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**Effects of Vegetation Type and Species  
Composition on Carbon Stocks in semi-arid  
Ethiopian Savannas**

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M. Sc. Thesis

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## Declaration

I, Beatrice Breuer, born on the 16<sup>th</sup> of September 1985, Matriculation number: 394949, hereby declare on my honor, that this Master Thesis entitled

“EFFECTS OF VEGETATION TYPE AND SPECIES COMPOSITION ON CARBON STOCKS IN SEMI-ARID ETHIOPIAN SAVANNAHS”,

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## Abstract

CO<sub>2</sub> is one of the most important GHGs in the atmosphere. Its concentration is steadily increasing, causing severe climate change effects. These changes are of enormous importance for the people living in the semi-arid savannahs of the Borana region in southern Ethiopia. Having negative impacts on the pastoral production systems that play an important role in this area, the dependency on traditional systems might be no longer sufficient to sustain food security. The establishment of a system of payment for environmental services (PES) could be a feasible opportunity for alternative income generation. PES systems are based on the process of carbon sequestration, i.e. storing the atmospheric carbon in the terrestrial biosphere. In this context, grasslands and savannah ecosystems are increasingly the focus of attention, as they hold a great potential, due to their large global extension.

The aim of this pilot study was to gain information on the current amount of carbon stored in the aboveground biomass and in the soil in this area, and to evaluate the impact of vegetation type and species composition on the belowground carbon stocks.

In a 10 km<sup>2</sup> study area 4 dominant vegetation types were characterized (grassland, bushland, tree savannah and bush-tree savannah). 20 30x30 m plots were installed, representing 5 plots per vegetation type. In every plot, soil samples were taken in 4 depths to determine SOM, SOC, pH and CaCO<sub>3</sub> content. The SOC concentration was measured using the Loss-on-ignition method. Soil bulk density was measured in 2 depths (0-10, 10-30) with 5 repetitions each in every plot. Species were identified for the analysis of species composition. Biomass of trees and bushes was estimated using allometric equations. Biomass of understorey vegetation was destructively measured. A one-way ANOVA and a cluster analysis were carried out for the statistical analysis. The vegetation type had a great influence on the accumulation of aboveground biomass and aboveground carbon stocks, being highest in tree savannahs ( $51.9 \pm 16.1 \text{ t ha}^{-1}$  and  $25.9 \pm 8.1 \text{ t C ha}^{-1}$ ), and lowest in grasslands ( $0.8 \pm 0.4 \text{ t ha}^{-1}$  and  $0.4 \pm 0.2 \text{ t C ha}^{-1}$ ). Soil organic carbon stocks were generally high in this area ( $326.4 \pm 28.6 \text{ t C ha}^{-1}$  to  $394.9 \pm 28.6 \text{ t C ha}^{-1}$ ) and showed no significant differences between the vegetation types. Species composition changed to more annuals and herbaceous species with increasing woody vegetation and cluster analysis showed that the distribution of vegetation types was partially dependent on the soil type. These results provide initial data to assess the carbon sequestration potential of the semi-arid savannahs of the Borana region in Ethiopia.

**Key words:** carbon stocks, aboveground biomass, vegetation type, species composition, semi-arid savannah

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**List of Abbreviations**

°C	degree Celsius
AGB	aboveground biomass
AGCS	aboveground carbon stocks
B	bushland
BD	bulk density
BT	bush-tree savannah
C	carbon
CaCO <sub>3</sub>	Calcium carbonate
CDM	Clean Development Mechanisms
cm	centimeter
CO <sub>2</sub>	carbon dioxide
G	grassland
GHG	Greenhouse gases
Gt	giga ton
ha	hectare
kg	kilogram
km <sup>2</sup>	square kilometer
m	meter
m <sup>2</sup>	square meter
mm	millimeter
N	nitrogen
PES	Payment for environmental services
Pg	picogram
ppmv	parts per million by volume
SOC	soil organic carbon
SOCS	soil organic carbon stocks
SOM	soil organic matter
t	ton
T	tree savannah
VT	vegetation type

# 1 BACKGROUND

This Master-Thesis has been part of the project “Livelihood diversifying potential of livestock based carbon sequestration options in pastoral and agro pastoral systems in Africa”, conducted by ILRI (International Livestock Research Institute). One major focus of the project is the estimation of the carbon sequestration potential of rangelands and the assessment of how land-use management decisions can avoid or reduce carbon emissions to the atmosphere. This thesis will provide data about the potential of various vegetation units to sequester carbon by determining the above and belowground biomass and carbon stocks, respectively.

Grassland ecosystems, with tropical and subtropical savannahs and woodlands, comprise the largest terrestrial biome (Hudak *et al.* 2003). They include rangelands, shrub lands, pasture land and croplands sown with pasture and fodder crops and cover 3.5 billion ha or 26 % of the world land area (Ramankutty *et al.* 2008; Conant 2010). A considerable amount (20%) of the world’s soil organic carbon is stored in grasslands. Globally, about 343 billion tons of C are estimated to be accumulated in grassland areas (Conant 2010). Anderson (1991) estimated the soil carbon stocks of the African continent at 30% of the world’s total.

People are dependent on grasslands to a large extent for food and forage production. The conversion of native grasslands to cultivated croplands has been observed for centuries. Further, grasslands are the base for milk and beef production and about 1 billion of the world’s poorest people rely strongly on livestock (Steinfeld *et al.* 2006).

In the Borana region of southern Ethiopia, livestock production is the main source of income generation and food security. However, due to increasing climatic changes, like extreme weather events and the competition with other land uses, this dependency might no longer be sufficient to sustain food security and alternative possibilities for income generation need to be considered.

Carbon sequestration would be a feasible opportunity for these poor, vulnerable and marginalized pastoral and agro-pastoral communities to diversify their income. One possibility could be the payment for environmental services (PES). These are based on the carbon sequestration potential and the decline in carbon emissions which are related to livestock and rangeland management practices (Reid *et al.* 2004). Moreover, industrialized countries may invest in GHG emission mitigation projects in developing countries. Developing countries can then sell the sequestered C in agro-forestry systems to industrialized countries, which is an attractive economic chance for subsistence farmers (IPCC 2000; Takimoto *et al.* 2008).

## 2 INTRODUCTION

CO<sub>2</sub> is one of the most important Greenhouse gases (GHGs). Over the last centuries its concentration in the atmosphere has noticeably increased, namely from 280 ppmv in 1750 to 380 ppmv in 2005 (Lal 2004b; Lal 2008a), and it is predicted that the concentration of CO<sub>2</sub> and other GHGs will rise even more. The current rate of increment of CO<sub>2</sub> is 1.7 ppmv yr<sup>-1</sup> (IPCC 2007).

This leads to changes, especially in the global climate. These changes include rising temperatures and more extreme events of erratic rainfalls. This goes along with higher incidences of drought and floods (USDA NRCS 2000). In dry areas, with low soil cover during dry periods, soil respiration is enhanced and the vulnerability to soil erosion and run-off due to erratic rainfall increases. As a consequence, the soil organic carbon (SOC) pool will decrease as well as the structural stability of the soil. Thereby, major soil cycles (water, carbon and nitrogen) are disrupted (Lal 2004b).

These changes are of enormous importance especially for people living on the Borana Plateau, which belongs to the semi-arid rangelands of Southern Ethiopia (Coppock 1994). It has negative impacts on the pastoral production systems which play an important role in this area. In combination with an increasing population pressure, and therefore a challenge to compete with other land uses, the dependency on traditional pastoral and agro-pastoral livelihoods is no longer sufficient to sustain food security and the most basic standard of living.

Hence, a solution has to be found to “remove” carbon (C) from the atmosphere. It has been suggested, that storing the atmospheric C in the biosphere of the terrestrial system could be one opportunity to balance the GHG emissions (Albrecht and Kandji 2003).

In general, agricultural lands may have a great potential in terms of C sinks, because they are able to absorb huge quantities of C. Soils contain twice as much C as the atmosphere and approximately three-quarters of the total terrestrial organic carbon pool (Prentice *et al.* 2001). As reported in the literature, the soil comprises 1115 to 2200 Pg of C (Batjes 1992; Eswaran *et al.* 1993; Sombroek *et al.* 1993). Especially, the combination of trees and crops and/or animals may store high amounts of C, particularly if they are managed in an equitable way (Albrecht and Kandji 2003).

Agroforestry systems are already widely recognized as a strategy for soil C sequestration (Albrecht and Kandji 2003; Takimoto *et al.* 2008; Nair *et al.* 2009), especially since forestry

is a crucial, existing element of the Clean Development Mechanisms (CDM) of the Kyoto Protocol (FAO 2010).

Nowadays, the role of grasslands and savannah ecosystems and their potential to sequester C is coming more and more into focus, due to the large global extend of these environments (Conant *et al.* 2001; Reid *et al.* 2004; Witt *et al.* 2011).

Savannahs cover approximately 20% of the global land cover and even 50% of the African continent (Ajtay *et al.* 1979). They are defined by the coexistence of woody (including trees) and herbaceous or grassy vegetation. Further, they can be classified more in detail by their relative amounts of these plant functional types (PFTs) (Williams and Albertson 2004).

In grasslands, C is accumulated in two different pools. In the soil, C is stored in dead and living biomass and aboveground in living biomass and litter. Living aboveground biomass consists of annual and perennial grasses and woody vegetation like shrubs, bushes and trees. After Ordóñez *et al.* (2008), these C pools range from 0.15 t C ha<sup>-1</sup> to 33 t C ha<sup>-1</sup> in tropical grasslands. Soil organic carbon (SOC) includes living roots, soil microbial biomass and dead organic residues. Estimates for tropical grasslands range from 38 to 148 t C ha<sup>-1</sup> in the topsoil (0-30 cm) (Steinbeiss *et al.* 2007; Ordóñez *et al.* 2008).

The quantity of litter is very variable and depends strongly on the species composition (herbaceous or woody vegetation), land use and management factors like burning or fertilization (Ammann *et al.* 2007; Shimoda and Takahashi 2009; Sanaullah *et al.* 2010). Carbon dynamics (sinks and sources) in grasslands are very complex and depend on a range of biotic and abiotic factors, including climatic, environmental and management factors as well as the species composition and their diversity. Chapin *et al.* (1997) highlighted the relationship between soil C storage and biodiversity. It is expected, that increasing biodiversity leads to the protection of the resilience and productivity of grasslands. In addition, ecosystem service provision is improved on the local scale (Hooper *et al.* 2005) and higher biodiversity leads to increased primary productivity (Hector *et al.* 1999).

However, it is still not so much known about the interconnection between different vegetation types and C stocks. The main question of this study is, whether the aboveground biomass or vegetation (formation) type can be used as an indicator to estimate belowground C stocks.

### 3 OBJECTIVES & HYPOTHESIS

#### 3.1 Objectives

The vast grazing areas of the Borana Plateau hold a great potential for carbon sequestration and thereby reducing the CO<sub>2</sub> emissions from the atmosphere. In addition, to protect this area from further degradation, PES would be a practicable alternative for people living in the Borana Plateau, who heavily and almost uniquely rely on the production of livestock, to diversify their income.

This pilot study evaluates the current state of the C-stocks (above- and belowground) of the Borana Plateau. It gives information about how much carbon is actually stored in the soils and the vegetation, as this knowledge is crucial for predictions of the potential for carbon sequestration.

SOC measurements in the field are very accurate and provide site-specific information. However, they are labor intensive, costly and time consuming. Therefore, this study links specific vegetation types or vegetation patterns to the organic carbon content stored in the soil. Through upscaling, this would be a feasible and low cost possibility to predict the carbon state of larger areas.

Specific objectives of this study were to:

- Identify prominent vegetation types of the area
- Specify these vegetation types in terms of structure and species composition
- Destructively measure biomass of understorey vegetation
- Determine biomass and carbon content of aboveground vegetation with the help of allometric equations
- Measure organic carbon content of the soil underneath every identified vegetation type
- Link the soil organic carbon content to the respective vegetation type

### 3.2 Hypothesis

Carbon sequestration in agricultural soils and vegetation is meant to be a feasible opportunity to reduce GHG emissions, and thus to control to a certain extent the ongoing climate change effects. Tropical and subtropical grassland ecosystems play a major role in this context, due to their immense expands over the whole world. Savannahs are defined by the coexistence of woody (trees, bushes/shrubs) and herbaceous vegetation which can occur in different amounts. As a result of litter composition, carbon inputs, fluxes and storage ability depend on vegetation.

In this context following hypothesis were tested:

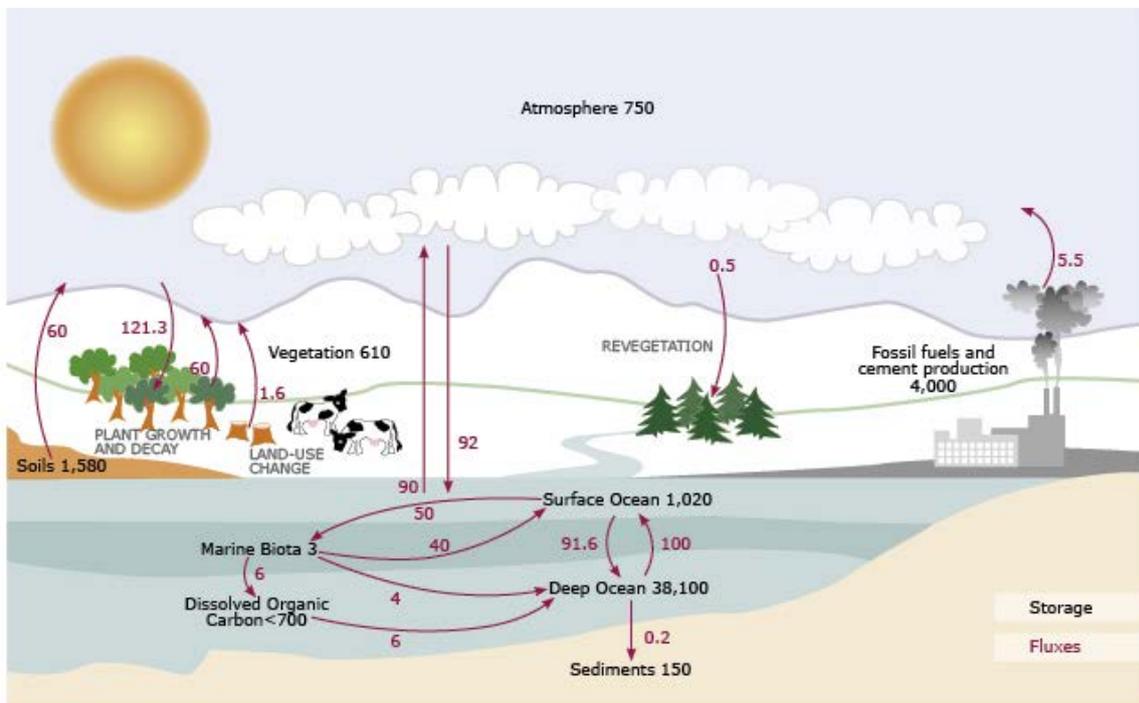
- The aboveground biomass and carbon stored in the vegetation types [ $t\ ha^{-1}$ ] will increase with increasing system diversity and in the order:  
Grassland < Bush land < Tree savannah < Bush Tree savannah
- Changes in the main vegetation of aboveground biomass lead to changes in litter composition, which results in differences in the belowground carbon stocks. According to the aboveground biomass it is assumed, the higher the systems diversity, and the higher the aboveground biomass the higher the belowground carbon stocks in the order: Grassland < Bush land < Tree savannah < Bush Tree savannah
- In terms of carbon distribution with depth, changes in vegetation life form leads to differences in the main rooting depth and root distribution. In addition, the share of root biomass in deeper soil layers will be higher in vegetation types with woody vegetation than without. This contributes to higher carbon inputs and the belowground carbon stocks will be different among the vegetation types.
- The vegetation types are a result of different vegetation formations. Trees and bushes deliver additional or unique habitats for specific plant species. In terms of species diversity and species composition, there will be differences between the vegetation types. Further, species composition (e.g. the presence of N-fixing legumes) changes the amount of carbon that can be stored in soils. Therefore, the differences in species composition result in differences in carbon stocks.

## 4 STATE OF THE ART

### 4.1 The global Carbon cycle

Carbon (C) is crucial for all life on Earth. The dry weight of most living organisms consist about half of carbon.

The global carbon cycle is divided into five major C pools; the Atmosphere, Biosphere, Pedosphere, Hydrosphere and Lithosphere (Figure 1). They are all interconnected by pathways of exchange (Schlesinger 1997). The process of the C cycling is complex, as C occurs in different chemical forms in the different pools and various complex processes play a major role in the fluxes between the pools. In addition, also changes in climate can influence the atmospheric concentration of CO<sub>2</sub> (Lal 2001b).



**Figure 1** The global carbon cycle. Red arrows are net fluxes of Carbon in Pg. ([ozcoasts.gov.au/glossary/images/carbon\\_cyclefig1.jpg](http://ozcoasts.gov.au/glossary/images/carbon_cyclefig1.jpg))

The largest C pool is the oceanic pool (Hydrosphere), which is estimated at 38,000 Pg and increasing at the rate of 2.3 Pg C yr<sup>-1</sup>. The geological C pool (Lithosphere) is estimated at 4130 Pg and mainly consists of fossil fuels, where coal is the main part (85%). The combustion of fossil fuels plays a major role in releasing CO<sub>2</sub> to the atmosphere and thereby the geological C pool is depleted. The third largest pool is the pedologic pool with around 2500 Pg estimated to 1 m depth. The atmospheric pool consist of around 760 Pg of C, with CO<sub>2</sub> being the most important form. Finally, the biotic pool is the smallest one, where

approximately 560 Pg of C is stored. The combination of the pedologic and the biotic pool is defined as the terrestrial C pool (Lal 2008a).

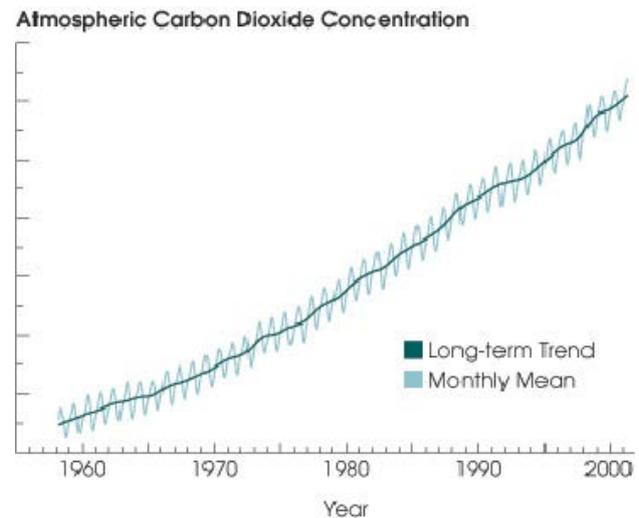
The cycling of C through the terrestrial biosphere occurs at varying time scales (Prentice *et al.* 2001). One of the most important fluxes of C is the flux between the atmosphere and the land vegetation (Schlesinger 1997; Lal *et al.* 1998), as it is the fastest one. The uptake of C by the vegetation follows a diurnal and seasonal cycle what is called the “Keeling curve”

(Figure 2). During daytime in the growth period, vegetation removes CO<sub>2</sub> through photosynthesis from the atmosphere, which

is then stored in organic matter. Depending on various biotic and abiotic factors, CO<sub>2</sub> is returned via plant, soil and microbial respiration. (Falkowski *et al.* 2000). However, when conditions are too cold or too dry, these processes are interrupted (Riebeek and Simmon 2011). The gross primary production of the vegetation is about 120Pg C yr<sup>-1</sup>. This is balanced by vegetation respiration (60Pg C yr<sup>-1</sup>) and the decomposition of soil organic matter (SOM) (60Pg C yr<sup>-1</sup>) (Lal 2008b). On a global basis, forests form the primary terrestrial C storage (Falkowski *et al.* 2000), and have a huge impact on the global C budget. As a result of land use change, e.g. deforestation, C stored in the living biomass and in the soil is released, causing an increase in atmospheric CO<sub>2</sub>. Conversely, in case of reforestation of formerly agricultural land, C is stored in the newly created biomass and atmospheric CO<sub>2</sub> concentrations will decrease (Riebeek and Simmon 2011).

In contrast, fossil fuel reserves and sedimentary rock deposits (like limestone, dolomite and chalk) in the lithosphere form the relatively immobile stock and are part of the slow C pool (IPCC 2001). Fluxes in the fast C cycle take place in a lifespan, whereas C in the slow cycle can resist up to thousands of years.

Therefore, the pedosphere plays a central role in the global C cycle, with a C pool three times the atmospheric pool and almost four times the biotic pool (Lal 2001a) (Figure 1). A slight increase or decrease in the net flux of CO<sub>2</sub> from the pedosphere would have a significant impact on the global C budget (Amundson 2001). For instance, a change of 1 Pg of the soil C pool leads to CO<sub>2</sub> changes of 0.47 ppm in the atmosphere (Lal 2001b).



**Figure 2** Fluctuations of the atmospheric CO<sub>2</sub> concentration (Graph by Robert Simmon, based on data from the NOAA Climate Monitoring & Diagnostics Laboratory)

Current CO<sub>2</sub> concentration in the atmosphere was estimated to be 391 ppmv or 0.0391% (Tans 2012) and is increasing at the rate of 0.5 % yr<sup>-1</sup>.

The role of Africa in the global C cycle becomes increasingly interesting. However, the knowledge about its potential is still notably limited. Current studies mainly concentrate on the emissions of C due to land use change and fires (Williams *et al.* 2007a; Ciais *et al.* 2011), as these are the most important contributors in Africa. On the other hand, the C sequestration potential of grasslands, savannahs and agroforestry systems, which are covering vast areas of Africa, is meant to be outstanding (Williams *et al.* 2007a). Therefore, it has yet to be identified, whether Africa is a net sink or source of atmospheric C.

## 4.2 Carbon pools in the soil

The pedologic C pool can be mainly subdivided into two; the soil organic carbon (SOC) and the soil inorganic carbon (SIC). Globally, the pedosphere stores about 2500 Pg C of which 1550 Pg is accumulated in the SOC pool and 950 Pg in the SIC pool (Lal 2008a).

The SIC pool consists of elemental C and carbonate minerals like calcite, dolomite and gypsum, and encompasses primary and secondary carbonates. The primary carbonates result through the process of weathering of parent material. Secondary carbonates are formed through the decomposition/resolution of carbonate bearing minerals and the re-precipitation of weathering products. In addition they can be built through the chemical reaction of atmospheric CO<sub>2</sub> with Ca<sup>2+</sup> and Mg<sup>2+</sup> or other salts in soils, which are entering the local ecosystem e.g. in form of calcareous dust, irrigation water, fertilizer or manure. The process of secondary carbonate formation and leaching of carbonate and bicarbonate lead to the sequestration of inorganic C in soils, and are of major importance i.e. in arid and semiarid regions (Lal 2001b; Lal 2008a).

The SOC pool is composed of highly active humus and comparatively immobile charcoal C. The soil organic matter (SOM) content of soils is the major determinant of SOC, as it is the sum of all organic C-including substances in soils. It is assumed, that SOC has a share of approximately 58% in SOM (Batjes 1996). SOM consists of a mixture of plant and animal residues in different phases of decomposition, of substances which are synthesized through microbial activity and/or chemical breakdown of products. Further it consists of living biomass other than plants, like micro-organisms and small animals (Schnitzer 1991; Amundson 2001). In general, SOM is subdivided into humic and non-humic substances. The latter are substances which have still recognizable chemical characteristics like carbohydrates, proteins, peptides, amino acids, fatty acids and waxes. These compounds are degraded in soils

relatively easily and their life span is short. Humic substances are materials which are amorphous, dark-colored, hydrophilic or aromatic. They build up the major part of SOM and are less susceptible to chemical and biological degradation (Schnitzer 1991).

The whole SOC pool is divided into three different parts which are distinguished according to their time of residence (Parton *et al.* 1987). The first one is the active or labile pool. It comprises mainly young SOM like fresh plant material and root exudates that are relatively easily degradable. Thus the labile pool has a rapid turnover, which leads to a resting time usually not more than one year. Since it is very sensitive to land management and environmental conditions, it may significantly influence the short-term C and N-cycling in terrestrial ecosystems (Schlesinger *et al.* 1990). The second one is the slow pool. Decomposition rates are classified as intermediate and residence times range from 10-100 years. The last one is the passive pool, in which C is prevented from decomposition for 100 to 1000 years. This is, because SOC is bound due to physical (e.g. occlusion within soil structures or clay-particle attachment) or chemical causes such as persistent organic compounds (Amundson 2001).

There are various biotic and abiotic factors having a strong influence on the content and the adherence of C in the soil, with climate, soil texture, vegetation and human activity (land use) being the most important ones. Any change of any factor leads to a different soil C mass, resulting in a modification in C storage (Amundson 2001). Climate has a major influence on the distribution and storage of C in soils. It is the key determinant of decomposition rate and turnover times, as the amount of SOM is linked to mean annual precipitation and mean annual temperature (Amundson 2001). This comes along with differences in SOC. Generally, SOC stocks are positively correlated with increasing moisture content, but negatively correlated with increasing temperature. Soil texture influences the SOC content, with clay content being the dominant factor (Krull *et al.* 2001). First, clay has stabilizing properties on organic matter. They are saturated with cations and tend to remain in a flocculated state. Thereby, they reduce the exposure and mineralization of organic C that is adsorbed on clay particle surfaces or in between packets of clay. Then, the pore size distribution of soils limits decomposer organisms to reach potential organic substrates. At pore sizes lower than 3 mm, decomposition by bacteria is inhibited, as they are not able to enter. Hence, SOC is better protected in soils with a higher clay content compared to more sandy soils. In addition the presence of multivalent cations controls the decomposition rate. Soils with  $\text{Ca}^{2+}$ , Fe- and Al-oxides have higher SOC accumulation (Sombroek *et al.* 1993). In particular, the coating of fresh residues by  $\text{CaCO}_3$  stabilizes and reduces mineralization of organic matter (Krull *et al.* 2001). Further, soils of

volcanic origin tend to have great accumulations of SOC (Batjes 1996), because  $Al^{3+}$  is bound to organic matter and decelerates the decomposition.

The determination of SOC in a soil can be relatively accurately conducted, since most parts of humus are accumulated near the soil surface and decrease with depth (Jobbágy and Jackson 2000). The measurement of SIC is more difficult, especially in arid and semiarid regions, as it accumulates at depth and often forms hardened layers (e.g. petrocalcic horizons) (Díaz-Hernández 2010).

The role of C stored in soils is central in terms of global climate change processes. Depending on the circumstances, soils can act as potential sinks or sources of atmospheric  $CO_2$  (Trumbore 1997; Lal 2004a). Thus, it is important to determine C stocks and ecological condition of the semiarid Ethiopian savannahs, to quantify their potential for C sequestration.

### **4.3 Classification of Vegetation types**

Vegetation types (VTs) are single units of a whole vegetation continuum which circumscribe and define parts of it. They provide a useful tool for basic and applied research (e.g. on biodiversity) and thereby serve for environmental research and ecosystem management (Jennings *et al.* 2009; De Cáceres and Wiser 2012). Vegetation is a complex system and the components, especially plant species, are difficult to measure (Carranza *et al.* 1998). Depending on the aim of research, the classification of vegetation can be based on different criteria such as physiognomy, structure, plant functional traits, species composition and climatic conditions or soil properties (UNESCO. 1973; Pratt and Gwynne 1977; Carranza *et al.* 1998; Jennings *et al.* 2009). The sub-divided units are usually vegetation stands that are limited by plot boundaries, or pixels or polygons of an image. However, the units can also stretch over these borders, or specific vegetation strata within these boundaries can occur (De Cáceres and Wiser 2012). This depends on the level of abstraction (e.g. associations, alliances, classes, divisions or formations) and the sampling or analytical approach, like sampling units, resemblance measures, data transformation, and so on. Nevertheless, all methods are accepted and legally applied (Mucina 2009).

Therefore, there is no unique classification method to define VTs. However, it would be desirable to establish standard procedures for vegetation classification, as the purpose and the use of the vegetation classification are not country- or region-specific (De Cáceres and Wiser 2012). Moreover, standardized classification can enhance our understanding of plant ecology and may provide comparable units of species composition and their abundance, what will improve general ecology (Jennings *et al.* 2009).

The FAO (2005) delivers an approach that includes the most important vegetation traits for the classification of land cover types or VTs. A classification can be carried out *a priori* or *a posteriori*. The latter uses vegetation assessments that are collected without an evaluation. Specific traits (e.g. life form, cover and height) form a vegetation type using PC software or other subsequent classification methods. The *a priori* classification system is widely used (FAO 2005). Thereby, all possible classes any user may derive, are predefined in the classification system, independent of scale and tools used. The major advantage of this system is its effectiveness to achieve standardization of classification between different users. However, a problem arises concerning the quantity of predefined classes. In order to describe any vegetation type occurring anywhere in the world, a huge number of classes are needed. This increases flexibility<sup>1</sup> but to the disadvantage of standardization (FAO 2005). Thus, a harmonization between flexibility and standardization is crucial.

To solve this problem, the vegetation classification system of the FAO (2005) suggests the following general rules for classification of natural and semi-natural vegetation.

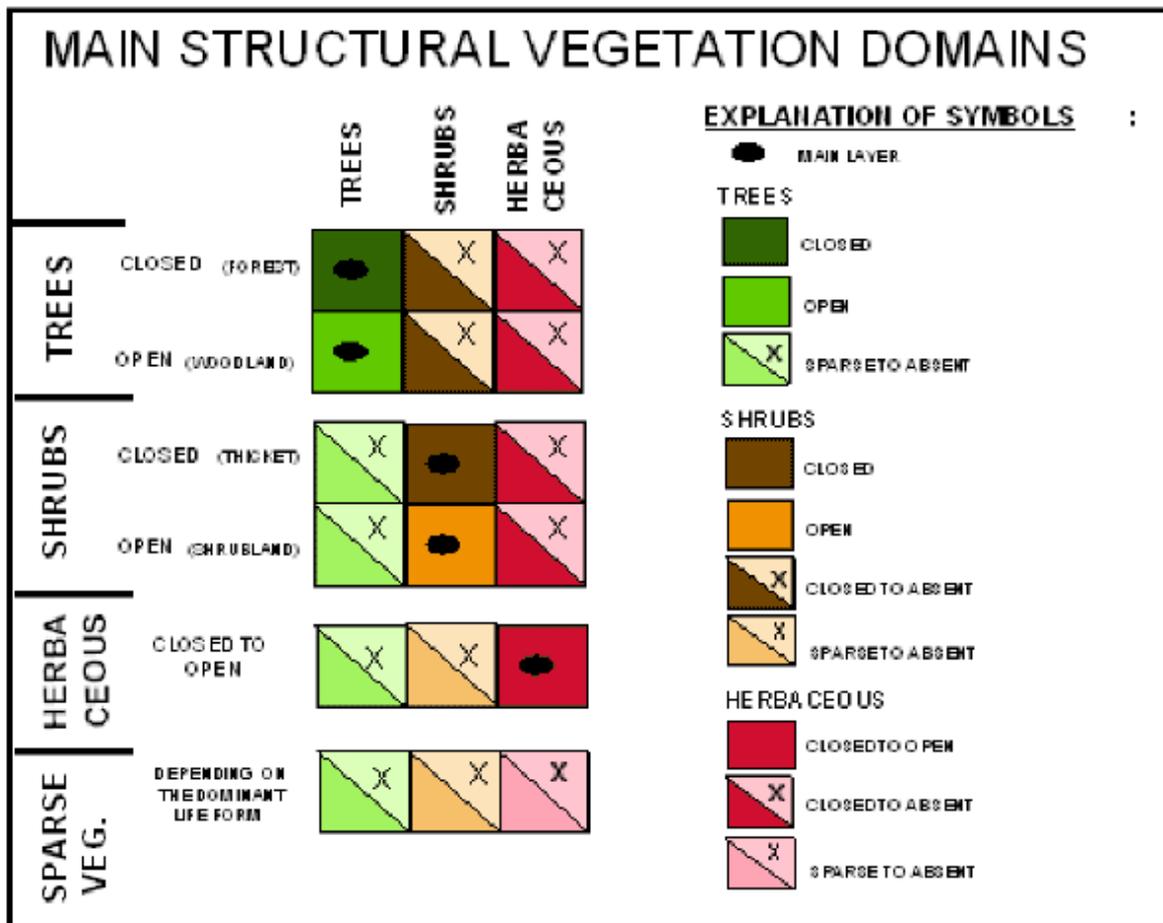
A given VT is defined by the combination of various independent diagnostic attributes (*classifiers*). The higher the number of classifiers used, the higher the level of detail in the description of a vegetation type, thus, the more specific the class. This means, that not only the class name is deciding the VT, but the classifiers used to define the class.

Two main characteristics are crucial for the determination of a VT; the definition of *life form* and their *dominance*. The life form is the physiognomic appearance of a plant or a group of plants, who have certain morphological characteristics in common (Küchler and Zonneveld 1988, cited in FAO 2005). Life form can be differentiated into woody plants, which are further subdivided into trees and bushes, and herbaceous plants (forbs and graminoids). For the distinction between trees and bushes, the height of plants can be used as a valid indicator. To define the dominance, the main criterion is the highest canopy layer. Thereby, the dominance follows the tree–bush–herbaceous layer. It is dependent on the cover of the dominant life form. This means, that the dominant life form has to have a cover of either “closed” or “open”. If the cover is only sparse, the dominance is subjected to another life form whose cover is “closed” or “open” (FAO 2005) (Figure 3). In addition, a further subdivision of the physiognomic term can be made in terms of species composition (Pratt and Gwynne 1977).

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<sup>1</sup> Flexibility in this context means, to enable the classification system to describe sufficient classes to cope with the real world. In addition, class boundary definitions should be unambiguous and clear. At the same time, however, classes have to be as neutral as possible in describing the vegetation type, to be feasible for a variety of end-users and disciplines (FAO 2005)

Further classifiers, that can be used to determine a VT more precisely, are *Macropattern* and *Stratification*, however they will not be further described (for more information see FAO 2005).



**Figure 3** Main structural Vegetation Domains (Di Gregorio and Jansen 1996, in FAO 2005)

The research on current vegetation in Ethiopia is of crucial importance, as the natural vegetation has been modified through human influence, and there remain only a few patches of natural vegetation communities (Woldu *et al.* 1989). The description of dominant VTs of the Borana Plateau, and the link to their respective C stocks above- and belowground, will provide a baseline for upscaling methods to predict C sequestration potential of broader areas.

#### 4.3.1 Typical Grassland/Savannah vegetation

In general, savannahs are defined by the co-existence of trees and grasses (Scholes and Archer 1997). The distribution of these two contrasting life forms, and their density, cover and height, are essential for the understanding of general functions and processes of savannah ecosystems (Sankaran *et al.* 2004). The forming and dominance of either woody or herbaceous vegetation in a savannah ecosystem, is highly influenced by a number of interacting factors such as climate, soil properties, resource competition, fire and grazing,

operating at different spatial and temporal scales (Scholes and Archer 1997). In addition, the impact of human activity is nowadays an important driver and determining factor for the existence of particular plant life forms. According to Pratt and Gwynne (1977) and White (1983), major VTs of east African savannahs are presented below.

### **Woodland**

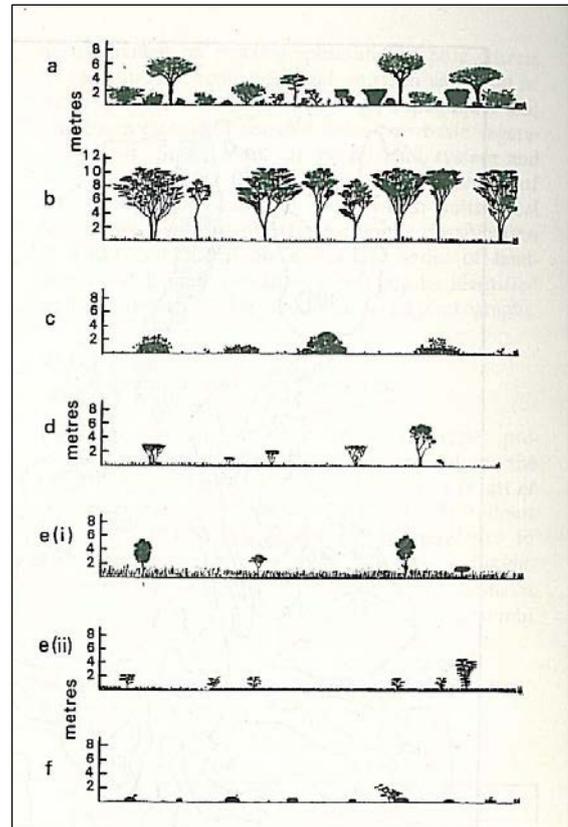
Woodland is land with an open stand of trees up to 20 m in height, and which cover more than 20%. The canopies of the trees are often in contact, but are not densely interlaced (Figure 4b). If shrubs/bushes are present, they count for less than 10% of the total cover. The ground cover is dominated by grasses and other herbs.

### **Bushland**

Bushland is land, dominated by bushes or trees with a shrubby habit, usually between 3 and 7 m, which is covered by at least 40%. Bushy trees up to 10 m in height and some occasional emergents can be present as well (Figure 4a). If bigger trees are more frequent within the bushland, the term “wooded bushland” can be used. In general, subtypes are classified respective to the genera of the dominant woody plants. The herbaceous ground cover is usually poor. Bush land thicket is an extreme form where the bushes build a closed stand and passing-through is difficult.

### **Shrubland**

Shrubland is land, which is covered by more than 20% shrubs up to 6 m (often less). Trees are seldom but can occur at a maximum of 10% of the total cover (Figure 4c). The ground cover depends highly on the rainfall and the soil condition. With sufficient rainfall, grasses are dominant on deep sandy soils, while stony and rocky places are favored by woody plants. Comparably, as in bush lands, shrub land thickets can be recognized, too.



**Figure 4** Physiognomic vegetation types. a) Bushland; b) Woodland; c) Shrubland; d) Bush grassland; e) Wooded grassland (i: tall wooded grassland; ii: dwarf tree grassland); f) Dwarf shrub grassland (Pratt and Gwynne 1977)

***Grassland***

In this VT, grasses and other herbs are the dominant life forms, with the former more frequent. Occasionally, trees, bushes and shrubs are present widely scattered or grouped. However, their canopy must not exceed 2% of the total cover; otherwise they are classified as “wooded/bush/shrub grassland” (see below). Sub-types of grasslands are classified with respect to their height (if it is not in the range of 25-150 cm), genera of dominant grasses, degree of swampiness or the dominance by annual grasses or other herbs.

***Tree grassland or wooded grassland***

This refers to grasslands with scattered or assemblies of trees, with a canopy cover lower than 20% of the total surface.

***Bush grassland***

Bush grassland is defined by the presence of scattered or grouped trees and shrubs in grasslands. Normally they occur with different amounts, but both are always conspicuous, and together, they cover not more than 20% (Figure 4d). Sub-types are classified according to the grassland type and the genera of the dominant woody plants. This includes grass height, the dominance of annuals, dominant genera (grass/woody plants) and the degree of swampiness.

***(Dwarf) Shrub grassland***

Shrub grasslands are grasslands which consist of scattered or grouped shrubs with a canopy cover of less than 20% of the area. For the classification of sub-types, the same criteria exist as for bush grasslands (see above). A special type form dwarf shrub grasslands. These are defined by often sparse grasslands with usually dwarf shrubs at a maximum of 70 cm in height. Bigger shrubs are occasionally widely scattered. The term “dwarf” refers to all vegetation types, where shrubs and trees are smaller than 70 cm and 2 m, respectively.

**4.4 Dependence of carbon stocks on vegetation and species composition**

Savannah ecosystems count to the most extensive C4 grassy biomes. Usually, they form “patchy mosaic landscapes” with a relatively continuous cover of grass and herbaceous vegetation and patches of scattered or grouped trees and/or bushes (Scholes and Archer 1997). Woody plant invasion is an ongoing process (Jackson *et al.* 2002), which is the extension of woody species into grasslands and savannahs. With the obvious change in vegetation aboveground, the changes belowground are less conspicuous, but equally important. The

modification of the dominance of either herbaceous or woody vegetation has a strong impact on primary production, plant allocation and rooting depth up to several meters belowground (Scholes and Archer 1997; Jackson *et al.* 2000; Jackson *et al.* 2002). As a consequence, important ecosystem functions, such as the nutrient and hydrological cycling and C storage is affected as well (Trumbore 1997; Jobbágy and Jackson 2000). SOM is the dominant C (and nitrogen) pool of grasslands. Together with the C pool of woody plant biomass, they are the two terrestrial C pools most likely to change (Jobbágy and Jackson 2000; Amundson 2001). Depending on the age, productivity and density of the stand, different amounts of C are stored in new woody biomass (Jackson *et al.* 2002).

The storage of organic C in the soil depends on the balance of inputs by the plant production of the particular vegetation and the outputs caused by decomposition (Schlesinger 1977). Jobbágy and Jackson (2000) hypothesized, that the vegetation pattern above- and belowground is a crucial factor for the vertical distribution of SOC. Therefore, plants of terrestrial ecosystems play a major role in the long term C uptake (Steinbeiss *et al.* 2008). Carbon is stored in plants as biomass and represents the short term C storage pool. Microbial communities in soils convert the plant biomass to SOC and form the long term C storage pool. The quality and quantity of C entering the terrestrial systems through decomposition, and the resulting total amount of organic C in the soil, is mainly dependent on climate and land use. Rees *et al.* (2005) state, that approximately 50% of the C, accumulated through photosynthesis, is relocated belowground. In the soil continuum, C is divided into root growth, rhizosphere respiration and addition to SOM. According to Falkowsky *et al.* (2000), living biomass holds between 600 and 1,000 gigatons (Gt) of C and is mainly stored as woody biomass. Trees and other woody vegetation have a strong influence on the capture of C. With the high amount of biomass aboveground, they are able to store around 45% of the terrestrial C (Bond 2008). In savannah ecosystems, where trees are present, ca. 30 t C ha<sup>-1</sup> can be stored in aboveground vegetation compared to 1.8 t C ha<sup>-1</sup> in grasslands without woody vegetation (Grace *et al.* 2006).

Furthermore, C can enter the soil via the root system, what is called rhizodeposition. Several processes, like exudation, secretion, sloughing and lysis of cells and root tissue senescence, cause the release of C (Rees *et al.* 2005). Therefore, another important trait of plants, controlling the C stocks of soils, is their expansion belowground. It is widely recognized, that plant life forms (grasses, bushes and trees) have different depths and distributions of their roots (Jackson *et al.* 1996). In general, the maximum rooting depth of woody vegetation exceeds the one of herbaceous vegetation. Grasses and herbs have an average rooting depth of

2-2.5 m, while trees and shrubs are found to have a rooting depth of 5 and 7 m on average (Canadell *et al.* 1996). Grasses have a dense fibrous root system, which allows them to explore the soil more intensively than it is the case for tree roots. In contrast, trees are able to scan the soils more extensively and to a larger extent. So, they find high-resource patches which are not occupied by grasses (Bond 2008). This can be explained by the specific root length of the different vegetation life forms. Jackson *et al.* (1997) found, that grasses had higher specific root length than any other life form (grasses: 118 m g<sup>-1</sup>; shrubs: 30 m g<sup>-1</sup>; trees: 12.2 m g<sup>-1</sup>). Fine roots are an important sink for C gained in net primary productivity, and the primary production stored belowground often exceeds the one aboveground (Jackson *et al.* 1997). This leads to a higher input of C into the soil in grasslands compared to woodlands. Further, the root:shoot ratio of the different vegetation forms is central for the C allocation above and belowground. According to Jackson *et al.* (1996), root:shoot ratios of grassland are in the range of 4 to 6, while the range for woodlands is much smaller.

The distribution of soil nutrients within the soil profile is another factor influenced by the different vegetation life forms. Jackson *et al.* (2002) assessed that SOC is more deeply distributed at sites with woody vegetation cover. 60 % of SOC was stored in the depth from 1 to 3 meters in woodland compared to 40 % in grasslands. However, if only the first meter of soil is considered, the allocation of C is the other way round. Here, only one-fifth of the C amount of grasslands is stored in woodlands.

Nevertheless, not only the plant life form of ecosystems, but also the diversity of plants and community composition is found to be an important factor in increasing C storage in soils (Catovsky *et al.* 2002; Fornara and Tilman 2008; Sebastia *et al.* 2008).

The impacts of plant diversity on litter decomposition derive from litter mixing effects and through the building of a micro climate (Catovsky *et al.* 2002). Plant species diversity and composition is able to enhance net storage of C and N in soils in two main ways; first through a higher amount of C and N, that is entering the soil, and second through a decrease of their losses via respiration, volatilization and leaching (Catovsky *et al.* 2002; De Deyn *et al.* 2008). Fornara and Tilmann (2008) stated that the diversity effects on primary productivity in grasslands depend heavily on the presence of N-fixing legumes. In prairie grasslands on sandy soil with N being the limiting factor, they found out, that plant diversity increased the accumulation of C and N. This was mainly because of the co-existence of C4 grasses and legumes. N inputs were improved by the legumes, what facilitates the growth of C4 grasses and caused N retention. These findings are further supported by Steinbeiss *et al.* (2008), who observed higher soil C pools under higher plant species richness. In addition, the C:N ratio of

a plant community affects the decomposition rate (Dubeux Jr *et al.* 2006). The smaller the C:N ratio, the higher the amount of N, the higher the rate of decomposition, and the higher the amount of C in the soil. Thus, with greater species diversity, i.e. including N-fixing legumes, the amount of C restored in the soil increases.

#### 4.5 The role of Grasslands in carbon sequestration

“...*Grasslands store about 343 billion tons of C – nearly 50 percent more than is stored in forests worldwide.*” (FAO 2010)

The term “soil carbon sequestration” refers to the removal of CO<sub>2</sub> from the atmosphere by plants and the storage in varying C pools, and is calculated in the timespan of a year (Lal 2001b; Lal 2004b). The resulting effects are increased SOC density in the soil, improved distribution of SOC with depth and the stabilization of SOC through incorporation in micro-aggregates (Lal 2004b). Terrestrial ecosystems in general have a great potential in sequestering C for the mitigation of increased atmospheric CO<sub>2</sub>. However, grasslands in particular hold a considerable amount of the world’s SOC, due to their vast expansion. About 52.5 million km<sup>2</sup> or 40.5 % of the Earth’s surface are covered by grassland ecosystems in a wider sense (Suttie *et al.* 2005). In a narrower sense, tropical savannah ecosystems have a share of 20 % of the terrestrial area (Neely *et al.* 2009). This suggests that these ecosystems make a significant contribution in the global C cycle.

In grasslands, more C is stored in the soil than in the vegetation. White *et al.* (2000) point out, that 231 Gt of C are stored aboveground compared to 579 Gt C in the soil under grasslands. Conversely, forests store more C in their aboveground biomass (trunk, branches, and leaves) than in the soil.

Land use change, especially the conversion of grasslands and pasture into cropland, counts to the most important contributors of C emissions from the soil to the atmosphere. It is assumed, that 5.5–6 Gt CO<sub>2</sub> could be technically mitigated through adjusted management in agriculture. Thereof, 1.5 Gt CO<sub>2</sub> is from grazing land management, 0.6 Gt from restoration of degraded land and >1.5 Gt from cropland management. Almost 70% of this potential can be achieved in developing countries (IPCC 2007a). Further, Tennigkeit and Wilkes (2008) estimate that improved rangeland management alone has the biophysical potential to sequester 1.3–2 Gt CO<sub>2</sub> until 2030, globally.

Smith *et al.* (2008) lists a few integrated management interventions to reduce GHG emissions and to increase C sequestration in grassland ecosystems. The most important are: (i)

managing grazing intensity, (ii) fire management, (iii) restoration of organic soils and degraded lands and (iv) extending the use of perennial crops.

In addition, these management practices in grasslands will not only enhance the potential for C sequestration, but it will have beneficial effects for ecosystem services, like greater biodiversity, better water-holding capacity of the soil, and reduced soil erosion, and further increases food production. By accomplishing a good management, grassland soils will still sequester C for up to 50 years (Lal *et al.* 1998; Conant *et al.* 2001), which results in the mitigation potential of 4–9% CO<sub>2</sub>-emissions in Africa per year (Batjes 2004). Batjes (2004) further estimated that taking just the grasslands in Africa, improved management practices on only 10 % of the area, soil C stocks could be increased by 1,328 million tons C per year in the next 25 years.

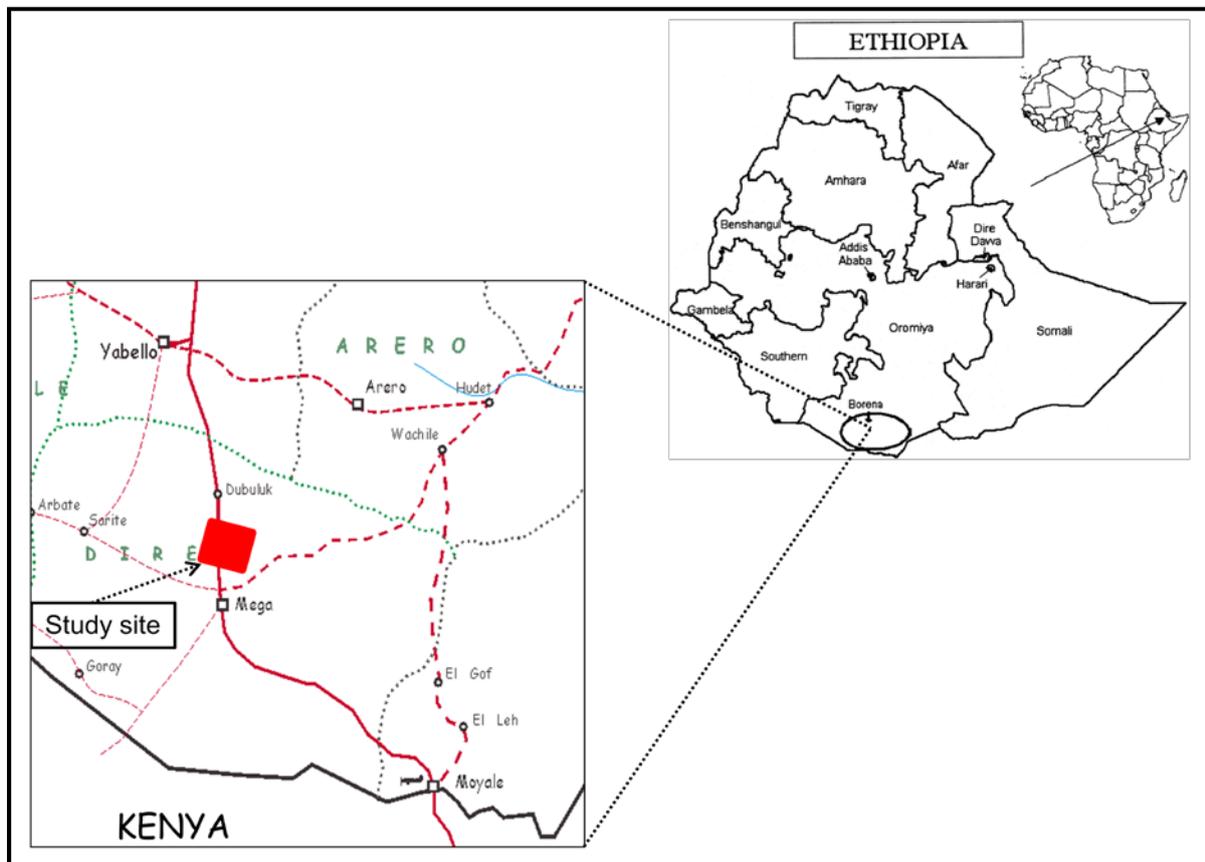
Degradation of dry land pasture soils led to notable reductions of SOC during the last decades. However, through the restoration of grasslands these lands will act again as C sinks via the fixation of atmospheric CO<sub>2</sub> on one hand and via reduction of erosion-induced CO<sub>2</sub> loss on the other. Furthermore, the C loss in dry soils is smaller compared to wet soils due to longer residence times and reduced decomposition (Neely *et al.* 2009). Therefore, grasslands in dry lands of the world are essential for long-term C storage.

Thus, world's grasslands yet play an important role in balance of atmospheric CO<sub>2</sub> and in addition hold a great potential for future mitigation practices if they are managed in an equitable way.

## 5 MATERIALS & METHODS

### 5.1 Study area

The study was conducted in South Ethiopia, Oromia Region, Borana Zone. The experimental site comprises a 10 km<sup>2</sup> field (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), close to the Kenyan border (Moyale) (Figure 5). The Borana Plateau covers a total area of 95,000 km<sup>2</sup>. Around 350,000 inhabitants live in this region keeping about one million cattle, small ruminants and camels (Homann *et al.* 2008). The landscape is characterized by moderately undulating hills with an altitude of about 1,000–1,500 m a.s.l. and may reach elevations up to 2,000 m a.s.l. (Coppock 1994).

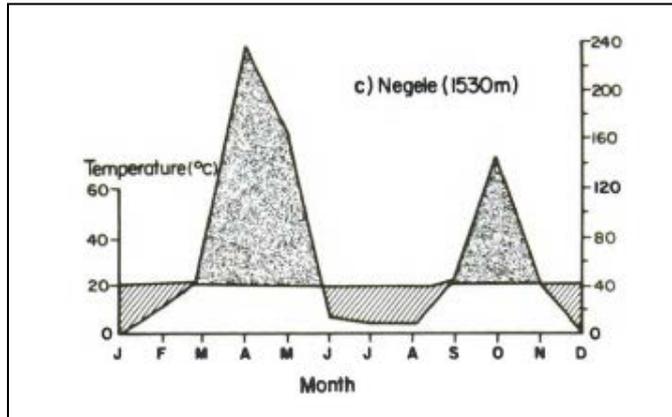


**Figure 5** Map of the Research Area and Study Site location between Dubuluk and Mega, Borana Region, Southern Ethiopia ([http://www.africa.upenn.edu/eue\\_web/borz0200\\_map.jpg](http://www.africa.upenn.edu/eue_web/borz0200_map.jpg), modified)

#### 5.1.1 Climate

The climate is characterized as semi-arid. The amount of annual rainfall shows great differences with location and varies between 110 mm/year in the south and 600 mm/year in the north. Rainfall shows a bimodal pattern (Figure 6). Between March and May,

approximately 60% of annual rainfall (main rainy season) occurs, 30% follow between September and November (short rainy season) (Homann *et al.* 2008). In contrast, temperature-variations are not so significant, as mean annual temperature varies between 15°C and 24°C with only little seasonal changes. Long lasting droughts occur regularly every 20 years, while isolated dry years occur every 5 years (Coppock 1994). However, the time span between droughts is decreasing and the drought in 1999/2000 took place just 3 years after the previous one (Homann 2004).



**Figure 6** Climate chart of the study area (ILCA, unpublished data)

### 5.1.2 Agro-ecological zones

Ethiopia has a wide range of temperature and rainfall pattern. As shown in Figure 7 the country is divided into 17 agro-climatic zones based on a combination of six altitude layers (ranging from <500 m a.s.l. to >3700 m a.s.l.) and three rainfall categories (Dry: <900 mm/year; Moist: 900–1400 mm/year; Wet: >1400 mm/year) (RELMA in ICRAF 2005). The study area is lying at around 1500 m a.s.l. with an annual average rainfall of less than 900 mm. Therefore it forms a transition zone between “Dry Kolla” and “Dry Weyna Dega”.

	<b>Bereha</b>	<b>Kolla</b>	<b>Weyna-Dega</b>	<b>Dega</b>	<b>Wurch</b>	<b>Alpine Wurch</b>
	< 500 m	500 – 1500 m	1500 – 2300 m	2300 – 3200 m	3200 - 3700 m	> 3700 m
<b>Dry</b> < 900 mm	Dry Bereha	Dry Kolla	Dry Weyna-Dega	Dry Dega	Dry Wurch	Dry Alpine Wurch
<b>Moist</b> 900-1400 mm	Moist Bereha	Moist Kolla	Moist Weyna-Dega	Moist Dega	Moist Wurch	Moist Alpine Wurch
<b>Wet</b> > 1400 mm	<i>Not existing</i>	Wet Kolla	Wet Weyna-Dega	Wet Dega	Wet Wurch	Wet Alpine Wurch

**Figure 7** Agro ecological zones of Ethiopia (RELMA in ICRAF 2005)

### 5.1.3 Geology and Soils

Soils of the Borana Plateau are influenced by four geological formations: (1) Precambrian basement complex and crystalline rocks which comprises granite, gneisses and magmatite, (2) sedimentary deposit like sand stone and lime stone, (3) volcanic basalt and tuff and (4) quaternary deposit, namely alluvial deposit and alluvial-in situ weathering rock (Oromiya Soil Survey Report, unpublished).

Important soil forming factors of the area were climate, parent material, relief/topography, organisms (flora and fauna) and human activity. A combination and interaction of these factors led to different soils and their characteristics. Parent material has to be emphasized in soil development, because various soil minerals will result from the break down under weathering of different rocks. The breakdown of basaltic rocks results in forming clay textured soil, while the breakdown of granite and gneiss results in a sandy, sandy loam, loamy and sandy clay loam texture (Oromiya Soil Survey Report, unpublished).

Major soil types found in the study area were Cambisols, Vertisols and Calcisols. Cambisols are relatively young soils and typical for temperate zone, but occur in tropical regions as well (WRB 2006). Colors varied from reddish-brown to white brown and brown. Vertisols are typical soils of the seasonal tropics and subtropics, mainly in regions with changing rainfall amounts. Due to their high amount of clay, with ability to swelling and shrinking, they are very sticky when wet and hard when they dry out, forming deep cracks in the dry season. In the study area, they were found in depressions and their color varied from dark brown to dark grey. Calcisols are common in arid and semi-arid areas and occur mainly on highly calcareous parent material (Oromiya Soil Survey Report, unpublished). Calcisols identified in the study area were white-grey-brownish and had a loamy texture. (Soils of the study area and their properties see Appendix I)

### 5.1.4 Vegetation

Native vegetation of the Borana Plateau is composed of diverse mixtures of woody and herbaceous vegetation and is therefore characterized as tropical savannah (Pratt and Gwynne 1977). Important characteristics of savannah systems are their variation in proportion of woody and herbaceous material and drastic composition shifts due to heavy grazing, browsing, fire and severe droughts (Northon-Griffiths, 1979; Walker and Noy-Meir, 1982, cited in Coppock 1994). It is assumed, that grazing might favor trees whereas browsing rather promotes grass vegetation (Walker and Noy-Meir, 1982, cited in Coppock 1994). Coppock (1994) hypothesizes, due to heavy grazing and the absence of fire perennial woody plants are dominating many plant communities. 5-75% of total plant cover in Borana consists of

perennial woody plants (Coppock 1994). An essential feature of perennial plants in this area is their persistence, because of the bimodal uncertain pattern of rainfall. Even small rainfall events can induce greening. In addition, their permanent rooting system is a good prevention against erosion (Ukkerman, 1991, cited in Coppock 1994).

Dominant tree species found in the area were *Acacia tortilis*, *A. nilotoca*, *A. bussei* and *A. seyal*. Bush and shrub species identified were mainly *A. mellifera*, *A. drepanologium* and *A. nubica* often associated with *Solanum* ssp. and *Ocimum* ssp. Grasslands showed a wide range of species composition depending on the site factors and soil type. *Pennisetum* ssp. was mainly found on Vertisols and soils with a good water holding capacity. On other soil types a mixture of annual and perennial plants was identified. *Sporobulus* ssp., *Eragrostis* ssp., *Cenchrus ciliaries* L., *Cynodon dactylon* L. and herbaceous plants like *Crotalaria* ssp and *Bidens* ssp. were dominating these areas.

### **5.1.5 Land Use**

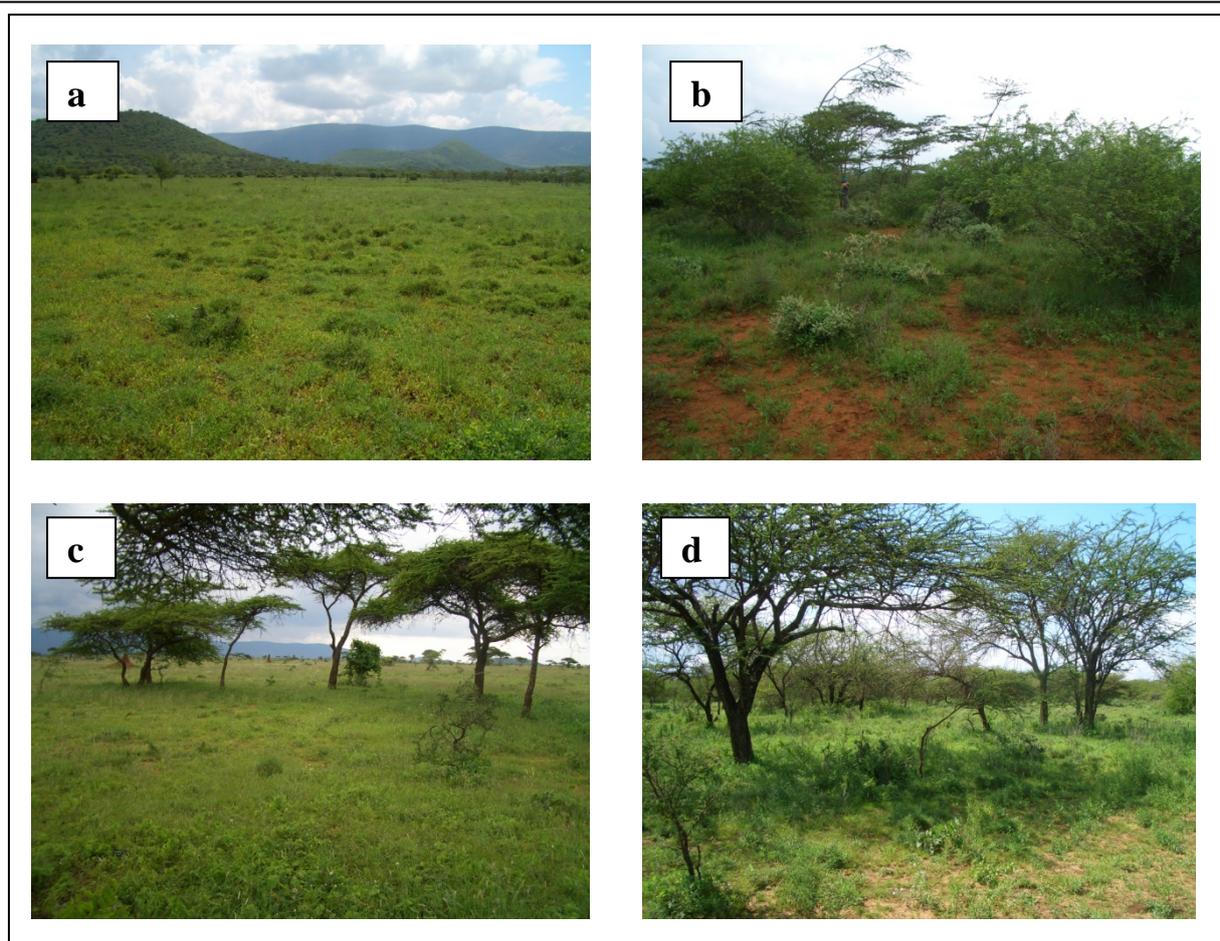
The traditional land use system of the Borana zone was a pastoral system characterized by cattle grazing and browsing by sheep, goats and camels (Oromiya Soil Survey Report, unpublished). As surface water was only seasonally available, rainy season grazing was dominant (Homann *et al.* 2008).

Since the 1970, research and development efforts to improve rangeland productivity led to a transition from traditional pastoralism to semi-sedentary grazing systems. Major changes resulting in this modification were (i) the construction of additional watering ponds, causing permanent settlement within formerly seasonal pastures and the possibility for year-round grazing, (ii) the official prohibition of burning and (iii) increasing crop cultivation due to extension services (Homann *et al.* 2008).

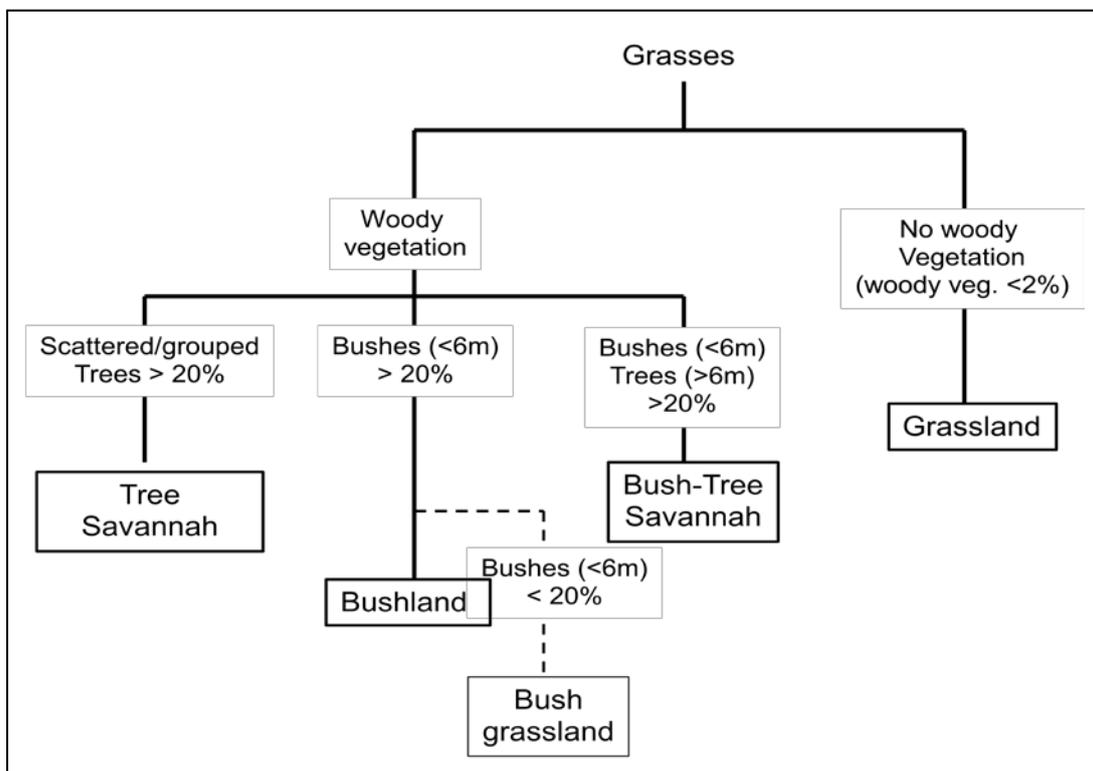
## **5.2 Experimental Setup**

### **5.2.1 Determination of representative vegetation types (VTs)**

To get an overview of the natural vegetation and plant communities that are most representing the area, first of all the study area was surveyed by foot. With the help of a “Google Earth” satellite image, prominent vegetation cover was determined visually. By ground-trouthing in North-South and East-West direction, the vegetation cover and current plant communities were categorized. Natural vegetation was then classified into four different vegetation types (VTs): open grassland (G), tree savannah (T), bushland (B) and a combination of bush and tree savannah (BT) (Picture 1). The decision-tree for the VTs is shown in Figure 8.



**Picture 1** Identified vegetation types in the study area. a) Grassland; b) Bushland; c) Tree savannah; d) Bush-Tree savannah



**Figure 8** Decision Tree for the four vegetation types (modified after Pratt and Gwynne 1977)

### **5.2.2 Site selection**

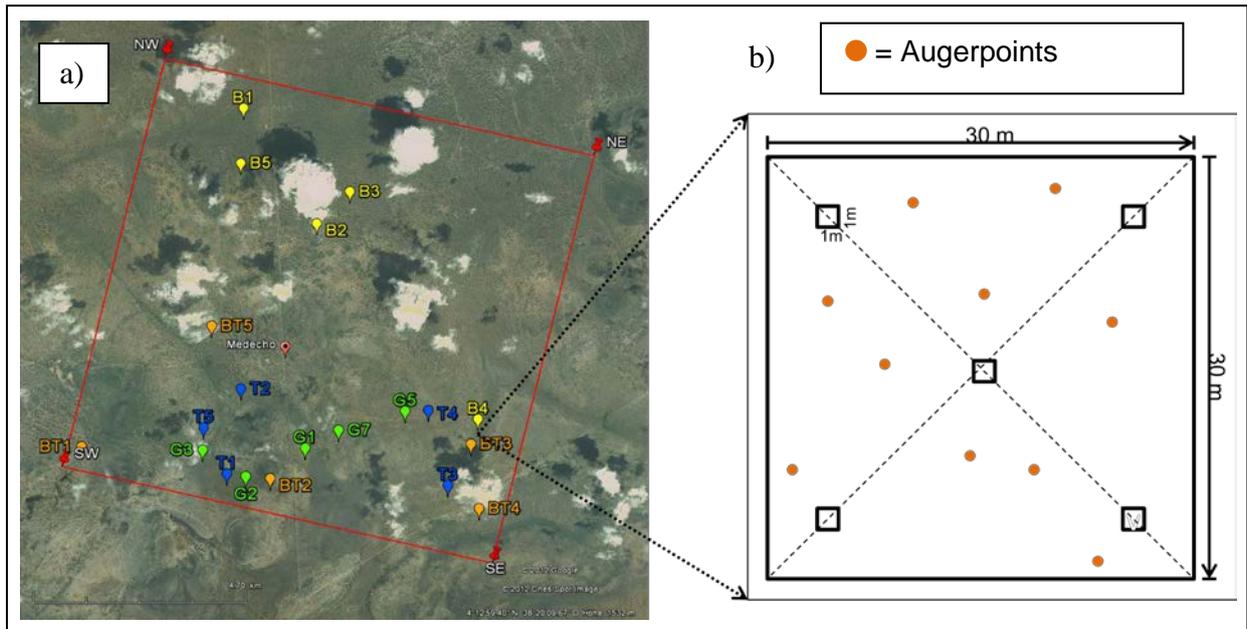
Representative plots were selected by visual observation and with the help of a satellite image (googleearth.com). For the visual observation, small hills within and bordering the study area were climbed to get an overview and pictures were taken in every geographic direction. After that, these pictures were analyzed and compared to the satellite image. Possible locations of the searched VT were marked in the satellite image to get the GPS coordinates. Using a GPS (60CSx Garmin, USA), the preselected locations were visited and discussed if they match with the classified VT in terms of vegetation cover, species composition and stand density. If the criteria were fulfilled, the plot was chosen for further investigation.

### **5.2.3 Plot and Sampling design**

Overall, twenty 900 m<sup>2</sup> sample plots were established, representing 5 plots per VT. GPS coordinates of each selected sampling plot were taken with a GPS (60CSx Garmin, USA) and mapped within the satellite image as shown in Figure 9a.

Each of the 900 m<sup>2</sup> plots used for field measurement had the same sampling design (Figure 9b). As tree stand densities were generally very low in this area, a plot size of 30x30 m was chosen to include at least three trees per plot in the “trees savannah” VT. In order to better connect the outcome with each other, the investigated plots of the different VTs had all the same size. For the destructive measurement and species identification of understorey vegetation (mainly grass and small herbaceous vegetation) five subplots with a size of 1x1 m were established along two diagonal lines in the plot.

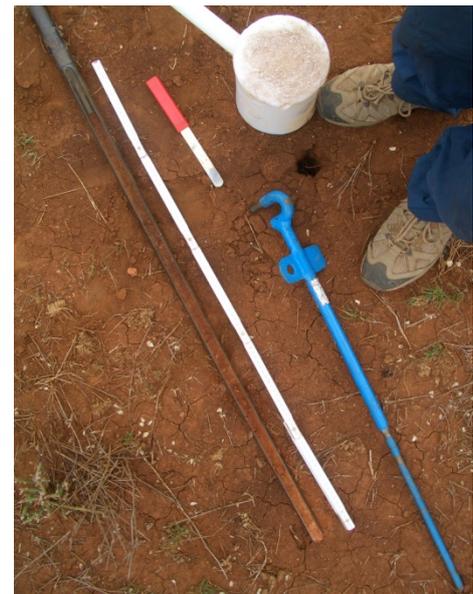
Using a Puerckhauer auger, 10 randomized soil samples of one meter depth were taken within the 900 m<sup>2</sup> plots. Soil bulk density was measured at two different positions in each plot in two different depths (0-10 cm and 10-30 cm, respectively).



**Figure 9** Plot and sampling design. (a) Distribution of the sampled plots within the 10 km<sup>2</sup> study area and (b) Sampling design of each 30 m<sup>2</sup> Plot.

### 5.2.4 Soil sampling

Soil samples were taken once before and once after the rainy season to display seasonal changes. Ten randomly chosen auger points were taken within the five plots of every of the four different VTs, using a Puerkhauer auger up to one meter depth if possible, or until the parent material was reached (Picture 2). The samples were separated in four different depth: (a) 0-10 cm, (b) 10-30 cm, (c) 30-60 cm and (d) 60-100 cm and filled into a labeled plastic bag. The samples were used for laboratory analysis of total carbon (TC), SOM, soil organic carbon (SOC), pH and carbonate (CaCO<sub>3</sub>) content. In addition one auger point was used for soil type identification to describe texture, color and carbonate content after using a Munsell chart and HCl acid.



**Picture 2** Puerkhauer auger and soil sampling equipment

### 5.2.5 Bulk density

For the determination of soil bulk density (BD), two 40 cm deep holes were dug at two different positions in each of the 20 plots. Any place with soil compaction, e.g. due to foot trails, was avoided. In two different depths (0-10 cm and 10-30 cm) standardized coring cylinders with a volume of 100 cm<sup>3</sup> were pushed into the soil vertically using a rubber hammer and a block of wood (Picture 3). The sampling needed to be carried out carefully, to

avoid any disturbance of the soil. The coring cylinder, containing the soil, was then dug out of the soil using a spatula. Excess soil was removed from both sides of the coring cylinder with a knife and the cylinders were closed with a plastic cap. For transport, the soil was filled into a plastic bag and labeled with the respective ID. In every plot five replications per depth were taken ( $n=200$ ).



Picture 3 Bulk density sampling

### 5.2.6 Sampling of vegetation (destructive/non-destructive)

At all sampling locations, observed site factors, like closeness to a village or foot trails, elevation and GPS coordinates were recorded. Trees and bushes were documented in a map and species were identified with the help of a local expert.

#### 5.2.6.1 Trees

All sampled trees within the plot ( $900 \text{ m}^2$ ) were numbered and their location recorded in a map. For estimating the tree biomass of each tree, allometric equations from literature were used. Therefore, circumference at breast height (1,3 m) (DBH), basal circumference at 0,3 m from ground ( $D_{30}$ ), stem height ( $H_S$ ), total tree height ( $H_T$ ), height at lower end of canopy ( $H_C$ ), tree crown width ( $C_W$ ) and length ( $C_L$ ) were measured.

Stem height and circumferences in the two heights were measured using a measuring tape. Some measured trees were odd-shaped at measuring height, e.g. forking trees or bulging trees. These trees were measured according to Hairiah *et al.* (2001) (Figure 10).

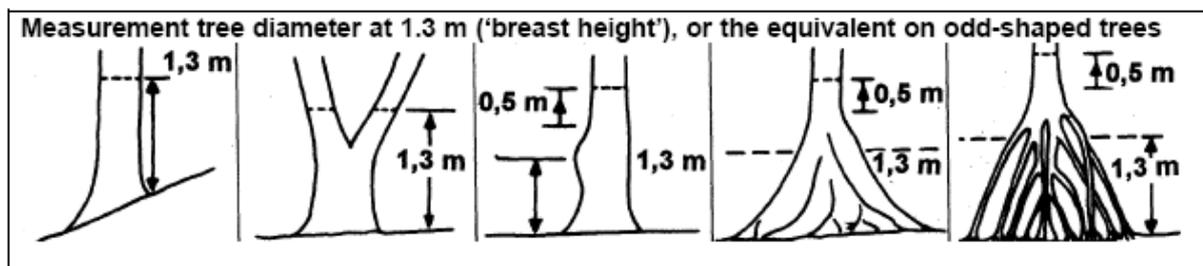


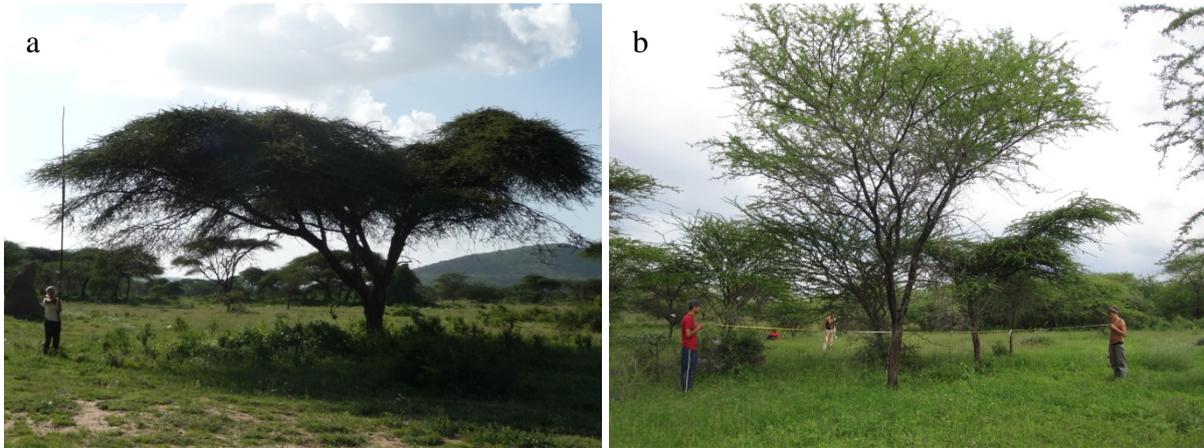
Figure 10 Measuring procedure on odd-shaped trees (Hairiah *et al.* 2001)

Total tree height and height at lower end of canopy were measured using a wooden stick of seven meters, marked with colored tape at 50 cm intervals. The stick was lifted until the end

matched with the top of the canopy (Picture 4a). The missing centimeters were measured with a ruler and added to the seven meters of the stick.

Canopy width and length were measured with a measuring tape by two persons standing at the margins of the canopy in two orthogonal directions (Picture 4b). Canopy diameter ( $C_d$ ) was then calculated as the average of  $C_w$  and  $C_L$ . Ground cover was calculated with the circle area:

$$\text{Circle Area [m}^2\text{]} = \pi \times (C_d)^2/4$$



**Picture 4** Tree height (a) and crown width and length (b) measurement

Aboveground biomass of trees was then calculated using allometric equations below:

For *Acacia tortilis*, *A. bussei* and *A. nilotica* (Hofstad 2005)

$$Y = 0,0096 \times (H_T + C_w + C_L)^{3,3015}$$

Where  $H_T$  is total height [m],  $C_w$  is crown width [m] and  $C_L$  is crown length [m].

For *A. drepanolobium* (Okello *et al.* 2001)

$$Y = 3,77 \times D_{30} + 1,1682$$

Where  $D_{30}$  is basal diameter at 0.3 m from ground [cm].

### 5.2.6.2 Bushes/Shrubs

The sampling of bushes was similar to trees. The position of every bush/shrub was recorded in a map and they were classified into three different size categories (small/medium/big), defined through visual observation. Due to early branching, and a dense habitus, only the basal circumference ( $D_{30}$ ) at 0.3 m from the ground was measured, using a measuring tape. Further, the canopy width ( $C_w$ ) and length ( $C_L$ ) were measured in the same way as it was done for trees (see section 5.2.6.1). Bush height ( $H_B$ ) was estimated using a wooden stick, marked with colored tape at 50 cm intervals, standing next to the bush. Three bushes of every

size category and of every different species were randomly chosen for measurement. The amount of aboveground biomass of every bush was calculated using the following formula:

For *A. mellifera* and *A. nubica* (Hofstad 2005)

$$Y = 0,0548 \times (H_T + C_W + C_L)^{2,5767}$$

Where  $H_T$  is total height [m],  $C_W$  is crown width [m] and  $C_L$  is crown length [m].

For *Ocimum* ssp., *Lantana* ssp. and *Solanum* ssp. (Sah *et al.* 2004)

$$Y = 0,446 \times CA^{0,869} \times H_T^{1,112}$$

Where CA is Circle Area [m<sup>2</sup>] and  $H_T$  is total height [m].

The average of the different size categories and species was calculated and upscaled for the whole plot corresponding to the number of species.

### 5.2.6.3 Species composition

Five subplots along two diagonal lines were positioned in the main plot. Species composition was classified with the help of a local expert. Total ground cover [%] and abundance of every species [%] was estimated visually and recorded. The total number of species per plot was determined as a parameter to measure biodiversity.

### 5.2.6.4 Harvest of understorey vegetation

For this destructive method, three subplots of 1 m<sup>2</sup> were established in the plot along a diagonal line. All vegetation (mainly grasses, weeds and small shrubs) within the subplot was cut at ground level packed in oven proof labeled paper bags and oven-dried at 65°C until weight constancy (Picture 5). Subsequently, dry weight was recorded and averaged for the three subplots. Potential dry matter production per hectare was calculated with the following formula:

$$DM [g m^{-2}] \times 1000 = DM[kg ha^{-1}]$$



**Picture 5** Harvest of under storey vegetation, cutting and packing into oven proof paper bags

## 5.3 Laboratory Analysis

### 5.3.1 Organic carbon in the soil (belowground)

#### Loss-on-Ignition (LOI) Method

Loss-on-Ignition is a common and often applied method to estimate soil organic matter (SOM) content. During a burning process at 550°C, organic matter is oxidized to carbon dioxide (CO<sub>2</sub>) and ash (Heiri *et al.* 2001) which can be measured by the weight loss of the samples.

Soil samples were air dried, sieved (2 mm fraction) and then ball-milled for 3 minutes for a complete homogenization. 5 g of soil were weighed into ceramic crucibles with a mass balance (0.01 g). As most of the soils investigated were very clayey (> 40%) the samples were oven dried at 180°C for 12 hours, to remove the crystalline water captured between the clay particles (personal communication with Prof. Dr. K. Stahr). After drying, the crucibles with the soil were weighed again and the moisture loss was recorded. Then, the samples were put in a muffle furnace and heated up at 550°C for 4 hours (Kamau-Rewe *et al.* 2011). After burning in the muffle furnace, the samples were put in a desiccator to avoid further water enrichment while cooling down. Then the ash was weighed again and the weight loss was recorded.

The soil organic matter and resulting soil organic carbon content were calculated as follows:

$$\text{Soil organic matter (SOM) content [\%]} = \frac{(DW_{180} - DW_{550})}{DW_{180}} \times 100$$

$$\text{Soil organic carbon (SOC) content [\%]} = \text{SOM [\%]} \times 0.58$$

$$\text{Soil organic carbon stock (SOCS) [kg m}^{-2}\text{]} = \text{SOC [\%]} \times \text{BD} \times \text{soil depth [cm]}$$

(Batjes 1996; Heiri *et al.* 2001; Li *et al.* 2010)

#### Elemental Analyzer

To test results obtained from LOI and to proof measuring accuracy, some samples were measured with an elemental analyzer (vario macro EL, Hanau, Germany) for the determination of organic carbon.

Three plots of every vegetation type were selected according to their soil properties. Then, three out of ten auger points of these plots were randomly selected and the four depths were measured separately.

150 mg of soil per sample was weighed with an electric balance (Precisa 405M-200A) into tin capsules and burned in a combustion chamber at 950 °C. First, total carbon (TC) content [%] of the oven dried samples was measured. Second, the remaining inorganic carbon (IC) content of the same samples, which were pretreated by the loss-on-ignition method, was measured.

The soil organic carbon content in the samples was then calculated as follows:

$$C_{org} = (C_{org} + C_{anorg})_{180} - (C_{anorg})_{550}$$

### 5.3.2 Total carbon in aboveground vegetation

The total carbon content of the biomass of understorey vegetation has been measured using an elemental analyzer (vario macro EL, Hanau, Germany).

In each plot, three subplots (1 m<sup>2</sup>) were established. The aboveground biomass was cut at ground level and dried in paper bags at 65°C for two days until the dry weight was stable. After drying, the samples were homogenized using an electric grinder. A subsample of 10 g was ball-milled for three minutes. Similar to the measurement of organic C in the soil, 40 mg were weighed into tin capsules with an electric balance (Precisa 405M-200A), and burned in a combustion chamber at 950°C. The carbon and nitrogen content were measured in % and converted into the Carbon Stock [t C ha<sup>-1</sup>] using the formula below:

$$\frac{C[\%]}{sample[g]} = C[g]/1g$$

$$C[g] \times DW_{vegetation\ subplot}[g] = C[g\ m^{-2}] \times 1000 = C[t\ ha^{-1}]$$

### 5.3.3 Bulk density

To determine bulk density, soil samples were filled in oven proof paper bags and labeled with an ID number. The samples were then oven dried at 105°C for 48 hours until weight constancy. After cooling down in a desiccator, the samples were weighed again.

Soil bulk density [g m<sup>-3</sup>] was then calculated as shown in the formula below:

$$BD [g\ m^{-3}] = oven\ dried\ soil [g] / Volume\ of\ the\ soil [cm^3]$$

### 5.3.4 pH Measurement (after DIN 19684)

For the pH measurement 3 out of 10 augers were randomly selected and the 4 depths (0-10 cm, 10-30 cm, 30-60 cm and 60-100 cm) were measured separately, accounting for a total number of 12 measurements per plot and 240 for all 20 plots in different VTs.

5 g of air dried and sieved (2 mm) soil was mixed with 12.5 ml 0.01 M calcium chloride (CaCl<sub>2</sub>) – solution. The samples rested for 3 hours and were stirred every 30 min using a glass stirrer. Before measurement, the samples were stirred again. After coarse particles had settled

down, the pH-electrode was dipped into the supernatant. As soon as the pH value was constant ( $\geq 30$  s) it was noted at two decimal places.

Previous to every measurement, the pH-electrode has to be calibrated in the expected measurement range with two different calibration solutions.

### **5.3.5 Carbonate Content (after DIN ISO 10693)**

Soil carbonate content was analyzed using Scheibler method. 2 to 5 g sieved (2 mm) and oven-dried (105°C) soil samples were treated with 10% hydrochloric acid. Carbonates in the soil react with the acid and the resulting CO<sub>2</sub> can be measured.

With the following formula, the CaCO<sub>3</sub> content was calculated:

$$\% CaCO_3 = \frac{ml\ CO_2 \times mm\ Hg \times 0,1605}{(273 + t) \times E}$$

Where  $t$  is the ambient temperature [°C],  $E$  is the weight of the sample [g] and  $mm\ Hg$  is the air pressure [mm Hg].

## **5.4 Statistical analysis**

The statistical analysis was done with the statistical package SAS 9.3. A one-way ANOVA was operated using the “mixed” procedure, to test for fixed and random effects. The data was tested for normal distribution. If they were not normally distributed, they were transformed using logarithms. Outliers were eliminated to achieve normal distribution. Level of significance was set at  $p < 0.05$  and a t-test was applied to test for significant differences between the means.

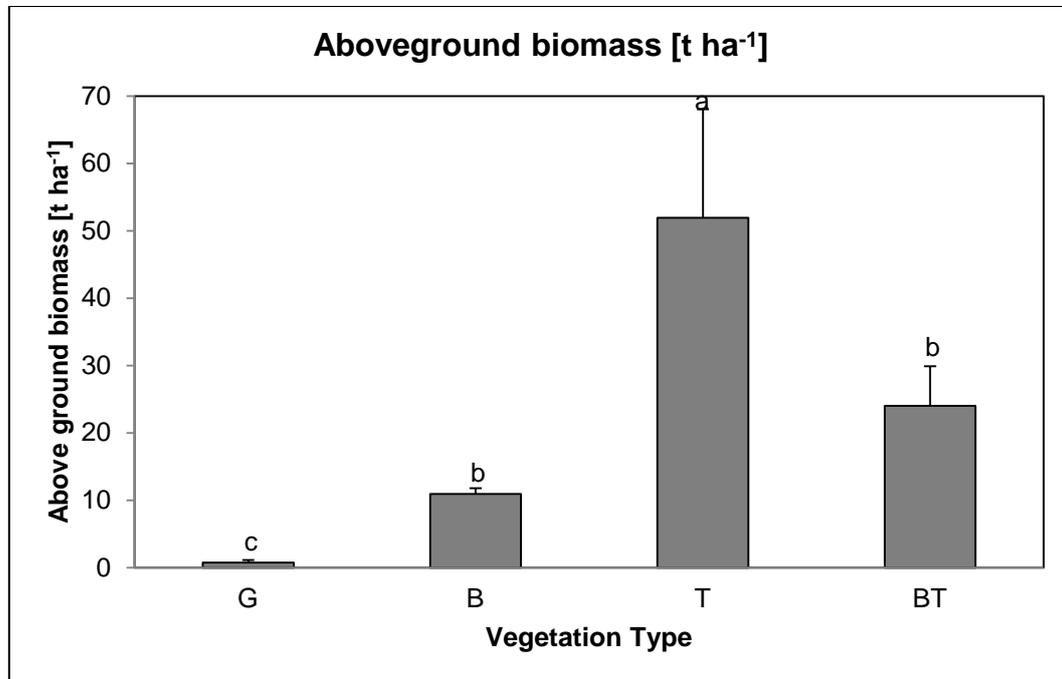
Graphs and diagrams were produced with the program Excel 2007.

In addition, a Cluster analysis was conducted using the program IBM SPSS Statistics 20. A hierarchical model using Ward-Model (Minimum variance method) and with Euclidian distance as similarity index, was applied.

Detailed data on SAS calculations are found in Appendix III.

## 6 RESULTS

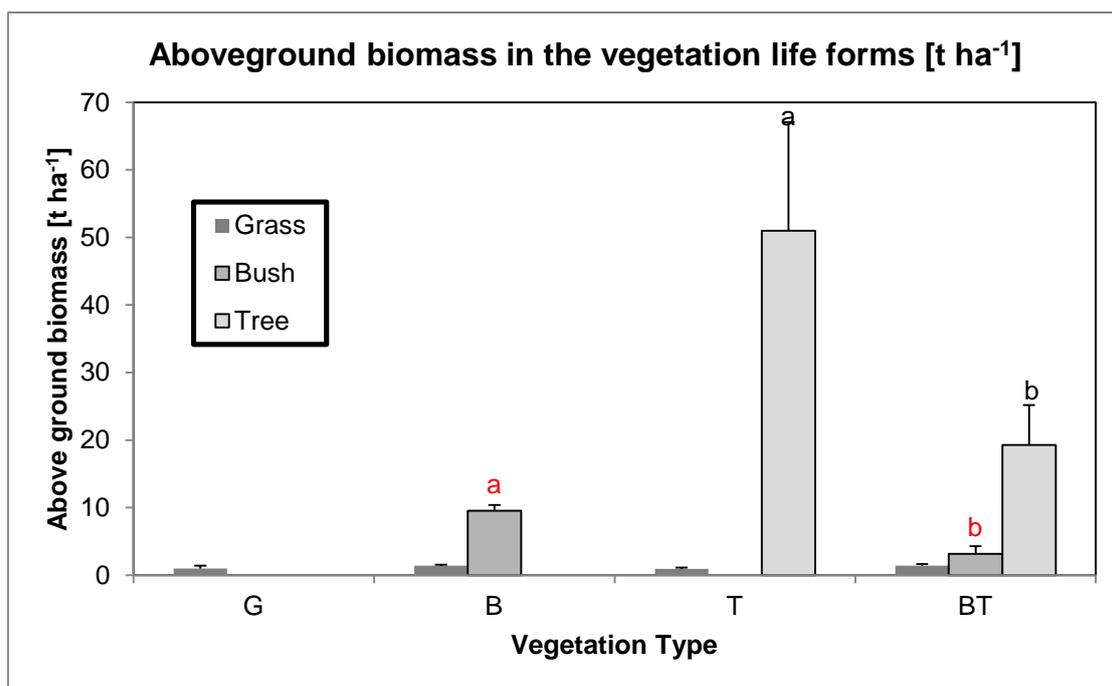
### 6.1 Aboveground biomass



**Figure 11** Aboveground biomass [t ha<sup>-1</sup>] in the different vegetation types. Means with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

Figure 11 shows the aboveground biomass (AGB) of the four different vegetation types (VTs). AGB was significantly different ( $p < 0.05$ ) between the VTs. The Tree savannah (T) had the highest AGB ( $51.9 \pm 16.1$  t ha<sup>-1</sup>), and was significantly different ( $p < 0.05$ ) from the other VTs. Between the Bush-Tree savannah (BT) and Bushland (B), there were no significant differences and an AGB of  $24.0 \pm 5.9$  t ha<sup>-1</sup> and  $10.9 \pm 0.9$  t ha<sup>-1</sup> was measured, respectively. The lowest AGB was measured in Grasslands (G) with  $0.8 \pm 0.4$  t ha<sup>-1</sup>, which was significantly different ( $p < 0.05$ ) to the other VTs.

AGB was further divided into the different life forms within the VTs. The Biomass Production of trees and bushes was dependent on the VT, as shown in Figure 12. The AGB of bushes ranged from  $3.15 \pm 1.13$  t ha<sup>-1</sup> in BT to  $9.55 \pm 0.85$  t ha<sup>-1</sup> in B. The amount of AGB in bushes was significantly higher ( $p < 0.05$ ) in B. Tree biomass was significantly higher in T compared to BT, ranging from  $19.27 \pm 5.9$  t ha<sup>-1</sup> in BT to  $50.98 \pm 16.09$  t ha<sup>-1</sup> in T. Grass production ranged from 0.96 to 1.40 t ha<sup>-1</sup> and showed no significant differences among the VTs.

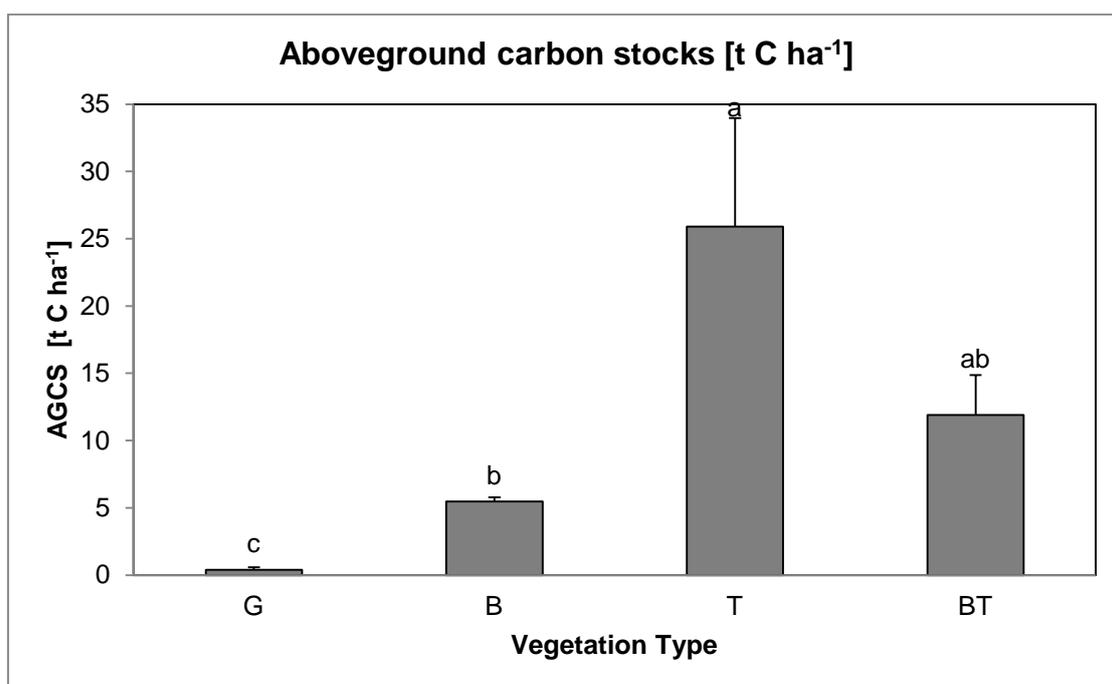


**Figure 12** Aboveground biomass [t ha<sup>-1</sup>] in different vegetation life forms within the four VTs. Means with different letters and the same color are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bush land, T = Tree savannah, BT = Bush-Tree savannah

## 6.2 Carbon stocks

### 6.2.1 Aboveground Carbon stocks

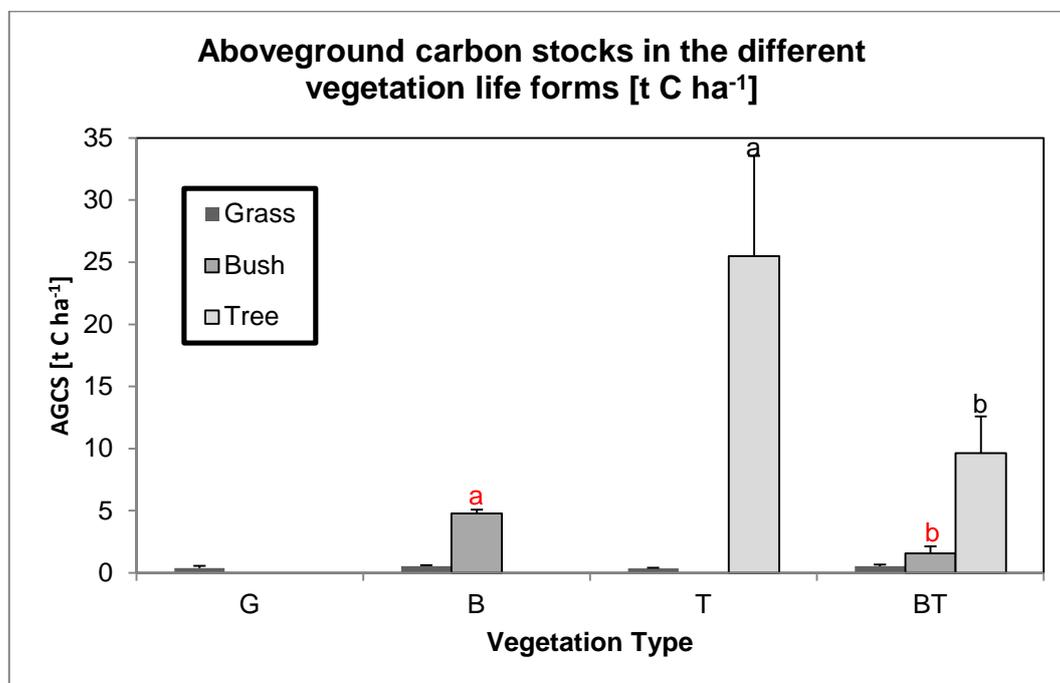
Mean aboveground carbon stocks [t C ha<sup>-1</sup>] of the different VTs are shown in Figure 13 (G,  $0.4 \pm 0.2$  t C ha<sup>-1</sup>; B,  $5.5 \pm 0.4$  t C ha<sup>-1</sup>; T,  $25.9 \pm 8.1$  t C ha<sup>-1</sup>; BT,  $11.9 \pm 2.9$  t C ha<sup>-1</sup>).



**Figure 13** Aboveground carbon stocks [t C ha<sup>-1</sup>] in the different vegetation types. Means with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

The aboveground carbon stocks (AGCS), stored in the vegetation, were different between the VTs in the order  $G < B < BT < T$ . T showed the highest AGCS. The AGCS of T were significantly higher ( $p < 0.05$ ) than those of B and G, but were not significantly different to BT. G and B also showed significant differences in AGCS ( $p < 0.05$ ). Between B and BT no significant differences were measured.

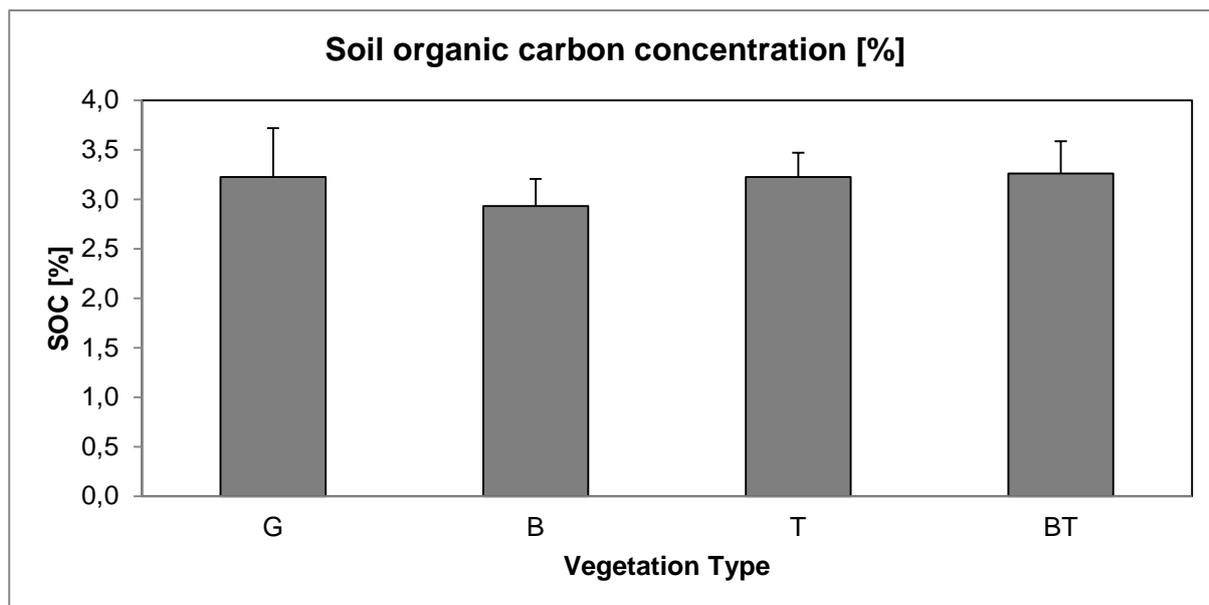
When looking at the different vegetation life forms (Figure 14), carbon allocation differed significantly among the VTs. Carbon accumulated in the bushes ranged from  $1.58 \pm 0.57 \text{ t C ha}^{-1}$  in BT to  $4.77 \pm 0.32 \text{ t C ha}^{-1}$  in B. The amount of C in trees was  $25.49 \pm 8.07 \text{ t C ha}^{-1}$  in T and  $9.63 \pm 2.97 \text{ t C ha}^{-1}$  in BT. Corresponding to the AGB (Figure 12), significantly more Carbon ( $p < 0.05$ ) was stored in bushes of B than BT, and significantly more in trees of the T compared to BT ( $p < 0.05$ ).



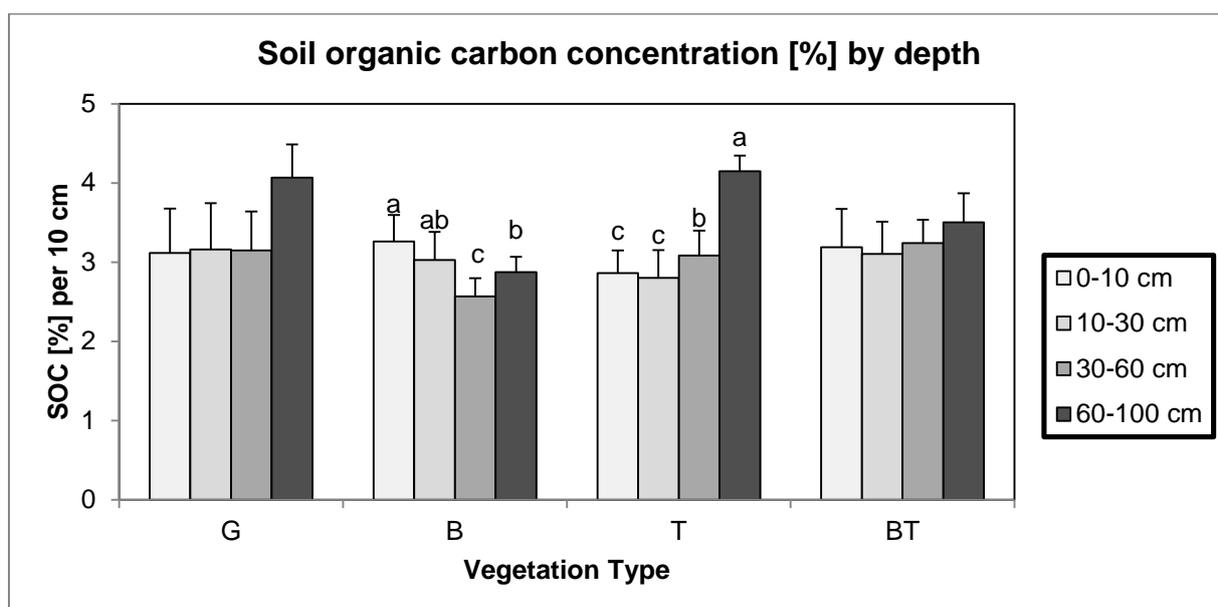
**Figure 14** Aboveground carbon stocks [ $\text{t C ha}^{-1}$ ] in the different vegetation life forms within the four vegetation types. Means with different letters and different colors are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

## 6.2.2 Belowground carbon stocks

Figure 15 shows the mean soil organic carbon (SOC) concentration in percent of the different VTs. SOC (%) ranged from  $2.93 \pm 0.27 \%$  in B, over  $3.22 \pm 0.49 \%$  and  $3.22 \pm 0.25 \%$  in G and T, to  $3.26 \pm 0.33 \%$  in BT. However, the difference in SOC [%] between the VT was not significant ( $p < 0.05$ ).



**Figure 15** Average soil organic carbon concentration [%] over 1m depth in the different vegetation types. Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah



**Figure 16** Soil organic carbon concentration [%] in four depths in the different vegetation types. Letters indicate significant differences between soil depths of 10 cm depth within the same vegetation type at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

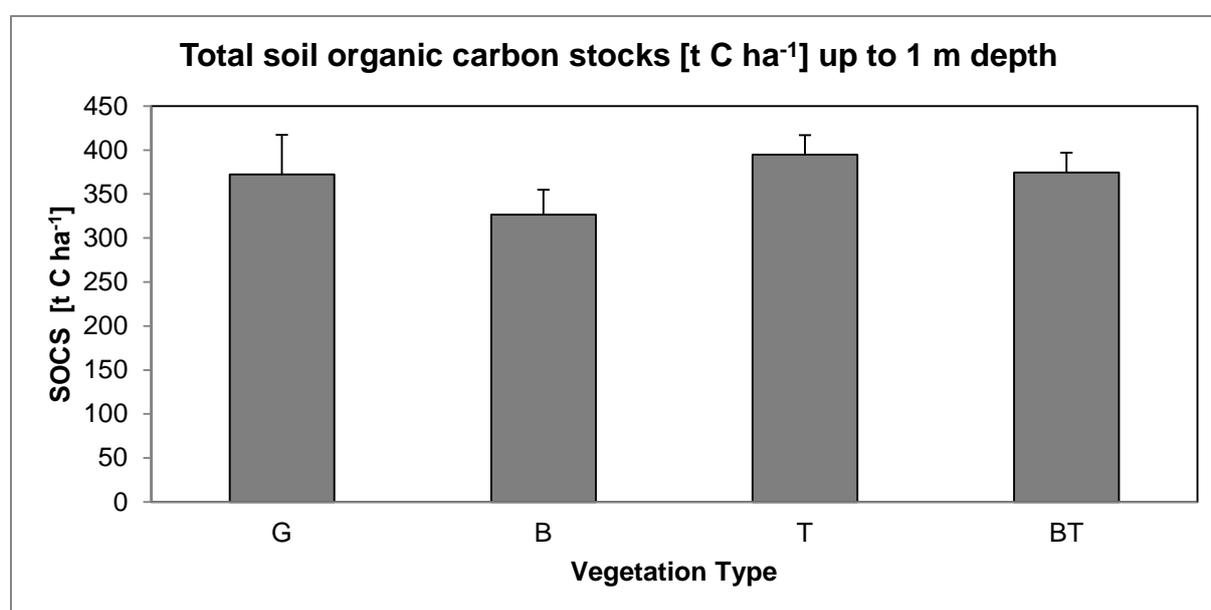
SOC concentration [%] varied between 2.57 % and 4.15 % across the VTs and different depths (Figure 16). VT had no significant influence on SOC concentration ( $p < 0.05$ ). Only soil depth showed significant differences within the VT of B and T. In B the two first soil layers (0-30 cm) and the layer 60-100 cm were significantly higher in SOC concentration ( $p < 0.05$ ) than the soil layer (30-60 cm). Nonetheless, the differences between the layer 10-30 cm and

60-100 cm were not significant ( $p < 0.05$ ). In T, SOC concentration increased significantly with increasing soil depth. SOC concentration in the topsoil (0-30 cm) was significantly lower ( $p < 0.05$ ) than the following layers and the concentration in layer 30-60 cm was significantly lower ( $p < 0.05$ ) than the one in the deeper soil layer (60-100 cm).

Across the VTs, the first 60 cm showed no significant changes in SOC concentration ( $p < 0.05$ ). As shown in Table 1, the SOC concentration of the subsoil were significantly higher ( $p < 0.05$ ) compared to the other layers.

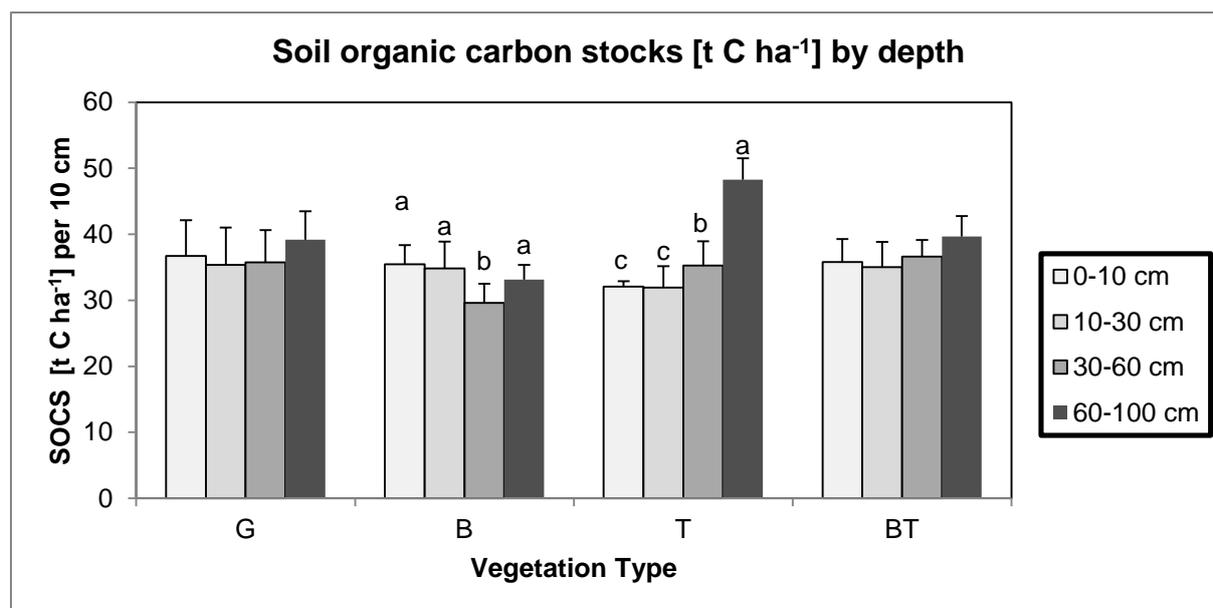
**Table 1** Soil organic carbon concentration [%] in the four different depths. Means with different letters are significant different

Trait	Treatment	Depth	Lsmean transf.	Std error transf.	Significance ( $p < 0.05$ )
SOC	Depth	0 -10 cm	1.072	0.07361	b
		10-30 cm	1.041	0.07361	b
		30-60 cm	1.040	0.07363	b
		60-100 cm	1.133	0.07415	a



**Figure 17** Total soil organic carbon stocks [t C ha<sup>-1</sup>] up to 1m depth in the different vegetation types. Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

In terms of total soil organic carbon stocks (SOCS) [t C ha<sup>-1</sup>] up to one meter depth, no significant differences ( $p < 0.05$ ) were observed between the VTs. The amounts of carbon stored in the soil in the first meter varied between  $326.4 \pm 28.6$  t C ha<sup>-1</sup> in B,  $372.3 \pm 44.8$  t C ha<sup>-1</sup> in G,  $374.4 \pm 22.5$  t C ha<sup>-1</sup> in BT and  $394.9 \pm 22.0$  t C ha<sup>-1</sup> in T (Figure 17).



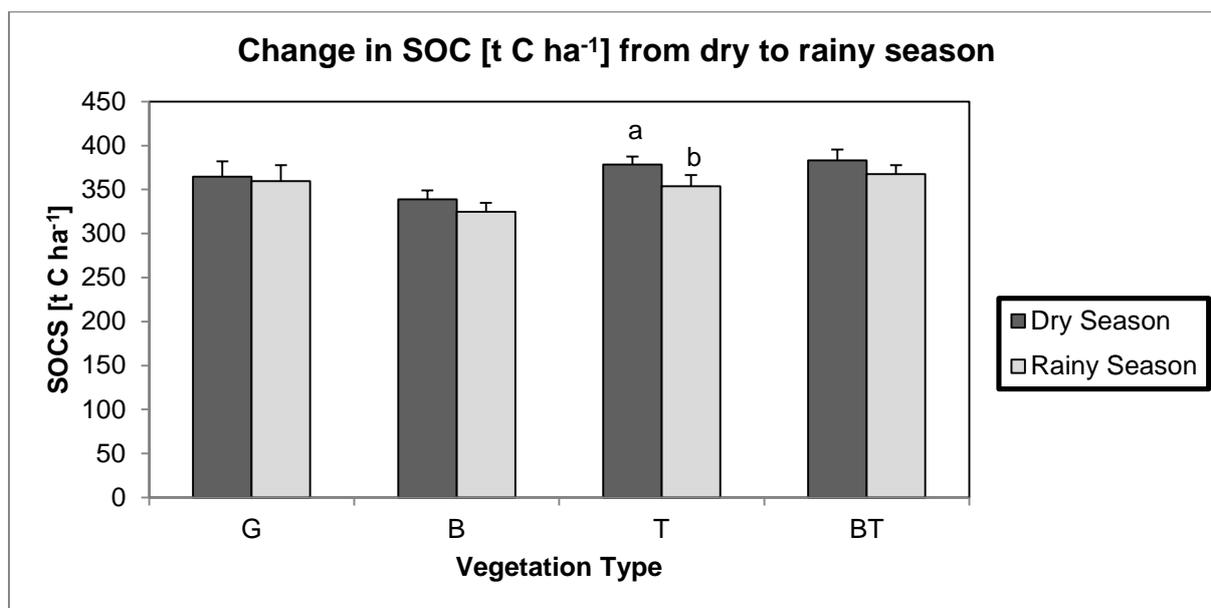
**Figure 18** Soil organic carbon stocks [t C ha<sup>-1</sup>] in four depths in the different vegetation types. Means of depths within the same vegetation type with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

Within the VTs, SOCS [t C ha<sup>-1</sup>] varied on average from 29.60 t/ha to 48.27 t/ha in the different soil layers per 10 cm depth (Figure 18). There were no significant differences between the different VTs ( $p < 0.05$ ). Within B and T the significant differences occurred between the different soil layers. In B there were no significant differences in the first 30 cm. SOC stocks of the soil layer 30-60 cm were significantly lower than the soil layers 0-10 cm, 10-30 cm and 60-100 cm. However, there were no significant differences ( $p < 0.05$ ) between the first 30 cm and the deeper soil layers (>60 cm). In T, again there were no significant differences between the first and the second soil layer. In contrast to B, SOCS were significantly higher in the soil layer 30-60 cm and in the deepest layer (60-100 cm) compared to the first two layers. Across the VTs, there were no significant differences within the first 60 cm. The amount of SOC (t/ha) in the soil layer from 60-100 cm was significantly higher ( $p < 0.05$ ) compared to all layers above (Table 2).

**Table 2** Soil organic carbon stocks [t C ha<sup>-1</sup>] in the four different depths. Means with different letters are significantly different.

Trait	Treatment	Depth	Lsmean	Std error	Significance ( $p < 0.05$ )
SOC	Depth	0 -10 cm	35.297	1.9019	b
		10-30 cm	34.107	1.9028	b
		30-60 cm	34.214	1.9028	b
		60-100 cm	37.322	1.9257	a

### 6.2.3 Seasonal changes in SOC stocks

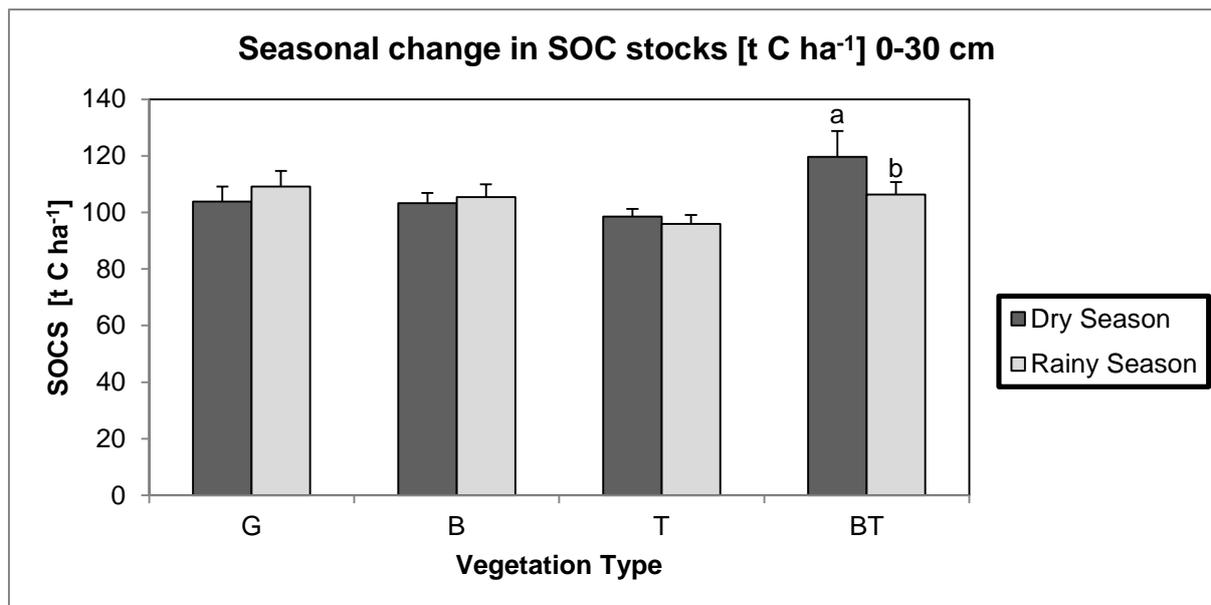


**Figure 19** Seasonal change in SOC accumulation [t C ha<sup>-1</sup>] from dry season to rainy season. Means with different letters within the same vegetation type are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

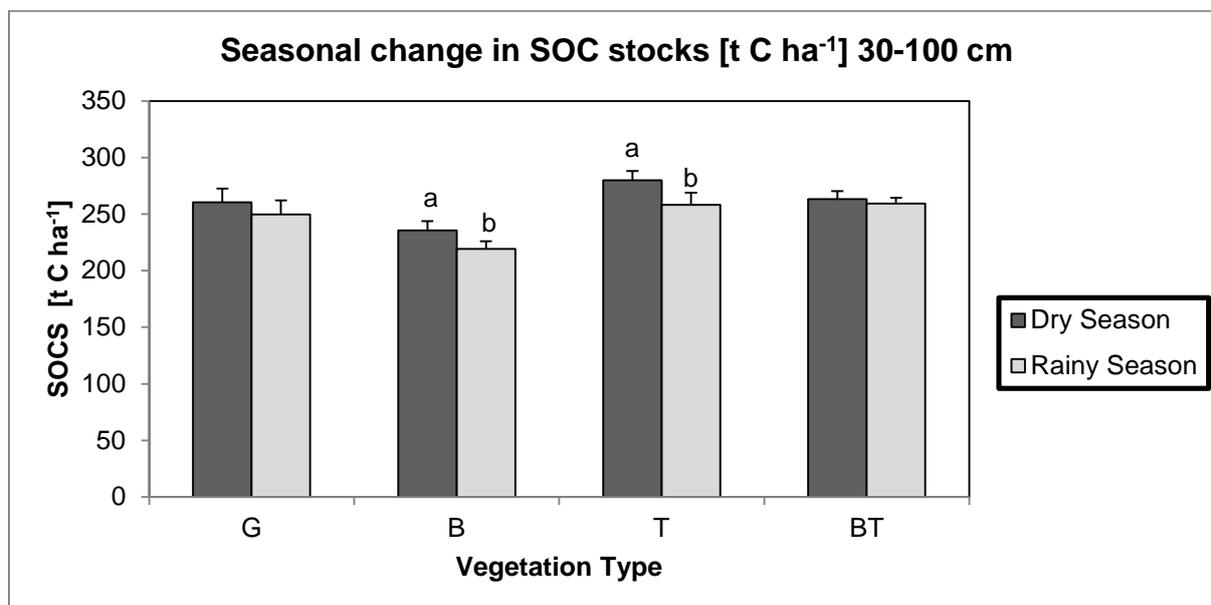
Figure 19 shows the changes in SOCS from dry season to rainy season. On average, SOCS in one meter depth ranged from 339 to 383 t ha<sup>-1</sup> in the dry season, while SOCS in the rainy season ranged from 325 to 367 t C ha<sup>-1</sup>. Between the VTs, season had no significant influence ( $p < 0.05$ ) on the carbon stored in the soil. Within the VTs, only in T significantly less SOC was stored in the soil in the rainy season compared to the dry season.

Figure 20 and Figure 21 show the SOCS [t C ha<sup>-1</sup>] in two different depths (0-30cm and 30-100cm, respectively). In the upper soil layer SOCS from 99-120 t C ha<sup>-1</sup> in the dry season, and 96-109 t C ha<sup>-1</sup> in the rainy season, were allocated. In deeper soil layers the SOCS ranged from 236 to 280 t C ha<sup>-1</sup> in the dry season and from 219 to 259 t C ha<sup>-1</sup> in the rainy season.

Between the VTs no significant differences occurred in any depth. However, when looking at the single VT, in the soil layer 0-30cm, significantly less ( $p < 0.05$ ) carbon was accumulated in BT in the dry season than in the rainy season. Soil layer 30-100 cm showed significant differences ( $p < 0.05$ ) between the seasons in B and T, where SOCS decreased from dry to rainy season.



**Figure 20** Seasonal change in SOCS [t C ha<sup>-1</sup>] from dry season to rainy season in the soil layer 0-30 cm. Means with different letters within the same vegetation type are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah



**Figure 21** Seasonal change in SOC stocks [t C ha<sup>-1</sup>] from dry season to rainy season in the soil layer 30-100 cm. Means with different letters within the same VT are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

### 6.3 Species composition

A total of 72 species were identified in the research area, of which 28 were grass species and belonged to the family of *Poaceae*. 44 species were herbaceous species and belonged to 22 different families. Trees and bushes identified in the area were *Acacia* species counting to the family of *Mimosaceae*. Further, dominant shrubs were *Grewia bicolor*, *Grewia villosa*, *Lantana rhodesensis*, *Solanum somarense* and *Ocimum lamiifolium* (Table 3).

**Table 3** Habitus, Family and Distribution of species of the research area of the Borana Plateau, Ethiopia

Species	Habitus <sup>2</sup>	Family	Vegetation type <sup>3</sup> and Distribution <sup>1</sup>			
			G	B	T	BT
<i>Aristida adscensionis</i> L.	a	Poaceae	+			
<i>Cenchrus ciliaris</i> L.	p	Poaceae	C	P	D	P
<i>Cynodon dactylon</i> L.	p	Poaceae	P		P	P
<i>Chrysopgon plumulosus</i> (L.) Pers.	p	Poaceae	P	C	C	P
<i>Chloris roxburghiana</i> Schult.	p	Poaceae		P		
<i>Chloris virgata</i> sw.	a	Poaceae				
<i>Panicum coloratum</i> L.	p	Poaceae	P	+	P	P
<i>Eragrostis papposa</i> Ruem & Schult. Steud	p	Poaceae	P	+	C	C
<i>Eragrostis cilianensis</i> (All.) Lutati	a	Poaceae	+	P	P	P
<i>Enneapogon cenchroides</i> Ruem & Schult. C.E. Hubbard	a	Poaceae				
<i>Leptothrium senegarense</i> (Kuth.)	p	Poaceae				+
<i>Microchloa kunthii</i> esv.	a	Poaceae	C		+	+
<i>Sporobulus pyramidalis</i> P. Beauv.	a	Poaceae	C	C	C	C
<i>Sporobulus festivus</i> A. Rich.	a	Poaceae	P		P	
<i>Setaria varticillata</i> (L.) P. Beauv.	a	Poaceae		P	P	C
<i>Tragus berteronianus</i> Schult.	a	Poaceae		P		+
<i>Tragus heptaneuron</i> Clayton	a	Poaceae				
<i>Brachiaria humidicola</i> (Rendle) Schweick.	a	Poaceae	P	+	C	C
<i>Brachiaria eruciformis</i>	a	Poaceae				
<i>Pennisetum mezianum</i> (Vahl.) Lanza Mattei	p	Poaceae	D	D	P	D
<i>Pennisetum stramineum</i> Pete V.	p	Poaceae		P	P	P
<i>Commelina latifolia</i> A. Rich	a	Poaceae	C	C	P	C
<i>Commelina subulata</i> Rott.	a	Poaceae		P		P
<i>Bothrichloa radicans</i> A. Camus.	p	Poaceae		+		+
<i>Digitaria velutina</i> Forssk. P. Beauv.	a	Poaceae			+	
<i>Tetrapogon cenchriformis</i> (A. Rich) W.D. Clayton	p	Poaceae		+		
<i>Lintonia nutans</i> , stapf.	p	Poaceae	+	P	P	P
<i>Dactyloctenium aegypticum</i> (L.) Pers	a	Poaceae	+	P	+	P
<i>Sida ovata</i> Forssk.	a	Malvaceae	+	+	P	P
<i>Becium verticillifolium</i> beke cufed.	p	Lamiaceae		+	+	P
<i>Ocimum basilicum</i> L.	a	Lamiaceae	P	P	+	
<i>Ocimum lamiifolium</i> Hocht.ex Benth.	p	Lamiaceae		C		D

<i>Portulaca oleracea</i> L.	a	Portulacaceae	P	+	P	+
<i>Bidens pilosa</i> L.	a	Compositae		+	+	
<i>Launaea cornuta</i> (Hochst. ex. Oliv. & Hiern.) C. Jeffrey	a	Nyctalinaceae	+		P	P
<i>Boerhaavia erecta</i> L.	a	Compositae		+	+	P
<i>Amaranthus graecizams</i> L.	a	Amaranthaceae	P		P	P
<i>Plantago lanceolata</i> L.	p	Plantaginaceae				+
<i>Erucastrum arabicum</i> Fisch & Mey.	a	Compositae	C	P	C	C
<i>Anthemis tigreensis</i> A. Rich	a	Compositae		+		+
<i>Crotalaria incana</i> L.	a	Fabaceae	P	P	P	
<i>Crotalaria agatiflora</i> subsp. <i>engleri</i> (Baker f.) Polhill	a	Fabaceae		C		+
<i>Indigofera spinosa</i> Forssk.	p	Fabaceae	C		P	+
<i>Indigofera volkensii</i> Taub.	p	Fabaceae				
<i>Helichrysum glumaceum</i> D.C.	a	Asteraceae		C	P	P
<i>Dyschoriste hildebrandtii</i> (S.Moore)	p	Acanthaceae	P	P	+	C
<i>Achyranthes apera</i> L.	a	Amaranthaceae		P		P
<i>Kyllinga bulbosa</i> P. Beauv.	a	Cyperaceae	P	+	+	+
<i>Cyperus amauropus</i> Steud.	p	Cyperaceae	P	+		+
<i>Heliantropium cinrascens</i> D.C.	a	Boraginaceae				
<i>Tribulus terrestris</i> L.	p	Zygophyllaceae				
<i>Oxygonum sinuatum</i> (Meisner) Dammer	a	Zygophyllaceae	P	+	+	+
<i>Psydrax schimperiana</i> (A.Rich)	a	Rubiaceae	+	P	C	
<i>Chenopodium opulifolium</i> Koch.	a	Chenopodiaceae				+
<i>Acacia mellifera</i> Vahl Benth.	p	Mimosaceae		D		C
<i>Acacia nubica</i> Benth.	p	Mimosaceae				C
<i>Grewia bicolor</i> Juss.	p	Tiliaceae				P
<i>Grewia villosa</i> Willd.	p	Tiliaceae				P
<i>Lantana rhodesensis</i> Moldenke.	p	Verbenaceae		P		D
<i>Solanum incanum</i> L.	p	Solanaceae	P	P	P	P
<i>Solanum giganteum</i> Jacq.	p	Solanaceae				
<i>Vernonia cinerascens</i> Schultz Bip.	p	Asteraceae				
<i>Solanum somarense</i> Franchet	p	Solanaceae		C	C	D
<i>Acacia seyal</i> Del.	p	Mimosaceae		P		
<i>Acacia tortilis</i> (Forssk.) Hay.	p	Mimosaceae			D	C
<i>Acacia nilotica</i> (L.) Del. Var. <i>Nilotica</i>	p	Mimosaceae			D	C
<i>Acacia drepanolobium</i> Harms.	p	Mimosaceae		D	C	P
<i>Acacia bussei</i> Harms. ex. Sjöstedt.	p	Mimosaceae		D		D
<i>Balanites aegyptiaca</i> (L.) Del.	p	Balanitaceae				
<i>Ipomoea marmorata</i> Britt & Rendle	p	Convolvulaceae		+		
<i>Euphorbia nubica</i> n. Br.	p	Euphorbiaceae	P		P	P
<i>Artemisia annua</i> L.	a	Asteraceae	+	+	+	P

<sup>1</sup>D = dominant (> 15%), C = common (> 5-15%), P = present (< 5%), + = present, but ≤ 1% (Tefera *et al.* 2007a, modified)

<sup>2</sup>a = annual, p = perennial

<sup>3</sup>G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

**Table 4** Most common species and their frequency of occurrence [%] in the different vegetation types (Tefera *et al.* 2007a, modified)

Species	Vegetation type <sup>1</sup>			
	G	B	T	BT
<i>Brachiaria humidicola</i>	1.57	0.51	4.95	6.58
<i>Cenchrus ciliaris</i>	8.53 <sup>a,b</sup>	3.67 <sup>a,b</sup>	16.39 <sup>a</sup>	2.44 <sup>b</sup>
<i>Chrysopgon plumulosus</i>	1.55	4.11	5.02	3.98
<i>Commelina latifolia</i>	6.94 <sup>a,b</sup>	4.17 <sup>a</sup>	2.62 <sup>b</sup>	5.24 <sup>a</sup>
<i>Eragrostis cilianensis</i>	0.35	1.72	1.62	2.14
<i>Eragrostis papposa</i>	3.54 <sup>a,b</sup>	0.12 <sup>b</sup>	4.68 <sup>a</sup>	5.88 <sup>a</sup>
<i>Erucastrum arabicum</i>	2.63	4.13	7.19	5.21
<i>Lintonia nutans</i>	0.74 <sup>b</sup>	2.11 <sup>a</sup>	1.52 <sup>b</sup>	3.98 <sup>a</sup>
<i>Panicum coloratum</i>	1.69	0.68	1.54	2.04
<i>Pennisetum mezianum</i>	26.87 <sup>a</sup>	31.38 <sup>a</sup>	2.00 <sup>b</sup>	19.06 <sup>a</sup>
<i>Portulaca oleracea</i>	2.91 <sup>a</sup>	0.24 <sup>b</sup>	2.20 <sup>a</sup>	0.25 <sup>b</sup>
<i>Solanum incanum</i>	1.36	0.87	1.46	2.67
<i>Sporobulus pyramidlis</i>	10.56 <sup>a,b</sup>	8.61 <sup>a</sup>	10.19 <sup>a,b</sup>	5.30 <sup>b</sup>

<sup>1</sup>G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

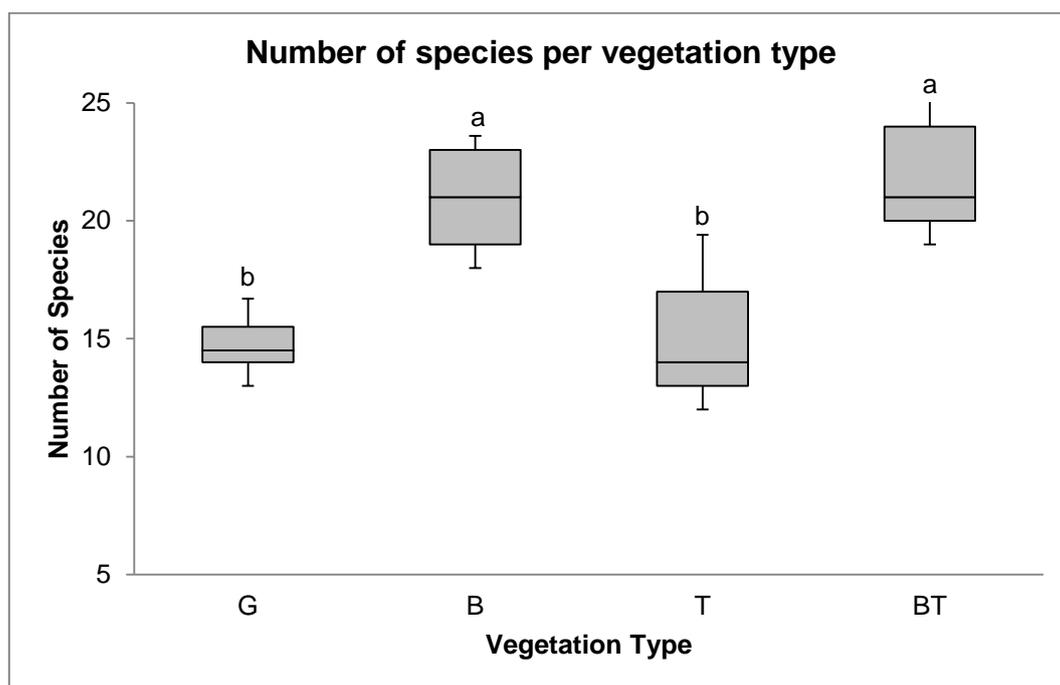
Means in the same row with different superscript letters are significantly different ( $p < 0.05$ )

The most common species and their average frequency of occurrence in the different VTs are presented in Table 4.

In this context, common species are defined as species which are present in every VT with a frequency of occurrence of at least 1%. Of the total species identified, 13 species were classified as commonly distributed over the four VTs. Of these, 6 species were annuals (*Brachiaria humidicola*, *Commelina latifolia*, *Eragrostis cilianensis*, *Erucastrum arabicum*, *Portulaca oleracea* and *Sporobulus pyramidlis*). *B. humidicola*, *E. cilianensis* and *E. arabicum* showed no significant differences ( $p < 0.05$ ) in their frequency of occurrence among the VTs. Frequency of *C. latifolia* in B and BT was significantly different to T. The proportion was highest in G but no significant difference was evident compared to the other VTs. The percentage of *P. oleracea* was significantly higher ( $p < 0.05$ ) in G and T in relation to B and BT. Coverage of *S. pyramidlis* was nearly the same in G and T. The occurrence in BT was significantly lower ( $p < 0.05$ ) than in B.

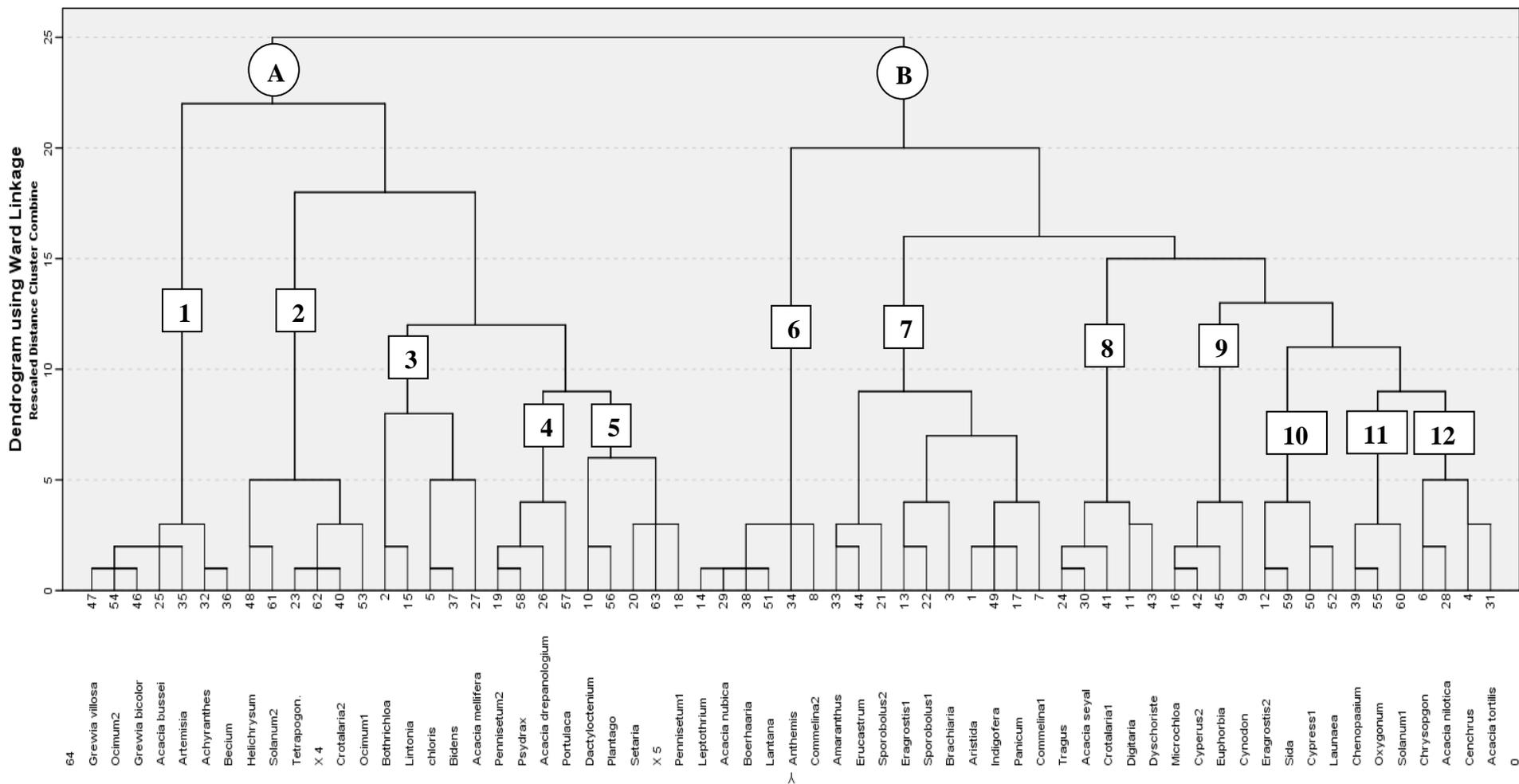
Further, commonly distributed perennial species comprised *Cenchrus ciliaris*, *Chrysopgon plumulosus*, *Eragrostis papposa*, *Lintonia nutans*, *Panicum coloratum*, *Pennisetum mezianum* and *Solanum incanum*. For *C. plumulosus*, *P. coloratum* and *S. incanum* there was no

evidence of significant differences between the VTs ( $p < 0.05$ ). *C. ciliaris* and *P. mezianum* had on average the highest frequency of occurrence. Although, the amount of *Cenchrus ciliaris* in T was almost twice as high as in G and four times higher than in B, there were no significant differences ( $p < 0.05$ ). The proportion of *P. mezianum* was the lowest in T (2%) and covered  $\geq 19\%$  in G, B and BT. *E. papposa* obtained a very low percentage in B ( $< 1\%$ ), what was significantly lower ( $p < 0.05$ ) compared to the occurrence in T and BT. *L. nutans* was significantly more prevalent ( $p < 0.05$ ) in G and T, than in B and BT.



**Figure 22** Distribution of the number of species in the different vegetation types. Solid line, boxes and whiskers indicated the median, second and third quartiles and first and fourth quartiles, respectively. Means with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

The number of species identified was significantly dependent on VT. On average, 15 species were counted in G and T, 21 species in B and 22 in BT (Figure 22). However, Tree savannah showed high variations and up to 21 species per plot could be found. Nevertheless the number of species in B and BT was significantly higher ( $p < 0.05$ ) compared to G and T.



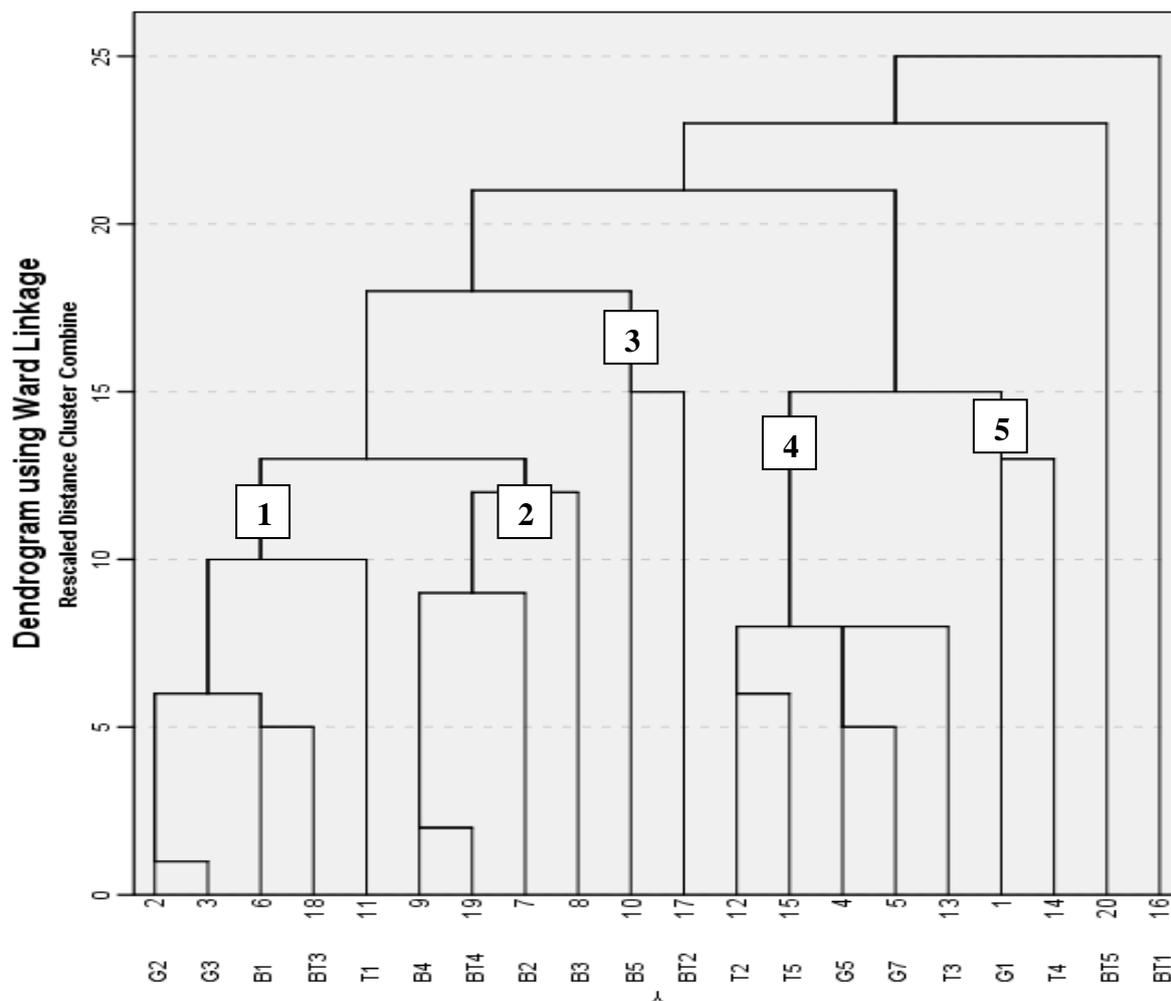
**Figure 23** Dendrogramm of the Cluster analysis of the sampled species; distance parameter = Euclidian distance; Ward linkage method. Species names are acronyms (Appendix IV); A, B = main clusters; 1-5, 6-12 subdivided clusters of the main clusters.

The dendrogram of the Cluster Analysis of the different species and their abundance within the four VTs is shown in Figure 23. There is an obvious partitioning into two main clusters. Cluster A comprises species, which were mainly observed in B and BT, and which were not or just to a small amount found in G and T. Cluster B includes most of the common species (Table 4), species that are more or less evenly distributed across the VTs, and those which are totally absent in one of the VTs. On the vertical axis of the dendrogram, the dissimilarity index in percent is displayed, calculated by the Euclidian distance values. Cluster A is built at a dissimilarity index of 23% and Cluster B is built at a dissimilarity index of 20%. Cluster A can be further divided into five sub-clusters. Cluster 1 reflects species communities that were uniquely or with a high abundance found in the first repetition of BT (BT1). Cluster 2 and 3 include species with a high frequency, especially in Bush land plots. Cluster 4 and 5 represent those species communities on soils with a good water-holding capacity or species often associated with *Acacia drepanolobium*.

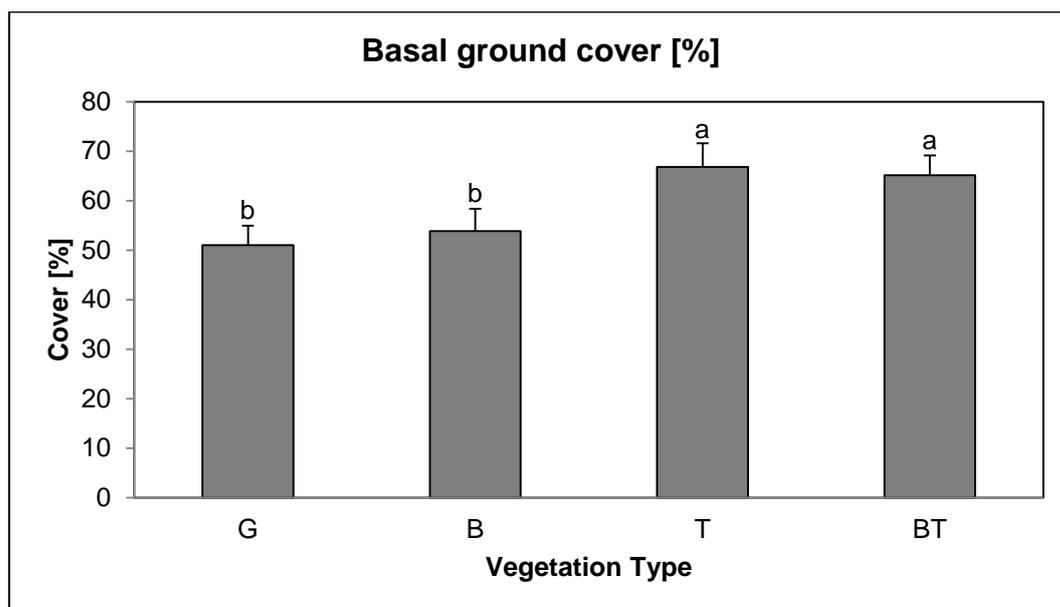
Cluster B also shows the separation into several sub-clusters. Cluster 6 comprises species which are not observed in grassland plots and only with low frequency in tree savannah plots, and which have mainly a shrubby vegetation life form. Cluster 7 consists of half of the most common species presented in Table 4 which occur in communities that are associated with grassland and tree savannah plot. Species in Cluster 9 and 10 are totally absent or of minor importance in bush land plots. Cluster 12 represents a typical tree savannah Vegetation type with *Acacia nilotica* and *Acacia tortilis* being the dominant tree species and *Cenchrus ciliaris* and *Chrysopogon plumulosus* as dominant species in the grass layer.

The dendrogram of the Cluster Analysis of the different sampled plots is displayed in Figure 24. According to the analysis five main sub clusters are built. Cluster 1 comprising of G2, G3, B1, BT3, T1; Cluster 2 comprising B4, BT4, B2; B3; Cluster 3 includes B5 and BT2; Cluster 4 consists of T2, T5, G5, G7, T3 and Cluster 5 of G1 and T4. The plots BT5 and BT1 stand alone and cannot be matched with any other group.

Cluster 1 and 4 reflect those plots which are grouped together due to their soil types, which results in similar species composition. In Cluster 1, all plots on calcic Vertisols are grouped together and in Cluster 4 plots on Cambisols (chromic/calcaric) of the same area group together. Cluster 2 is composed of plots that have the same soil type as Cluster 4 but there are differences in their species composition. Cluster 3 and 5 respectively include only two plots. However, due to their soil types and species composition, they are relatively similar.



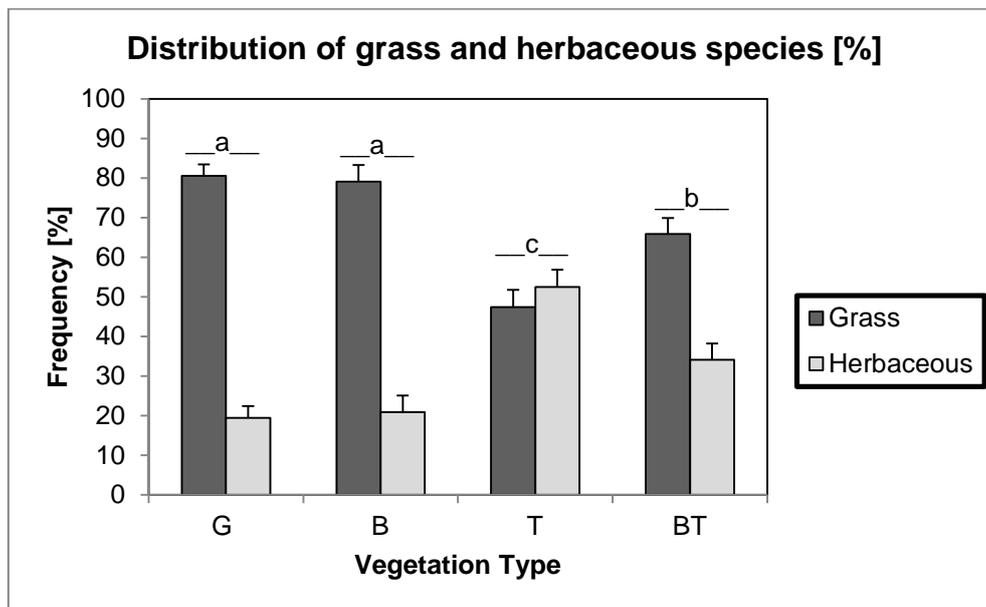
**Figure 24** Dendrogram of the Cluster Analysis of the sampled plots; distance parameter = Euclidian distance; Ward linkage method. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush Tree savannah; 1-5 = main clusters



**Figure 25** Basal ground cover [%] of the different vegetation types. Means with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

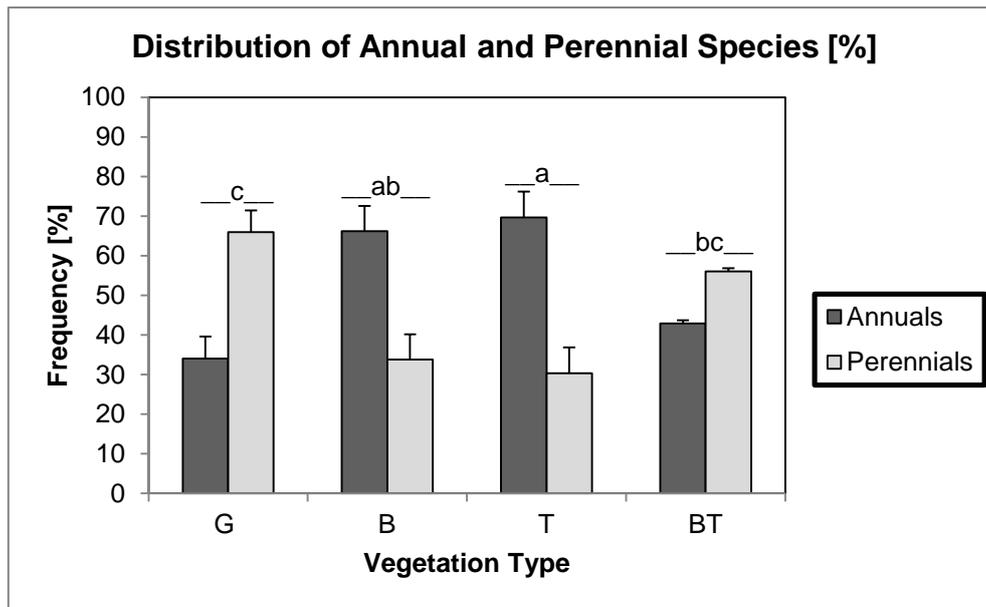
The means of the ground cover [%] of the grass and herbaceous layer in the different VTs are shown in Figure 25 (G,  $51 \pm 2.4$  %; B,  $54 \pm 4.1$  %; T,  $67 \pm 3.0$  %; BT,  $65 \pm 3.2$  %). VT had a significant influence on soil cover. In G and B significantly less soil was covered ( $p < 0.05$ ) compared to T and BT.

Ground cover has been further investigated concerning the composition of grass and herbaceous species as well as the composition of annual and perennial species in the respective VT (Figure 26 and Figure 27).



**Figure 26** Species composition [%] of grass and herbaceous species in the different vegetation types, based on frequency of occurrence. Means with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

VT significantly changed the distribution of grass and herbaceous species (Figure 26). Between G and B there was only little variance and no significant difference. On average, G was covered with  $80.5 \pm 2.9$  % grass species and  $19.5 \pm 2.9$  % herbaceous species. B was covered with  $79.1 \pm 4.2$  % and  $20.9 \pm 4.2$  % of grass and herbaceous species, respectively. T and BT had higher amounts of herbaceous species ( $52.5 \pm 4.4$  % and  $34.1 \pm 4.1$  %, respectively) and were significantly different to G and B as well as to each other. In T,  $47.5 \pm 4.4$  % of identified species were grasses. This was significantly less than in all other VTs. The amount of grass species in BT was  $65.9 \pm 4.1$  %, and significantly different to G, B and T.



**Figure 27** Species composition [%] of annual and perennial species in the different vegetation types, based on frequency of occurrence. Means with different letters are significantly different at  $p < 0.05$ . Bars represent the standard error of the mean. G = Grassland, B = Bushland, T = Tree savannah, BT = Bush-Tree savannah

Figure 27 indicates that the composition of annual and perennial species also showed differences among the VTs. The percentage of annual species was higher in B and T, while in T and BT perennial species were dominating. On average, annuals in G covered  $34.1 \pm 5.5$  %, and were significantly less than in B ( $66.2 \pm 6.4$  %) and T ( $69.7 \pm 6.5$  %), but there were no significant differences compared to BT ( $42.9 \pm 0.8$  %).

The coverage of perennial species was lowest in T ( $30.3 \pm 6.5$  %) and significantly different to G ( $65.9 \pm 5.5$  %) and BT ( $56.1 \pm 0.8$  %). Further, perennial species were significantly less in B ( $33.8 \pm 6.4$  %) than in G.

Biomass of trees was divided into the different species. On average, biomass of *Acacia drepanolobium* was  $48.4 \text{ kg tree}^{-1}$ , and biomass of *A. tortilis*, *A. nilotica* and *A. bussei* was  $309.5 \text{ kg tree}^{-1}$ ,  $407.2 \text{ kg tree}^{-1}$  and  $332.6 \text{ kg tree}^{-1}$ , respectively. Table 5 illustrates that there were no significant differences ( $p < 0.05$ ) between the biomass of *Acacia bussei*, *A. nilotica* and *A. totilis*. However, biomass of *A. drepanolobium* was significantly ( $p < 0.05$ ) less compared to the other species.

**Table 5** Aboveground biomass [kg tree<sup>-1</sup>] of the different tree species. Means with different letters are significantly different.

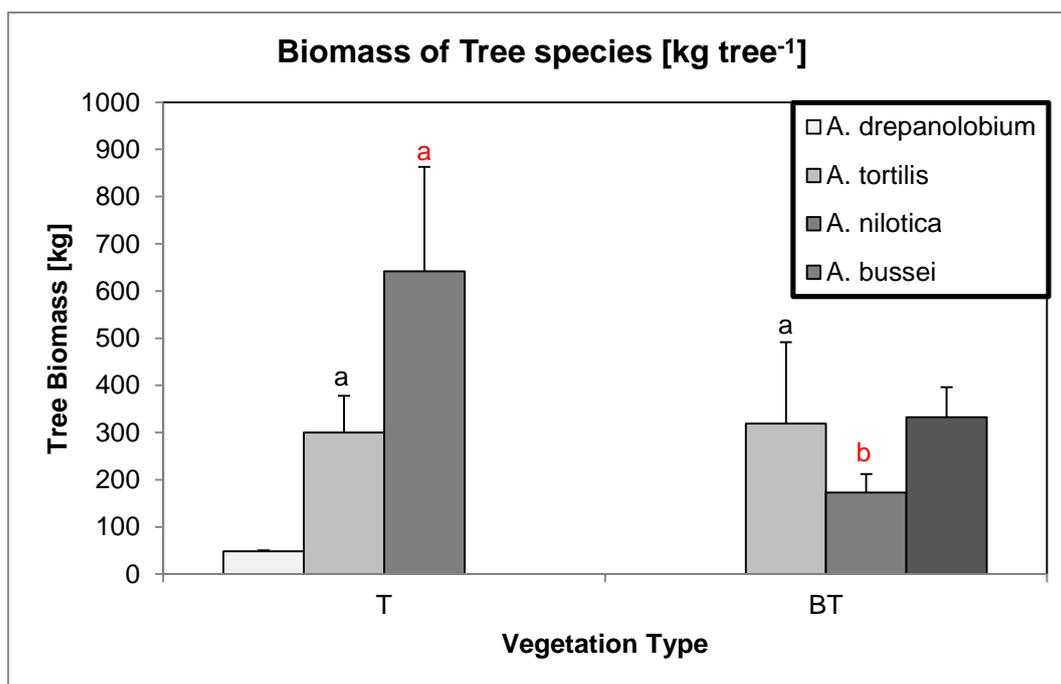
Trait	Treatment	Species	AGB (kg tree <sup>-1</sup> )	Lsmean transf.	Std error transf.	Significance (p<0.05)
Biomass	Species	<i>A. bussei</i>	309.5	5.618	0.2028	a
		<i>A. drepanolobium</i>	48.4	3.863	0.1723	b
		<i>A. nilotica</i>	407.2	5.599	0.2134	a
		<i>A. tortilis</i>	332.6	5.348	0.2073	a

Further, biomass of tree species was subdivided into the two VTs, T and BT. *A. drepanolobium*, as a tree form, only occurred in T, while *A. bussei* was restricted to BT (Figure 28). Biomass of *A. tortilis* was  $300.1 \pm 78.0$  kg tree<sup>-1</sup> in T and  $318.9 \pm 172.8$  kg tree<sup>-1</sup> in BT. For *A. nilotica*, a biomass of  $641.5 \pm 221.4$  kg tree<sup>-1</sup> was measured in T compared to  $172. \pm 39.2$  kg tree<sup>-1</sup> in BT.

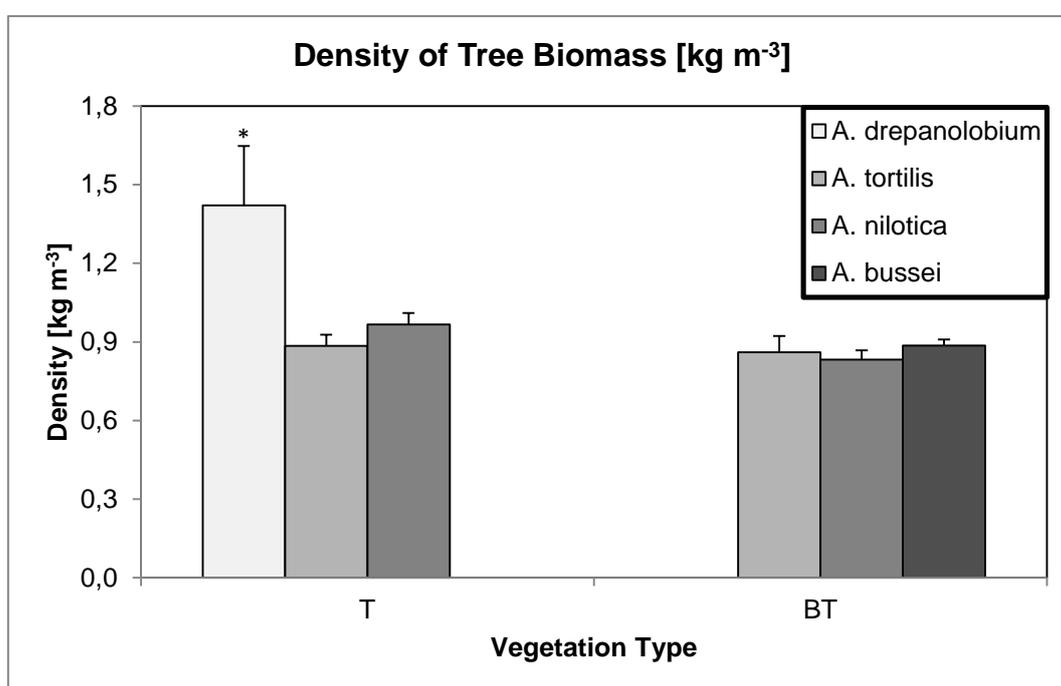
In the case of *A. nilotica*, VT had a prominent influence on the production of biomass. Significant more biomass (p<0.05) of *A. nilotica* was measured in T compared to BT.

In terms of carbon sequestration, the density of biomass plays an important role. Means of density of tree biomass [kg m<sup>-3</sup>] for the different species in two VTs (T and BT) are presented in Figure 29. Compared to Table 5 one may conclude, that tree species with a high amount of total biomass have a low biomass density and vice versa.

The density of *A. tortilis*, *A. nilotica* and *A. bussei* range from 0.83 to 0.97 kg m<sup>-3</sup> with only little variations, while the average density of *A. drepanolobium* was significantly higher (p<0.05) with 1.42 kg m<sup>-3</sup>.



**Figure 28** Aboveground biomass of tree species [kg tree<sup>-1</sup>] in two different vegetation types. Means with different letters in the same color are significantly different between the VTs at  $p < 0.05$ . Bars represent the standard error of the mean. T = Tree savannah, BT = Bush-Tree savannah



**Figure 29** Density of tree species [kg m<sup>-3</sup>] in two different vegetation types. Means with \* indicate significant difference at  $p < 0.05$ . Bars represent the standard error of the mean. T = Tree savannah, BT = Bush-Tree savannah

## 7 DISCUSSION

### 7.1 Influence of vegetation type and species composition on aboveground biomass and related carbon stocks

The first hypothesis of this master thesis states that the aboveground biomass in the four different vegetation types (VTs) and the associated biomass carbon contents are different. It was assumed, that with increasing complexity, the aboveground biomass and carbon contents also increases; being lowest in grasslands and highest in bush-tree savannahs. Figure 11 shows that there are significant differences in aboveground biomass (AGB) ranging from 0.8 t ha<sup>-1</sup> in grasslands to 51.9 t ha<sup>-1</sup> in tree savannahs. These results can be compared to findings of Brown (1997), who estimated an AGB of 50 t ha<sup>-1</sup> in open woodlands in African savannahs.

Corresponding to the AGB, the aboveground carbon stocks (AGCS) also differed between the VTs (Figure 13). The highest AGCS were measured in tree savannahs with 25.9 t C ha<sup>-1</sup> and the lowest in grasslands with 0.4 t C ha<sup>-1</sup>. Savannah ecosystems are composed of a mixture of woody and grass or herbaceous vegetation, respectively (Scholes and Archer 1997). As might be expected, the AGCS vary depending on the current vegetation cover. According to Grace *et al.* (2006), the C stocks of savannahs worldwide range from 1.8 t C ha<sup>-1</sup> without woody vegetation to 30 t C ha<sup>-1</sup> with the presence of trees. This supports the assumption, that with increasing woody vegetation (i.e. trees and bushes) the AGCS also increases. Also Jackson *et al.* (2002) observed an increase in plant biomass C with increasing woody vegetation cover in the range from 0.3 to 44 t C ha<sup>-1</sup>, what reflects more or less the amount of C stored in the vegetation measured in this study. The shift in dominance from herbaceous to woody vegetation influences the primary production and plant allocation (Jackson *et al.* 2002) and thereby leads to an increase of C storage in the biomass. The amount of C stored in new woody biomass is dependent on the age, productivity and density of the stand. However, as mature trees have only little new net growth, the amount of C assimilated will not exceed the amount of loss via respiration (Mannetje 2007). That means that old trees will stop accumulating C at a certain threshold. In contrast, grasslands have a high turnover rate (Sims and Singh 1978). Depending on the climatic condition, grasses accumulate C until the end of their growth period. Then, they decay and release the stored C again to the atmosphere. Therefore, the C storage in savannah vegetation is also dependent on the precipitation. Tiessen *et al.* (1998) estimated that the C inputs from biomass in grassland-dominated

savannahs range from 0 t C ha<sup>-1</sup> yr<sup>-1</sup>, in dry periods, when soil cover is completely absent to between 5 and 15 t C ha<sup>-1</sup> yr<sup>-1</sup> in the rainy season, when vegetation starts growing again.

Contrary to the assumptions, AGB of T exceeded the one of BT. The measured large differences can be explained as BT is a kind of “transition state” between B and T. Saplings are able to grow, as grazing and fire pressure is reduced. Thus, these trees are younger compared to trees in T and therefore not so much biomass has been accumulated yet. On the other hand it might be a methodological reason due to the allometric equations used. Studies that provide allometric equations for bushes and shrubs are scarce. This is especially the case for mid-storey vegetation of Southern Ethiopia. *Solanum somarense*, *Ocimum lamiifolium* and *Lantana rhodesensis*, for instance, were the most common shrubby species associated with *Acacia* species in B, T and BT. Unfortunately, there were no allometric equations available, and an alternative equation was used, which might have underestimated the mid-storey aboveground biomass and C stocks. Also Brown (2002) and Chave *et al.* (2004) point out, that the specific variables used for the regression model, like DBH, height and/or wood density, have a great influence on the results.

The subdivision of the AGB and AGCS into the different vegetation life forms showed that there were significant differences between the VTs (Figure 11 and Figure 13). AGB and AGCS of bushes were 3 times higher in B than in BT and AGB and AGCS of trees were around 2.5 times higher in T than in BT. Reported C stocks for tree biomass in the literature are in the same range as those found in this study. For instance, Ryan *et al.* (2011) reported aboveground tree C of 21.3 t C ha<sup>-1</sup> in Miombo woodlands. Despite the variations of the results, trees always had the highest AGB. These findings are in agreement with e.g. Nascimento and Laurance (2002) and Henry *et al.* (2009).

In terms of species composition and the change in AGB and AGCS, the results show that the differences of the woody vegetation species were not significant, except for *A. drepanolobium*. Average values ranged from 48.4 kg tree<sup>-1</sup> to 407.2 kg tree<sup>-1</sup>. In a study about the AGB of different tree species in the sudanian savannah-woodlands, Sawadogo *et al.* (2010) found similar amount in AGB for three different *Acacia* species varying from 26.5 kg tree<sup>-1</sup> to 361.5 kg tree<sup>-1</sup>.

AGB [kg tree<sup>-1</sup>] of *A. nilotica* differed significantly ( $p < 0.05$ ) between T and BT (Figure 28). In T, the AGB was almost 300% higher compared to BT. This again may be an indicator that trees in T are much older and had more time to accumulate biomass, rather than that different species are producing more or less biomass than others. However, in case of *A.*

*drepanolobium* the results indicate that the AGB is much lower compared to all other species (Table 5). That could be due to the fact, that *A. drepanolobium* usually occurs in a shrubby form and does not exceed 3 m in height (Palmer *et al.* 2008), what was also observed during this study.

It has been assumed, that increasing diversity will increase biomass and thereby C stocks, especially due to the fact of more complete use of resources. In this study, species diversity of woody vegetation had no significant influence on AGB storage. Even though in BT were more woody species than in T, the AGB was lower. This supports previous findings of Kirby and Potvin (2007) who found no evidence for a relationship between tree-species diversity and AGCS.

AGB of understorey vegetation showed no significant differences between the VTs, although the AGB of the grass layer was almost 50 % higher in B and BT in relation to G and T. In addition, B and BT showed a higher species diversity indicated by the number of species per Plot (Figure 22). The finding of this study did not support the result of previous research. Spehn *et al.* (2000) found a linear increase in AGB with increasing species number, with legumes having an additional positive effect. Días and Cabido (2001), Hector *et al.* (1999) and Tilman *et al.* (1997) go along with these findings. However, Hooper and Vitousek (1997) also claim, that functional properties of particular species and specific combinations of species control the amount of biomass development, rather than species richness per se. Nonetheless, the productivity and thereby the AGB of savannahs is usually controlled by the low precipitation, the occurrence of distinct and prolonged droughts and by soil characteristics in terms of water holding capacity (Grace *et al.* 2006).

## **7.2 Link between aboveground biomass, species composition and belowground carbon stocks**

One of the main objectives of this master thesis was to find out, whether there is a relationship between the vegetation type and the carbon stock that is stored in the soil continuum. It was supposed that the soil organic carbon stocks (SOCS) are positively correlated to the amount of AGB through the input from litter and root exudates. This means, the higher the AGB, the higher the SOC content and SOCS.

The results show, that there was neither a significant difference in SOC content [%], nor in SOCS [ $\text{t ha}^{-1}$ ] (Figure 15 and Figure 17). However, the findings of the current study do not support the previous research. In a study of Yimer *et al.* (2006) in southern Ethiopia, SOC

differed significantly between the VTs and the presence of trees usually enhanced the allocation of SOC (Belsky *et al.* 1989; Throop and Archer 2008; Kahi *et al.* 2009). Trees and bushes in arid and semi-arid regions form “islands of fertility”. In this zone, SOC and soil nutrients accumulate, due to increasing above- and belowground litter inputs, “scavenging” of the adjacent interspaces to zones beneath the canopy and lower decomposition rates of lignin-rich woody litter (Belsky *et al.* 1989; Vetaas 1992). Further, woody plants may act as windbreaker, where aeolian deposits accumulate in the sub-canopy space. Also animal faeces, stem flow, higher moisture content through shading and thereby reduced decomposition rates and evapotranspiration can lead to increased C contents under canopies (Morris *et al.* 1982; Belsky *et al.* 1989; Belsky *et al.* 1998).

On the other hand, it has been stated, that the belowground net primary production (BNPP) is a more direct source of C to soil pools than aboveground net primary production (ANPP). BNPP can be significantly higher in native grasslands (McCulley and Jackson 2012). For example, the introduction of conifer trees in pastures led to a decrease in SOCS by 12 % (Guo and Gifford 2002) and bush encroachment reduced SOCS by 20 % compared to former pasture (Jackson *et al.* 2002; McCulley and Jackson 2012). The latter was also observed in this study; all measurements in the VT of B resulted in lower SOCS compared to G.

Although the differences were small and not significant, more C was accumulated in T and BT compared to G and B. This may result from the higher groundcover (Figure 25) and thereby reduced soil temperature and soil respiration.

Nevertheless, the high variability of soils within the VTs, especially within the grassland plots, may be the reason that no significant relationship between the belowground C stocks and VTs were proven. This also accords with earlier findings of Kirby and Potvin (2007). In addition, soil samples were taken randomly on the whole plot. Throop and Archer (2008) report a decreasing effect of the tree on SOC with increasing distance from the bole. Lower SOCS in the intercept may have offset the positive effect of woody vegetation. Then, grasslands were mostly located in depressions, where occasional flooding might lead to reduced decomposition rates and accumulation of SOM. This hypothesis is also supported by the ideas of Michelsen *et al.* (2004).

It is important to recognize, that a low woody cover does not obligatory result in lower SOCS. This fact has also been stated by Ryan *et al.* (2011). Takimoto *et al.* (2008) observed even higher SOC stocks in abandoned land than in agro-forestry systems. The results make clear, that the SOCS significantly exceed the AGB in all four VTs. In B, T and BT, SOCS were 30,

8 and 16 times higher, respectively, compared to AGB. In G the SOCS were even 465 times higher. These results are consistent with those of e.g. Michelsen *et al.* (2004) who measured soil C stocks in different wooded grasslands that were 19, 14, and 48 times higher than the aboveground vegetation.

A strong influence of species diversity and species richness on SOCS was pointed out in previous studies (Fornara and Tilman 2008; Sebastia *et al.* 2008; Steinbeiss *et al.* 2008). However the enhanced accumulation of C in soil was mainly due to the combination of C4 grass species and N-fixing legumes (Fornara and Tilman 2008) or the presence of tall herbs (Steinbeiss *et al.* 2008). Hence, key functional groups played the major role for soil C sequestration (De Deyn *et al.* 2009). The species composition of the study area differed slightly between the VTs. Nevertheless, every plot investigated was made up by a mixture of C4 grasses and legumes like *Crotalaria* ssp., *Indigofera* ssp. and *Acacia* ssp. The similar mixture of the key functional groups in all VTs might have overlain the effect of species richness as such.

In this study a higher species richness did not significantly lead to higher SOCS. This finding is consistent with other research (De Deyn *et al.* 2009). In the plots of B and BT the highest species richness was observed, but, as mentioned before, no significant differences in SOCS were measured. However, Mannelje (2007) points out that the introduction of improved grasses is enhancing the C storage potential compared with native savannahs. In the Llanos of Colombia, 237 t C ha<sup>-1</sup> were measured by Fisher *et al.* (1994) in improved savannahs, most of it stored in the 40-100 m deep soil layer. The introduction of *Brachiaria humidicola* resulted in C storage of 223 t C ha<sup>-1</sup> and 268 t C ha<sup>-1</sup> compared to 197 t C ha<sup>-1</sup> under unimproved pastures. Similar values were also observed by Ayarza *et al.* (1987, cited in Mannelje 2007), Tarré *et al.* (2001) and Boddey *et al.* (2002). *B. humidicola* belongs to the most common species of the study area (Table 4). In addition, they were more frequent in T and BT, where also the SOCS were slightly higher.

SOC contents ranged from 2.93 % to 3.26 % and SOCS varied between 326.4 t ha<sup>-1</sup> and 394.9 t ha<sup>-1</sup> measured to 1 m depth (Figure 15 and Figure 17). Similar SOCS were reported by Michelsen *et al.* (2004) (284 t C ha<sup>-1</sup>) during a study in Gambella, West Ethiopia. Also Watson *et al.* (2000, cited in Neely *et al.* 2009) observed SOCS of 265 t C ha<sup>-1</sup> in the first meter in tropical savannah ecosystems.

However, these values seem rather high for semi-arid savannah systems as they exceed in all four VTs the global summaries (Jobbágy and Jackson 2000). SOCS in tropical savannahs are

generally low due to low input and high soil respiration rates (Tiessen *et al.* 1998; Chen *et al.* 2003). Ryan *et al.* (2011) reported SOC content of 3 % on the soil surface, decreasing to 1 % at 15 cm depth. Resulting SOCS (0-50 cm) ranged from 32 to 133 t C ha<sup>-1</sup>. However, the soil texture in that study was mainly sand (46 to 76 %) that has lower SOM contents.

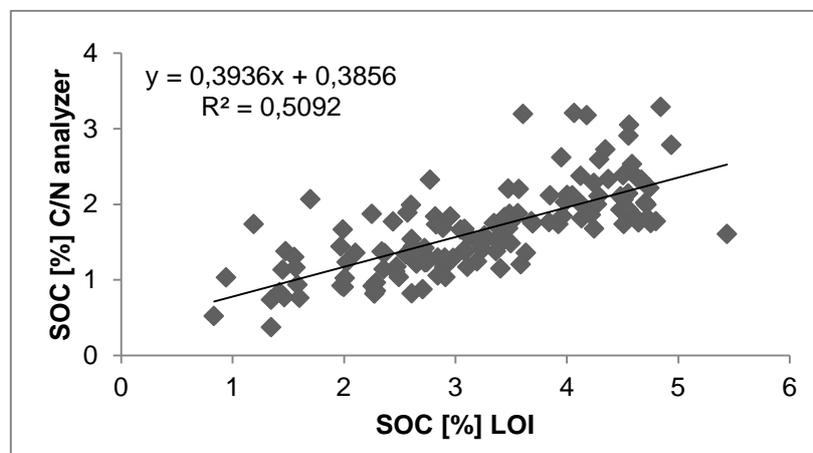
Nevertheless, the results may be explained by several factors. Savannas have the potential to store C in the long term (Jobbágy and Jackson 2000; Neely *et al.* 2009). During the last three years, long lasting droughts occurred in Southern Ethiopia. The lack of water may have led to low to zero decomposition of organic material, what resulted in increasing SOCS over time (Hoffmann *et al.* 2012).

The strong influence of soil texture on the SOCS is often stressed (Schimel *et al.* 1994; Bird *et al.* 2002; Takimoto *et al.* 2008). SOC contents in soils with high clay and silt content are found to be higher compared to soils with a coarse texture. This can be related to the stabilizing effect of these particles. Through the high surface area, the formation of organo-mineral complexes is enhanced, that protects C from microbial mineralization. Soils of the study area were determined as Cambisols and Vertisols with a high clay content (20-60 %). Higher SOCS in clay rich calcic Vertisols were proven in the same study area in previous research (Glatzle, unpublished). In addition clay rich soils also contain a high level of multivariate cations. Especially Ca<sup>2+</sup> is stabilizing soil C and protects it from decomposition (Oades 1988). Generally, high CaCO<sub>3</sub> contents were measured in the study area (0.3-11.3 %). This may also lead to higher SOCS; through carbonate coating of fresh organic matter the decomposition is reduced (Krull *et al.* 2001).

Also the management can have an effect on the allocation of SOC. vegetation burning is a common management tool in savannas. In addition the production of charcoal is an important activity for income generation. These two actions combined lead to the incorporation of remaining charcoal into the soil and thereby to an increased SOC content. Repeated burning in wooded savannas increases the soil C content (Minami *et al.* 1993, cited in Mannetje 2007). Also Kimble *et al.* (2001) highlights, that the presence of charcoal in the soil can distort the results.

Then again, high SOC contents may have also aroused due to a methodological problem. The LOI method was chosen to measure the SOC content. Additionally, around 10 % of the samples were measured with the CN elemental analyzer to test accuracy. Figure 30 shows that SOC contents measured with the CN analyzer were mostly 50 % lower than SOC contents measured with the LOI method. It has been reported, that LOI has serious shortcomings since

the volatilization of all material is measured. For instance allophane and gibbsite was found to lose considerable amounts of its mass upon heating from 100 to 800°C (Sollins *et al.* 1999). In contrast, the CN analyzer only measures C in form of CO<sub>2</sub> and is therefore much more accurate.



**Figure 30** Comparison between SOC contents [%] measured with C/N analyzer and LOI method

Previous studies claimed that compaction, leading to an increased bulk density (BD), significantly influences and overestimates the amount of SOCS calculated. Therefore, if soils with different BD are compared, a correction factor is needed for valid results (Fearnside and Imbrozio Barbosa 1998).

In terms of SOC distribution with depth, no significant differences were measured between the VTs. SOC concentrations varied between 2.5 and 4% and SOCS ranged from 29.6 to 48.3 t C ha<sup>-1</sup> (Figure 16 and Figure 18). This means, SOC was more or less evenly distributed in all layers of all VTs. Only within the VTs B and T SOC differed significantly between the different depths. In T, SOC was higher in the layer 60-100 cm than in the soil layers above. An explanation could be the greater root biomass in deeper soil layer than in shallower horizons. Trees in tropical savannahs were observed to grow up to 68 m deep into the soil. This is especially the case in arid environments or environments with a long dry season (Canadell *et al.* 1996).

Jackson *et al.* (2000) and Jackson *et al.* (2002) observed a deeper distribution of SOC at sites under woody vegetation. Takimoto *et al.* (2008) also found considerable amounts of SOC stored in lower depth across different land-use systems. In this case, higher SOCS were linked to higher clay contents in the subsoil. In addition, SOCS in deeper soil layers could also result from the dense and immense root system and the deep rootage of tropical grasses. Various species often grow deeper than 1 m depth. This is supported by Ayarza *et al.* (1993, cited in Mannetje 2007) and Fisher *et al.* (1994).

In savannah ecosystems, soil biological activity (especially termites) is an important factor influencing soil structure. Through the so called “bioturbation”, soil C is equally distributed within the soil profile and soil structure is enhanced, what has positive impacts on the SOC pool (Lal 2004b). An additional “mixture effect” results through peloturbation. Clayey soils are affected by alternate swelling and shrinking. In dry periods clay-soils dry out and form deep cracks. Organic matter from the surface falls into these cracks and is mixed into deeper layers during swelling of the soils in the rainy season. Further, microbial activity and soil respiration decreases with increasing depth, which reduces decomposition (Ammann *et al.* 2007). Soils of dry areas have high carbonate concentrations (Batjes 1996). Especially in deeper soil layers they can form indurated layers, where C is fixed (Díaz-Hernández 2010).

Finally, it was assumed, that with increasing growth rate of the vegetation in the rainy season and increased microbial activity, the SOCS would also increase during the seasonal change from dry to rainy season. Surprisingly, the opposite was the case. As shown in Figure 19 SOCS showed a decreasing trend from dry to rainy season to 1 m depth. This was also the case in deeper soil layers (30-100 cm; Figure 21). However, in the upper soil layer, SOCS increased slightly in G and B (Figure 20). There are several explanations for this outcome. After three years of drought and still low soil cover, the effect of the kinetic energy of raindrops might have caused erosion and run-off of the upper soil layer. In especially in BTs, which were mostly located at slight inclinations, this could be the reason for the drop in SOCS. This idea has been confirmed by Mannetje (2007), who states, that soil erosion is a major cause of SOC loss. Secondly, the reduction in SOCS in deeper soil layers might be due to the fact, that with increasing soil moisture, microbial biomass is more active. In addition with increasing root growth and thereby root exudates, especially in B and T, the microbial mineralization is very fast. New inputs from the vegetation do not occur during this time and together with increased soil respiration the SOCS decrease. The slight increase of SOCS in the topsoil of G and B could be explained by a high production of fine roots, which was initiated immediately after the first rain event.

### **7.3 Impact of vegetation type on species diversity, species communities and basal ground cover**

In this study it was hypothesized, that a change in the dominant vegetation life form (grasses, bushes and trees) will lead to different species composition due to additional niche formation.

A cluster analysis was performed to test whether the VTs are distinguishable according to their species composition.

The VTs identified in this study were more or less consistent with those of previous studies in the Borana Plateau (Tefera *et al.* 2007a; Tefera *et al.* 2007b). Furthermore, all identified woody species are reported as the most common ones (Tefera *et al.* 2007b).

The dendrogram of the cluster analysis (Figure 23) resulted in two main clusters, which were further divided into several sub-clusters. It was observed, that species in cluster A were most frequent in the VTs B and BT. Bush species in the study area were mainly *Acacia drepanolobium*, *A. nubica* and *A. mellifera*, which were only found in B and BT. Some grass and herbaceous species uniquely found in these two VTs may have been favored through the these bush species. This could occur either via an additional niche opportunity, like reduced light intensity, higher moisture content under the bush canopy (Belsky *et al.* 1993) or through enhanced nutrient availability. Riginos *et al.* (2009) found that enriched soil nitrogen content under *A. drepanolobium* could have been the driving factor for increased biomass. On the other hand it has been reported, that bush encroachment changes the species composition of the grass layer (Knapp *et al.* 2007). Thus, the competition for nutrients can be an explanation for the different species composition in B and BT, as bush encroachment in savannahs is an important process. The competition for resources might therefore eliminate some species, while others will be promoted. For instance, *P. stramineum* was found to be the only species which is directly linked to woody vegetation (Riginos *et al.* 2009). This goes ahead with the current study; *P. stramineum* was exclusively observed in VTs with a woody cover.

In addition, there were some clusters which represented the species composition of one single plot within one VT (e.g. BT1). This is mainly due to some species, which were not occurring in any other plot sampled, no matter which VT.

Further, Cluster 12 represented the typical species composition that was observed in T. *Acacia tortilis* and *A. nilotica* were the dominant tree species and *Cenchrus ciliaris* and *Chrysopogon plumulosus* were the dominant grass species.

The results of the cluster analysis in Figure 24 show that the sampled plots are grouping together as a result of their edaphic properties. It is assumed, that soil characteristics strongly influence the size, density and patterning of woody vegetation in arid and semi-arid systems (Hughes *et al.* 2006). It was conspicuous, that woody vegetation was mostly found on Cambisols, whereas grasslands were dominant on Vertisols. Also Williams *et al.* (2007b) found a negative correlation between woody plant abundance and clay content. This can be explained by the different root systems of the two contrasting life forms and how they access

water from coarse and fine-textured soils (Scholes and Archer 1997). The results suggest that open grasslands with a shallow, dense rooting system (Bond 2008) may be favored on fine-textured soils, which preserve water in the upper soil layers (Cluster 1 and 4). In contrast, woody vegetation has a deeper and more extensive root system (Bond 2008). Therefore, they may be supported on coarse-textured soils, where precipitation water percolates to deeper depths (Cluster 2, 3 and 5). This idea is also supported by Knoop and Walker (1985). Thus, coarse textured soils are more susceptible to woody encroachment.

Species of the understorey vegetation layer partially correspond with those reported by Tefera *et al.* (2007a). The distribution of different species in the grass and herb layer form specific associations with species in the tree- and bush layer. The most obvious one was the association between *A. drepanolobium* and *P. mezianum*. Both species are mostly found in combination on clay soils with a good water holding capacity. In addition, *E. cilianensis* was often present in this community, too. Palmer *et al.* (2008) states that *A. drepanolobium*, mainly present as bush, is usually distributed on soil with high clay content and hindered drainage. Common species associated with *A. tortilis* and *A. nilotica* in T were *C. ciliaris* and *C. plumulus*. The latter were also present in B and BT. Then, together with *S. pyramidlis* and *C. roxburhiana* they were frequently found in a community with *A. bussei*. The same communities were also observed by Dalle (2004), who investigated community types and species composition of herbaceous and woody plants. In G the species composition was probably mainly driven by the soil properties. On clayey soils, communities of *Pennisetum* ssp., *Setaria verticillata* and *Brachiaria humidicola* were found, whereas communities of different sedges, *Sporobolus* ssp. and *Cenchrus ciliaris* were dominating on other soil types.

A significantly higher basal ground cover was measured in T and BT (Figure 25). This concurs with findings of Belsky *et al.* (1993), who found an increase of 95% of herbaceous production under woody vegetation. It is accepted knowledge, that trees, especially *Acacias*, enhance soil nutrients in the soil beneath their canopies, resulting in increased herbaceous productivity (Belsky *et al.* 1993; Ludwig *et al.* 2004).

In addition, the presence of trees led to a shift from grass species to herbaceous species (Figure 26, Picture 6). The results accord with those of Ludwig *et al.* (2004); 10-20% of the vegetation was covered by herbs in grasslands, while this was 40-50 % under woody vegetation. The shading effect might be the determining factor influencing the occurrence of grass and herbaceous species. Ludwig *et al.* (2001) showed that herbs are more tolerant to shade, than open grassland grasses. Also Scholes and Archer (1997) pointed out that C3- and

herbaceous species are favored by tree shading and C4 grasses are more frequent in open grasslands.



**Picture 6** Increased herbaceous production under Acacia tree canopy

Also the distribution of annual and perennial species was influenced by the VT. Higher amount of perennial species in the open grasslands is probably due to the severe overgrazing of these areas. Annual species decline, whereas undesirable perennial species like *P. mezianum* or *Crotalaria* ssp. are enhanced. Then again, the shading and nutrient facilitation under woody species could be the reason for higher abundance of annual species in these VTs.

However, a clear difference in species composition between the VTs was not proven, rather a shift in their frequency of occurrence.

#### **7.4 Is it possible to assess vegetation types in the dry season?**

Due to the long lasting drought during the last three years in the Borana region of southern Ethiopia, the classification of representative VTs was rather difficult. The landscape was totally dried out and vast areas were prone to wind erosion due to mostly bare soil. Therefore, a basic vegetation classification based the growth- and dominant vegetation life form and dominance was conducted, as it is supposed by UNESCO (1973) and FAO (2005).

Broad areas, where woody cover was mainly absent and where some remaining dry plant residues and bunch grasses were observed were classified as grasslands. If some scattered or grouped trees occurred in these areas, they were classified as tree savannahs. Areas which

were obviously encroached by bushes (<6m) with a high soil cover, were classified as bushland and bushy areas with increasing occurrence of trees (> 6m) as bush-tree savannah. The resulting vegetation formations after the rainy season proof, that in the case of B and T the classification of the dry season would result in same VTs. This is mainly due to the fact that the aboveground vegetation stand of large vegetation life forms does not disappear during dry periods. However, when they regrow, they are affecting the surrounding understorey vegetation. “Bare” areas that were previously classified as G, in fact, were covered by diverse herbaceous vegetation after the rainy season. Nevertheless, depending on the soil properties, they differed in their species composition, growth habit and basal cover. Species on clay rich soils were mainly perennials that develop dense bunches and some annual herbs (Picture 7). Species on more coarse textured soils were single stand grasses and herbs and species that are known to grow mainly on degraded or disturbed soils (e.g. *Erucastrum arabicum*) (Grubben 2004). An additional subdivision of these two grasslands would be preferable, since in this study, they resulted in high variations of SOCS within the same VT. The vegetation of BT did not always show the predefined characteristics for the classification after the rainy season. In some cases, dried-out mid-storey woody vegetation, which was expected to regrow with the beginning of the rainy season, died off during the dry period. Therefore, bushes were not always present in BT. However, they were not comparable to T either, as their stands were more dense including also small trees.

Nowadays, common classification systems to define VTs are mainly based on vegetation reflectance indices. This is a widely used and relatively simple method to classify broad areas for different ecological research aspects. However, problems might arise in long lasting dry periods, when vegetation cover is low to zero, especially in grasslands, what has been observed in this study. Thus, remote sensing derived data could lead to a misinterpretation of the local vegetation.



**Picture 7** Grassland plots on clayey soils before (a) and after (b) the rainy season

## 8 CONCLUSION & OUTLOOK

The objective of this study was to compare the carbon (C) storage potential above- and belowground of four different vegetation types (VTs); grassland, bushland, tree savannah and bush-tree savannah, and to evaluate the effects of aboveground vegetation on belowground carbon stocks.

VT had a significant influence on the total of aboveground biomass (AGB) and the aboveground carbon stocks (AGCS). More biomass was accumulated in tree savannahs compared to grasslands. This means, with increasing woody vegetation the biomass accumulation increased, too. These results prove the first hypothesis.

Other than expected, no significant differences in soil organic carbon stocks (SOCS) occurred between the different VTs. Thus, the results contradict the second hypothesis. It was assumed, that due to higher nutrient input through litter fall and reduced soil respiration through shading effects, the SOCS will increase with increasing woody vegetation and system diversity. Due to a high variability in soils, high clay and carbonate contents the results have to be treated with caution. Nonetheless, SOCS exceeded by far the AGCS, signaling the high potential of savannah soils to sequester C.

Carbon distribution with depth did not show significant differences across the VTs. Thus, the third hypothesis was not fulfilled. Only within the VT, soil organic carbon (SOC) differed between the four depths. In tree savannahs more C was stored in deeper soil layers compared to the topsoil, probably due to higher rooting depth of tree roots compared to some grass and herbaceous species.

It was hypothesized that the different VTs will differ in their species composition and diversity and thereby will influence the SOC accumulation. The results show a shift to more annual and herbaceous species with increasing woody vegetation and, especially tree biomass. Higher species richness and some species in particular, were exclusively observed in bushlands and bush-tree savannahs, highlighting the importance in terms of biodiversity. The influence of soil properties was high, especially on the distribution of woody vegetation within the study area and the composition of the herbaceous layer. Since the SOCS were not different between the VTs, the effects of species composition and species diversity could not be definitely determined.

In terms of carbon sequestration under the different vegetation types for the establishment of a PES system and the alternative of income generation, it may be concluded, that the mixture of grass and woody species stores more carbon when the above and belowground carbon pool