssp.* Grasslands varied in their composition. On Vertisols perennial *Pennisetum* species dominated and on Cambisols a mixture of annual and perennial grasses and herbs was observed. Dominant species here were for example *Cenchrus ciliaris*, *Cynodon dactylon*, *Eragrostis cilianensis*, and *Sporobulus nervosus*.

The pastoral system is the current land use system, which is above all cattle grazing and browsing by sheep, goats and camels. There is also some crop cultivation mostly sorghum, maize and haricot bean (Oromiya Pastoral Area Development Commission, unpublished).

4.2 Experimental setup

4.2.1 Study plots

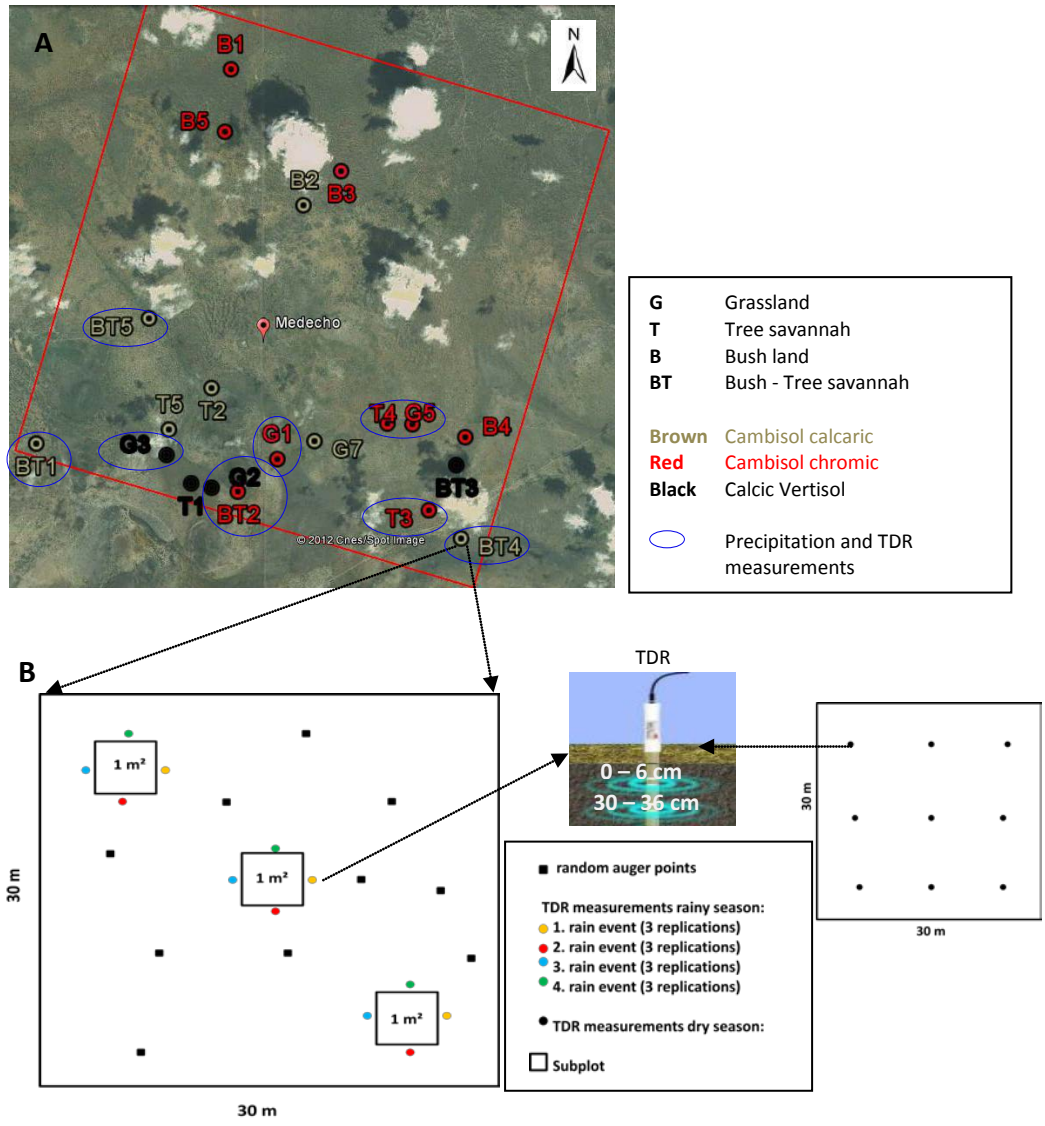

Figure 9: (A): "Google Earth" satellite image of the 10 x 10 km study area with the positions of the 20 investigated plots (Source: www.googleearth.com). (B): Schematic sketch of the experimental setup of the plots.

4.2.2 Characterisation of vegetation types

In order to characterise different vegetation types, to know their frequency and density in the landscape, the 10 x 10 km study area was surveyed by foot. During these explorations pictures of the research area were taken in all directions by climbing on hills situated in and around the area. Furthermore, to gather information about the soils, augers were taken at

regular distances. The four visually identified vegetation types were Grassland (G), Tree savannah (T), Bush land (B) and Bush-Tree savannah (BT) (Figure 10). With help of the information gained from the on-site survey and the pictures taken, a “Google Earth” satellite image of the study area was appointed into the four identified vegetation types. Next appropriate sites for the plots were located on the satellite image. After that, these sites were visited by using a handheld GPS (60CSx Garmin, USA). If the vegetation type of the visited site matched the vegetation type of the preselected site of the satellite image, a 30 x 30 m plot was chosen. For each of the four vegetation types, five 30 x 30 m plots were chosen, giving a total investigated plot number of 20. The geographical position of every plot was determined using the GPS and recorded. In each plot three 1 x 1 m subplots were selected in a slant to classify the plant species and to harvest the aboveground understory biomass (Figure 9). Due to logistical and time problems no precipitation and TDR measurements took place at the Bush land plots. Therefore, for this master thesis the collected samples for the Bush land were not processed.

Grassland

Tree savannah

Bush land

Tree-Bush savannah

Figure 10: Photos of the four different vegetation types.

4.2.3 Soil augering for soil type identification and soil sampling

After the FAO Guidelines for soil description (Jahn et al., 2006) soil augering doesn't allow a comprehensive soil profile description. These guidelines are made for simple soil observation and identification in soil mapping. For that purpose they provide a satisfactory indication of the soil characteristics. Furthermore, augers can be used to collect soil samples. In each of the 20 plots soil samples of one meter depth were taken with a "Pürckhauer" auger at 10 random points (10 replications for each plot) (Figure 9B). The soil type of each plot was identified on the basis of these auger samples (Figure 11). Soil samples were taken in the dry season and at the end of the short rainy season in four depths: depth a (0 – 10 cm), depth b (10 – 30 cm), depth c (30 – 60 cm) and depth d (60 – 100 cm). Every sample was filled into a plastic bag and labelled with an ID number.

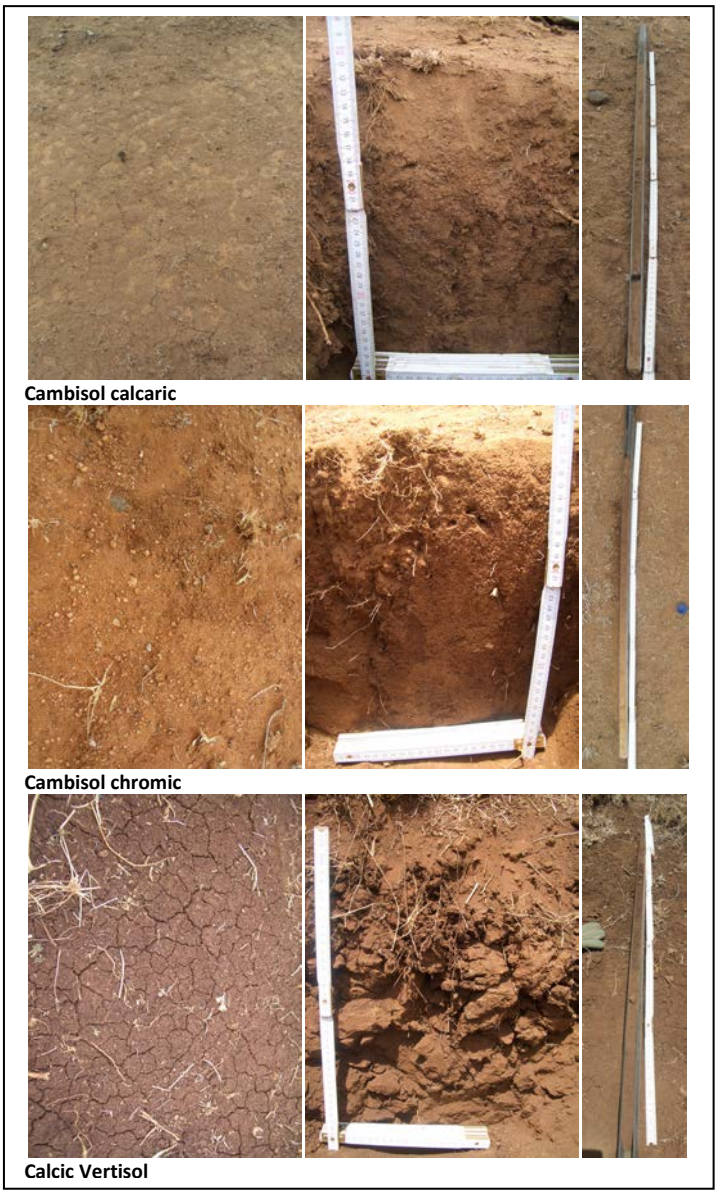

Figure 11: Photo of the three different soil types

4.2.4 Soil sampling for determination of bulk density

For the sampling of the soil for the determination of the bulk density, two 40 cm deep pits were dug. Coring rings of defined volume (100 cm^3) were used to collect the samples. The sampling had to be done very carefully to ensure that the soil was not disturbed. It was carried out by driving the coring ring vertically into the soil using a rubber mallet and a block of wood (Figure 12). The coring ring containing the soil was then cautiously dug out of the soil to prevent any loss of soil from the ring. Excess soil on the outside of the coring ring was scraped off with a knife. The ring's content was filled into a plastic bag and labelled with an ID number. For every plot, soil bulk density samples were taken in two depths (depth a: 0 -10 cm and depth b: 10 – 30 cm). For each depth there were five replications. Replications 1 to 3 were taken in the first pit and 4 to 5 in the second pit.

Figure 12: Photos of coring rings.

4.2.5 Destructive and non-destructive aboveground biomass measurements

4.2.5.1 Destructive aboveground biomass measurements

As mentioned before, to classify the plant species and to harvest the aboveground understory biomass, three 1 x 1m subplots were selected in a slant in each of the 30 x 30 m plots. Species were classified by visual observation with the help of a local expert. Next the vegetation in the subplots was harvested, down to 7 cm grass height, and collected in plastic bags. Later on, the vegetation samples were oven dried at 65°C until the dry weights reached constancy. The dry weight of each sample of the three subplots was recorded and averaged so that the potential dry matter production of one hectare of understory vegetation of each vegetation type could be calculated. These data were needed to estimate the aboveground understory carbon stock (t ha^{-1}) and thus getting an idea of how much organic carbon is stored in the understory vegetation (mainly grasses, weeds and small shrubs) of each vegetation type. After oven drying the vegetation samples, they were homogenized by using

first garden scissors and then an electric grinder. A subsample of 10 g of each sample was taken to Germany for further analysis (see section 4.3.4.1)

4.2.5.2 Non-destructive aboveground biomass measurements

The trees of the five tree plots and the trees and bushes of the five bush-tree plots were measured non-destructively. Before measuring, the location and the amount of the trees respectively bushes and trees were recorded in a map. By measuring the tree and bush biomass in a non-destructive way, the trees and bushes didn't have to be harvested. For this measurement method, allometric equations from the literature were used.

Therefore the trees had to be measured at circumference at breast height (1,3 m) (***DBH***), basal circumference at 0,3 m from the ground ($\boldsymbol{D_{30}}$), stem height ($\boldsymbol{H_S}$), total tree height ($\boldsymbol{H_T}$), height at lower end of canopy ($\boldsymbol{H_C}$), tree crown width ($\boldsymbol{C_W}$) and length ($\boldsymbol{C_L}$). ***DBH***, $\boldsymbol{D_{30}}$, $\boldsymbol{C_W}$, $\boldsymbol{C_L}$ were measured with the help of a measuring tape. $\boldsymbol{H_T}$ and $\boldsymbol{H_C}$ were measured by using a 7 m long wooden stick, marked in 50 cm intervals. The aboveground tree biomass (kg biomass/tree) was, depending on species, calculated by using the following equations found in the review publication from Henry et al. (2011):

Acacia drepanolobium: **BM/tree = 3,7704 * *DBH* [cm] + 1,1682**

A. tortillis, A. nilotica and *A. bussei:* $\mathbf{BM/tree = 0{,}0096*(\ H_T\ [m]+\ C_W\ [m]+\ C_L\ [m])^{3{,}3015}}$

The measuring process for the bushes was more or less the same as for the trees. The bushes were grouped into three different size classes (small, medium and big) through visual observation. $\boldsymbol{D_{30}}$, $\boldsymbol{C_W}$ and $\boldsymbol{C_L}$ of the bushes were also measured with the help of a measuring tape and the bush height (H_B) with the help of the wooden stick. The aboveground bush biomass (kg biomass/bush) was also, depending on species, calculated by using the following equations found in the review publication from Henry et al. (2011):

Acacia drepanolobium: **BM/bush = 3,7704 * *DBH* [cm] + 1,1682**

Acacia bussei: $\mathbf{BM/bush = 0{,}0096*(\ H_T\ [m]+\ C_W\ [m]+\ C_L\ [m])^{3{,}3015}}$

A. mellifera and *A.nubica:* $\mathbf{BM/bush = 0{,}0548*(\ H_B\ [m]+\ C_W\ [m]+\ C_L\ [m])^{2{,}5767}}$

Ocimum, Lantana, Solanum: $\mathbf{BM/bush = 0{,}446 * CA\ [m^2]^{\ 0{,}869} * H_B^{\ 1{,}112}}$

For each plot the total aboveground biomass (kg biomass/plot) was calculated. Next, divided by the total plot area (900 m²), to get the total aboveground biomass for one square meter, and then transformed into tons per hectare. Assuming that the biomass consists of 50 %

carbon, the total aboveground biomass in [t ha-1] was multiplied by 0.5 to get the total aboveground C stock in [t ha-1].

4.2.6 Measurement of precipitation and soil moisture content

At 10 of the 15 investigated plots precipitation and soil moisture content were measured (Figure 9). These 10 plots were chosen after the following criteria: (i) the same vegetation type on the same soil type, (ii) the same vegetation type on different soil types and (iii) the plots should be somewhat accessible after a rain event. Rain gauges were installed at the plots to measure precipitation [mm]. The soil moisture content was measured in the dry season and in the short rainy season using a mobile TDR (Time Domain Reflectometry) sensor (HH2 Hand Held Device from Delta T with a SM300 Soil Moisture Sensor). In the dry season soil moisture content was measured at nine regular points within the plots in two different depths; depth 1: 0-6 cm and depth 2: 30-36 cm. In the rainy season the measurements took place just beside the subplots, also in the depths: 0-6 cm and 30-36 cm, latest one day after a rain event Because the metal rods of the sensor are 6 cm long, it measures the volumetric water content in a 6 cm wide soil layer. In total, precipitation and soil moisture content was measured in the rainy season after four rain events (Figure 9B).

Figure 13: Photos of TDR

4.2.7 Statistical analysis

Data were analysed using the statistical program SAS 9.3. A one-way ANOVA was carried out to check for significant differences between the different vegetation types and soil types. Differences were considered significant at $P<0.05$. The statistical significance of the differences between means was tested by using a t-test. To check for significance between the different slops of the regression lines the program StatTools (Comparing two regression lines program) was used. Graphs and diagrams were made with the help of the software program SigmaPlot 10.0.

4.3 Laboratory analysis

4.3.1 Soil bulk density

Each of the bulk density samples taken in the field were filled from the plastic bags into oven proof paper bags and labelled with the corresponding ID number, followed by oven drying the samples at 105°C for 48 h, until the weights of the samples reached constancy. Next the paper bags were removed from the oven and cooled in a desiccator before weighing the paper bags containing the oven dried soil and then weighing the empty paper bags. Soil bulk density (g cm^{-3}) was then calculated as shown in the equation 1 below:

$$BD = (ODW_{sample} - ODW_{paper\ bag}) / CV \qquad \text{(Equation 1)}$$

where ***BD*** is the bulk density (g cm^{-3}) of the soil sample, ODW_{sample} weight of the oven dried soil sample (g), $ODW_{paper\ bag}$ weight of the empty oven dried paper bag (g) and ***CV*** the core volume (cm^3) of the used soil core (here 100 cm^3).

4.3.2 Soil pH Measurement

5 g air-dried fine earth (< 2mm) was mixed with 12.5 ml of 0.01 M calcium chloride solution, followed by a three hour resting period. During the three hours of resting the mixture had to be stirred every 30 min using a glass stirrer. The pH electrode (WTW inoLab pH 720) was dipped into the mixture and the pH-value was measured.

4.3.3 Determination of SOC stocks

4.3.3.1 Determination of SOM concentration by loss-on-ignition method

Loss-on-ignition is a common and widely used method to determine the SOM concentration by weighing the soil sample before and after an ashing treatment. The method is based on the principle, that all SOM is oxidized to CO_2 and ash at the chosen temperatures between 500 and 550°C, whereas the carbonates remain unaffected (Bisutti et al., 2004; Heiri et al., 2001). After Heiri et al. (2001) at temperatures above 900°C CO_2 evolves from the thermal dissociation of carbonates. For the determination of the SOM concentration, every soil sample was ball-milled for three minutes to homogenize the soil. Five g of ball milled soil was weighed into a crucible and oven dried at 180 °C for 24 h. This pre-treatment of every sample, at the chosen temperature of 180°C (personal communication with Prof. Dr. Karl Stahr), was necessary to remove the water from the clay minerals of the clay fraction. Neglecting the loss of water from clay minerals in soils with high clay content can produce

serious error (Bisutti et al., 2004). The weight of the empty crucible (g) had to be determined at the beginning of the process. After the 12 h oven drying, the samples were cooled in a desiccator to room temperature and the weight of the samples after oven drying (g) was also written down. Next the oven dried samples were put into the muffle furnace at 550° for 4 h to burn all the SOM. After the 4 h the remaining ashes of the samples were cooled in a desiccator to room temperature and the weight recorded.

4.3.3.2 Calculation of SOM concentration

The concentration of SOM (%) was calculated as shown in the equation 2 below:

$$SOM = (W_{180} - W_{550}) / W_{180} \times 100 \quad \text{(Equation 2)}$$

where ***SOM*** is the soil organic matter concentration (%) of the soil sample, W_{180} weight of the soil sample after oven drying at 180°C (g) and W_{550} weight of the soil sample after burning at 550°C (g).

4.3.3.3 Calculation of SOC concentration

Based on the work of Sprengel in 1826 the general assumption is that 58 % of the SOM is SOC (Pribyl, 2010). The concentration of SOC (%) was calculated as shown in the equation 3 below:

$$SOC = SOM \times 0{,}58 \quad \text{(Equation 3)}$$

where ***SOC*** is the soil organic carbon concentration (%), ***SOM*** the soil organic matter concentration (%) calculated with equation 2 and ***0.58*** the conversion factor for SOC.

4.3.3.4 Calculation of SOC stock

The SOC stock (t ha^{-1}) was calculated as shown in the equation 4 below:

$$SOC\ stock = BD \times SOC \times D \quad \text{(Equation 4)}$$

where ***SOC stock*** is the soil organic carbon stock (t ha^{-1}), ***BD*** the bulk density (g m^{-3}) calculated with equation 2, ***SOC*** soil organic carbon concentration (%) calculated with equation 3 and ***D*** the soil sampling depth (cm).

4.3.4 Elemental analyser

The elemental analyser varioEL analyser (elementar, Hanau, Germany) was used for the determination of total carbon concentration of the understory plant material.

For the measurement, 40 mg of the plant sample were weighed into tin capsules by using an electrical balance (Precisa 405M-200A). The tin capsules containing the plant samples are then burned in a combustion chamber, filled with wolfram and copper, of the analyser at 950°C. The carbon compounds are thereby thermally oxidised to CO_2 and the nitrogen compound are reduced via NO_x to N_2. Next, the gas mixture is separated by an integrated gas chromatography and then measured with the help of a thermal conductivity detector. The output of the measured sample is in % carbon and % nitrogen.

The understory (grass) carbon stock (t ha^{-1}) was calculated as shown in the equation 5 below:

$$\boldsymbol{UPC\ stock = BM_{UPM} /100 * C_{UPM}} \qquad \text{(Equation 5)}$$

where ***UPC stock*** is the understory plant carbon stock (t ha^{-1}), $\boldsymbol{BM_{UPM}}$ the biomass of the understory plant material (t ha^{-1}) and $\boldsymbol{C_{UPM}}$ the carbon concentration (%) of the understory plant material analysed with the C/N analyser.

5 Results

5.1 Carbon stocks

5.1.1 Total Aboveground Biomass and Aboveground C stocks [t ha^{-1}]

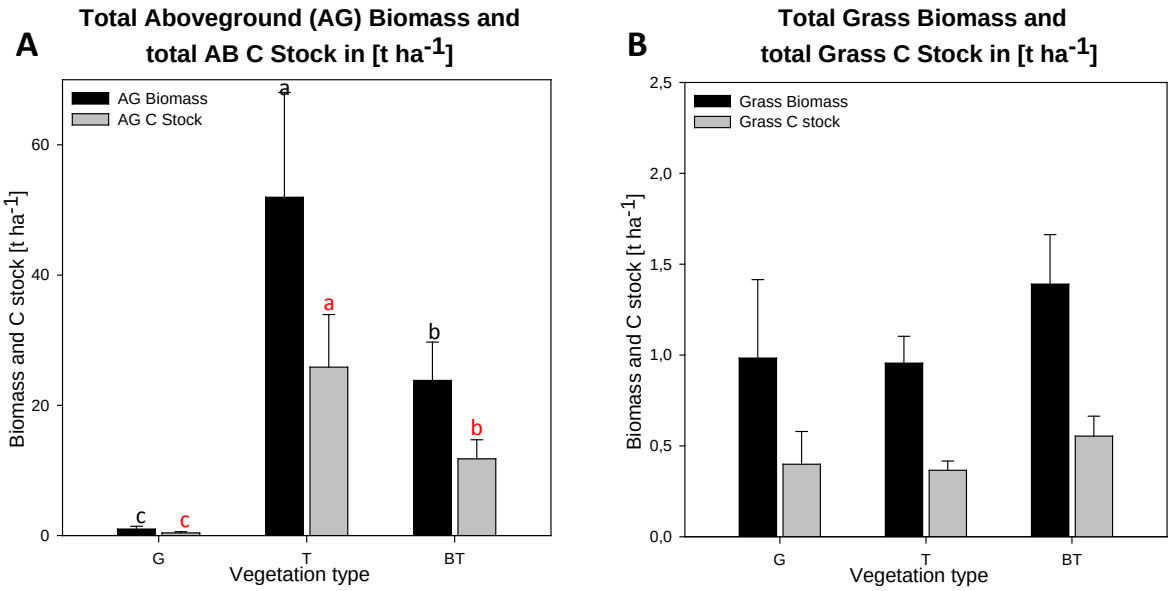

Figure 14: (A) Total aboveground biomass [t ha^{-1}] and total aboveground C stock [t ha^{-1}] (B) Grass biomass [t ha^{-1}] and grass C-stock [t ha^{-1}] for different vegetation types are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush–Tree savannah.

Figure 14 A shows the total aboveground (AG) biomass and the total AG C-stock (C, that is stored in the vegetation) of the three different vegetation types. The total AG biomass and the total AG C-stock were significantly different (P < 0.05) between the vegetation types. The Tree savannah (T) had the highest amount of total AG biomass and total AG C-stock (51.9 (±16.1) t ha^{-1} and 25.9 (±8.1) t ha^{-1}, respectively), followed by the Bush–Tree savannah (BT) with 23.8 (±5.9) t ha^{-1} and 11.77 (±2.9) t ha^{-1}, respectively. The lowest amount for total AG biomass and total AG C-stock was found in the Grassland (G) with 0.98 (±0.4) t ha^{-1} and 0.4 (±0.2) t ha^{-1}, respectively. Figure 14 B presents the total biomass and total C-stock of the understory vegetation, consisting mainly of grasses, of the three different vegetation types. There was neither significant difference between the amounts of total grass biomass, nor between the amounts of total grass C-stock for the three different vegetation types. Nevertheless, the BT had the highest amounts of total AG biomass and total AG C-stock with

1.39 (±0.3) t ha^{-1} and 0.55 (±0.1) t ha^{-1}, respectively. G and T had similar amounts in total AG biomass and total AG C-stock.

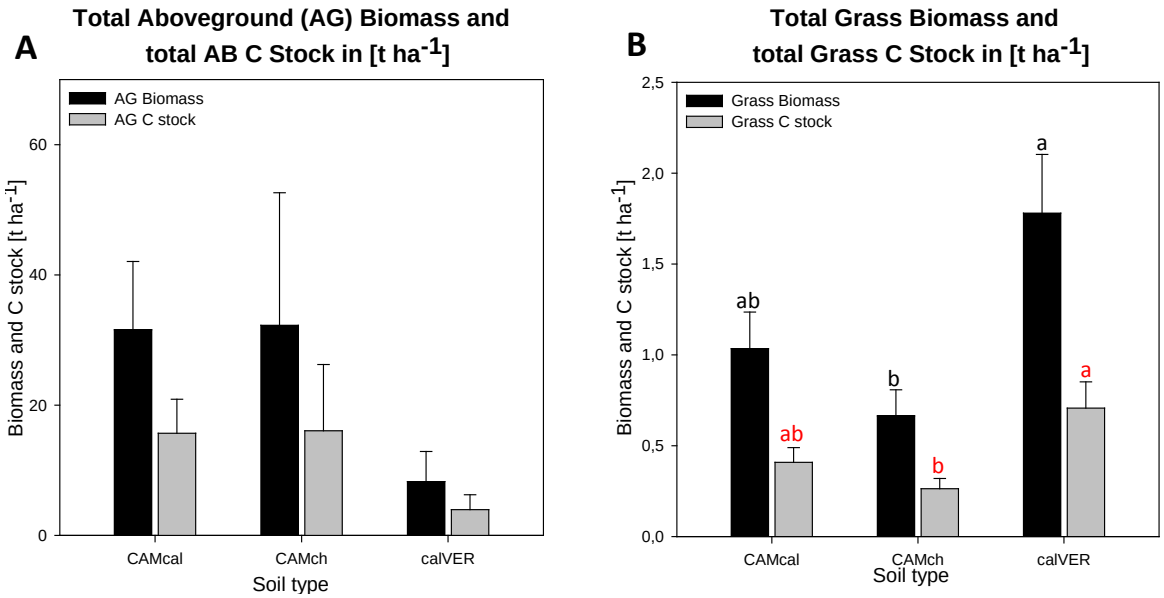

Figure 15: (A) Total aboveground biomass [t ha^{-1}] and total aboveground C stock [t ha^{-1}] (B) Grass biomass [t ha^{-1}] and grass C-stock [t ha^{-1}] for different soil types are indicated. Means followed by the same letter are not significantly different at P<0.05. Bars show the standard error over the repetitions. CAMcal = Cambisol calcaric, CAMch = Cambisol chromic and calVER = calcic Vertisol.

In Figure 15 A the total AG biomass and the total AG C-stock of the three different soil types, found in the study area, are shown. Neither significant differences were found between the amounts of the total AG biomass, nor between the amounts of total AG C-stock for the three different soil types. The amounts of the Cambisol calcaric (CAMcal) and the Cambisol chromic (CAMch) are similar with 31.6 (±10.5) t ha^{-1} and 32.3 (±20.4) t ha^{-1} for the total AG biomass and 15.7 (±5.2) t ha^{-1} and 16.1 (±10.2) t ha^{-1} for the total AG C-stock. The calcic Vertisol (calVER) had the lowest amounts of total AG biomass and the total AG C-stock (8.3 (±4.6) t ha^{-1} and 3.9 (±2.3) t ha^{-1}, respectively). Figure 15 B compares the amount of total grass biomass of each soil type and of total grass C-stock of each soil type. The total grass biomass and total grass C-stock amounts of the calVER (1.8 (±0.3) t ha^{-1} and 0.7 (±0.1) t ha^{-1}, respectively) were the highest and significantly different (P<0.05) from the amounts of the CAMch (0.7 (±0.1) t ha^{-1} and 0.3 (±0.1) t ha^{-1}, respectively) but not from the amounts of the CAMcal (1.03 (±0.2) t ha^{-1} and 0.4 (±0.1) t ha^{-1}, respectively). The CAMch had the lowest amounts of total grass biomass and total grass C-stock and was not significantly different from the higher amounts of the CAMcal.

5.1.2 Total Soil Organic Carbon Stock [t ha^{-1}]

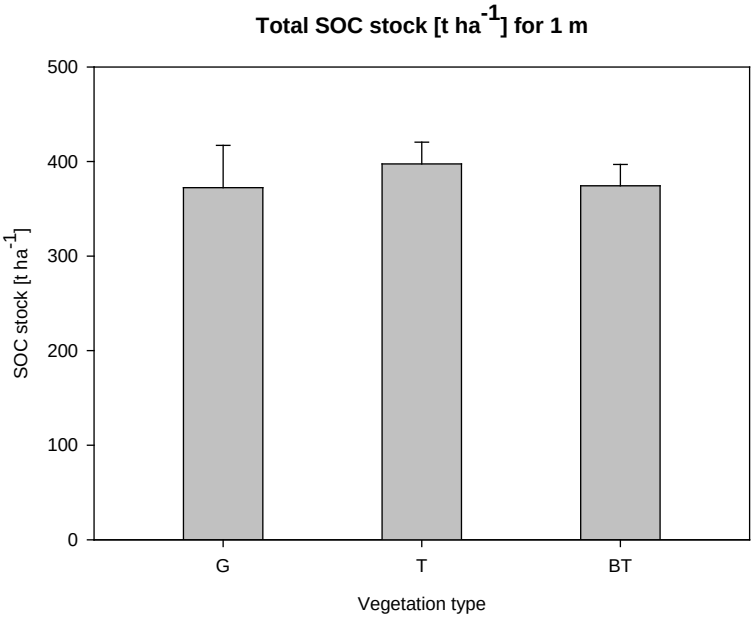

Figure 16: Total belowground SOC stocks [t ha^{-1}] for different vegetation types for 1 m are indicated. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush–Tree savannah.

The total SOC stocks [t ha^{-1}] amounts over 1 m for the three different vegetation types G, T and BT were 372.3 (±44.8) t ha^{-1} BT, 397.5 (±23.1) t ha^{-1} and 374.4 (±22.5) t ha^{-1}, respectively (Figure 16). None of these differences between the amounts for the vegetation types were statistically significant. G had, with a standard error of 44.8 t ha^{-1}, the highest variations between the five repetitions.

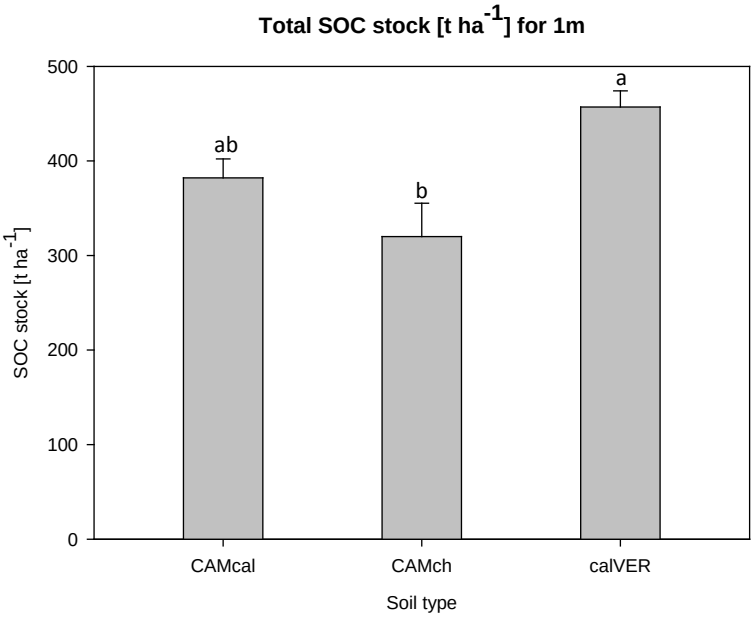

Figure 17: Total belowground SOC stocks [t ha^{-1}] for different vegetation types for 1 m are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. CAMcal = Cambisol calcaric, CAMch = Cambisol chromic and calVER = calcic Vertisol.

In terms of the total SOC stocks [t ha^{-1}] over 1 m for the different soil types, significant difference (P<0.05) was observed between the CAMch and the calVER (Figure 17).The highest amount of SOC was stored in the first meter of the calVER (457 (±17.1) t ha^{-1}). The CAMcal was neither significantly different to the CAMch nor to the calVER and stored 382.1 (±20) t ha^{-1} SOC in the first meter. The CAMch with 320 t ha^{-1} had the lowest stock of SOC and with 35.3 t ha^{-1} the highest standard error.

5.2 SOC concentrations [%]

5.2.1 Changes in SOC concentrations [%] by and within the same depth

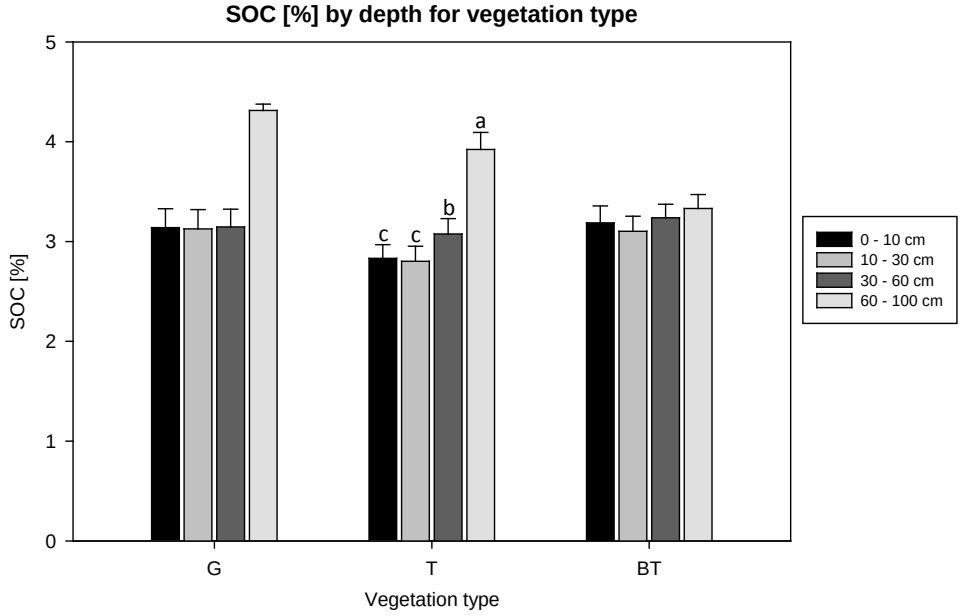

Figure 18: SOC [%] concentrations for different vegetation types by depth are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush – Tree savannah.

Figure 18 presents the SOC concentrations [%] for the different vegetation types in the four different sampled depths, to show whether the SOC concentration within a vegetation type changes by depth. The SOC concentrations varied between 2.8 (±0.1) % and 4.3 (±0.1) % across the vegetation types and different depths. No significant differences (P<0.05) were found between the different depths of the G and the BT, only for the T there were significant differences between the different depths. Depth 0 – 10 cm and 10 – 30 cm were not significantly different from each other, but the SOC concentration of the two depths (2.83 (±0.1) % and 2.80 (±0.1) %, respectively) were significantly lower to the concentrations of depth 30 – 60 cm and 60 – 100 cm (3.1 (±0.2) % and 3.9 (±0.2) %, respectively). The SOC

concentration of depth 30 – 60 cm was significantly lower to the concentration of depth 60 – 100 cm.

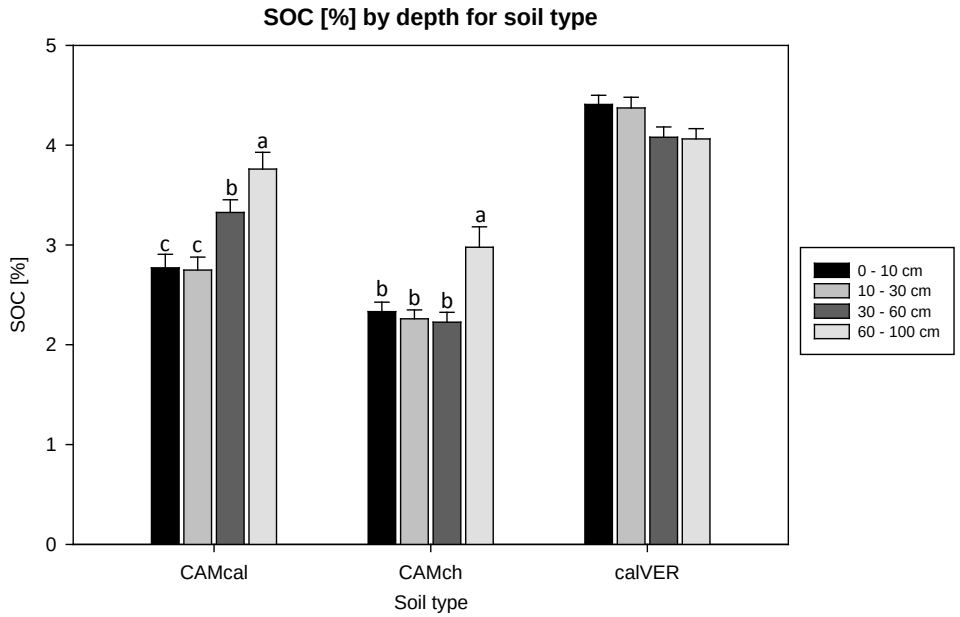

Figure 19: SOC [%] concentrations for different soil types by depth are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. CAMcal = Cambisol calcaric, CAMch = Cambisol chromic and calVER = calcic Vertisol.

Figure 19 shows the SOC concentrations [%] for the different soil types in the four different sampling depths. The SOC concentrations [%] across the soil types and different depths ranged between 2.2 (±0.1) % and 4.4 (±0.1) %. For CAMcal and CAMch there were significant differences between the four depths, but not for the calVER. For the CAMcal depth 0 – 10 cm and 10 – 30 cm were not significantly different from each other, but with a SOC concentration of 2.8 (±0.1) % and 2.70 (±0.1) % they were significantly lower compared to the concentrations of depth 30 – 60 cm and 60 – 100 cm. Depth 60 – 100 cm with 3.8 (±0.2) % had the highest SOC concentration and was significantly different to the SOC concentration of depth 30 – 60 cm (3.3 (±0.1) %). For the CAMch no significant differences were found between the depths 0 – 10 cm, 10 – 30 cm and 30 – 60 cm. Nevertheless, they slightly decreased in the order: depth 0 – 10 cm (2.33 (±0.1) %) > depth 10 – 30 cm (2.26 (±0.1) %) > depth 30 – 60 cm (2.23 (±0.1) %). With a SOC concentration of 3.0 (±0.2) % the depth 60 – 100 cm was significantly higher to the three depths above.

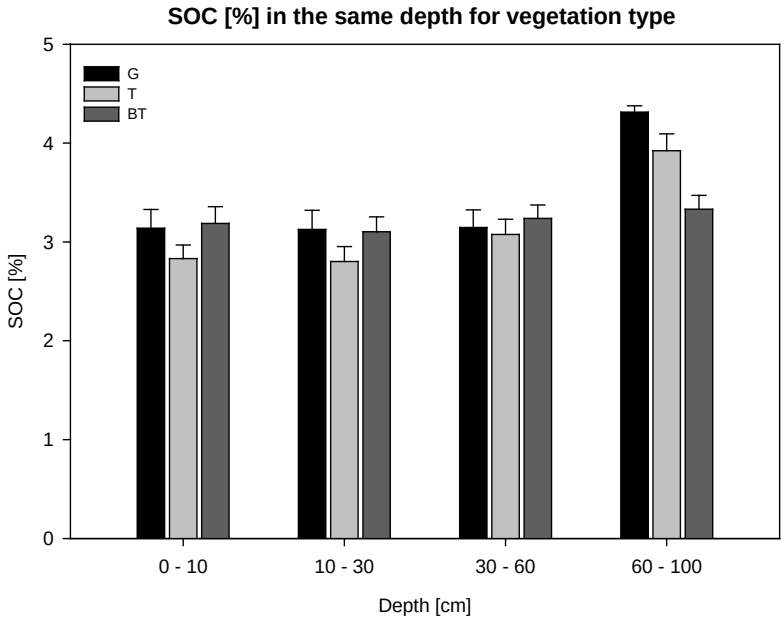

Figure 20: SOC [%] concentrations for different vegetation types in the same soil depth for the four different depths are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush – Tree savannah.

Mean SOC concentrations between the different vegetation types in the same soil depth are compared in Figure 20. None of the differences between the concentrations of G, T and BT in the same depth for all four soil depths were statistically significant.

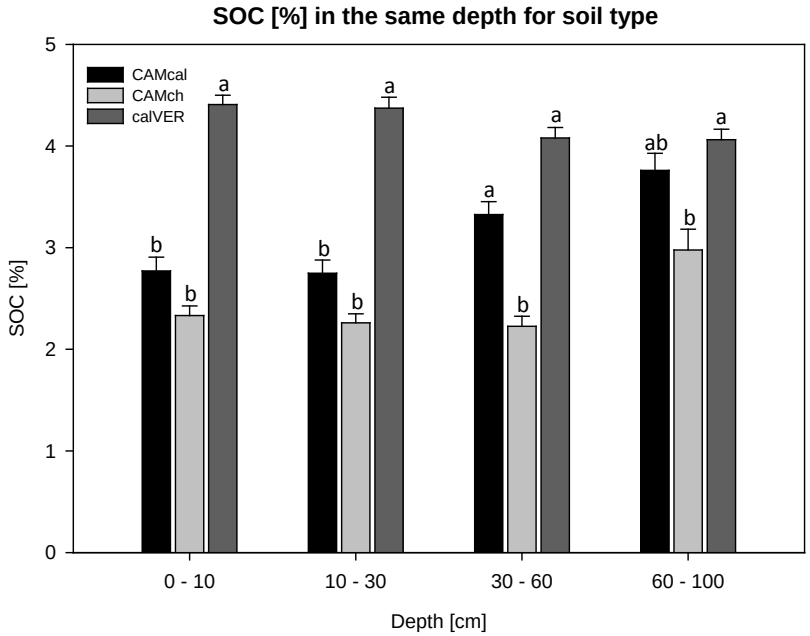

Figure 21: SOC [%] concentrations for different soil types in the same soil depth for the four different depths are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. CAMcal = Cambisol calcaric, CAMch = Cambisol chromic and calVER = calcic Vertisol.

Looking at the comparison between the different soil types in Figure 21, in terms of the SOC concentrations in the same depth significant differences were found for all four different

depths. In depth 0 – 10 cm calVER was significantly different ($p < 0.05$) to the other two soil types. With a mean SOC concentration of 4.4 (±0.1) % it was about double the concentration of the CAMcal (2.8 (±0.1) %) and the CAMch (2.3 (±0.1) %). CAMcal and CAMch were not significantly different from each other. Similar conditions occurred in depth 10 – 30 cm. In depth 30 – 60 cm the calVER had with 4.1 (±0.1) % again the highest mean concentration of SOC and was significantly different ($p < 0.05$) to the CAMch (2.2 (±0.1) %) but not to the CAMcal (3.3 (±0.1) %). CAMcal and CAMch were significantly different ($p < 0.05$) from each other. Also in depth 60 – 100 cm the calVER had the highest mean SOC concentration (4.1 (±0.1) %) and was significantly different ($p < 0.05$) to the CAMch but not to the CAMcal. The CAMch had, just like in the three depths above, the lowest mean SOC concentration (3.0 (±0.2) %) and was not significantly different to the CAMcal (3.8 (±0.2) %).

5.2.2 Seasonal change in SOC concentrations [%]

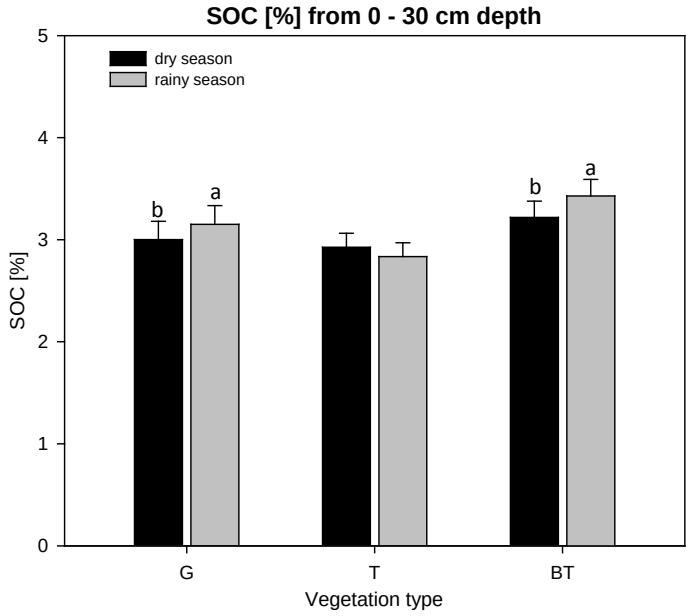

Figure 22: SOC [%] concentration for different vegetation types for dry and rainy season at 0 – 30 cm depth are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush – Tree savannah.

Figure 22 presents the seasonal change of the mean SOC concentration from the dry season to the rainy season in the first 30 cm of the soil within the vegetation type. In the dry season the mean SOC concentrations varied from 2.9 (±0.1) % to 3.2 (±0.2) % and in the rainy season from 2.8 (±0.1) % to 3.4 (±0.2) %. Within the vegetation types, G and BT had significantly higher ($p < 0.05$) SOC concentrations in the rainy season compared to the dry season. In the G it increased from 3.0 (±0.2) % to 3.2 (±0.2) % and in the BT from 3.2 (±0.2) %

to 3.4 (±0.2) %.Though the SOC concentration for the T decreased from 2.9 (±0.1) % to 2.8 (±0.1) %, this difference was not statistically significant (P<0.05).

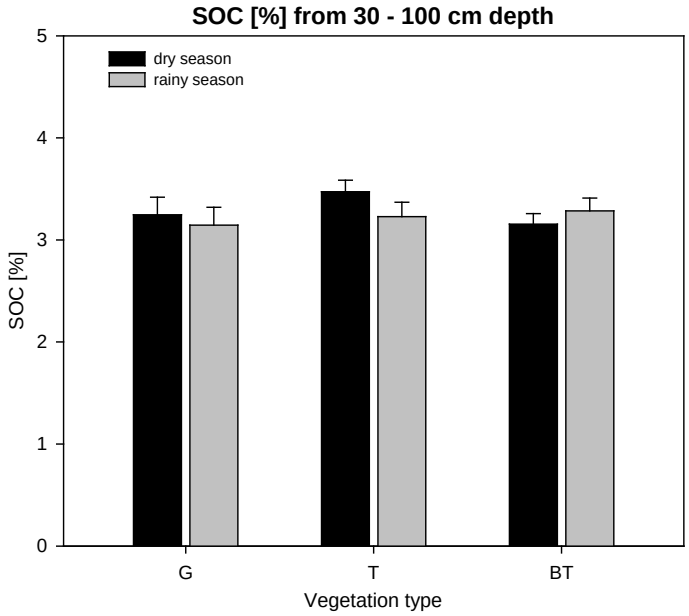

Figure 23: SOC [%] concentrations for different vegetation types for dry and rainy season at 30 – 100 cm depth are indicated. Means followed by the same letter are not significantly different at P < 0.05. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush – Tree savannah.

Different to Figure 22, Figure 23 presents SOC [%] concentrations for different vegetation types for dry and rainy season at 30 – 100 cm depth. It shows that no statistically significant (P<0.05) seasonal change of the mean SOC concentration from the dry season to the rainy season occurred in the depth 30 – 100 cm.

5.3 Descriptive summary of the Plots for the soil types

Table 2: Summary soil types

Plot ID	Coordinates	Meter a.s.l.	Soil type	Soil colour	Bulk density (g cm^{-3}) (0-10/10-30 cm)[1]	pH (0-10/10-30/ 30-40/40-60 cm)[1]	Carbonate (%) (0-10/10-30/ 30-40/40-60 cm)[1]	SOC (%) (0-10/10-30/ 30-40/40-60 cm)[1]
G2	N4°11.042/ E38°16.278	1539	Calcic Vertisol	black - brown	1.11/1.16	8.12/7.75/7.82/7.79	2.28/2.26/2.92/2.80*	4.31/4.46/4.39/4.35
G3	N4°11.481/ E38°15.772	1542	Calcic Vertisol	black - brown	1.12/1.03	7.64/7.64/7.67/7.65	0-2/2-10/2-10/2-10**	4.71/4.65/4.29/4.28
G5	N4°11.736/ E38°18.281	1539	Cambisol chromic	red - brown	1.14/1.14	7.30/7.49/7.68/7.85	0.31/0.25/3.08/11.27*	2.85/2.71/2.80
G7	N4°11.551/ E38°17.451	1542	Cambisol calcaric	white - brown	1.32/1.17	7.27/7.57/7.66/7.84	2-10/2-10/2-10/10-25**	2.18/2.47/2.92
T1	N4°11.088/ E38°16.054	1541	Calcic Vertisol	black - brown	0.76/1.06	7.73/7.74/7.74/7.78	0-2/2-10/2-10/2-10**	4.56/4.55/4.47/4.52
T2	N4°12.167/ E38°16.291	1536	Cambisol calcaric	brown	1.19/1.01	7.16/7.32/7.50/7.79	0-2/0-2/2-10/2-10**	2.49/2.33/2.62/3.17
T3	N4°10.749/ E38°18.737	1522	Cambisol chromic	red - brown	1.23/1.24	6.85/7.04/7.50/7.89	0-2/0-2/2-10/10-25**	2.69/2.56/2.30/3.01
T4	N4°11.724/ E38°18.565	1526	Cambisol chromic	red - brown	1.30/1.20	7.17/7.21/7.62/7.78	0/0-2/2-10/10-25**	2.56/2.34/2.47
T5	N4°11.705/ E38°15.802	-	Cambisol calcaric	white - brown	1.38/1.27	7.52/7.63/7.78/7.82	2-10/2-10/2-10/10-25**	2.59/2.33/3.22/3.14
BT1	N4°11.570/ E38°14.304	1577	Cambisol calcaric	white - brown	1.30/1.20	7.67/7.74/7.85/7.91	0.98/2.81/3.40/6.57*	2.59/2.74/2.87/3.18
BT2	N4°10.994/ E38°16.575	1541	Cambisol chromic	red - brown	1.23/1.17	6.76/6.90/7.45/7.67	0-2/0-2/2-10/2-10**	2.34/2.36/2.16/2.51
BT3	N4°11.254/ E38°19.056	1516	Calcic Vertisol	black - brown	1.04/1.20	6.51/6.98/7.46/7.58	0-2/2-10/2-10/2-10**	3.97/3.39/3.17/3.12
BT4	N4°10.425/ E38°19.097	1516	Cambisol calcaric	brown	0.98/0.98	7.66/7.74/7.77/7.96	0.94/0.70/5.21/9.16*	4.38/4.53/4.46/4.64
BT5	N4°12.965/ E38°15.592	1554	Cambisol calcaric	white - brown	1.23/1.17	7.70/7.73/7.84/7.99	2-10/2-10/2-10/10-25**	2.14/2.26/3.39

[1] Different sampling depths
*** Analyzed in the Laboratory by using a Scheibler apparatus after DIN ISO 10693**
**** Estimated according to the "Field Guide" (FAO, 2006) with hydrochloric acid (10w%)**

Table 2 is a summary of the location of each plot and which soil type is found there. Furthermore it provides an overview of the measured soil parameters bulk density, pH value, carbonate concentration and SOC concentration for different depth, and soil colour.

5.4 Relationship between precipitation [mm], soil moisture [Vol%], VT & ST

5.4.1 Mean soil moisture content [Vol%]

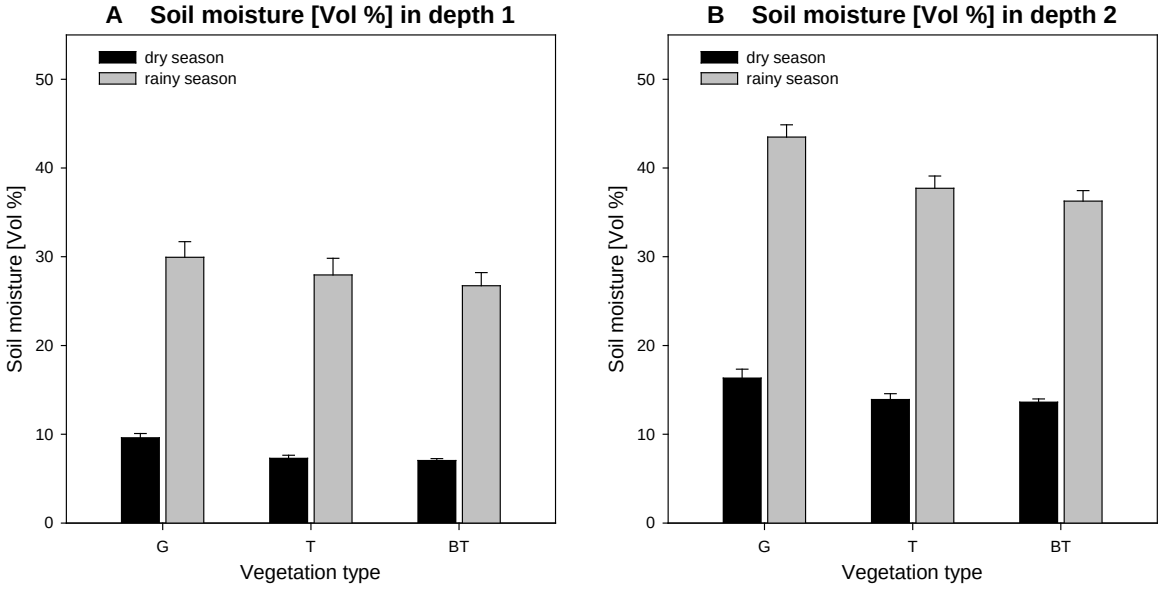

Figure 24: Soil moisture [Vol %] content for different vegetation types for dry and rainy season in (A) depth 1 (0-6 cm soil depth) and (B) depth 2 (30-36 cm soil depth) are indicated. Means followed by the same letter are not significantly different at P<0.05. Bars show the standard error over the repetitions. G = Grassland, T = Tree savannah and BT = Bush – Tree savannah.

Figure 24 A shows the average soil moisture content [Vol %] in the dry and rainy season between the three different vegetation types in the depth 0 – 6 cm. The soil moisture contents in the dry season are with 9.6 (±0.5) Vol % for G, 7.3 (±0.4) Vol % for T and 7.1 (±0.2) Vol % for BT similar. None of the differences between these vegetation types were statistically significant (P<0.05). The same applies for the soil moisture contents in the rainy season between the vegetation types. They are with 29.9 (±1.8) Vol %, 28.0 (±1.9) Vol % and 26.7 (±1.5) Vol % similar and not significantly different (P<0.05) to each other. Figure 24 B presents the soil moisture content [Vol %] in the dry and rainy season between the three different vegetation types in a deeper soil layer (30 – 36 cm). The results of Figure 24 B reflect more or less what is shown in Figure 24 A, just with higher mean soil moisture contents. The soil moisture contents were similar in the dry and rainy season between the vegetation types. No significant differences (P<0.05) were found.

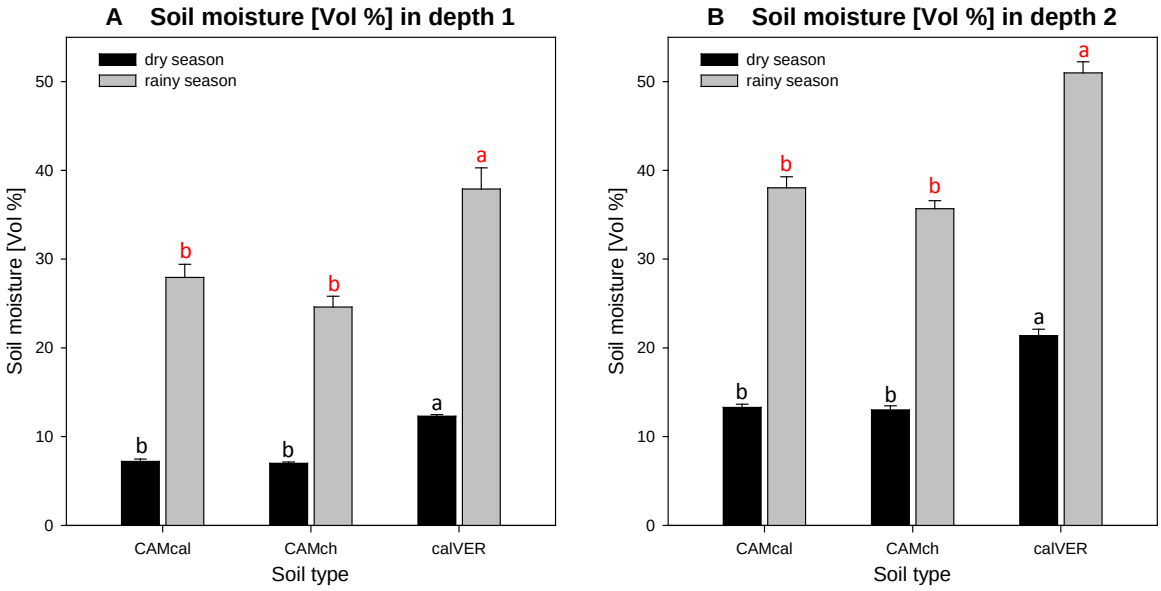

Figure 25: Soil moisture [Vol %] content for different soil types for dry and rainy season in (A) depth 1 (0-6 cm soil depth) (B) depth 2 (30-36 cm soil depth) are indicated. Means followed by the same letter are not significantly different at P<0.05. Bars show the standard error over the repetitions. CAMcal = Cambisol calcaric, CAMch = Cambisol chromic and calVER = calcic Vertisol.

The mean soil moisture content between the different soil types in the top soil layer (0–6 cm) for the dry season were for the CAMcal 7.2 (±0.3) Vol %, for the CAMch 7.0 (±0.2) Vol % and for the calVER 12.3 (±0.2) Vol % (Figure 25 A). The mean soil moisture content of the calVER was about double the contents of the CAMcal and CAMch. Furthermore, there was a significant difference (P<0.05) to the other two soil types. The soil moisture contents for the CAMcal and CAMch resembled each other and no significant difference was found. In the rainy season the calVER was significantly higher (P<0.05) with a mean soil moisture content of 38.0 (±2.4) Vol % then the other two. The CAMcal with 28.0 (±1.5) Vol % had a higher mean soil moisture content compared to the CAMch (24.6 (±1.2) Vol %), but no significant difference was found. In the deeper soil layer (30–36 cm), shown in Figure 25 B, in the dry season the mean soil moisture content for the CAMcal and CAMch were 13.3 (±0.4) Vol % and 13.0 (±0.5) Vol %, respectively. No significant differences (P<0.05) were found between these two soil types. The same applies for these two soil types in the rainy season; the mean soil moisture contents are with 38.0 (±1.3) Vol % for the CAMcal and 35.7 (±0.9) Vol % for the CAMch similar and no significant difference (P<0.05) was found. The calVER had in both seasons significantly higher mean soil moisture contents (dry season: 21.4 (±0.7) Vol % and rainy season: 51.0 (±1.2) Vol %) as the CAMcal and CAMch.

5.4.2 Relationship between precipitation [mm] and soil moisture [Vol%]

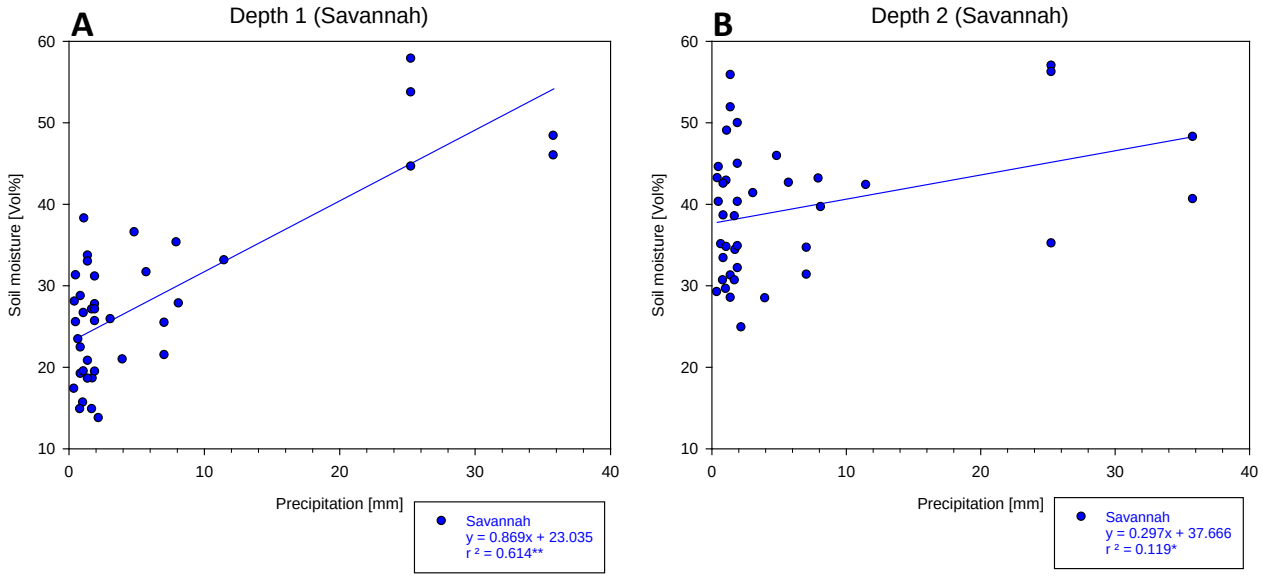

Figure 26: Relationship between precipitation [mm] and soil moisture [Vol%] in (A) depth 1 (0-6 cm) and in (B) depth 2 (30-36 cm). Values for the ecosystem savannah are indicated. One asterisk (*) points out that relationship is significant at P<0.05. Two asterisk (**) point out that relationship is highly significant at P<0.01.

In Figure 26 the relationship between rainfall and soil moisture content for the ecosystem savannah in A the top soil layer (depth1: 0 – 6 cm) and B the deeper soil (depth 2: 30 – 36 cm) is shown. In depth 1 the mean soil moisture content for the whole savannah before the four rain events was 23.0 Vol% and therefore lower than the mean soil moisture content in depth 2 (37.7 Vol%). The coefficient of determination with $r^2 = 0.614$ was higher in depth 1 than in depth 2 ($r^2 = 0.119$). Furthermore, the relationship between rainfall and soil moisture content for the ecosystem savannah was highly significant at P<0.01 in depth 1 and significant at P<0.05 in depth 2.

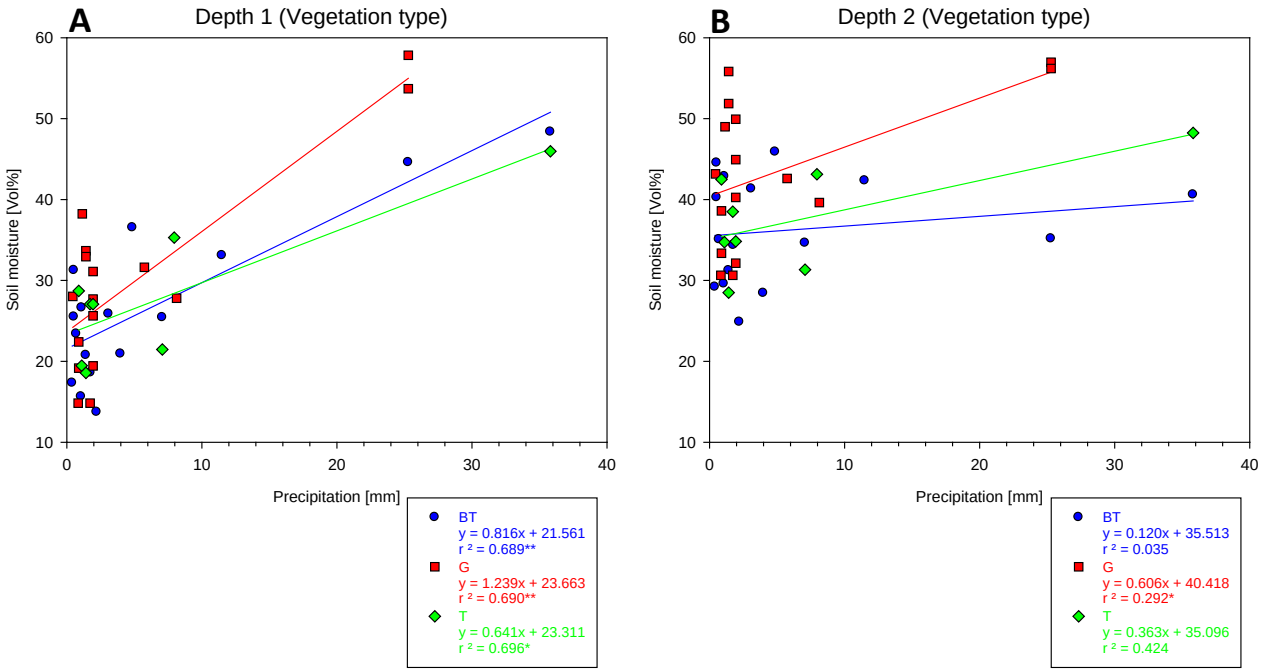

Figure 27: Relationship between precipitation [mm] and soil moisture [Vol %] in (A) depth 1 (0-6 cm) and in (B) depth 2 (30-36 cm). Values for different vegetation types Bush-Tree savannah (BT), Grassland (G) and Tree savannah (T) are indicated. One asterisk (*) points out that relationship is significant at P<0.05. Two asterisk (**) point out that relationship is highly significant at P<0.01.

The relationship between rainfall and soil moisture content between the different vegetation types in depth1 (0–6 cm) and depth 2 (30–36 cm) is presented in Figure 27 A and 27 B, respectively. In the top soil layer the coefficient of determination was similar for all three vegetation types and the relationship for the BT and G was highly significant at P<0.01 and for the T significant at P<0.05. Furthermore, all three vegetation types before the four rain events had occurred with about 23.5 Vol % similar mean soil moisture contents. The G regression line with 1.239 had a steeper slope compared to the slopes of the BT (0.816) and Tree savannah (0.641). Nevertheless, no significant difference between the slopes was found. The relationship between rainfall and soil moisture content in depth 2 (Figure 27 B) was significant at P<0.05 for G, but not for the BT and T. Neither were the slopes of the different regression lines significantly different to each other.

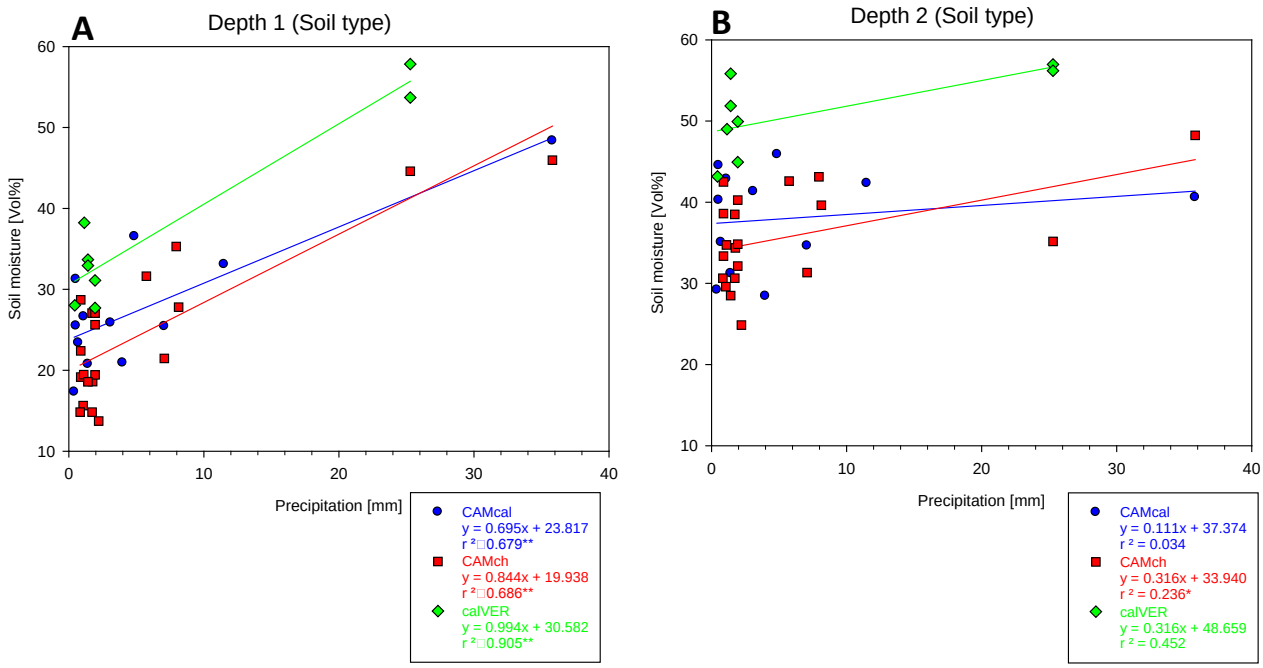

Figure 28: Relationship between precipitation [mm] and soil moisture [Vol %] in (A) depth 1 (0-6 cm) and in (B) depth 2 (30-36 cm). Values for the different soil types Cambisol calcaric (CAMcal), Cambisol chromic (CAMch) and calcic Vertisol (calVER) are indicated. One asterisk (*) points out that relationship is significant at P<0.05. Two asterisk (**) point out that relationship is highly significant at P<0.01.

Figure 28 shows the relationship between precipitation and soil moisture for three different soil types in A depth 1 (0–6 cm) and in B depth 2 (30–36 cm). In Figure 28 A, CAMcal and CAMch had a similar r^2 (about 0.7) and the relationship was highly significant at P<0.01. The calVER had with 0.905 a higher r^2 and the relationship was also highly significant at P<0.01. The slopes for the regression lines ranged between 0.695 and 0.994. The slopes of the different regression lines were neither in the top soil layer nor in the deeper soil layer significantly different from each other. In depth 2, only the relationship between rainfall and soil moisture for the CAMch was significant at P<0.05.

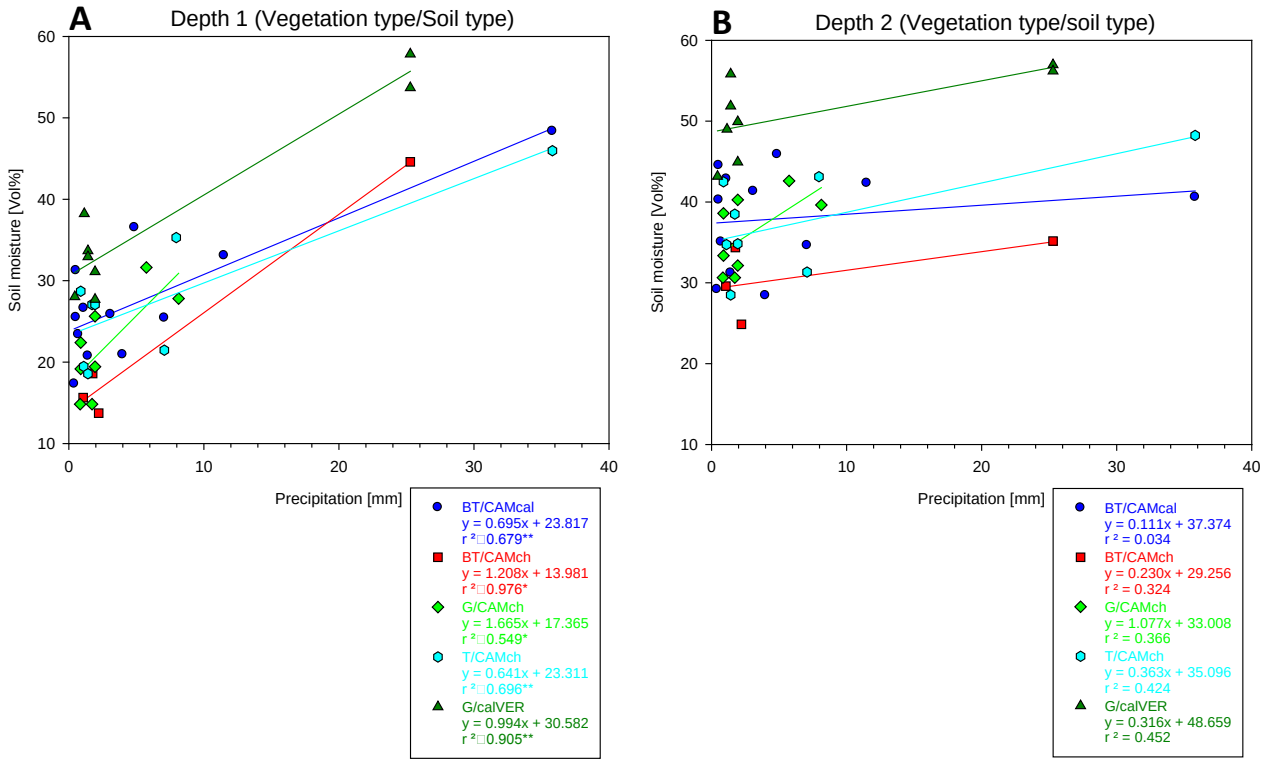

Figure 29: Relationship between precipitation [mm] and soil moisture [Vol %] in (A) depth 1 (0-6 cm) and in (B) depth 2 (30-36 cm). Values for the different vegetation types and corresponding soil types Bush-Tree savannah on Cambisol calcaric (BT/CAMcal), Bush-Tree savannah on Cambisol chromic (BT/CAMch), Grassland on Cambisol chromic (G/CAMch), Tree savannah on Cambisol chromic (T/CAMch) and Grassland on calcic Vertisol (G/calVER) are indicated. . One asterisk (*) points out that relationship is significant at P<0.05. Two asterisk (**) point out that relationship is highly significant at P<0.01.

Figure 29 presents the relationship between precipitation and soil moisture for the vegetation types and the corresponding soil types, again in two depths (Figure 29 A: 0 –6 cm and Figure 29 B: 30–36 cm). For the Bush – Tree savannah on Cambisol calcaric (BT/CAMcal), the T/CAMch and the G/calVER the relationship was highly significant at P<0.01 and for the BT/CAMch and G/CAMch it was significant at P<0.05. The slopes of the different regression lines were neither in the top soil layer nor in the deeper soil layer significantly different from each other. In depth 2, no relationship between rainfall and soil moisture was significant.

Table 3: Summery of vegetation cover data for the 10 plots were precipitation and soil moisture measurements took place.

Plot	Vegetation cover [%]	Soil type
BT1	60	Cambisol calcaric
BT2	53	Cambisol chromic
BT4	55	Cambisol calcaric
BT5	42	Cambisol calcaric
G1	60	Cambisol chromic
G2	50	Calcic Vertisol
G3	56	Calcic Vertisol
G5	35	Cambisol chromic
T3	44	Cambisol chromic
T4	73	Cambisol chromic

Table 4: Summary of Soil moisture content (± standard error) and precipitation data were precipitation and soil moisture measurements took place.

Plot ID	Soil type	Moisture content depth 1 (0-6 cm) [Vol %] Dry season	Moisture content depth 2 (30-36 cm) [Vol %] Dry season	Rain event	Precipitation [mm]	Moisture content depth 1 (0-6 cm) [Vol %]	Moisture content Depth 2 (30-36 cm) [Vol %]
BT1	Cambisol calcaric	8.14 ±0.54	14.78 ±0.41	1	4.86	36.53 ±2.2	45.90 ±1.51
				2	0.53	31.27 ±5.31	44.53 ±3.26
				3	0.53	25.50 ±3.68	40.27 ±10.77
				4	3.09	25.87 ±3.04	41.33 ±2.42
BT2	Cambisol chromic	6.57 ±0.27	14.63 ±0.96	1	25.29	44.60 ±4.08	35.17 ±14.72
				2	1.77	18.60 ±1.44	34.37 ±3.31
				3	1.06	15.63 ±1.63	29.60 ±1.74
				4	2.21	13.73 ±0.95	24.87 ±5.95
BT4	Cambisol calcaric	7.31 ±0.33	12.62 ±0.59	1	35.81	48.37 ±0.74	40.60 ±12.22
				2	1.11	26.63 ±0.81	42.87 ±2.64
				3	1.41	20.77 ±0.22	31.23 ±4.32
				4	7.07	25.43 ±1.27	34.63 ±0.91
BT5	Cambisol calcaric	6.18 ±0.22	12.46 ±0.65	1	11.49	33.10 ±5.14	42.33 ±4.56
				2	0.71	23.40 ±1.80	35.07 ±1.26
				3	0.40	17.33 ±1.17	29.20 ±3.30
				4	3.98	20.93 ±2.01	28.43 ±0.55
G1	Cambisol chromic	6.41 ±0.18	8.92 ±0.42	1	8.13	27.80 ±0.67	39.63 ±4.47
				2	0.88	19.17 ±1.57	33.37 ±4.38
				3	0.84	14.83 ±1.06	30.63 ±1.44
				4	1.95	19.43 ±2.37	32.13 ±1.76
G2	Calcic Vertisol	12.26 ±0.31	23.43 ±0.97	1	25.29	57.83 ±0.18	56.97 ±0.68
				2	1.41	33.67 ±0.40	55.83 ±1.18
				3	1.15	38.23 ±5.63	49.00 ±8.92
				4	1.95	31.10 ±0.74	49.93 ±2.46
G3	Calcic Vertisol	12.36 ±0.23	19.32 ±0.51	1	25.29	53.70 ±2.94	56.20 ±1.15
				2	1.41	32.93 ±1.43	51.87 ±1.46
				3	0.44	28.03 ±0.67	43.17 ±3.10
				4	1.95	27.70 ±0.63	44.93 ±4.25
G5	Cambisol chromic	7.39 ±0.13	13.67 ±0.71	1	5.75	31.63 ±2.01	42.60 ±3.99
				2	0.88	22.40 ±2.58	38.60 ±5.08
				3	1.72	14.83 ±1.06	30.63 ±1.44
				4	1.95	25.63 ±1.51	40.27 ±2.47
T3	Cambisol chromic	8.32 ±0.29	15.64 ±0.42	1	35.81	45.97 ±2.80	48.23 ±2.40
				2	1.11	19.47 ±2.80	34.73 ±2.82
				3	1.41	18.57 ±1.25	28.50 ±0.66
				4	7.07	21.47 ±1.27	31.33 ±2.40
T4	Cambisol chromic	6.24 ±0.42	12.20 ±0.95	1	7.96	35.30 ±1.32	43.13 ±3.12
				2	0.88	28.70 ±1.06	42.50 ±1.56
				3	1.72	27.07 ±1.38	38.50 ±3.31
				4	1.95	27.07 ±1.11	34.83 ±1.41

The precipitation measurements recorded after each of the four rain events and the soil moisture content (in two depths) for the dry season and after each rain event are listed in Table 4. It is striking, that the first rain event had the highest amounts of rain and that the standard error of the soil moisture contents in the rainy season are higher than the standard errors in the dry season.

5.5 Relationship between SOC [%] and soil moisture [Vol%]

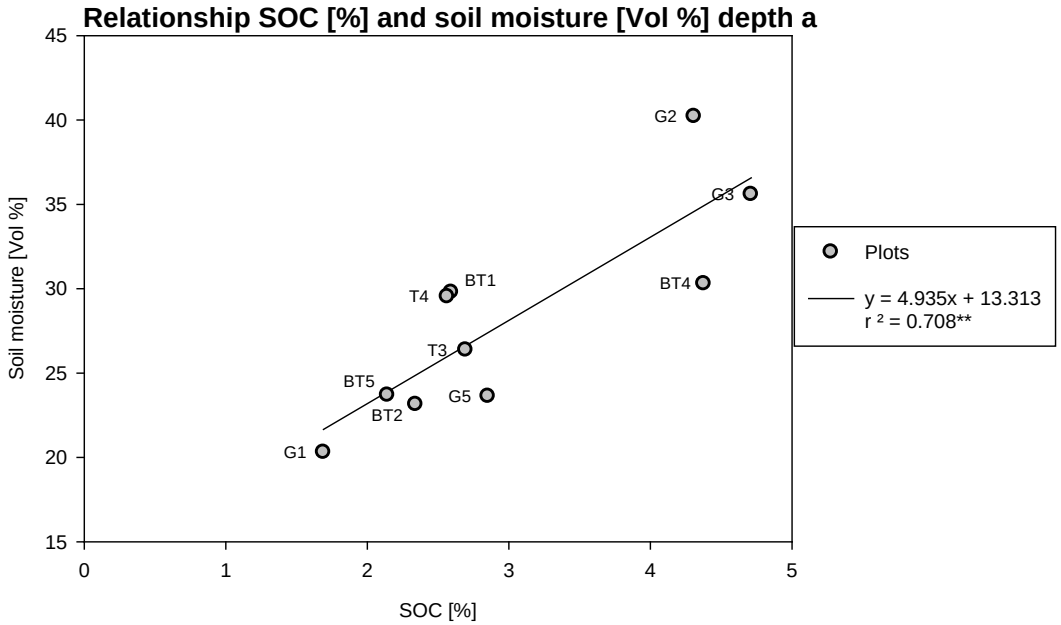

Figure 30: Relationship between SOC [%] and soil moisture [Vol %] in soil depth a (0-10 cm). Values for the plots BT1 BT2 BT4 BT5 (Bush – Tree savannah), G1 G2 G3 G5 (Grassland) and T3 T4 (Tree savannah) are indicated. Two asterisk (**) point out that relationship is highly significant at P<0.01.

The relationship between SOC and soil moisture in the top soil layer (0 –10 cm) for four BT plots, four G plots and two T plots is shown in Figure 30. The relationship was highly significant at P<0.01. Table 5 presents the soil type and the data about SOC concentration, soil moisture content and bulk density for each of the shown plots in Figure 30. Plot G1 had the lowest SOC concentration (1.69 %) and also the lowest soil moisture content (20.31 Vol %), but the highest bulk density (1.36 g cm^{-3}). Plot G3 had the highest SOC concentration (4.71 %) and the second highest soil moisture content (35.6 Vol %). The bulk density value was with 1.12 g cm^{-3}, compared to the other bulk density values, in the lower range. Plot BT4 (0.98 g cm^{-3}) showed the lowest bulk density value, with a high SOC concentration (4.38 %) and a medium range soil moisture content (30.3 Vol %).

Table 5: Summery of soil type, SOC concentration, soil moisture content, and bulk density data for 10 plots in soil depth a (from 0 till -10 cm).

Plot	Soil type	SOC [%]	Soil Moisture [Vol %]	Bulk density [g cm^{-3}]
BT1	Cambisol calcaric	2.59	29.79	1.30
BT2	Cambisol chromic	2.34	23.14	1.23
BT4	Cambisol calcaric	4.38	30.30	0.98
BT5	Cambisol calcaric	2.14	23.69	1.23
G1	Cambisol chromic	1.69	20.31	1.36
G2	Calcic Vertisol	4.31	40.21	1.11
G3	Calcic Vertisol	4.71	35.59	1.12
G5	Cambisol chromic	2.85	23.62	1.14
T3	Cambisol chromic	2.69	26.37	1.23
T4	Cambisol chromic	2.56	29.54	1.30

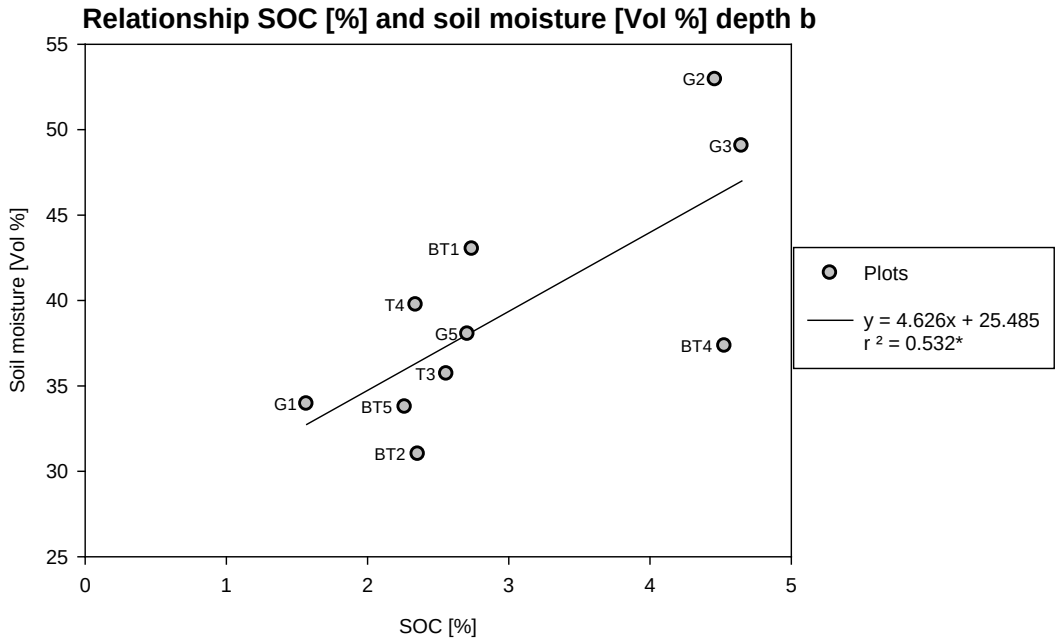

Figure 31: Relationship between SOC [%] and soil moisture [Vol %] in depth b (10-30 cm). Values for the plots BT1 BT2 BT4 BT5 (Bush – Tree savannah), G1 G2 G3 G5 (Grassland) and T3 T4 (Tree savannah) are indicated. One asterisk (*) points out that relationship is significant at P<0.05.

Figure 31 presents the relationship between SOC and soil moisture in depth b (10 – 30 cm) for the same plots as in Figure 29. The relationship was significant at P<0.05 and the r^2 with 0.532 was lower than the r^2 in the top soil layer (r^2 = 0.708). Table 6 presents the soil type and the data about SOC concentration, soil moisture content and bulk density for each of the shown plots.

Table 6: Summery of SOC, soil moisture, soil type and bulk density data for 10 plots in soil depth a (0-10 cm).

Plot	SOC [%]	Soil Moisture [Vol %]	Soil type	Bulk density [g cm^{-3}]
BT1	2.74	43.01	Cambisol calcaric	1.20
BT2	2.36	31.00	Cambisol chromic	1.17
BT4	4.53	37.33	Cambisol calcaric	0.98
BT5	2.26	33.76	Cambisol calcaric	1.17
G1	1.57	33.94	Cambisol chromic	1.30
G2	4.46	52.93	Calcic Vertisol	1.16
G3	4.65	49.04	Calcic Vertisol	1.03
G5	2.71	38.03	Cambisol chromic	1.14
T3	2.56	35.70	Cambisol chromic	1.24
T4	2.34	39.74	Cambisol chromic	1.20

6 Discussion

6.1 Difference between VT and ST in AG Biomass/C-stock and SOC stock

The first hypothesis of this master thesis was that the aboveground (AG) C-stocks differ between the vegetation types (VT) and soil types (ST). The results of Figure 14 A show, that with increasing complexity of the system (from Grassland (G) to Tree savannah (T) and Bush-Tree savannah (BT)) significantly ($P<0.05$) more carbon is stored in the vegetation. These findings are supported by Grace et al. (2006) who state that the AG C-stocks differ greatly according to the extent of woody plant cover (trees and bushes). This means, with increasing tree and/or bush cover the aboveground C-stock also increases. In terms of AG biomass, G had a significantly ($P<0.05$) lower amount compared to T and BT. According to Jackson et al. (1996) the root: shoot ratio of grasses is much higher than that of woody plants. Grasses allocate much more biomass belowground (40 – 80%) as root biomass than woody plants (20 – 60%) (Scholes and Hall, 1996). Woody plants allocate more biomass aboveground. The significantly higher ($P<0.05$) AG C-stock of the T compared to the BT was due to the fact, that the trees on the T plots were much bigger and older as the trees on the BT.

No significant differences were found between the AG C-stocks of the three different ST (Figure 15 A). Nevertheless, comparing the grass biomass between the ST in Figure 15 B the calVER had a significantly higher grass biomass amount to CAMcal and CAMch. Vertisols in this area have, according to the Soil Survey Report of the Oromiya Pastoral Area Development Commission (unpublished), a clay content of 56% and sand content of 31%. In contrast to that, the clay and sand content of the CAMcal and CAMch was reported to be between 16 – 28% and 55 – 68%, respectively. Vertisols are typically found in lower landscape positions, where seasonal waterlogging occurs, and have comparatively good chemical fertility (IUSS Working Group WRB, 2006). The high chemical fertility and, thus, higher nutrient availability, could be the reason for the lager grass biomass found on the calVER sites. Furthermore, Vertisols have a higher soil water holding capacity compared to Cambisols. This means, in the semiarid study area with uncertain and variable rainfall, more water and for longer periods is available for biomass production.

Although the differences between the AG C-stocks of the ST were not significant (Figure 15 A), the AG C-stocks of the CAMcal and CAMch were about four times higher than the calVER

AG C-stock. The data presented in Table 4 show, that T and BT were mainly found on the two coarser textured soil types CAMcal and CAMch. This could be due to the fact that trees and bushes prefer well drained soils without waterlogging.

The second hypothesis was that SOC stocks differ between the VT and ST. Regarding the biomass production aboveground, a difference of SOC stocks between the VT was assumed. Considering the results shown in Figure 16, there were no significant differences ($P<0.05$) of the SOC stocks between the VT for 1 m depth. According to Brown et al. (1990) grasslands can achieve similar or even higher SOC stocks than woody vegetation. Grasses maintain a continuous vegetation cover on the soil, reduce soil temperature and the rate of microbial activity, and may have high productivity and turnover rates that add organic matter, particularly from belowground, to the soil (Brown and Lugo, 1990). Opposite findings were published by Scurlock et al. (1998), Mlambo et al. (2007) and Belsky et al. (1998). All of them measured increased SOC levels under woody vegetation compared to grasslands. Mlambo et al (2007) stated that SOC increased under tree cover, probably due to litter fall and increased abundance of shade tolerant grass and herb species. Belsky et al. (1998) found soil nutrient enrichment and reduced solar radiation under trees. Additionally, according to Vetaas (1992) the respiration and evapotranspiration decreases under woody vegetation, improving the water availability and support understory plant growth. Due to reduced solar radiation and lower temperatures under woody vegetation less SOC was decomposed (Morris et al. 1982 cited in Vetaas, 1992).

Neither had the VT a significant influence ($P<0.05$) on the vertical distribution of SOC concentration by depth, except for the T (Figure 18). Nor were there any significant differences ($P<0.05$) in the SOC concentration between the VT in the same depth (Figure 20). On a global scale Jabbagy et al. (2000) found significant changes in SOC profiles among VT. This, in parts, could be explained by different root distribution and aboveground and belowground allocation pattern of C. An explanation for not finding any significant differences between the different VT for the SOC stocks or SOC concentrations in this study could be, that on a local scale the VT are too homogeneous. Or the more likely reason could be that the influence of the VT is overlain by the stronger influence of the ST.

The results presented in Figure 17 show that for the ST there were significant differences ($P<0.05$) in SOC stocks for 1 m depth. The clay rich calVER had the highest SOC stock. The same findings were reported by Warren et al. (1998), Don et al. (2007) and Mestdagh et al.

(2006), who also found higher SOC stocks in clay rich Vertisols compared to coarsely textured soils. This is most likely due to the stabilization effect of clay on SOC. Leinweber et al. (1999) found that more than 80% of organic C in Vertisols was stored in the clay fraction. Another reason for the higher stock amount could be the redistribution of SOC within the ecosystem through water erosion (Polyakov and Lal, 2004). During the field work in the rainy season redistribution of soil material through water erosion could be observed (Figure 32). Water erosion (a result of heavy rainfall) removes the top layer, where SOC concentration is

Figure 32: Photo of water erosion in study area

high, from soils in an elevated landscape positions and deposits it on soil in lower landscape positions. All of the calVER in this study were found in lower landscape positions. This is supported by the findings of Voroney et al., 1981 (cited in Polyakov and Lal, 2004), who reported an increase in SOC concentration on depositional areas on lower landscape positions.

Scholes et al. (1996) stated it is accepted knowledge that savannahs have low SOC amounts compared to tropical forests or temperate grasslands. Further they postulate that this is true in general, but not necessarily in all cases. Just like all vegetation types, also savannahs show a range of SOC levels. Watson (2000) estimated the average SOC stocks of tropical savannahs for 1 m depth to be 265 t ha^{-1}. Figure 20 shows that the SOC stocks in the study site were relatively high and ranged between 372 and 397 t ha^{-1}. According to Neely et al. (2009) there is some evidence that carbon has a longer resting time in dryland soils than in soils of the humid zones. During field work the first significant rain events occurred after a three year lasting drought period in Eastern Africa. Because of lack of water during the

drought microbial activity was at a minimum and hardly any decomposition and mineralization of SOM and plant residues took place.

6.2 SOC concentrations decrease with increasing soil depths

Due to the fact, that in the upper 30 cm of the soil the organic material is concentrated and the microorganisms are most active, the assumption is that SOC concentrations [%] decrease with increasing soil depth. The results of Figure 19 show for the CAMcal a significant increase ($P<0.05$) of SOC concentration in the last two depths and for the CAMch an increase in the last depth. This is contrary to the third hypothesis and to statements and findings of Hiederer (2009), Sombroek et al. (1993) and Warren et al. (1998). They all stated that SOC decreases with depth. One possible explanation for this could be the increasing carbonate (mainly $CaCO_3$) content by depth, shown in Table 2. In arid and semiarid regions the accumulation of secondary or pedogenic carbonates is pronounced (Schlesinger, 1982). In other climatic regions soils have no or just little amounts of secondary carbonates. This is due to solubilisation and leaching of the secondary carbonates with regular occurring precipitation (Sombroek et al., 1993). Primary or lithogenic carbonates are the base material for the formation of secondary carbonates when they are dissolved and translocated by water with organic acids and/or CO_2 (Bronick and Lal, 2005). Clough et al. (2000) observed that more SOC was protected in calcareous than in non-calcareous soils. Secondary carbonates have a stabilization effect on SOC. They protect SOC from decomposition and mineralisation by precipitating a thin carbonate coat around it (Krull et al., 2001) and by protecting SOC within Ca-organic aggregates (Clough and Skjemstad, 2000). Furthermore, according to Ammann et al. (2007) microbial activity and soil respiration reduces with increasing soil depth. This may lead to decreasing decomposition of SOC and increasing residue accumulation.

A second explanation for the increasing SOC concentration with depth could be a methodological problem. The Loss-on-ignition (LOI) method (to measure SOC concentration at 550°C) was chosen because of the vast number of soil samples. Furthermore compared to the Elemental C analyser and Walkley-Black method it is a rapid and inexpensive method (Zimmer and Abella, 2007; Salehi et al., 2011). Zimmer et al. (2007) concluded that the LOI method is a far less accurate method than the Elemental C analyser. To check the accuracy of the LOI method, additionally about 10 % of the samples were analysed with the Elemental

C analyser. Figure 33 shows, that the LOI method always overestimated the SOC concentrations. This is most likely due to the fact that the secondary carbonates in the soil of

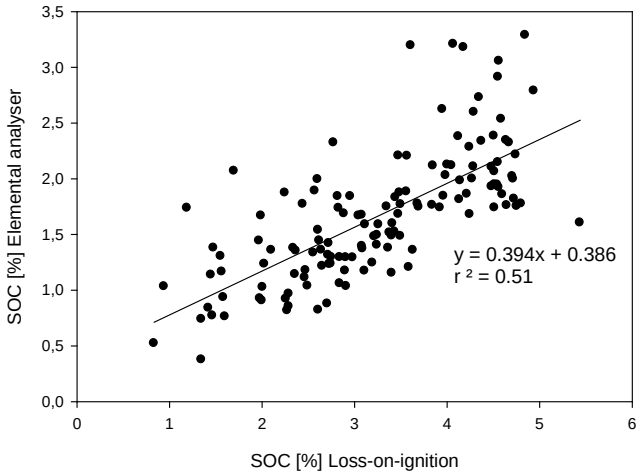

Figure 33: Relationship between SOC [%] measured by Loss-on-ignition and the more accurate Elemental analyser method.

the study area already thermally dissociate at 550°C. Although Bisutti et al. (2004) and Heiri et al. (2001) stated that carbonates in soils stay unaffected at this temperature. Nevertheless, these results go along with findings of Salehi et al. (2011) and Davids (1974), which stated that the thermal dissociation of carbonates already start at a temperature of 360°C and 430°C, respectively. As the carbonate content of the CAMcal and CAMch increase with depth (Table 2) in the course of the LOI measurement beside the SOC, also carbonates got burned and increase misleadingly the SOC concentration. This methodological measurement error could also be an explanation for the relatively high total SOC stocks (Figure 16 and 17) in this ecosystem.

In the calVER the SOC concentration slightly but not significantly decreased with depth. According to Leinweber et al. (1999) the uniform vertical distribution of SOC in Vertisols distinguishes them from other major soil types. The uniformly distribution is a result of the swelling and shrinking process caused by the high smectitic clay contents. During dry periods, the soil volume shrinks, and deep wide cracks form. Under the combined influence of livestock, wind and gravity organic matter (e.g. plant residues) and soil from the surface fall into the cracks and accumulate. With the start of the rainy season water enters the cracks coursing a swelling of the smectitic clay. Swelling of the accumulated soil at the bottom of the cracks causes an increase of volume and an upward movement of the soil

mass (VOS t NC and Virgo, 1969). This process of intermixing of surface material with lower soil layers could the reason for the uniform vertical distribution of SOC.

6.3 Relationship between precipitation, soil moisture, VT and ST

The mean soil moisture contents were assumed to differ among the VT, ST and soil depth. The results shown in Figure 28 A and B present that there is no significant difference in soil moisture contents between the VT in both depths, neither for the dry season nor for the rainy season. This is contrary to the findings of Abdallah et al. (2012). They reported of higher soil moisture contents under woody vegetation than in open Grasslands due to the positive effect of shade from the canopies. The soil moisture content was higher as a result of decreased evapotranspiration. On the other hand Ludwig et al. (2004) found lower soil moisture contents under woody vegetation than in open Grassland although hydraulic lift occurred. However, the hydraulic lift did not result in increased soil moisture content because the trees took up more water than they exuded. Furthermore, they reported from higher soil moisture content in deeper soil layers compared to the surface layer. These results agree with the results shown in Figure 28 A/B and 29 A/B. For both datasets, VT and ST, the deeper soil layer (depth 2: 30-36 cm) had higher soil moisture contents than the surface soil layer (depth 1: 0-6 cm). Also it can be seen that in the rainy season the standard errors in depth 2 were always smaller than for depth 1. This means, the variation of soil moisture content becomes smaller with increasing soil depth. These results indicate that the influences of meteorological forces (e.g. rainfall, radiation) on soil moisture dynamics are reduced gradually with depth. Similar findings were reported by Dong et al. (2003). Furthermore, according to Snyman (2005) semiarid rangeland grasses have the main part of their roots in the first 15 cm of the soil. So below that not so much water goes lost through transpiration.

In Figure 29 A/B can be seen that the clay rich calVER (56% clay and 31% sand) had the highest mean soil moisture contents compared to the coarser textured CAMcal and CAMch (16 – 28 % clay and 55 – 68 % sand). These results go along with findings of Dong et al. (2003) and Rodriguez-Iturbe et al. (1999) who had higher mean soil moisture contents in finer textured soils compared to coarser textured soils. Finer textured soils have a higher water holding capacity due to their higher clay content. The clay fraction has with <2 µm the smallest particle size compared to the silt and sand fraction that ranges from 2 – 63 µm and

63 – 2000 µm, respectively. The smaller the particle size the more specific surface area is available for the water to absorb to and the smaller the pores are. Moreover, finer textured soils have a higher share of fine pores (<0.2 µm). Water that is stored in fine pores is unavailable for plants and microorganism. The coarser textured soils have because of their higher porosity a higher infiltration and water conductivity (Scheffer and Schachtschabel, 1992). The high water conductivity and low water holding capacity results in a faster loss of water trough evaporation and drainage, explaining the lower mean soil moisture contents for the CAMcal and CAMch.

The aim of Figure 24 to 27 was to show where, according to the different VT and ST, the rainwater could be found again as soil moisture and in which proportion. If the infiltration of rainwater into the soil, as reflected in the slope of the linear relation between soil moisture content and precipitation, were different between the VT and ST. Unfortunately no statistically significant differences between the slopes were found, meaning that there was no difference between the infiltration behaviour of the different VT and ST. One reason for not finding any significant difference could be the high variation in soil moisture content within the same VT (Figure 27) and ST (Figure 28) after small rain events. This could be due to the fact, that the replications for the same VT or ST were too dissimilar (e.g. the soil moisture content before the rain or soil texture). Furthermore because of local conditions in the study area, it was not possible to measure the exact rain water amount after every of the four rain events. Of the ten installed rain gauges, at least three were stolen or destroyed each time. Missing rainfall measurement for the plots where the rain gauges were gone, were assumed to be the same as the rainfall measurement made at the nearest plot.

Though not significant, the slopes are still different from each other. In Figure 27 it can be seen that G infiltrated the most (had the steepest slope) followed by BT and T. Although more accurate measurements may be needed in the future, these preliminary results agree with the results of Smit et al. (2000), who found increased infiltration of rainwater in plots were tree thinning occurred. This was associated with the establishment of grassland. On the other hand Hester et al. (1997) state that infiltration is often highest under trees and bushes, due to the accumulation of organic matter under woody vegetation and the reduction of the kinetic energy of the rain by canopy interception. Nevertheless, the higher infiltration of rainwater for G in this study could be due to the properties of the different soil types they were found on. As seen in Table 4 the G plots used for this infiltration study grew

either on CAMch or calVER. The CAMch had with supposedly 55 -64 % a high percentage of sand and according to Rodriguez-Iturbe et al.(1999) rain infiltrates quickly and effectively into sand. Figure 29 A shows that G on CAMch has the highest infiltration amount. Although the calVER are known to have low infiltration rates because of their high clay content and resulting low water conductivity, Figure 28 A shows the highest infiltration amount for this soil type. This is most likely due to the presence of cracks (Figure 34) at the beginning of the rainy season. The cracks are macropores that form preferential flow pathways for the infiltrating water, so the water can infiltrate faster into the soil. Besides Abdelkadir et al. (2011) found, that lower dry bulk density and higher soil organic carbon contents (what is applicable for this soil type shown in Table 5) in soils resulted in higher infiltration and water holding capacities.

Figure 34: 2 to 3 cm wide cracks in investigated calVER due to shrinking of the clay fraction in the dry season.

In the surface layer (Figure 27 A to 29 A) the relationship between precipitation and soil moisture was mostly highly significant at $P<0.01$. In the deeper soil layer (depth 2: Figure 27 B to 29 B) the soil moisture content was in general higher and the relationship between precipitation and soil moisture was mostly not significant. This is another indication of the fact that with increasing depth the influence of meteorological forces is reduced. Nevertheless the influence of soil texture increases with depth (Dong et al., 2003). Butler et al., 1977 (cited in Russell and Graecen, 1977) stated that generally the texture of the surface soils is coarser and with increasing depth the clay content increases and the texture gets finer. These findings go along with observations made during the field study by feeling the constituents of the soil along a 1 m auger.

6.4 Relationship between SOC and soil moisture content

Soil organic carbon can retain and store up to four times its own weight in water. Based on this fact, it was assumed that soil moisture content [Vol%] is higher in soils with higher SOC concentrations [%]. The results of Figure 30 and 31 show, that in general with increasing SOC concentration there is an increase in soil moisture. These results agree with the results of De Jong (1983) and Rawls et al. (2003) who found that the increase in organic carbon content meant higher soil moisture content and higher water-holding-capacity. Furthermore according to Morris (2004) a 1 % increase in SOM will result in a 4 % increase in stored soil water. Khaleel et al. (1981) stated that there was an increase of water-holding-capacity in soils with an increase of organic waste application. Water-holding-capacity of soils is primarily controlled by the number of pores, pore-size distribution and the specific surface area of the soil fractions. Because of increased aggregation through SOC the total pore space is increased. Furthermore, as a result of deceased bulk density through SOC the pore-size distribution is altered and the relative number of fine pores increases. The soil moisture content is also mostly determined by the specific surface area of the soil fractions were the water is absorbed to. Sandy soils have far less surface area than clay rich soils and thus retain much less water. However, increasing the SOC concentration in sandy soils increases the specific surface area and water-holding-capacity (Khaleel et al., 1981). Rawls et al. (2003) concluded that the relationship between SOC and soil moisture content is affected by both the amount of organic carbon and the proportion of texture. This could explain the difference in soil moisture contents between the plots in this study with around the same SOC concentrations. In Figure 30 and 31 for example plot G2 and BT4 have nearly the same SOC concentration but different soil moisture content. This is probably due to the fact that plot G2 is a clay rich calVER. Because of the higher clay content compared to BT4 it can hold more water.

6.5 Changes in SOC concentration from dry to rainy season

The last hypothesis of this Master thesis was, that the increasing soil moisture content in the rainy season leads to an increase in vegetation productivity and increase in microbial activity, assuming a change in SOC concentration [%] from dry to rainy season. As mentioned in section 3.1.3, based on its turnover rate SOC can be grouped into three pools. The active SOC pool has the lowest turnover rate (<10 years) and contains soluble fresh plant residues

including fine roots (< 2 mm in diameter), microbial biomass, particulate organic C and/or light fraction C. Shen et al. (2008) observed a relatively larger seasonal change (from dry to rainy season) in the active SOC pool than in the slow SOC pool (10-200 years) and no change in the passive SOC pool (>100 years). Considering the turnover rate of the active SOC pool and that it reacts more sensitive to climatic factors (e.g. increased rainfall) and disturbance (Allen et al., 2010), the significant changes ($P<0.05$) shown in Figure 22 are solely due to this pool. Shen et al. (2008) reported that with increasing precipitation the fine root biomass pool increased to. Furthermore Campbell et al. (1976) found that remoistening of soils by rainfall led to a growth of microorganisms in the soil surface. A reason for the significant increase of the SOC concentration for the G and BT, shown in Figure 22, could be an increase of fine root and microbial biomass C caused by the rain.

According to Hinderer (2009) in the first 30 cm of the soil the organic material is concentrated and the processes of C mineralization and immobilization are more active. Van Gestel (1992) and Fierer et al. (2003) found, that the concentrations of microbial biomass C deceased rapidly with depth. Furthermore, Snyman (2005) found the main part of the grassroots of a semiarid rangeland in the first 15 cm of the soil. Also the surface of soils is rich in for microorganism available C substrates (active SOC pool) from the input of root exudates, surface litter and root detritus. In contrast, the rates of C input to the lower soil layers are in general low and the SOC tends to be part of the slow and passive pool, so being of limited availability for microorganism (Fierer et al., 2003) and having higher turnover rates. This could explain why there are no significant changes in SOC concentration within the VT form dry to rainy season in the soil depth 30-100 cm shown in Figure 23.

7 Conclusion

In terms of total AG C-stock the amounts did differ significantly between the three different vegetation types, but not between the different soil types. In the Tree savannah the AB C-stock was the highest followed by Bush-Tree savannah, the lowest amount was found in Grassland. Regarding the first hypotheses that aboveground C-stocks differ between the VT and ST. The results prove the hypothesis for the VT, but not for the ST.

Results prove the second hypothesis (SOC stocks differ between the VT and ST) false regarding the VT, but true regarding the ST. The highest C-stock was found for the calVER within 1 m of depth. This can be explained by the stabilization effect of clay on SOC and the redistribution of SOC trough water erosion from soils in elevated landscape position to soils in lower landscape position.

For the CAMcal and CAMch a significant increase of SOC concentration occurred with increasing soil depth. For the calVER there were no significant differences within the depths. This contradicts the third hypothesis after that SOC concentrations decrease with increasing soil depths. Secondary carbonates have a stabilization effect on SOC. As the carbonate content increases with depth in the CAMcal and CAMch, the stabilisation effect increases. A second explanation for the increasing SOC concentration with depth could be a methodological problem. As the carbonate content increased with depth, in the course of the LOI measurement, beside the SOC, also carbonates got burned and increased misleadingly the SOC concentration. The uniformly SOC distribution within the calVER is a result of the swelling and shrinking process caused by the high smectitic clay content of these soils.

There was no significant difference in soil moisture contents between the VT but between the ST. The calVER had the highest mean soil moisture content because finer textured soils have a higher water holding capacity due to their higher clay content. The surface soil layer (depth 1) always had lower soil moisture contents. The relationship between precipitation and soil moisture was, compared to the deeper soil layer (depth 2), always highly significant at $P>0.01$. These two results indicate that meteorological forces have greater impact on the surface soil layer.

Furthermore, the results, shown in figures 30 and 31, prove the fourth hypothesis that soil moisture content is higher in soils with higher SOC concentrations. However, they indicate that the soil moisture content is also affected by the proportion of texture.

The SOC concentration changes significantly from dry to rainy season in the first 30 cm of the soil. Explainable most likely due to the increase in the active C pool (fine roots and microbial biomass), by reason of having the lowest turnover rate and being more sensitive to climatic factors (increased rainfall).

The general conclusion of this master thesis is, that the soil types have significantly ($P<0.05$) more influence on SOC concentrations, SOC stocks and soil moisture differences than the vegetation types.

In this study several questions remain unanswered. Regarding soil moisture and water dynamics more accurate measurements are needed to further clarify and confirm the preliminary results of this study. To gain knowledge about the SOC and nutrient turnover of this area, which is strongly influenced by the seasons due to bimodal rainfalls, studies on soil respiration and microbial activity would be highly valuable. Furthermore, gaining information about the root growth over the season would give answers on the potential of belowground C-stocks.

References

Abdallah, F., and Chaieb, M. (2012). The influence of trees on nutrients, water, light availability and understorey vegetation in an arid environment. Applied Vegetation Science, v. 15, no. 4, p. 501-512.

Abdelkadir, A., and Yimer, F. (2011). Soil water property variations in three adjacent land use types in the Rift Valley area of Ethiopia. Journal of Arid Environments, v. 75, no. 11, p. 1067-1071.

Allen, D.E., Pringle, M.J., Page, K.L., and Dalal, R.C. (2010). A review of sampling designs for the measurement of soil organic carbon in Australian grazing lands. Rangeland Journal, v. 32, no. 2, p. 227-246.

Ammann, C., Flechard, C., Leifeld, J., Neftel, A., and Fuhrer, J. (2007). The carbon budget of newly established temperate grassland depends on management intensity. Agriculture, Ecosystems & Environment, v. 121, no. 1, p. 5-20.

Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E., and Harris, A.T. (2004). Grazing systems, ecosystem responses, and global change. Annual Review of Environment and Resources, v. 29, no. 1, p. 261-289.

Batjes, N.H. (1996). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, v. 47, no. 2, p. 151-163.

Batjes, N.H., and Sombroek, W.G. (1997). Possibilities for carbon sequestration in tropical and subtropical soils. Global Change Biology, v. 3, no. 2, p. 161-173.

Bellot, J., Sanchez, J.R., Chirino, E., Hernandez, N., Abdelli, F., and Martinez, J.M. (1999). Effect of different vegetation type cover on the soil water balance in semi-arid areas of south eastern Spain: Physics and Chemistry of the Earth, Part B. Hydrology, Oceans and Atmosphere, v. 24, no. 4, p. 353-357.

Belsky, A., Amundson, R., Bergstrom, L., and Kirchmann, H. (1998). Influence of savannah trees and shrubs on understorey grasses and soils: new directions in research. *In* Bergström, L., and Kirchmann, H. (1998). Carbon and nutrient dynamics in natural and agricultural tropical ecosystems, CAB International, Wallingford, UK, p. 153-171.

Bisutti, I., Hilke, I., and Raessler, M. (2004). Determination of total organic carbon - An overview of current methods. TrAC - Trends in Analytical Chemistry, v. 23, no. 10-11, p. 716-726.

Bond, W.J. (2008). What limits trees in C4 grasslands and savannas?. Annual Review of Ecology, Evolution, and Systematics, v. 39, no. 1, p. 641.

Bond, W.J., and Midgley, G.F. (2000). A proposed CO2-controlled mechanism of woody plant invasion in grasslands and savannas. Global Change Biology, v. 6, no. 8, p. 865-869.

Bronick, C., and Lal, R. (2005). Soil structure and management: a review. Geoderma, v. 124, no. 1, p. 3-22.

Brown, S., and Lugo, A.E. (1990), Effects of forest clearing and succession on the carbon and nitrogen content of soils in Puerto Rico and US Virgin Islands. Plant and Soil, v. 124, no. 1, p. 53-64.

Campbell, C., and Biederbeck, V. (1976). Soil bacterial changes as affected by growing season weather conditions: a field and laboratory study. Canadian Journal of Soil Science, v. 56, no. 3, p. 293-310.

Chen, X., Hutlay, L.B., and Eamus, D. (2003). Carbon balance of a tropical savanna of northern Australia. Oecologia, v. 137, no. 3, p. 405-416.

Clough, A., and Skjemstad, J. (2000). Physical and chemical protection of soil organic carbon in three agricultural soils with different contents of calcium carbonate. Australian Journal of Soil Research, v. 38, no. 5, p. 1005-1016.

Conant, R.T., and Paustian, K. (2002). Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochemical Cycles, v. 16, no. 4, p. 1143.

Coppock, D.L. (1994). The Borana Plateau of southern Ethiopia: synthesis of pastoral research, development and change, 1980-91. ILCA (International Livestock Centre of Africa), Addis Ababa, p. 393.

Davies, B.E. (1974). Loss-on-ignition as an estimate of soil organic matter. Soil Science Society of America Journal, v. 38, no. 1, p. 150-151.

De Deyn, G.B., Cornelissen, J.H.C., and Bardgett, R.D. (2008). Plant functional traits and soil carbon sequestration in contrasting biomes. Ecology Letters, v. 11, no. 5, p. 516-531.

De Jong, R. (1983). Soil water desorption curves estimated from limited data. Canadian Journal of Soil Science, v. 63, no. 4, p. 697-703.

Don, A., Schumacher, J., Scherer-Lorenzen, M., Scholten, T., and Schulze, E.D. (2007). Spatial and vertical variation of soil carbon at two grassland sites--Implications for measuring soil carbon stocks. Geoderma, v. 141, no. 3-4, p. 272-282.

Dong, W., Yu, Z., and Weber, D. (2003). Simulations on soil water variation in arid regions. Journal of Hydrology, v. 275, no. 3, p. 162-181.

FAO. (1993). 1992 Production Yearbook. Food and Agriculture Organization of the United Nations Rome, Italy.

Fernandez-Illescas, C.P., Porporato, A., Laio, F., and Rodriguez-Iturbe, I. (2001). The ecohydrological role of Soil texture in a water-limited ecosystem. Water Resources Research, v. 37, no. 12, p. 2863-2872.

Fiedler, F.R., Frasier, G.W., Ramirez, J.A., and Ahuja, L.R. (2002). Hydrologic response of grasslands: effects of grazing, interactive infiltration, and scale. Journal of Hydrologic Engineering, v. 7, no. 4, p. 293-301.

Fierer, N., Schimel, J.P., and Holden, P.A. (2003). Variations in microbial community composition through two soil depth profiles. Soil Biology and Biochemistry, v. 35, no. 1, p. 167-176.

Gärdenäs, A.I. (1998). Soil organic matter in Forest Soils - Effects of Climate and Water Balance [Doctoral thesis]. Swedish University of Agricultural Sciences Uppsala - Department of Soil Sciences, 283 p.

Grace, J., José, J.S., Meir, P., Miranda, H.S., and Montes, R.A. (2006). Productivity and carbon fluxes of tropical savannas. Journal of Biogeography, v. 33, no. 3, p. 387-400.

Hadas, A., Swartzendruber, D., Rijtema, P.E., Fuchs, M., and Yaron, B. (1973). Physical aspects of soil water and salts in ecosystems. Springer Verlag, Berlin Heidelberg New York, 4, 460 p.

Hassink, J. (1992). Effects of soil texture and structure on carbon and nitrogen mineralization in grassland soils. Biology and Fertility of Soils, v. 14, no. 2, p. 126-134.

Hassink, J., Bouwman, L.A., Zwart, K.B., Bloem, J., and Brussaard, L. (1993). Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. Geoderma, v. 57, no. 1-2, p. 105-128.

Heiri, O., Lotter, A.F., and Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology, v. 25, no. 1, p. 101-110.

Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentini, R., Bernoux, M., and Saint-André, L. (2011). Estimating tree biomass of sub-Saharan African forests: A review of available allometric equations. Silva Fennica, v. 45, no. 3, p. 477-569.

Hester, J.W., Thurow, T.L., and Taylor Jr, C.A. (1997). Hydrologic characteristics of vegetation types as affected by prescribed burning. Journal of Range Management, p. 199-204.

Hiederer, R. (2009). Distribution of organic carbon in soil profile data. Office for Official Publications of the European Communities, Luxembourg, 126 p.

Hu, S., Coleman, D.C., Carroll, C.R., Hendrix, P.F., and Beare, M.H. (1997). Labile soil carbon pools in subtropical forest and agricultural ecosystems as influenced by management practices and vegetation types. Agriculture, Ecosystems and Environment, v. 65, no. 1, p. 69-78.

IUSS Working Group WRB (2006). World reference base for soil resources 2006. World Soil Resources Reports No. 103. FAO (Food and Agriculture Organization of the United Nations), Rome, 127 p.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E., and Schulze, E.D. (1996). A global analysis of root distributions for terrestrial biomes. Oecologia, v. 108, no. 3, p. 389-411.

Jackson, R.B., Mooney, H.A., and Schulze, E. (1997). A global budget for fine root biomass, surface area, and nutrient contents. Proceedings of the National Academy of Sciences of the United States of America, v. 94, no. 14, p. 7362-7366.

Jahn, R., Blume, H., Asio, V., Spaargaren, O., Schad, P., and FAO. (2006). Guidelines for soil description. FAO (Food and Agriculture Organization of the United Nations), Rome, 4, 97 p.

Jobbágy, E.G., and Jackson, R.B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications, v. 10, no. 2, p. 423-436.

Kamara, A., McCarthy, N., and Kirk, M. (2001). The Effect of Environmental Variability on Livestock and Land-Use Management: The Borana Plateau, Southern Ethiopia.

Kay, B., Lal, R., Kimble, J., Follett, R., and Stewart, B. (1998). Soil structure and organic carbon: a review. *In* Lal, R., Kimble, J., Follett, R., Kimble, J., and Stewart, B.(1998). Soil processes and the carbon cycle., CRC Press Inc., p. 169-197.

Khaleel, R., Reddy, K., and Overcash, M. (1981). Changes in soil physical properties due to organic waste applications: A review. Journal of environmental quality, v. 10, no. 2, p. 133-141.

Krull, E., Baldock, J., and Skjemstad, J. (2001). Soil texture effects on decomposition and soil carbon storage. Net ecosystem exchange.Coop.Res.Ctr.for Greenhouse Accounting, Canberra, ACT, Australia, p. 103-110.

Lal, R. (2004a). Soil carbon sequestration impacts on global climate change and food security. Science, v. 304, no. 5677, p. 1623-1627.

Lal, R. (2001). Soil carbon sequestration and the greenhouse effect. *In* Soil carbon sequestration and the greenhouse effect. Proceedings of a symposium, 90th Annual Meeting, Baltimore, MD, USA, 18-22 October 1998., Soil Science Society of America Inc.

Lal, R., Kimble, J., Follett, R., Kimble, J., and Stewart, B. (1998). Pedospheric processes and the carbon cycle. *In* Soil processes and the carbon cycle., CRC Press Inc., p. 1-8.

Lal, R. (2004c). Carbon sequestration in dryland ecosystems. Environmental management, v. 33, no. 4, p. 528-544.

Lal, R. (2004b). Soil carbon sequestration to mitigate climate change. Geoderma, v. 123, no. 1-2, p. 1.

Leinweber, P. (1999). New Evidence for the Molecular Composition of Soil Organic Matter in Vertisols.. Soil Science, v. 164, no. 11, p. 857-870.

Liancourt, P. (2012). Temporal and spatial variation in how vegetation alters the soil moisture response to climate manipulation. Plant and Soil, v. 351, no. 1-2, p. 249.

Ludwig, F., de Kroon, H., Berendse, F., and Prins, H.H.T. (2004). The influence of savanna trees on nutrient, water and light availability and the understorey vegetation. Plant Ecology, v. 170, no. 1, p. 93-105.

Mestdagh, I., Lootens, I.P., Van Cleemput, O., and Carlier, L. (2006). Variation in organic-carbon concentration and bulk density in Flemish grassland soils. Journal of Plant Nutrition and Soil Science, v. 169, no. 5, p. 616-622.

Mlambo, D., Mwenje, E., and Nyathi, P. (2007). Effects of tree cover and season on soil nitrogen dynamics and microbial biomass in an African savanna woodland dominated by Colophospermum mopane. Journal of Tropical Ecology, v. 23, no. 4, p. 437-448.

Morris, G.D. (2004). Substaining National Water Supplies by understanding the Dynamic Capacity that Humus has to increase Soil Water Storage Capacity [M.Sc.]. The University of Sydney.

Moyano, F.E., Vasilyeva, N., Bouckaert, L., et al. (2012). The moisture response of soil heterotrophic respiration: Interaction with soil properties. Biogeosciences, v. 9, no. 3, p. 1173-1182.

Nair, P.K.R. (2011). Methodological Challenges in Estimating Carbon Sequestration Potential of Agroforestry Systems. *In* Kumar, B.M. and P.K.R. Nair (2011). Carbon Sequestration Potential of Agroforestry Systems, Springer, v. 8, p. 3-16.

Neely, C., Bunning, S., and Wilkes, A. (2009). Review of evidence on drylands pastoral systems and climate change. Food and Agriculture Organization of the United Nations, Rome, Land and Water Discussion Paper 8, 38 p.

Ordóñez, J., De Jong, B., García-Oliva, F., et al. (2008). Carbon content in vegetation, litter, and soil under 10 different land-use and land-cover classes in the Central Highlands of Michoacan, Mexico. Forest Ecology and Management, v. 255, no. 7, p. 2074-2084.

Oromiya Pastoral Area Development Commission, unpublished, Borena Land Use Study Projekt - Dawa sub basin - Soil Survey Report.

Pärtel, M., and Wilson, S.D. (2002). Root dynamics and spatial pattern in prairie and forest. Ecology, v. 83, no. 5, p. 1199-1203.

Polyakov, V.O., and Lal, R. (2004). Soil erosion and carbon dynamics under simulated rainfall. Soil Science, v. 169, no. 8, p. 590-599.

Pribyl, D.W. (2010). A critical review of the conventional SOC to SOM conversion factor. Geoderma, v. 156, no. 3-4, p. 75-83.

Rawls, W., Pachepsky, Y.A., Ritchie, J., Sobecki, T., and Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. Geoderma, v. 116, no. 1, p. 61-76.

Rees, R.M. (2005). The role of plants and land management in sequestering soil carbon in temperate arable and grassland ecosystems. Geoderma, v. 128, no. 1-2, p. 130.

Reid, R.S., Thornton, P.K., McCrabb, G.J., Kruska, R.L., Atieno, F., and Jones, P.G. (2004). Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics?. Environment, Development and Sustainability, v. 6, no. 1, p. 91-109.

Rodriguez-Iturbe, I., D'odorico, P., Porporato, A., and Ridolfi, L. (1999). On the spatial and temporal links between vegetation, climate, and soil moisture. Water Resources Research, v. 35, no. 12, p. 3709-3722.

Russell, J.S., and Graecen, E.L. (1977). Soil factors in crop production in a semi-arid environment. University of Queensland Press.

Salehi, M., BENI, O.H., Harchegani, H.B., Borujeni, I.E., and Motaghian, H. (2011). Refining soil organic matter determination by loss-on-ignition. Pedosphere, v. 21, no. 4, p. 473-482.

Scheffer, F., and Schachtschabel, P. (1992). Lehrbuch der Bodenkunde. Spektrum Akademischer Verlag, Heidelberg Berlin, v. 16.

Schlesinger, W.H. (1982). Carbon storage in the caliche of arid soils: a case study from Arizona. Soil Science, v. 133, no. 4, p. 247-255.

Schnitzer, M. (1991). Soil organic matter - the next 75 years. Soil Science, v. 151, no. 1, p. 41-58.

Scholes, R., and Hall, D. (1996). The carbon budget of tropical savannas, woodlands and grasslands. Scope-Scientific Committee on Problems of The Environment International Council of Scientific Unions, v. 56, p. 69-100.

Scurlock, J., and Hall, D. (1998). The global carbon sink: a grassland perspective. Global Change Biology, v. 4, no. 2, p. 229-233.

Shen, W., Jenerette, G.D., Hui, D., Phillips, R.P., and Ren, H. (2008). Effects of changing precipitation regimes on dryland soil respiration and C pool dynamics at rainfall event, seasonal and interannual scales. J.Geophys.Res, v. 113, p. G03024.

Smit, G., and Rethman, N. (2000). The influence of tree thinning on the soil water in a semi-arid savanna of southern Africa. Journal of Arid Environments, v. 44, no. 1, p. 41-59.

Snyman, H. (2005). Rangeland degradation in a semi-arid South Africa—I: influence on seasonal root distribution, root/shoot ratios and water-use efficiency. Journal of Arid Environments, v. 60, no. 3, p. 457-481.

Sombroek, W.G., Nachtergaele, F.O., and Hebel, A. (1993). Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. A Journal of the Human Environment, v. 22, no. 7, p. 417.

Steinbeiss, S., Temperton, V.M., and Gleixner, G. (2007). Mechanisms of soil carbon storage in experimental grasslands. Biogeosciences Discussions, v. 4, no. 5, p. 3829-3862.

Tennigkeit, T., and Wilkes, A. (2008). Carbon Finance in Rangelands: An assessment of the potential for carbon finance in rangelands. International Council for Research in Agroforestry-World Agroforestry Centre, China, 29 p.

Van Gestel, M., Ladd, J., and Amato, M. (1992). Microbial biomass responses to seasonal change and imposed drying regimes at increasing depths of undisturbed topsoil profiles. Soil Biology and Biochemistry, v. 24, no. 2, p. 103-111.

Vaughan, D., and Malcolm, R. (1985). Soil organic matter and biological activity. Kluwer Academic Publishers ,Netherlands, v. 16, 450 p.

Vetaas, O.R. (1992). Micro-site effects of trees and shrubs in dry savannas. Journal of Vegetation Science, v. 3, no. 3, p. 337-344.

VOS t NC, J., and Virgo, K. (1969). Soil structure in Vertisols of the Blue Nile clay plains, Sudan. Journal of Soil Science, v. 20, no. 1, p. 189-206.

Warren, G., Meredith, J., Bergstrom, L., and Kirchmann, H. (1998). Isotopic composition of organic carbon in some soils of semiarid Africa. *In* Bergström, L., and Kirchmann, H. (1998). Carbon and nutrient dynamics in natural and agricultural tropical ecosystems, CAB International, Wallingford, UK, p. 23-32.

Watson, R.T. (2000). Land use, land-use change, and forestry: UK, Cambridge University Press.

Zimmer, B.W., and Abella, S.R. (2007) Estimating organic carbon from loss-on-ignition in northern Arizona forest soils. Soil Science Society of America Journal, v. 71, no. 2, p. 545-550.