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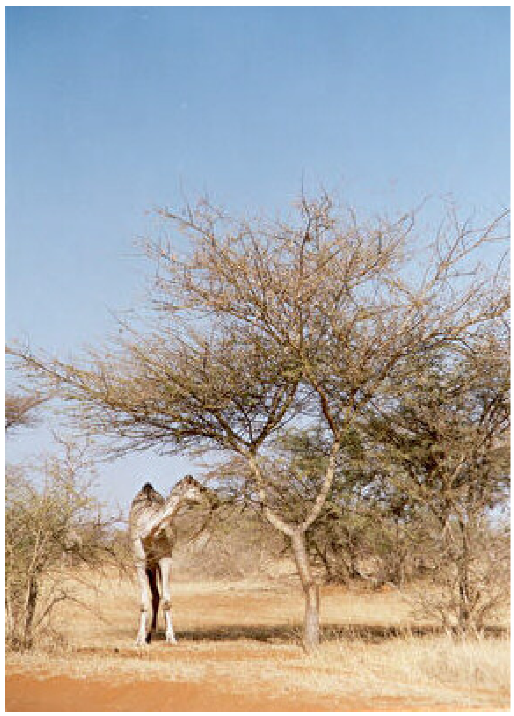
Seminarieuppsatser Nr. 91

Acacia senegal, Soil Organic Carbon and Nitrogen Contents: A Study in North Kordofan, Sudan



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ABSTRACT

In 2001, the Intergovernmental Panel on Climate Change approved human impact (mainly through the emission of carbon dioxide (CO_2)) on global warming. The Kyoto Protocol is a global contract that proposes the reduction of CO_2 and five other greenhouse gases by 2012 to at least 5% below the level of 1990. One reduction strategy included in the Protocol is the Clean Development Mechanism (CDM). It suggests that industrialized countries invest in projects in developing countries that sequester carbon and promote sustainable development in the host country. A controversial issue within the Protocol is the acceptance of carbon sequestration in sinks (soils and vegetation) as a means to reduce atmospheric CO_2.

This master thesis was conducted in collaboration with the Centre for Environmental Studies at Lund University (MICLU) in the context of carbon sequestration in soils of semi-arid regions. MICLU's research is concentrated on North Kordofan, Sudan, a region suffering from severe environmental degradation.

The basic idea of the study was to investigate if soils beneath *Acacia senegal* have the potential to sequester soil organic carbon (SOC) on a higher level than other land use types. *Acacia senegal* is a leguminous tree species traditionally cultivated during fallow periods. Fieldwork was carried out during February 2002 and included interviews with farmers, soil sampling and biomass measurements. The thesis focused on the following questions: (1) Does *Acacia senegal* influence SOC and nitrogen content of the topsoil? (2) Does nitrogen influence the SOC content beneath *Acacia Senegal* stands? (3) Are SOC contents simulated by the Introductory Carbon Balance Model (ICBM) similar to my field observations?

The study shows that: (1) There is a significant difference between SOC and nitrogen content in the topsoil of fallow fields with *Acacia senegal* and that of crop fields. (2) There is a significant positive correlation between SOC and nitrogen content under both fallow fields with *Acacia senegal* and under undisturbed sites without *Acacia senegal*. (3) The SOC content simulated by the ICBM does not coincide with the SOC content measured in 2002.

The number of soil samples taken was small and further research has to be done to confirm the results of this study. The ICBM has to be calibrated to semi-arid conditions with a time series of a well-investigated area before it can be used as a meaningful tool for soil carbon simulations.

SAMMANFATTNING

Under året 2001 kom forskare i hela världen överens om att globala klimatförändringar existerar och att människliga aktiviteter har påverkat dem, framförallt genom utsläpp av koldioxid (CO_2). Kyoto Protokollet är en global överenskommelse som kräver en minskning av CO_2 utsläpp (med 1990 som basår) och fem andra växthusgaser med 5% fram till 2012. Ett sätt som nämns i Kyoto Protokollet att reducera kolutsläpp är den så kallade Clean Development Mechanism (CDM). CDM baseras på att industriländer investerar i projekt i utvecklingsländer som tar upp kol och samtidigt främja hållbar utveckling i landet. En kontroversiell idé inom Kyoto Protokollet är kolsänkor (marken och vegetationen) som en möjlighet att minska atmosfäriskt CO_2.

Denna magisteruppsats skrevs i samarbete med Miljövetenskapligt Centrum vid Lunds Universitet (MICLU). MICLUs projekt är koncentrerade på kol-upptagning i marker i semi-arida områden. Forskning utförs i Norra Kordofan, ett område med stora miljöproblem i Sudans Sahel region.

Grundidén med min studie är att undersöka om marken under *Acacia senegal* kan ta upp förhållandesvis mer kol än andra markanvändningstyper. *Acacia senegal* är ett kvävefixerande träd som odlas traditionellt under trädesperioden. Fältarbetet utfördes i februari 2002 och bestod dels ut av intervjuer med bönder, men också av jordprover och mätningar av biomassan. Mitt arbete fokuserade på följande frågeställningar: (1) Påverkar *Acacia senegal* kol- och kvävehalten i det översta markskiktet? (2) Påverkar kvävehalten i det översta markskiktet kolhalten under *Acacia senegal*? (3) Är de kolvärden som jag simulerade med Introductory Carbon Balance Model (ICBM) lika med mina mätningar?

Resultaten visar att: (1) Kol- och kvävehalten i översta markskiktet skiljer sig signifikant mellan fält i träda med *Acacia senegal* och odlade fält. (2) Det finns en signifikant korrelation mellan kol- och kvävehalten i både under fält i träda med *Acacia senegal* och under fält med ostörd vegetation. (3) De kolvärden som simulerades med ICBM stämmer inte överens med mina mätningar.

Antalet jordprover var för små och mer forskning måste genomföras för att kunna konfirmera mina resultat. ICBM måste anpassas till semi-arida förhållande genom att kalibrera den med data serier tagit ur ett semi-arid område som löper över en lång tidsperiod. Sedan kunde ICBM betecknas som ett användbart redskap för simuleringar av kolhalt i mark.

LIST OF CONTENTS

1 INTRODUCTION

Sub-Saharan Africa is the only region in the world where food production has been stagnant over the last 40 years although population has strongly increased (Sanchez, 2002). Although scientists have been working for many years on climate change related to human activities, it was only in 2001 that the Intergovernmental Panel on Climate Change (IPCC) confirmed the human impact on global climate change (IPCC, 2001). In 1997, the Kyoto Protocol was established. It is the only global contract, which aims to reduce global emissions of greenhouse gases, of which carbon dioxide (CO_2) is one of the most important. The protocol proposes several methods to reduce emissions, e.g. the Clean Development Mechanism (CDM). It allows industrial countries to invest in projects in developing countries, which aim to reduce or avoid emissions and promote sustainable development [1][1]. Recent research suggests carbon sequestration in soils as a method for climate change mitigation but the parties to the Kyoto Protocol have not yet decided if this possibility should be included in the global contract or not (Ardö & Olsson, 2002b).

This master thesis is part of a multidisciplinary research project, initiated by the Centre for Environmental Studies at Lund University (MICLU), Sweden. A main objective of MICLU's research activities is to investigate if carbon sequestration in soils is a means to promote sustainable development and alleviate poverty in developing countries[2]. This study focuses on the investigation of SOC and nitrogen content beneath *Acacia senegal* stands in North Kordofan, Sudan. *Acacia senegal* is a leguminous tree species well adapted to climate conditions and traditionally integrated into the system of shifting cultivation in Sudan. *Acacia senegal* stands have decreased strongly in the study area, which resulted in environmental degradation and declining incomes of the local farmers (Keddeman, 1994). The assumption behind this study is that soils beneath *Acacia senegal* might have a higher carbon and nitrogen content compared to other land uses. *Acacia senegal* is said to be a nitrogen-fixing plant while nitrogen is a limiting nutrient in savannah regions (Breman & Kessler, 1995). Additional nitrogen might lead to improved growth of *Acacia senegal* and other plants during the fallow period and to better growth of future crops during the cropping period.

The prediction of the development of carbon pools in the soil is important when deciding upon different land use options. Therefore, the second part of the thesis focuses on a model simulating carbon stocks in the soil.

[1] Note that I refer to web addresses without specific author separately from references in paper format. A number in brackets indicates a web address. All web addresses are listed in chapter 10.

[2] For example, a current research project is investigating gum arabic production for environmental protection and income generation in the Sahel (ongoing, 2000 - 2003).

2 OBJECTIVE

The main objective is to investigate if soils under *Acacia senegal* have a higher content of Soil Organic Carbon (SOC) and nitrogen when compared to soils with different vegetation cover. The first part of the study focuses on the following questions:

- Does *Acacia senegal* influence SOC and nitrogen content of the topsoil?
- Does nitrogen content in the topsoil influence the SOC content of an *Acacia senegal* field?

The second part of the thesis focuses on the evaluation of a simple model simulating SOC contents:

- Is the SOC content, simulated by the Introductory Carbon Balance Model (ICBM), similar to my field observations?

3 The Study Area

3.1 Sudan

Sudan is the largest country in Africa and is situated in Northeast Africa (figure 3.1). Its capital is Khartoum. It has a population of around 36 million people of which almost 50% of the population is under 14 years old. Agriculture employs up to 80% of the workforce although it contributes to Sudan's GDP with barely 40%. Around 5% of the land is arable land, 46% is comprised of permanent pastures and 19% is comprised of forests and woodland. Since 1989, a military dictatorship has ruled the country and the fundamentalist National Islamic Front party dominates the government. The civil war in the South (officially a religious war between Christians and animists in the South and the Arabic league in the North) has weakened the country's economy, cost the lives of more than 1.5 million people and caused the displacement of millions of people[3].

Droughts and unreliable rainfalls since the 70s have exacerbated the situation. Olsson (1993) states that a collapsing food and livestock market, an unjust credit system for the farmers and a lack of an adequate transportation system are the main causes of the food shortage during drought. War, drought and an ineffective government are main reasons for the fact that the country is one of the poorest in the world today. These factors have also led to severe environmental problems such as deforestation, desertification and degradation of soils and consequently to unreliable food production (Ajoub, 1999).

3.2 Umm Ruwaba District

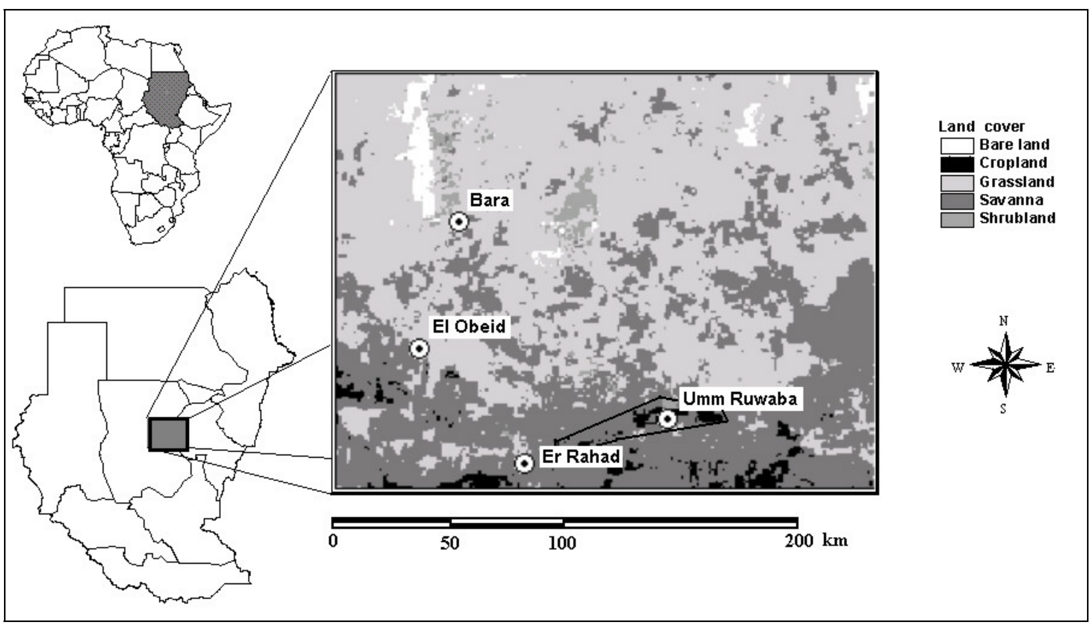

Figure 3.1: The black line around Umm Ruwaba encircles the study area. The rectangle shows the study area of MICLU where research has been going on for 20 years.

The study area is situated in Umm Ruwaba District, Northern Kordofan Province, around 350 km SSW of Khartoum. The study area lies between latitude 12,70°N and 13°N and

[3] These facts originate from the World Fact Book 2001 of the CIA (CIA, 2001).

longitude 30,70°E to 31,50°E, which equals an area of approximately 70 km by 30 km (Figure 3.1). As there is a road through Umm Ruwaba, its surroundings had been chosen for fieldwork. Different land use types could be accessed comparatively easy.

In some villages surrounding Umm Ruwaba, farmers were interviewed. Each of the four interviews was conducted with the village elder (sheik) and a group of on average 10 farmers. Each question provoked a lively discussion, which means that the answers reflect the opinion of many. Additionally, a research team interviewed farmers in the Bara region (Figure 3.1). The knowledge gained during interviewing allowed the researcher a better understanding of constraints and problems that farmers have to cope with. However, the interviews are not part of the method for this masters thesis as socio-economic issues are beyond the scope of this study.

3.2.1 Climate

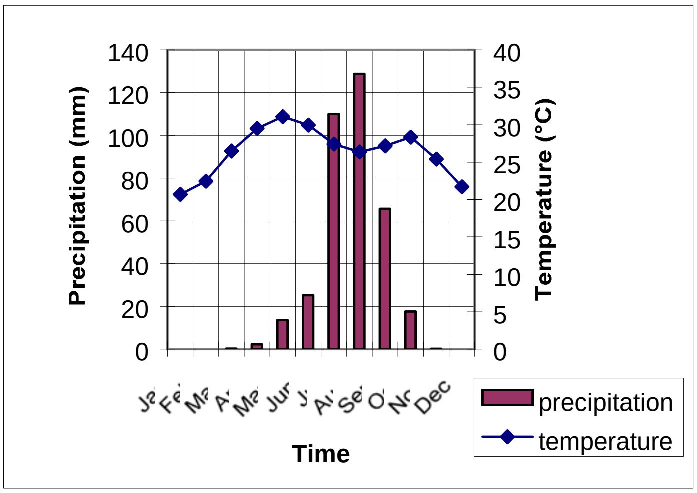

Figure 3.2: Climate data for El Obeid 1941 – 1991

The climate is semi-arid with a short rainy season[4] from June to September and a long dry season (Khogali, 1991) (Figure 3.2). Mean annual precipitation in Umm Ruwaba is around 360 mm (Save the Children, 1988). The precipitation is often of high intensity and few occasions. The dry period is around nine months long. Mean annual temperature is 26°C with January being the coldest month and May the hottest (Olsson & Rapp, 1991). The most severe droughts recorded were in 1984 and 1985.

3.2.2 Vegetation, Topography and Soils

The study area is a mosaic of forest savannah and grassland (Olsson & Rapp, 1991). Savannahs include grasslands with at least 10% of canopy cover; they are the transition zone between closed forests and grasslands or deserts. The major factor determining savannah vegetation is rainfall (Breman & Kessler, 1995). Tropical savannahs cover about half the area of Africa. They are socioeconomically important areas as they contain a growing percentage of the world's population, a majority of its rangelands and livestock (Scholes & Archer, 1997).

The study area lies within the gumbelt, a broad strip of sandy soil between the 250 mm and 400 mm isohyets, where different kind of *Acacia* species are the dominant tree types (Figure 3.3) (Save the Children, 1988). Common trees are *Acacia senegal* (hashab), *Balanites aegyptica* (hejlij), *Acacia raddiana* (sayal), *Acacia albida* (haraz), *Maerua crassifolia* (sereh), *Adansonia digitata* (tebeldi), *Leptadinia pyrotechnica* (merrikh), *Ziziphus mauritiana* (nabag)

[4] Rainy and growing season are defined as the period in which monthly precipitations in mm are equal to or greater than twice the mean temperature in °C: precipitation > 2 x temperature. The northward movement of the Intertropical Convergence Zone and the SW monsoon of the Gulf of Guinea provoke the rains during rainy season (Le Houérou, 1989).

and broad-leafed species of the family C*ombretaceae*. Common grasses are *Aristida pallida*, *Eragrostis tremula* (banu) and *Chenchrus bifolius* (haskanit) (Olsson & Rapp, 1991; Save the Children, 1988; Jakubaschk, February 2002). As a sign of severe soil exhaustion, *Calotropis procera* (usher) is now one of the dominant tree species in the study area (Save the Children, 1988).

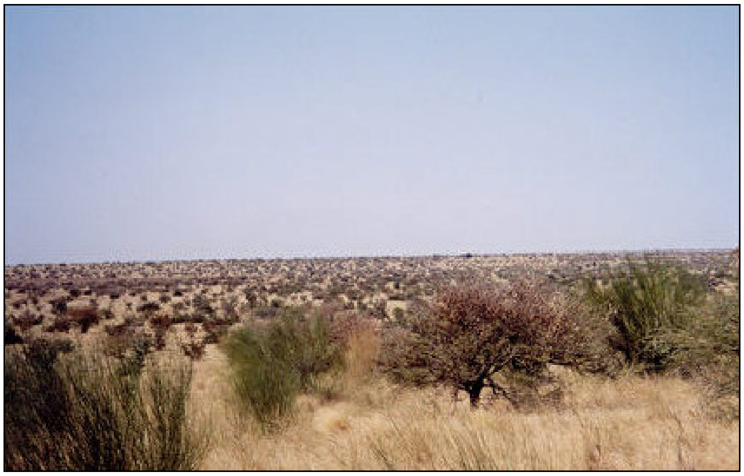

Figure 3.3: Parts of the gumbelt

The area is flat and of low elevation (200-600 m) and is covered with sandy soil (Le Hourérou, 1989). The only elevations are Inselbergs, isolated rocky outcroppings of a reddish colour. In the Southwest of Umm Ruwaba longitudinal sand dunes run in a North-South direction giving the landscape a rippled form (Save the Children, 1988).

Cambic arenosols, coarse textured soils with aeolian origin, dominate the area (Figure 6.1) (FAO Soil Database, 1995 & 1998). The soils are locally called *goz* and the texture is characterised by 60-70% coarse sand, 20-30% fine sand and 5-10% clay (Ardö & Olsson, 2002b). These soils are low in nutrients and organic matter and have a high sensitivity to erosion (Ayoub, 1999). *Goz* soils absorb almost the entire precipitation as the moisture filters through the sand and little is lost to evaporation or runoff. The sandy soils are easy to till, weed and clear by hand, but the effect of variable rainfall is more severe on sandy than on clay soil (Save the Children, 1988).

Chromic vertisols, locally named *gardud*, are clay soils mixed with aeolian sand (Warren, 1970). The soil type occurs mainly South of Umm Ruwaba. *Gardud* soils require more rainfall for plant growth than *goz* but they are more fertile and can be cultivated for longer periods (Save the Children, 1988).

3.2.3 People

Most people in Sudan are of African origin (52%) while 39% are of Arabic origin (CIA, 2001). All village people that I talked to belonged to the Gawama'a tribe, which is the dominant tribe in Umm Ruwaba District. They originate from sedentary farmers, who descended from Nubians and Arabs from the North. When they settled in Kordofan during the 16th and 17th century, they mixed with the Nuba tribe and gradually replaced them. Around 6% of the population is nomadic (Save the Children, 1988).

People have lived in the Sahelian zone for thousands of years. This implies that human activity has always been a main factor influencing the savannah ecosystem (Le Houérou, 1989). According to Le Houérou (1989), the rural population density in the Sahelian zone is far beyond the estimated human supporting potential capacities.

Smallholders have a three-fold strategy of survival: (1) food production on a subsistence level, mainly millet (dukm) and sorghum (dura), (2) production of cash crops for sale on the market and (3) off-farm work during the dry period (Elmekki & Barker, 1993).

3.2.4 Agriculture and Land Use

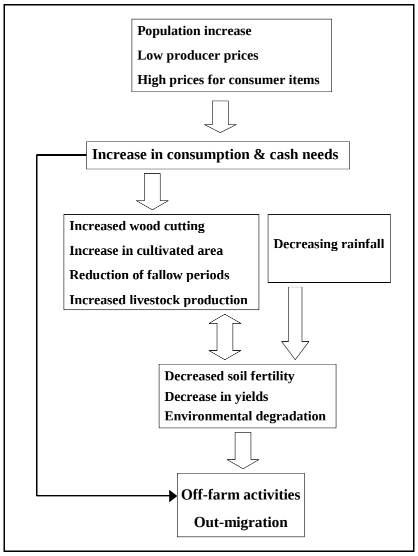

Figure 3.4: Simplistic model of economic and environmental change in Umm Ruwaba District, adapted from Save the Children (1988)

The study area is characterised by cultivation, grazing and livestock breeding (Khogali, 1991). Since the 1960s, the economic and environmental situation in the study area has worsened dramatically. During the last three to four decades, the population has increased, resulting in increased demand for food (Figure 3.4). Cultivation has become more or less continuous, but because of exhausted soils and a decline in rainfall, yields per area have decreased (Olsson, 1993; Elmekki & Barker, 1993). Once self-sufficient, the area is now dependant on subsidies and donations (Save the children, 1988; personal communication with Osama Tagelsir, director FNC Umm Ruwaba). Farming techniques have not improved over the past 40 years and the only way to improve food production was to enlarge the cultivated area. The area under cultivation increased seven-fold from 400 000 ha in 1960 to almost 3 million ha in 1980 (Save the Children, 1988). Today, soils are exhausted after years of woodcutting, cultivation and overgrazing (Buresh & Tian, 1998).

In the late 80s only 20-25% of the population migrated during dry season (Save the Children, 1988). Interviews revealed that migration to larger towns, mainly Khartoum, during dry period is as high as 50-80% today. Mainly men of different ages and young women migrate.

Figure 3.5: a millet crop (left side) and a millet field during dry season

The following is an example of an annual income of a farmer. Work in Khartoum yields around $80 per month over a maximum period of 9 months. This is a maximum amount of $720 for off-farm activities. Income from harvest depends very much on pests, market prices and soil fertility. During a normal year, farmers receive around $450-600 for their agricultural products. Additionally, the income through gum arabic yield might be around $400. It is obvious that the income earned by those who have migrated is an essential part of household income[5]. The agricultural production in the study area focuses on cash crops. The cultivation of cash crops - such as hibiscus (karkade), sesame (simsim), groundnuts (ful sudani) and

[5] Average numbers result from interviews made by Jakubaschk, C. in February 2002.

watermelon (bittikh) - has increased since the 1950s at the expense of cereal crops. Today, farmers only cover part of their millet and sorghum consumption with their own harvest (figure 3.5). To a large extent farmers rely on the market to purchase food (Save the Children, 1988).

3.2.5 Acacia senegal and Gum arabic

Crop rotation of *Acacia senegal* with sorghum or millet is the traditional agricultural system. The cropping period lasts 4 to 10 years, *Acacia senegal* fallow 10 to 20 years and gum tapping starts when the *Acacia* trees are 5 to 8 years old (Le Houérou, 1989; Gerakis & Tsangarakis, 1970). The predominance of *Acacia senegal* has evolved over generations through the systematic suppression of other trees and shrubs by the farmers (Save the Children, 1988). Fallowing is the predominant method in the tropics to reconstitute soil fertility and soil nutrients after the cropping period. During fallowing, soil bulk density decrease and soil porosity, soil moisture retention and soil organic matter increase; these improved soil properties enhance crop yields after fallow periods (Breman & Kessler, 1995).

During fallow periods, selling gum arabic is a traditional income source of smallholders (Seif el Din & Zarrong, 1996). Gum arabic is the natural resin, obtained by tapping the branches of the *Acacia senegal* tree (figure 3.6). It is mainly used in confectionery, flavourings, cosmetics and medicines (Seif el Din & Zarrong, 1996).

Figure 3.6: A farmer climbing a hashab tree to harvest gum arabic

Interviews with farmers revealed that 30 - 60% of *Acacia* trees died during the drought years. On average, only 6 - 25% of the villagers own and tap *Acacia senegal* trees today. In the 1960's, Sudan accounted for 90% of gum arabic on the world market (Larson & Bromley, 1991) and around half of the world's gum arabic was produced in Kordofan (Save the Children, 1988). In 1985 the volume of gum arabic sold at El Obeid crop market was only 5% of the volume sold in 1962 (Save the Children, 1988).

Keddeman (1994) stresses that demographic pressures and economic conditions are important factors for negligence and cutting of *Acacia senegal* trees, which leads to the shortening or disappearing of fallow periods. Low prices for gum arabic, budgeted by the state-controlled Gum Arabic Company, have discouraged farmers from growing trees and tapping (Save the Children, 1988). In 1991, due to considerable year-to-year variations in production and sale, a number of consumer countries had turned to synthetic substitutes (Larson & Bromley, 1991). As the government steers the prices, smallholders are used to adjust very fast to changing prices for their agricultural output and always try to cultivate the crops, which are likely to achieve the highest sales prices (Elmekki & Barker, 1993). If prices for gum arabic decrease in relation to food crops, farmers react by increasing the area used for crop production and thereby reduce the area of *Acacia senegal* woodlands.

However, the following positive characteristics may illustrate why *Acacia senegal* is an important part of the Sahelian environment.

- *Acacia senegal* fixes nitrogen in the soil during fallow periods and improves soil fertility (Gerakis & Tsangarakis, 1970).
- It is well adapted to the harsh environment of the Sahelian zone, with sandy soils and low rainfall (Olsson & Rapp, 1991).
- After the fallow period, the trees can be cut down and sold as fuel wood with a very high-energy content (Seif el Din & Zarrong, 1996).
- The pods and leaves serve as nutritious fodder for livestock (Seif el Din & Zarrong, 1996).
- The trees protect the soil against erosion (Gerakis & Tsangarakis, 1970, Lal, 2001b).

4 THEORETICAL BACKGROUND

4.1 The Carbon Cycle

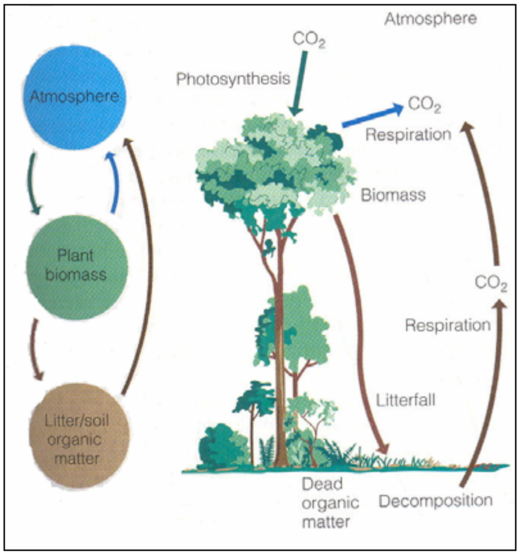

Figure 4.1: The carbon cycle (a) in pools and fluxes, (b) in terrestrial ecosystems, in Smith & Smith (1998)

Macronutrients are nutrients that plants need in large amounts. Carbon, nitrogen and phosphorus are some of the most important ones (Smith & Smith, 1998). Carbon is the basic building block of the carbohydrates, fats, proteins, nucleic acids (e.g. DNA) and all other organic compounds necessary for life (Miller, 2000). In general, plant roots are not permeable to organic molecules, which is why essential nutrient elements must be present in the soil solution in inorganic forms (Swift *et al*, 1979).

The source of carbon used by living organisms, is carbon dioxide (CO_2) from the atmosphere. The only process that can transform CO_2 into organic carbon is *photosynthesis*. Mainly green plants, also called the producers within an ecosystem, carry out photosynthesis by absorbing CO_2 from the atmosphere and converting it into simple sugars such as glucose ($C_6H_{12}O_6$) in the presence of the pigment chlorophyll and the enzyme rubisco[6] (Miller, 2000).

$$CO_2 + H_2O + sunlight \rightarrow C_6H_{12}O_6 + oxygen \qquad (1)$$

The plant then transforms the sugars into more complex carbon compounds, which build up leaves, stems, roots, flowers and seeds (Smith & Smith, 1998). The energy accumulated by plants is called primary production The total energy received through photosynthesis is called *gross primary production* (GPP). For production, maintenance and reproduction, plants need energy, which is liberated by respiration (R). Respiration converts glucose to CO_2. The energy that remains after the respiration is stored as organic matter, also called *net primary production* (NPP) (Smith & Smith, 1998):

$$NPP = GPP - R \qquad (2)$$

Water availability, nutrient availability and vegetation are the three main factors that control primary productivity in savannahs (Breymeyer *et al*, 1996).

CO_2 makes up only 0.036% of the volume of the troposphere but it is the driving element of the carbon cycle (Smith & Smith, 1998). Figure 4.1 shows a simplified model of the carbon cycle on land. Producers carry out photosynthesis while Consumers (such as animals and humans) and decomposers (such as bacteria) carry out aerobic respiration using the oxygen

[6] Chlorophyll is a pigment that absorbs energy from light, which helps to split the water molecule during the reaction. Rubisco catalyses the transformation of CO_2 into sugar.

produced through photosynthesis. Microorganisms decompose plant and animal litter and carbon bound in organic compounds is released back into the atmosphere as CO_2. The global carbon cycle depends on the movement of carbon (carbon fluxes) between global carbon pools. The largest carbon pool is the deep ocean, followed by the soil (the largest carbon pool on land), biota, the surface water and the atmosphere (Harvey, 2000).

4.2 The Nitrogen Cycle

4.2.1 The Nitrogen Cycle

Most of the nitrogen available exists in the form of N_2 in the atmosphere, which plants cannot take up. Plants only use inorganic nitrogen, mainly as ammonium (NH_4+), and nitrate (NO_3-) (Smith & Smith, 1998). The nitrogen cycle can be separated into different processes (Figure 4.3).

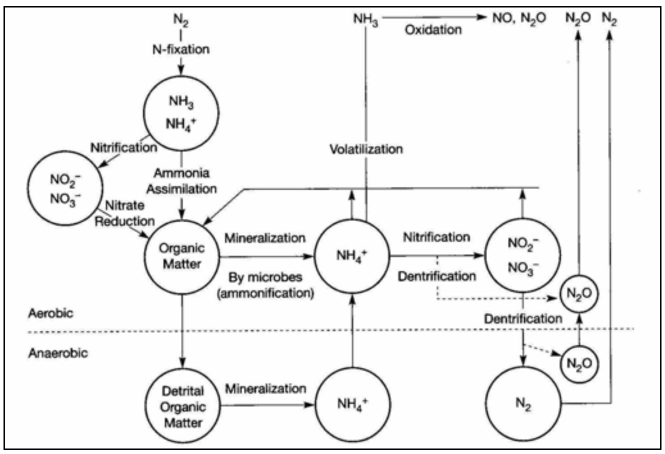

Figure 4.3: The nitrogen cycle, in Harvey (2000)

Nitrogen fixation is the process that converts N_2 into ammonia (NH_3). This is done by bacteria and blue-green algae. They exist either freely in soil or water or form symbiotic relationships with roots of higher plants (Sitte *et al*, 1998). When NH_3 reacts with water, NH_4+ is formed. The only plants that can "produce" nitrogen ready for take-up are leguminous plants. They form a symbiosis with nitrogen fixing bacteria living in their root nodules (Sitte *et al*, 1998). While the bacteria convert N_2 into a form usable by the plants, the plants provide the bacteria with some simple carbohydrates (Miller, 2000). In addition to the biological nitrogen fixation – accounting for around 140 x 10^6 t $year^{-1}$ - lightening fixes a small quantity of N_2 (Schlesinger, 1997).

Plants use NH_4+ either directly or bacteria convert it into NO_2 (nitrite)– which is toxic to plants - and than into NO_3-; this conversion is called *nitrification* (Miller, 2000). According to Bernhard-Reversat & Poupon (1980), most nitrogen in semi-arid regions is produced as NO_3- while the production of NH_4+ is very low.

Through the process of *assimilation*, plant roots absorb the available inorganic nitrogen and convert it to organic compounds (Sitte *et al*, 1998). Microorganisms and microbes decompose the plant litter. This process converts the nitrogen bounded in organic compounds back in its inorganic form. These processes make NH_4+ again available for plant use and are called *mineralisation* or *ammonification* (Swift *et al*, 1979). During *denitrification* specialised bacteria turn NH_3 and NH_4+ back into NO_3- and NO_2-, which is then reverted to N_2 and nitrous oxide gas (N_2O) (Miller, 2000).

Nitrogen affects the rate of photosynthesis because it is an essential building block of chlorophyll and the enzyme rubisco (Smith & Smith, 1998). In semi-arid areas, the available nitrogen is a factor limiting NPP (Schlesinger, 1997). This is why leguminous plants are important and recurrent in these regions (Sitte *et al*, 1998). Rainfall controls the nitrogen cycle in semi-arid regions as it limits vegetation growth and thus nitrogen utilization and return and controls nitrogen production by decomposition (Bernhard-Reversat & Poupon, 1980).

The C:N ratio takes into account the total (inorganic and organic) amount of carbon and nitrogen that is available in the soil. At any time, the pool of inorganic nitrogen (NH_4+ and NO_3-) in the soil is very small because plants take it up so rapidly that little nitrogen remains in inorganic form although the annual flux through the soil pool is large (Schlesinger, 1997). The C:N ratio has a strong influence on the decomposition of organic material. If the nitrogen content in the soil increases, e.g. through litterfall of plants with high nitrogen content, decomposition of SOC decreases. A reason for this is that microorganisms decompose as they are in need of nitrogen (Ågren & Bosatta, 1996). If a lot of nitrogen is available, they have to decompose less organic matter in order to satisfy their needs. If decomposition and therefore respiration decreases, the amount of CO_2 released to the atmosphere decreases and the SOC content increases. The C:N ratio varies with regard to different soil types and different types of organic material. In forests, for example, the ratio is around 20, but varying up to 100 for ecosystems with low decomposition and down to 10 for well decomposed organic material [2].

Nitrogen and carbon are interdependent. Leguminous plants need energy to fix nitrogen and they receive this energy by respiring organic carbon (Schlesinger, 1997). This means that there is a dependence of nitrogen fixation on organic carbon availability in plants. On the other hand – as mentioned before - the SOC content cannot be increased without simultaneously increasing the nitrogen content (Brady, 1990).

4.2.2 Acacia senegal and Nitrogen

Throughout the study, I assume that *Acacia senegal* fixes nitrogen. Several studies have revealed higher nitrogen contents under *Acacia senegal* compared to open ground or other tree species (Gerakis & Tsangarakis, 1970; Bernhard-Reversat & Poupon, 1980; El Tahir *et al*, 2002). For example, El Tahir *et al* (2002) investigated the soils under *Acacia senegal, Acacia seyal* and *Acacia tortillis* where *Acacia senegal* showed the highest nitrogen content.

However, this fact is not generally accepted. Bosch (1991) compared N, C and P contents under *Acacia senegal* fields and other land uses and did not find increased nitrogen contents under *Acacia senegal*. Research in the nursery at the Agricultural Research Station (ARC) in El Obeid showed that *Acacia senegal* trees only had nodules during the first four months, after that there is no evidence that *Acacia senegal* is fixing nitrogen (personal communication B. A. El Tahir, director of ARC El Obeid). Breman & Kessler (1995) state that nodulation on roots of *Acacia senegal* is limited in Sudan. Bernhard-Reversat & Poupon (1980) studied the nitrogen cycle of *Acacia senegal* in semi-arid Senegal. They state that investigated adult trees did not have nodules and assume that symbiotic fixation occurs only during the first years of tree life. According to Breman & Kessler (1995) and Buresh & Tian (1998) it is very difficult to estimate N_2 fixation and to find out if trees continue to fix N_2 during their growth. This is a reason why estimations vary strongly.

Even if *Acacia senegal* does not fix nitrogen from the atmosphere it is acknowledged that the nitrogen content under *Acacia senegal* is 2.5 to 3 times higher than under open ground (Bernhard-Reversat & Poupon, 1980). Nitrogen is returned to the soil by tree litter, leaching of leaves and branches by throughfall, herbaceous litter and roots. The plant nitrogen is mineralised and made available for plant uptake again. According to Bernhard-Reversat (1982), nitrogen mineralisation beneath *Acacia senegal* in semi-arid regions, peaks in June and August and decreases sharply in September before the end of the rainy season. During the rest of the year, nitrogen production is almost zero.

According to Bernhard-Reversat (1993), *Acacia senegal* litter contains more nitrogen than other tree species and the litter is decomposed very fast compared with litter of other tree species. As mentioned earlier, nitrogen is a limiting factor in the study area and if plant litter with high nitrogen content becomes available, it is decomposed extremely fast until the saturation level. The above-mentioned statements of Ågren & Bosatta (1996) explain the processes in areas where nitrogen is not limiting plant growth.

4.3 Decomposition and Soil Organic Matter (SOM)

According to Brady (1990), SOM "is the organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population". SOM is transformed continually and it lasts in the soil from a couple of hours to hundreds of years. SOM content of soils is low, although its influence on soil properties is strong. SOM increases water-holding capacity and is the major source of nutrients, such as nitrogen, phosphorus and sulphur. Further, it is the main source of energy for soil organisms, which means that soil fauna activity almost ceases if no SOM is available. SOM improves soil cation exchange capacity[7] (CEC) and soil aggregate stability which effects soil aeration, resistance to erosion, infiltration capacity and soil moisture retention (Breman & Kessler, 1995). An increase in SOM adds to soil fertility and crop production (Schlesinger, 1999). Around 58% of SOM is carbon (Post et al, 1999).

Decomposition occurs when chemicals in plant residues are broken down or drastically modified by soil organisms (Brady, 1990). The three main factors influencing decomposition are environmental conditions (moisture, temperature, oxygen, soil texture, soil nutrients), litter quality and the soil fauna (Breman & Kessler, 1995). In savannahs, litter accumulates on the soil surface during the dry season. During the rainy season, decomposition is rapid and the decomposition rate is much higher than the litter fall rate (Breman & Kessler, 1995). Nitrogen and lignin contents, precipitation and temperature are mainly controlling litter decomposition (Bernhard-Reversat, 1993). Litter and root production provide the main input of SOM.

In savannahs the major litter input site is below-ground (Schlesinger, 1997). Fine roots often contribute the majority of below-ground production (Jackson *et al*, 1996). Within ecosystems, decomposition performs two major functions: (1) the mineralisation of essential elements and (2) the formation of SOM (Swift *et al*, 1979). However, these two functions are conflicting. A high nutrient input to the soil requires a high decomposition rate while maintenance of SOM content requires a low decomposition rate (Breman & Kessler, 1995). In regions with dry periods the decomposition rate varies strongly during the year. During the rainy period, mainly in August and September, most of the litter material is decomposed while from November to May almost no decomposition occurs.

[7] CEC is defined as the sum total of the exchangeable cations that a soil can absorb. It quantifies the ability of a soil to provide a nutrient reserve for plant uptake (Brady, 1990).

4.4 Global Warming

4.4.1 The Kyoto Protocol

Over the 20th century, global average surface temperature has increased by 0.6 ± 0.2°C [8] and the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100 (IPCC, 2001). Human activities have increased the content of the key greenhouse gases CO_2, methane (CH_4) and nitrous oxide (N_2H) [2]. The concentration of CO_2 in the atmosphere has increased by 31% since 1750. About three-quarters of the anthropogenic emissions of CO_2 to the atmosphere during the past 20 years was due to fossil fuel burning while the remaining part is mainly due to land use change, especially deforestation (IPCC, 2001). It is very difficult to predict CO_2 concentration as it responds to changing climate on time scales ranging from a couple of months to thousands of years (Harvey, 2000). For example, several centuries after CO_2 emissions have occurred, about a quarter of the increase in CO_2 concentration caused by these emissions is still present in the atmosphere (IPCC, 2001).

In 1994, the United Nations Framework Convention on Climate Change (UNFCCC) entered into force. Its goal is to stabilize global greenhouse gases in the atmosphere at a level that prevents further anthropogenic interference with the climate system [4]. An important principle is that the industrialized countries, which are mainly responsible for emissions and thus for climate change, have the main financial burden to bear. As they are listed in *Annex I* of the Convention, they are also called *Annex I* countries while developing countries are called *Annex II* countries.

In 1997, at the third session of the conference of the parties (COP 3) in Kyoto, the Kyoto Protocol was adopted. As of September 2002, 74 countries had ratified [5] the Kyoto Protocol accounting for around 40% of world’s emissions. As soon as 55 countries, accounting for 55% of the world’s emissions in 1990, have ratified the document, it will come into force 90 days after the last ratification. Some of the countries responsible for most of the emissions today, e.g. the USA, Australia, China, the Russian Federation and the Newly Industrialized Countries such as Brazil, Malaysia and Thailand, have not yet signed [6]. The United States accounted for 36% of total emissions by industrialized countries in 1990, which is why it is very unlikely that the Kyoto Protocol will come into force if the US does not ratify (Holtsmark & Alfsen, 1998).

The Kyoto Protocol is the first document containing concrete and binding commitments for the *Annex I* countries to reduce greenhouse gas emissions. From 2008 to 2012 (the first commitment period), the industrialized countries must reduce their emissions of the six main greenhouse gases[9] by at least five percent compared to 1990. Burdens are distributed differently from country to country. *Annex II* countries don’t have any commitments while *Annex I* parties have different possibilities to meet their emission reduction targets [7]. At the domestic level, countries are free to choose the policies that are best suited. At the international level, the Protocol allows the implementation of so-called “flexible mechanisms”: (1) International Emission Trading, (2) Joint Implementation and (3) the Clean Development Mechanism (CDM).

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[8] IPCC publications refer to the term climate change as any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2001).

[9] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF6) (IPCC, 2001).

These instruments allow the trading of carbon quotas between countries. For this study, only the CDM, stated in Article 12 of the Protocol, is of importance. Its objective is to assist developing countries in achieving sustainable development with respect to greenhouse gas emissions and to assist industrialized countries in achieving their commitments under the Kyoto Protocol. It allows industrialized countries to move some of their emission reduction efforts into the developing world. Developing countries will benefit from reduction projects taking part in their countries, as they will receive certified emission quotas corresponding to the achieved emission reductions while industrialized countries can buy these quotas and cover in this way some of their reduction commitments (Holtsmark & Alfsen, 1998).

In the future, it might be difficult to determine the net emission reduction effects of CDM projects, especially as both - *Annex I* and *Annex II* countries - might be interested in exaggerating amounts of emission reductions (Holtsmark & Alfsen, 1998). Reasons why Africa could be set back in the run for CDM project money are low emission reduction potential, deficient institutional capacity and a weak private sector (Brooke & Turkson, 1999).

4.4.2 Carbon Sinks

The sequestration of atmospheric carbon in terrestrial sinks such as biomass and soils might be a possible way to reduce CO_2 contents in the atmosphere. This idea is one of the most controversial issues discussed within the Kyoto Protocol. Critics state that the accounting of soil carbon sinks might delay real emission reductions and the monitoring and verification of carbon sinks is difficult and expensive (Olsson & Ardö, 2002). When comparing the benefits of carbon sinks in biomass or soils, there are clear advantages of the latter: carbon stored in agricultural soils is less likely to be released than that in forests, as it contributes to soil fertility, soil carbon has a longer residence time compared with above-ground vegetation and there are clear social and economic benefits for people that own the agricultural land (Olsson & Ardö, 2002). Often the option of carbon sinks is stated as a possibility to buy time until better technologies and possibilities have been found to reduce fossil fuel emissions (Ringius, 1999).

4.5 Synthesis

Schlesinger (1999, 2000) states that agricultural practices such as nitrogen fertilisation, manure or irrigation contain “hidden carbon costs” in terms of emissions of CO_2 to the atmosphere. For irrigation, energy is needed to pump the water on the fields. Industrial production of nitrogen fertiliser is highly dependent on fossil fuels and the demand for fertilisers for food production is increasing worldwide. For this reason, there is renewed interest in biological nitrogen fixation as an alternative or supplement of chemical nitrogen fertiliser (Marschner, 1995).

Andrén & Kätterer (2001a) modelled the SOC content for different carbon inputs. They state that the increase of SOC is low for a doubling of carbon input, as around 50% of the crop residues are lost in respiration, which means increased CO_2 emissions to the atmosphere. Therefore, low input agricultural systems, e.g. in semi-arid areas, might have a higher potential for *net* carbon sequestration than intensive agricultural systems. Schlesinger (2000) advocates the regrowth of natural vegetation on abandoned agricultural land in order to receive a small sink for carbon in soils instead of the intensification of existing agricultural activities. The management practice is one of the most important features of how to keep carbon in the soil. Due to inappropriate land use and management practices, many soils in Africa are degraded and are therefore below their potential organic carbon levels (Batjes, 2001).

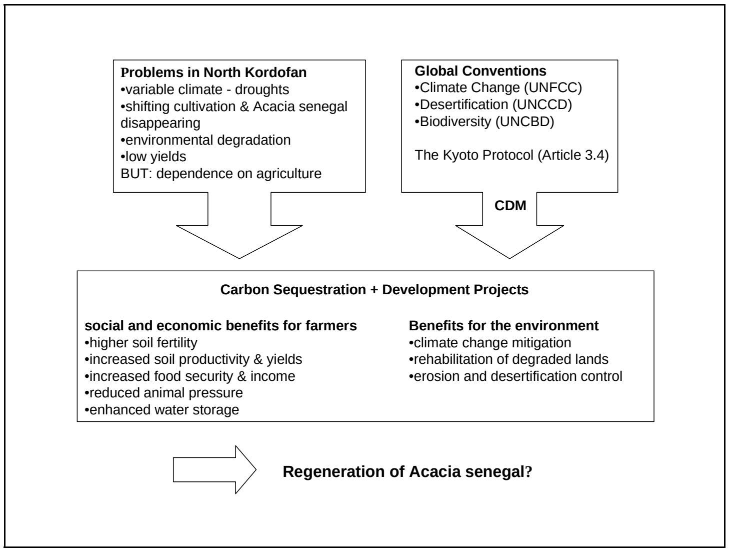

Figure 5.1: The framework of this study, partly adapted and modified after Tschakert (2001)

The regeneration of *Acacia senegal* might be a concept that combines climate change mitigation through carbon sequestration with socioeconomic benefits for the local population and environmental benefits (figure 5.1). The idea of regenerating *Acacia senegal* stands is not new. At least 10 internationally financed projects had been undertaken during the 80s and 90s in North Kordofan focusing on desertification control by reforestation of *Acacia senegal*; the largest one (“Restocking of the Gumbelt for Desertification Control”) – under the direction of UNSO and the Dutch government - ceased in 1994 (Keddeman, 1994). Carbon sequestration could be a new dimension in these kinds of projects following careful investigation of *Acacia senegal*’s potential to sequester carbon.

5 METHODS

5.1 Fieldwork

The fieldwork was carried out in the surroundings of Umm Ruwaba. It was divided into three parts: Interviewing smallholders[10], soil sampling and measuring biomass.

The following five land uses were investigated in this study:

- Fallow fields with *Acacia senegal* (*Fallow$_A$*)
- Fallow fields without *Acacia senegal* (*Fallow*)
- Crop fields (*Crops*)
- Virgin sites with *Acacia senegal* (*Virgin$_A$*)
- Virgin sites without *Acacia senegal* (*Virgin*)

As mentioned above, *Fallow$_A$* is a component of the traditional system of shifting cultivation. The density of the stands in the study area varied strongly. Most of the *Acacia senegal* stands were tapped. Collection of soil samples focused on old stands of around 15 to 20 years. This is the age at which the trees stop producing gum. They are cut down to ankle or knee height and the land is cleared for cultivation. For comparison, patches of *Fallow* sampled should have approximately the same age as those of *Fallow$_A$*. The patches of *Crops* used for sampling should be cultivated for at least one to two decades. During the dry season, animals graze on the fields. A V*irgin* site is an area with as small human impact (grazing, cultivation etc.) as possible. Soils of *Virgin* sites reflect a steady state condition for the soil in terms of organic matter content; therefore the carbon content of a soil in its native state usually is a good indicator of the sequestration potential of the soil (Cheng & Kimble, 2001). As all sites were not fenced or guarded the fields where samples were collected were grazed.

An attempt was made to cover all directions starting in Umm Ruwaba. As there is only one road in East-West direction passing through Umm Ruwaba, it was difficult to reach villages situated far to the North or South of Umm Ruwaba. *Gardud* soils dominate South of Umm Ruwaba. Hence, samples from sites far south were not collected. The selected villages are situated close to the road. Through a group interview with the head of the village ("sheik") and as many farmers as possible, fields that could be classified as one of the five land uses selected for the study were identified. The farmer himself or any person that knew land use and land use history of the fields guided the research team to the site. On the field, an area of 20 m by 20 m that corresponded to the average vegetation cover was studied. In accordance with Bosch's study, the fields chosen did not have a slope more than 3% and were not situated in an accumulation or erosion position (Bosch, 1991).

5.1.1 GPS Recording and Processing of Data

The position in the centre of each field was measured with a GPS, using the WGS84 map datum and the UTM projection. The GPS measures with an accuracy of ± 10 m (Ardö & Olsson, 2002b), which was accurate enough for the purpose of this study. The GPS data was used to visualise the soil sample sites in the study area.

[10] The results of the qualitative interviews described in chapter 3.2 are not mentioned here. The interviews conducted for fieldwork were restricted to information needed for soil sampling and biomass measurements.

5.1.2 Soil Sampling

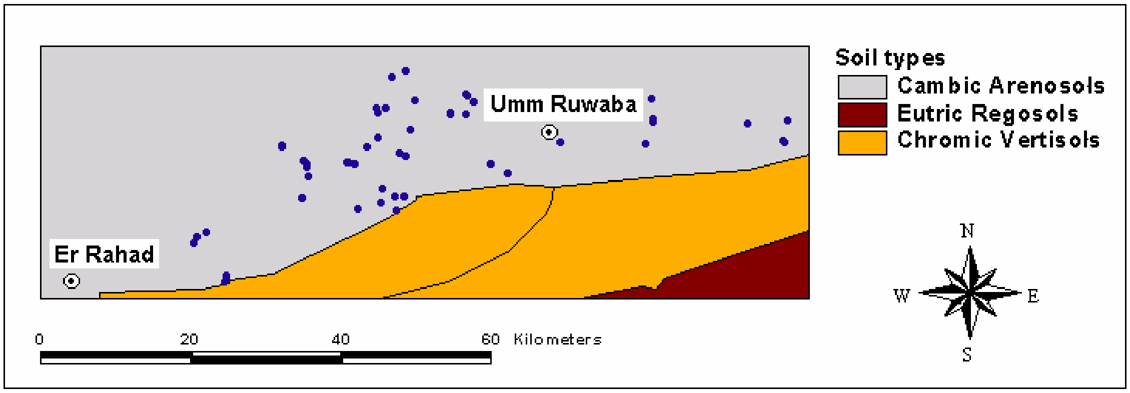

Figure 5.1: The study area, each point indicates the centre of a field (20 m times 20 m).

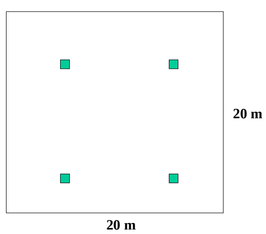

Figure 5.2: Draft of how the soil samples should be scattered in the field

Figure 5.1 shows the soil sample sites. Each point indicates a field of 20 m by 20 m. The field was staked with four sticks. On each field, four sites were selected (Figure 5.2). At each site, samples were taken at 0-20 cm depth and at most sites at 20-50 cm depth. As short-term effects - e.g. grazing, fire or accumulation through wind - influence the topsoil, samples were taken at different depths. As a general rule of thumb, the amount of soil should be at least 100 times as large as the sample to be collected (Kimble *et al*, 2001). The samples of each field, which were taken at the same depth, were thoroughly mixed in a big bowl and around 50 g were taken out of the mixed sample (Figure 5.3) (Deans *et al*, 1999).

On each field, the following information was gathered: land use and land use history, vegetation type and the soil type. On crop fields, information about cultivation methods and crop rotation was also gathered. Table 5.1 illustrates how the information needed was compiled. Appendix 2 includes the soil sample and biomass protocol as well as the soil sample questionnaire.

Table 5.1: Collected information on soil sample sites (for each field)

Information	**Gathering**
Geographical position	Determination with a GPS receiver, chapter 6.1.1
Vegetation type	Biomass protocol, see appendix 3
Recent land use, land use history	Soil sample protocol, see appendix 3
Cultivation methods on the crop field	Soil sample protocol, see appendix 3
Soil type	FAO soil database 1995 & 1998
Amount of biomass production/ year	Combination of estimation and measurement, chapter 6.1.3
Climate data	Climate station in El Obeid
Soil texture	Soil sampling
Carbon and nitrogen content of the soil	Soil sampling

Figure 5.3: The interpreter and the driver during soil sampling: with the stick (in the sample hole) we measured the depth and with the spade I scratched along the side of the hole to receive the soil. Then we mixed the sample in the bowl and put around 50 g into a plastic bag.

On fields with *Acacia senegal* or other trees, attention was paid to the fact that soil fertility beneath tree crowns often is higher than in areas distant to trees (Deans *et al*, 1999; Gerakis & Tsangarakis, 1970). Thus, soil samples were taken as far away from trees as possible. This implies that the real soil sample sites on fields with trees differ from the draft in Figure 5.2. Additionally, I took three soil samples to define the soil texture (around 300 g per sample). The soil type in the study area – according to the FAO soil map and my own observations – was consistent and therefore only a small amount of soil texture samples were taken.

5.1.3 Biomass Measurements and Estimations

The annual amount of carbon is an input to the ICBM model. As the available biomass is a crucial factor for how much carbon is available, it is necessary to estimate the amount of biomass produced per year on each site. Only a fraction of the produced biomass per year becomes litter while organic matter is only a fraction of this litter input. The biomass production can be divided into three different parts, 1) *Acacia senegal*, 2) all other tree species 3) grass and 4) crop fields. Each part is discussed separately, listing the measurements made, calculation of biomass, amount of litter year^{-1} and amount of organic matter year^{-1}.

Acacia senegal

Each field was studied visually and species composition and number of trees were noted. If there were trees on the field, one average tree of each species was chosen as a representative for the whole group. Trees and shrubs less than 50 cm large were not counted as trees.

The method of measuring and estimating the dry biomass of *Acacia senegal* follows Deans *et al* (1999), who studied the biomass in five *Acacia senegal* plantations of different ages in North Senegal. They found out that the tree biomass increased linearly from age 3 to 18 and that the biomass was linearly related to the measured stem cross-sectional area (CSA) at 30 cm height. Therefore, I measured the CSA at 30 cm height. If trees were multi-stemmed, all stems were measured and the diameters summed up (Rosenschein *et al*, 1999). The total aboveground biomass (in g) for *Acacia senegal* trees can be calculated as

$$y = 3.71 + 4.12 \times CSA \qquad \text{with } r^2 = 0.97 \qquad (3)$$

The fine-root biomass can be calculated as

$$y = 23.4 \times CSA^{0.512} \qquad \text{with } r^2 = 0.8 \qquad (4)$$

and the coarse-root biomass as

$$y = 0.0004 \times CSA^{1.737} \quad \text{with } r^2 = 0.89 \tag{5}$$

Deans *et al* (1999) estimated the belowground biomass to be 20%, aboveground biomass around 80% of total biomass of a tree at age 18.

Other tree species

Measurements for all other types of trees included CSA at breast height, canopy diameter, height and total number of stems. There were no equations available that allowed the biomass estimation of the specific tree species in this study. Olsson (1985) developed an equation for tree biomass estimation through destructive measurements of 39 trees in North Kordofan region[11]:

$$Y = 0.19 + 1.28 * X \quad \text{with } r^2 = 0.94 \tag{6}$$

where Y = $\log_{10}$ wet weight in kg and X = $\log_{10}$ squared crown diameter.
Olsson's method only describes above-ground biomass. As the data had to be comparable to the estimations for *Acacia senegal* trees, an equal root:shoot ratio of 0.2 was estimated. Additionally, wet weight was transformed into dry weight and water content was assumed to be 75% (Brady, 1990). Consequently, the equation became

$$Y = (0.19 + 1.28 * X) * 1.2 * 0.25 \tag{7}$$

Annual tree litter was assumed to be 16 % of total tree biomass (Tiessen *et al*, 1998).

Grass

As fieldwork was conducted during the dry season, the seasonal grass vegetation could not be measured. Instead, the annual biomass production was estimated from literature. Grass height, percentage of cover and local name were noted. Jackson *et al* (1996) describe the root biomass (dry weight) and root:shoot ratio for tropical grassland savannah, which allows calculating the total biomass (Table 5.2). Grass growth occurs only during the wet season while Jackson's value stands for tropical grasslands having water almost all year round. Therefore, Jackson's value was divided by three, accounting for the growing season of around four months in the study area. Further, the assumption was made that grazing diminishes the annual grass biomass by 50% (Tiessen *et al*, 1998). *Total biomass*$_{SA}$ is the grass dry weight in kg for 1 m^2 in the study area. Most of the time, the study sites had a mixed vegetation of scattered trees and grassland which means that *Total biomass*$_{SA}$ had to be multiplied by the fraction of grass cover that had been estimated.

Table 5.2: Biomass estimations for tropical grassland savannah in kg m^{-2}, source: A and B: Jackson et al (1996); C, D and E: calculations based on A and B. Total biomass$_{SA}$ is the grass dry weight in the study area in kg for 1 m^2.

A Root biomass	B Root/shoot ratio	C Biomass above-ground	D Total biomass	E Total biomass$_{SA}$
1.4	0.7	2	3.4	0.565

[11] The tree species included in the destructive measurements of Olsson (1985) were *Acacia albida*, *Acacia mellifera*, *Acacia senegal*, *Acacia seyal*, *Acacia tortillas*, *Andansonia digitata*, *Albizzia amara*, *Balanites aegyptiaca*, *Boscia senegalensis*, *Commiphora africana*, *Guiera senegalensis* and *Leptadenia pyrotechnica*.

Crop fields

Almost no above-ground crop biomass is left on the fields (Interviews, February, 2002). Hay and straw is used as building material. After the harvest and during the dry season, camels, goats and sheep graze the fields. In May, the crop remnants are piled up and burnt before the next sowing. This means that the crop remnants are only left on the field during dry season, when almost no decomposition occurs and the litter that is left in the beginning of May is burnt before the rainy season starts. This implies that only the root biomass of the crops of the year before which are still in the ground can be decomposed during rainy season (Tiessen *et al*, 1998). An additional input is manure from grazing animals, but this factor is very difficult to specify and is therefore left aside. The biomass estimation of the crop fields is based on calculations using the estimations of the field owners concerning their last yield and the biomass measurements of Elhag (1992) and Osman (2001) (table 5.3).

Table 5.3: Biomass of different crops (dry weight) in kg ha^{-1}

Crop	Hay/straw yield	Grain yield (G)	Total biomass	Grain yield in % of total biomass (G_p)
Millet	517	119	636	18.7
Sorghum	800	131	931	14.1
Sesame	239	136	375	36.3
Groundnut	714	343	1057	32.5

Source: Elhag, F.M.A. (1992) and Osman, A.K. (2001)

Using the data in table 5.3, the percentage of the grain yield of the total biomass (G_p) was calculated. The total biomass (Y) transformed to kg m^{-2} is calculated as

$$Y = \frac{G}{G_p * 100} \qquad (8)$$

According to Jackson *et al* (1996), the root:shoot ratio for crops is 0.1. Therefore, the root biomass (Y_r) is

$$Y_r = Y * 0.1 \qquad (9)$$

5.2 Analyses of Soil Samples

5.2.1 Bulk Density

Ardö & Olsson (2002b) measured a bulk density of 1.711 in the study area, using 10 samples collected in February 2001. The bulk density is the density of the undisturbed soil, which takes into account the density of the soil materials themselves, and their arrangement and structure. Bulk density is calculated using following equation:

$$Bulk\,density = \frac{Weight\ of\ a\ dry\ block\ of\ soil\ (g)}{Volume\ of\ block\ when\ sampled\ (cm^3)} \qquad (10)$$

A loose porous soil will have a smaller bulk density as a compact soil although the density of the soil material itself is the same. For example, the bulk density for cultivated soil may vary between 0.55 and 2.0 (Fitzpatrick, 1991).

5.2.2 Carbon

Soil samples were analysed for carbon and nitrogen at the laboratory of Plant Ecology, Lund University. As the results of the analyses will be used within other research projects at MICLU, it was necessary to conduct the analyses at the same laboratory. All samples were dried at 85°C for about 24 hours. Soil carbon was analysed using the Carbon Determinator LECO CR-12, which analyses organic and inorganic carbon. A sample of 4.5 g was put into a combustion boat and pushed into the oven. It was burnt at 1300°C and the carbon oxidized to CO_2. An infrared detector sensed the CO_2. A built-in microcomputer calculated the carbon concentration in percent of the weighed quantity of the sample. LECO CR-12 calculates carbon contents down to 0.01% of the weighed sample and its precision lies around ± 1% of the carbon content of the sample.

In the beginning and after each 20th sample processed, the device had to be calibrated using $CaCO_3$ which contains precisely 12% carbon. During calibration, the machine analyses three samples with 100-150g of $CaCO_3$ and calculates the mean of the results in percent. The mean is then equated with 12%. The Carbon Determinator calculates carbon in percent, but most authors refer to carbon contents in g m^{-2}. The use of the same unit simplifies to compare the results. The carbon content was calculated for 1 m^2 with a depth of 20 cm for soil samples taken at 0-20 cm depth and 30 cm for soil samples taken at 20-50 cm depth.

The bulk density (in g cm^{-3}) was multiplied with 10 000[12] to receive the weight of 1 cm covering 1 m^2. The result was multiplied with 20 and 30 respectively, which stand for the depth of the soil sample taken. This number was then multiplied with the percentage rate of carbon (Young, 1976).

$$C_1 = (Bulk\ density \times 10000) \times 20 \times \frac{C_0}{100} \tag{11}$$

C_1 is the output carbon content in g m^{-2} and C_0 is the carbon content in percent. As the carbon content of the soil samples is low, the precision of measurement results might be low. Therefore 25 soil samples were analysed twice in order to see if there was a high difference between the results. This was not the case. The average deviation was 0.0096%. This is a negligible quantity.

5.2.3 Nitrogen

Nitrogen content was calculated using the Kjeldahl method, which analyses organic nitrogen and ammonium (NH_4+). This is almost the total nitrogen content in plants, animals and soil matter. Nitrate (NO_3-) is not quantified (Ekologisk Metodik, 1981).

First, 1.5 g of the soil sample was weighed and placed into a test tube to which metallic sulphate (100g K_2SO_4 and 10g $CuSO_4$ * $5H_20$), a catalyst, and sulphuric acid (H_2SO_4) were added. The samples were heated to 360°C. During this process all proteins are split up and the organic nitrogen is converted into ammonia. The sample was diluted with deionised water to 100 ml. Then it was analysed for Total Kjeldahl Nitrogen using a Flow Injection Analyser (FIA). The instrument used was built by Foss Tecator (model 5012, detector model 5042). The instrument detects within the area of 10–1000 μg/l. The aqueous sample was injected into a carrier stream and mixed with sodium hydroxide. The joint stream passes along a PTFE membrane in a gas diffusion cell. The ammonia gas formed diffuses through the membrane

[12] $1m^2 = (100 \times 100)\ cm^2$

into an indicator stream. The resulting colour change of the indicator, which is proportional to the amount of ammonia in the sample, is measured at 590 nm.
The resulting amount of nitrogen is given in μmol l^{-1}. A more common unit for nitrogen is $\mu g\ g^{-1}$, which can be calculated using the following equation[13]:

$$N\, in\, \mu g\, g^{-1} = \frac{N_O * V * W_N * k}{W} \qquad (12)$$

N_0 is the nitrogen content in μmol l^{-1}, V is the total volume, W_N is the weight of nitrogen in g mol^{-1} and W is the weight quantity of the sample (1.5 g). In some cases, the sample was diluted twice or three times because the nitrogen concentration was too high to be detected by the FIA. The constant k indicates if the sample was diluted, e.g. if the sample was diluted to its double quantity, k equals 2.

5.2.4 Soil Texture

Soil texture is the proportion of different sized soil particles. The particles are separated into the diameter sizes clay (< 0.002), silt (0.002–0.06) and sand (0.06–2.0) measured in mm. (Fitzpatrick, 1991). The samples were analysed at the laboratory of Quaternary Geology, Lund University. The samples were sieved to wash away particles less than 0.06 mm. As the samples consisted mainly of sand, sieving was sufficient to detect the distribution of particle size.

5.3 The Introductory Carbon Balance Model

The third objective of this research study is to determine if the SOC content simulated with the ICBM are similar to my field observations. For better understanding, the hypothesis is as follows:

H_0: There is no difference between the modelled carbon values and the observed carbon values of the five different land uses.

5.3.1 Why Modelling?

A mathematical model tries to explain reality by interconnecting mathematical equations, which show and calculate processes within an ecosystem. Conducting experiments with the model develops a deeper understanding of the modelled ecosystem. Modelling can be used to elaborate appropriate regional strategies and to forecast future scenarios of ecosystem dynamics. By simulating the SOC content of different land uses and management practices over a defined time period, the dynamics can be evaluated and it can be estimated which strategy is most appropriate in the context of carbon sequestration. Most models, e.g. the CENTURY model are very complicated and it takes a lot of effort to understand the structure and assumptions behind. The ICBM focuses on the main processes and might thus be an easy tool to make first assessments of carbon sequestration suitability of different areas.

5.3.2 The Model Structure and Equations

The Introductory Carbon Balance Model (ICBM) is a simple model that is usually applied for a 30-years period with a 1-year time step. It can be used to predict the effects of changed inputs, climate, initial pools, litter quality etc. on soil carbon pools. It only includes processes that are comparatively well known and models the topsoil in 0-25 cm depth. Structure and equations are explained in Andrén & Kätterer (1997). The model can be applied using spreadsheets, e.g. in Excel. The files can be easily downloaded from the Internet [8]. Until

[13] Personal communication with Tommy Olsson, March 2002

today the model has been applied in Northern Europe and no study has been made that shows if and how the ICBM can be applied to semi-arid conditions.

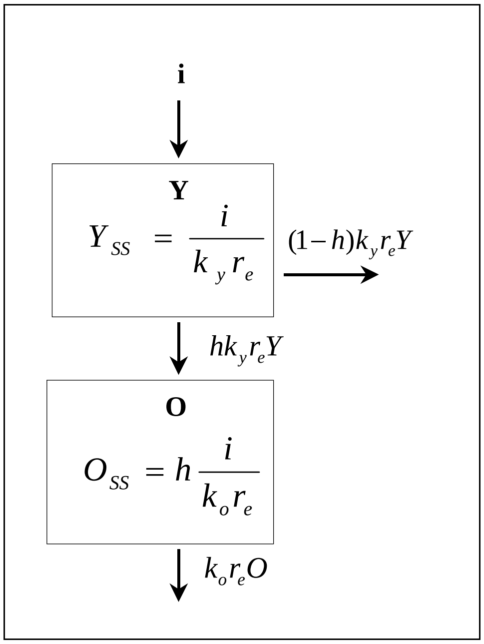

Figure 5.4: The structure of the ICBM [8]

The model has two pools - young (*Y*) and old soil carbon (*O*). It includes five parameters: The decay constants k_y and k_o, the mean annual carbon input *i*, the humification coefficient *h* and factor r_e (figure 5.4 and table 5.5). Y_{ss} and O_{ss} stand for the two pools in steady-state conditions.

All external factors (climate and land management practices) and edaphic factors (soil type) are condensed in r_e. There is no precise definition of what should be included in r_e, it is up to the modeller to decide which factors are considered to be most important for the area simulated (personal communication Thomas Kätterer). The parameter r_e influences the decomposition rates of *Y* and *O* equally and does not affect the humification coefficient *h*. As this is not realistic, one might decide to adjust *h* to different external conditions.

Table 5.5: The parameters and variables of the ICBM, their dimensions and the effect of a parameter increase on SOC contents, source: Andrén & Kätterer (2001a)

Parameter	**Abbreviation**	**Dimension**	**Effect of parameter increase on soil C mass**
Carbon input	i	$g\ m^{-2}\ year^{-1}$	positive
Decay constant for Y	k_y	$year^{-1}$	negative
Decay constant for O	k_o	$year^{-1}$	negative
Humification constant:	h	dimensionless	positive
External influences	r_e	dimensionless	negative

According to the model equations, an increase of r_e positively influences the decomposition constants k_y and k_o. An increase of either one of these three parameters causes a decrease of the SOC content. An increase of either annual carbon input *i* or the humification constant *h* adds to the SOC content.

5.3.3 Input Data – Estimation of Parameter Values

Carbon pools: Y and O

Ardö & Olsson (2002a) refer to SOC values of 851 and 227 g m^{-2} measured in Umm Higlig in 1963 and 2000, respectively. Umm Higlig lies within the *goz* soil area and is situated around 18 km north west of El Obeid. The mean SOC contents were obtained through 16 and 4 soil samples, respectively. In 1963, *Acacia senegal* dominated the area while grass cover was around 60%. The site has been fallow for 17 years. In 2000, the land had been fallow for at least five years and the area was covered with scattered *Acacia senegal* and *Calotropis procera*. Interpolation yielded a SOC content of 700 g m^{-2} in 1972. As no values for other land use types were available, it was used as an initial value for all land use types. Referring to data of Andrén & Kätterer (1997), only 0.02% of SOC is stored in the young carbon pool Y. Consequently, 0.035 kg C m^{-2} for Y and 0.665 kg C m^{-2} for O were used.

Annual carbon input: i

Annual biomass and litter production were estimated for the different land uses in chapter 6.1.3 using field measurements and data available in literature. Annual carbon input was assumed to be 50% of annual litter production (Sitte *et al*, 1998). The values estimated for each land use are listed in chapter 6.1.1.

Decay constants, k_y and k_o

Andrén & Kätterer (1997) suggest setting k_o to 0.006 year^{-1} for all land uses. Litter quality – a term describing how easily microorganisms can decompose the material – depends on the vegetation and is thus different for each land use type. For example, lignin is decomposed very slowly. This means that litter with high lignin contents is of low quality, resulting in a lower decay constant k_y. Table 5.6 summarizes the k_y values found in literature.

Table 5.6: k_y values for the different land use types

Land use	**k_y**	**Reference**	**Limitations**
Fallow_A	0.724	Bernhard-Reversat (1993)	Valid for 1200 mm y^{-1}
Fallow	0.344	CENTURY Model	Model simulation, no reference
Crop field	0.034	Pieri (1992)	Average of different crop fields in West Africa
Virgin_A field	0.724	Bernhard-Reversat (1993)	Valid for 1200 mm y^{-1}
Virgin field	0.344	CENTURY Model	Model simulation, no reference

Bernhard-Reversat (1993) states that the *Acacia* litter was decomposed very quickly due to its high N content, which led to a high rate of consumption by the soil fauna. This explains the higher k_y value for the two land uses with *Acacia senegal*, although the value might be too high as it was measured in a region where annual rainfall was four times higher than in the study area.

Humification coefficient: h

The humification coefficient is the fraction of *Y* that enters *O* each year. It depends on the litter quality of the vegetation and the clay fraction of the soil (Andrén & Kätterer, 1997). Andren & Kätterer (1997) suggest using a lower *h* value for sandy soils. For each land use type, *h* should be adjusted. The *h* value was based on a universal value of 0.03, suggested by Foley (1995). An *h* value of 0.02 was used for fields with *Acacia senegal* and 0.01 for all other fields. The lowered values take into account the sandy soils.

External influences: r_e

The estimation of r_e is based on the differences from the climate in central Sweden (r_e = 1) with an annual mean temperature of +5.4°C and a precipitation of 520 mm (Andrén & Kätterer, 1997). Andren & Kätterer (1997) state a r_e of 5.36 for a mean annual temperature of 25°C under non-limiting moisture conditions. This value was used for the wet period (3.5 months). It was assumed that r_e was 0.5 during the dry season (8.5 months). As an annual average, a value of 1.92 was determined and this value was used for simulation of all land use types.

Measured SOC contents

Table 5.7: Mean values of SOC in % at 0-20 cm depth in g m^{-2}

SOC in %	Depth 0-20cm				
	Fallow$_A$	*Fallow*	*Crops*	*Virgin$_A$*	*Virgin*
Mean	383	335	290	416	756

For comparison of the simulated data with my results, the mean values of carbon content in g m^{-2} at 0-20 cm depth (Table 5.7) were used. This study does not investigate the spatial distribution of the data.

5.3.4 Sensitivity Analysis

The values for the parameters are estimations. This is why, a sensitivity analysis for the parameters i, k_y, r_e and O_o was conducted. The parameter values of h, k_o and Y_o are very low and are therefore expected to exercise comparatively small influence on the model output as a whole. The model output for *Fallow$_A$* for a 25%, 50% and 100% increase and decrease of the four parameters, respectively were compared.

5.3.5 Model Limitations

The model simulates in a yearly time step up to 30 years. This means that model estimations will be quite rough, working with mean annual carbon input and mean values of annual temperature and precipitation.

When comparing the soil samples with model simulations it has to be taken into account that soil sampling occurred in February although soil samples were used as an estimate of the whole year. This means that monthly data will be compared with annual data. According to Breman & Kessler (1995), researchers are uncertain which influence seasonal rainfall and temperature patterns have on SOC contents. This is why this study relies on simulations with the CENTURY model conducted by Poussart (2002). They are valid for the study area and indicate that SOC content in the topsoil (0-20 cm) varies around 1 g m^{-2} within a year.

There are no parameters for different soil managements such as irrigation or harvest method and no parameter for fire. Everything is included in external factors, which are condensed in r_e. In none of the articles (Andrén & Kätterer, 2001; Andrén *et al*, 2001; Andrén & Kätterer, 1997; Kätterer & Andrén, 2000; Kätterer & Andrén, 1998) it is exactly defined which factors have been included in r_e and it is not well explained how external factors can be condensed in one parameter.

6 RESULTS

6.1 Fieldwork

6.1.1 Biomass Measurements and Soil Texture

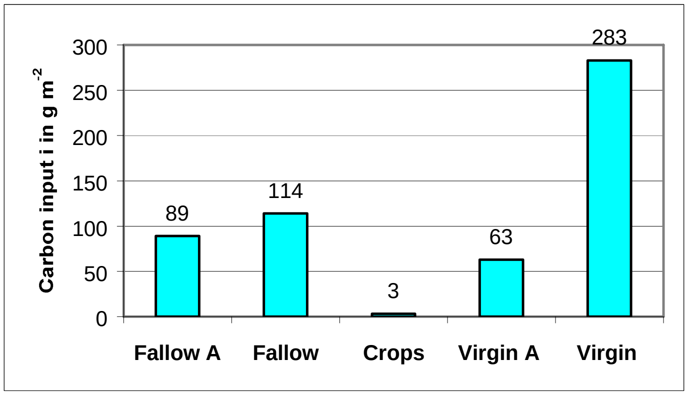

Figure 6.1: The annual mean carbon input

Figure 6.1 presents the results of the biomass calculations based on measurements and literature research. Appendix 4 comprises the biomass calculations. The results were used as carbon input in the ICBM. Land use *Virgin* has the highest amount of biomass per year, followed by $Fallow_A$, $Virgin_A$, *Fallow* and *Crops*.

The carbon input *i* varies between 3 and 283 g m^{-2} $year^{-1}$. The soil in the study area consists on average of 93.6% sand and 6.4% silt.

6.2 Normal Distribution of Data

Statistics were performed with MINITAB Version 13 and Excel. As the sample sizes of the groups are very low, it was necessary to conduct a normality test. I used the Anderson-Darling test[14] and chose a confidence level of 95%.

Table 6.1: Results Anderson-Darling normal distribution test

Groups	Sample size	P-value, C	C	P-value, N	N
Depth 0-20cm					
$Fallow_A$	15	0.440	yes	0.000	no
Fallow	8	0.311	yes	0.403	yes
Crops	16	0.824	yes	0.472	yes
$Virgin_A$	6	0.873	yes	0.318	yes
Virgin	6	0.165	yes	0.026	no
Depth 20-50cm					
$Fallow_A$	9	0.434	yes	0.590	yes
Fallow	7	0.016	no	0.736	yes
Crops	13	0.432	yes	0.699	yes
$Virgin_A$	5	0.059	yes	0.585	yes
Virgin	3	0.588	yes	0.199	yes

Within the carbon data, all groups have a normal distribution except *Fallow* at 20-50 cm depth. For nitrogen, $Fallow_A$ and *Virgin* (both at 0-20 cm depth) show a non-normal distribution. In these cases, the data is highly positively skewed which means that mean values are strongly influenced by a low number of high values. The data was transformed by taking the 10^{th} logarithm (Shaw & Wheeler, 1996) but this did not give a satisfying result either. Therefore, the Mann-Whitney test was used if a non-normal distributed data set was involved and the t-test if only normally distributed data was compared. For comparison, both tests for both groups were processed.

[14] If the p-value is above 0.05 the sample is normally distributed. If the p-value is below 0.05, the distribution is not normally distributed (see help manual MINITAB).

The Mann-Whitney test is a non-parametric test. Non-parametric implies that no assumption is made upon the distribution of the population investigated, which is why these kinds of tests can be used for non-normal data (Shaw & Wheeler, 1996). The disadvantage of a non-parametric test is that it is less powerful than a parametric test with equal sample size. Less powerful means that the probability of rejecting the null hypothesis although it is right is higher for a non-parametric test than for a parametric test. The centre value is the mean for parametric tests and the median for non-parametric tests.

6.3 Soil Sample Analyses

The results of soil sample analysis are listed in Appendix 3. The first objective of the thesis is to find out if *Acacia senegal* influences carbon and nitrogen contents. Sections 6.3.1 and 6.3.2, present the results of the laboratory work for SOC and nitrogen content. In addition, the results of t-test and Mann-Whitney test[15] were also presented. The data set of $Fallow_A$ was compared with the data sets of all other land uses. The confidence level is 95%. The sample number for each group varies between 3 and 18. For better understanding, H_0 is stated here:

H_0: There is no significant difference between the SOC (N) contents of $Fallow_A$ compared with *Fallow*, *Crops*, $Virgin_A$ and *Virgin* respectively.

6.3.1 Carbon

At 0-20 cm depth, *Virgin* has the highest SOC content, followed by $Virgin_A$, $Fallow_A$, *Fallow* and *Crops* respectively (table 6.2). At depth 20-50 cm, the order is exactly the same. The carbon content of the samples taken in the topsoil is much higher in comparison with the samples of depth 20-50 cm. Sometimes the SOC content is twice as high in the topsoil than beneath it. Only *Virgin* shows a different pattern: the C content is higher in depth 20-50 cm. The ranges of the samples at 20-50 cm depth are much smaller than those between 0-20 cm depth.

Table 6.2: Mean value and standard error for carbon, all groups

	Depth 0-20 cm (Topsoil)					**Depth 20-50 cm**				
	$Fallow_A$	*Fallow*	*Crops*	$Virgin_A$	*Virgin*	$Fallow_A$	*Fallow*	*Crops*	$Virgin_A$	*Virgin*
Carbon in %										
Mean value	0.112	0.098	0.084	0.122	0.221	0.076	0.066	0.063	0.095	0.500
Standard Error	0.006	0.008	0.005	0.008	0.075	0.005	0.004	0.003	0.007	0.259
Sample size	15	8	18	6	6	10	7	12	5	3

The standard error is low for all land uses except for *Virgin*. The carbon content ranges between 0.04 to 0.97%, which equals a range between 200 to 5000 g m^{-2} (figure 6.2).

[15] In the case of Mann-Whitney and t-test, MINITAB rejects H_0 if the p-value is lower than 0.05 (see help manual MINITAB).

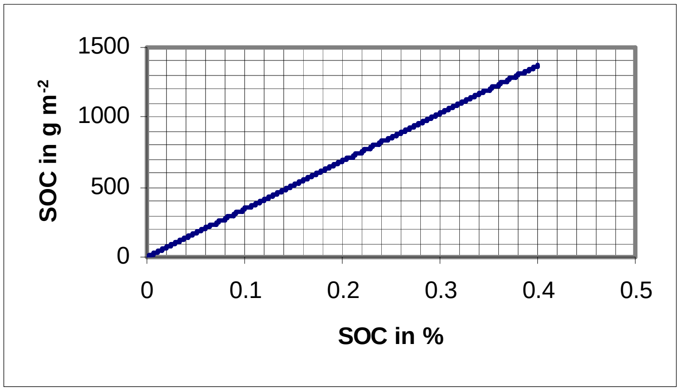

Figure 6.2: SOC in g m^{-2} as a function of SOC in %, valid the topsoil, 0-20 cm

The boxplot in figure 6.3 shows the spread of the data. The line drawn across each box indicates the median of the data. The bottom and top edges of the box mark the first and third quartiles, respectively. The vertical line marks the whole range of data. Extreme values are indicated as a star. Figure 6.3 illustrates that all land uses in both depths have relatively small ranges compared with *Virgin*. The SOC content of *Virgin*$_A$ and *Virgin* is higher than for the first three groups. Extreme values are only found within *Fallow* at both depths.

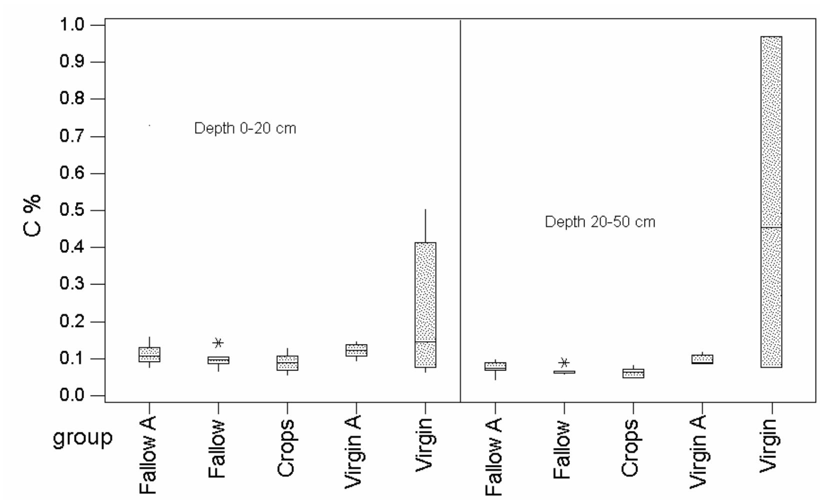

Figure 6.3: Boxplot of C content in % for each land use group

There is a significant difference between *Fallow*$_A$ and *Crops* at 0-20 cm depth while the SOC content of *Fallow*$_A$ is higher (Tables 6.2 and 6.3). The difference between *Fallow*$_A$ and *Fallow* at 20-50 cm depth is significant. The SOC content of *Fallow*$_A$ is higher.

Table 6.3: Results of t-test and Mann-Whitney test for carbon content in %. If H_1 is marked, H_1 had been accepted

Groups	**DF**	**P-value**	**H_0**	**H_1**	**Test used**
Depth 0-20cm					
Fallow$_A$ - *Fallow*	14	0.258	X		T-test
Fallow$_A$ - *Crops*	28	0.004		X	T-test
Fallow$_A$ - *Virgin*$_A$	10	0.257	X		T-test
Fallow$_A$ - *Virgin*	5	0.200	X		T-test
Depth 20-50cm					
Fallow$_A$ - *Fallow*	13	0.0499		X	Mann-Whitney
Fallow$_A$ - *Crops*	13	0.073	X		T-test
Fallow$_A$ - *Virgin*$_A$	9	0.052	X		T-test
Fallow$_A$ - *Virgin*	2	0.243	X		T-test

6.3.2 Nitrogen

In the topsoil, the highest mean N content was found for *Virgin*, followed by *Fallow*$_A$, *Virgin*$_A$, *Fallow* and *Crops*, respectively (table 6.4). At depth 20-50 cm, the highest mean N content was found in *Virgin*, followed by *Virgin*$_A$, *Crops*, *Fallow*$_A$ and *Fallow*.

Table 6.4: Mean value and standard error for nitrogen, all groups

	Depth 0-20 cm (Topsoil)					**Depth 20-50 cm**				
	Fallow$_A$	*Fallow*	*Crops*	*Virgin*$_A$	*Virgin*	*Fallow*$_A$	*Fallow*	*Crops*	*Virgin*$_A$	*Virgin*
Nitrogen in µg/g										
Mean	132.30	107.966	105.00	127.351	208.094	97.28	94.630	99.153	112.214	272.026
Standard Error	15.8	3.618	5.00	9.105	82.066	5.38	2.716	3.217	2.582	136.187
Sample size	15	8	18	6	6	10	7	12	5	3

Figure 6.4 shows that the ranges for nitrogen contents of the topsoil for all land uses (except *Virgin*) are wider than those for SOC contents. Again, *Virgin* shows the widest ranges. N contents vary between 60 and 570 µg g^{-1}. The extreme N content for *Fallow*$_A$ at 0-20 cm depth belongs to field in fallow since 20 years, covered with 2 trees while around 70% is bare land.

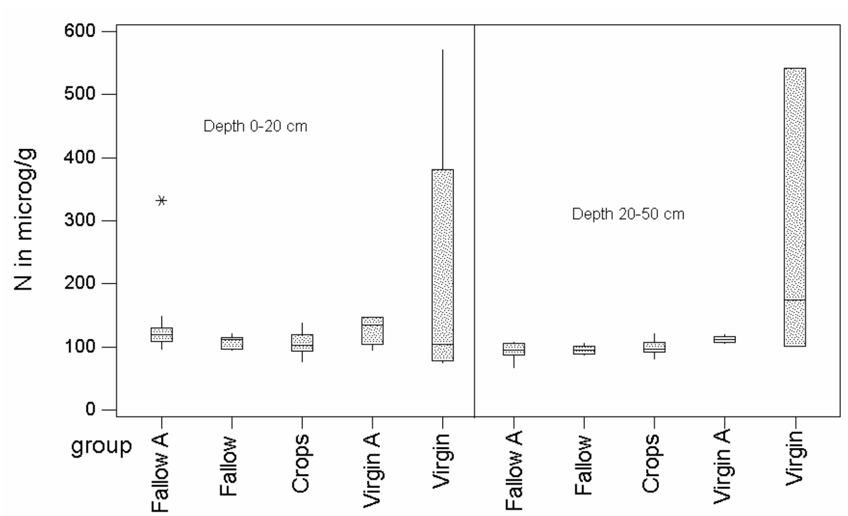

Figure 6.4: Boxplot of N content in µg g^{-1} for all groups

Table 6.5: Results of t-test and Mann-Whitney test for nitrogen contents in %

Groups	**DF**	**P-value**	**Ho**	**H1**	**Test used**
Depth 0-20cm					
Fallow$_A$ - *Fallow*	14	0.1293	X		Mann-Whitney
Fallow$_A$ - *Crops*	28	0.0312		X	Mann-Whitney
Fallow$_A$ - *Virgin*$_A$	10	0.5593	X		Mann-Whitney
Fallow$_A$ - *Virgin*	5	0.5081	X		Mann-Whitney
Depth 20-50cm					
Fallow$_A$ - *Fallow*	13	0.848	X		T-test
Fallow$_A$ - *Crops*	13	0.326	X		T-test
Fallow$_A$ - *Virgin*$_A$	9	0.004		X	T-test
Fallow$_A$ - *Virgin*	2	0.321	X		T-test

The nitrogen content of *Fallow*$_A$ and *Crops* differ significantly at 0-20 cm depth (table 6.5). *Fallow*$_A$ has a higher mean N content than *Crops*. At 20-50 cm depth, comparison of *Fallow*$_A$ with *Virgin*$_A$ shows a significant difference. *Virgin*$_A$ has a higher mean N content.

6.3.3 C:N Ratio

Overall, the C:N ratio varies between 23 and 180 while mean values are around 100. At 0-20 cm, *Virgin* has the highest C:N ratio, followed by *Virgin*$_A$, *Crops*, *Fallow* and *Fallow*$_A$ (table 6.6). At 20-50 cm, the mean C:N ratio of *Virgin* is highest, followed by *Virgin*$_A$, *Fallow*$_A$, *Fallow* and *Crops*. A high C:N ratio implies a high C value and low N value. It implies that the concurrence for nitrogen is very high, limiting plant growth.

The extremely low C:N ratio for *Fallow*$_A$ at 0-20 cm depth belongs to the sample with very high nitrogen contents (figure 6.5). At the same depth, within *Fallow*, the sample with the high SOC content has a high C:N ratio. In the same group, the sample with the lowest C:N ratio is a field with three trees and around 50% grass cover. The extremely low C:N ratio in *Crops* at 0-20 cm depth belongs to a field that has been continuously cultivated since 30 years. It has a very low carbon content while the nitrogen content is comparatively high.

Table 6.6: Mean and standard error for C:N ratio, all groups

	Depth 0-20 cm					**Depth 20-50 cm**				
	Fallow$_A$	*Fallow*	*Crops*	*Virgin*$_A$	*Virgin*	*Fallow*$_A$	*Fallow*	*Crops*	*Virgin*$_A$	*Virgin*
C:N ratio										
Mean	92.53	90.59	81.77	96.42	111.9	78.01	70.14	63.54	84.97	172.0
Standard Error	5.62	6.37	4.36	5.26	13.5	4.12	4.26	2.22	5.49	53.3
Sample size	15	8	18	6	6	10	7	12	5	3

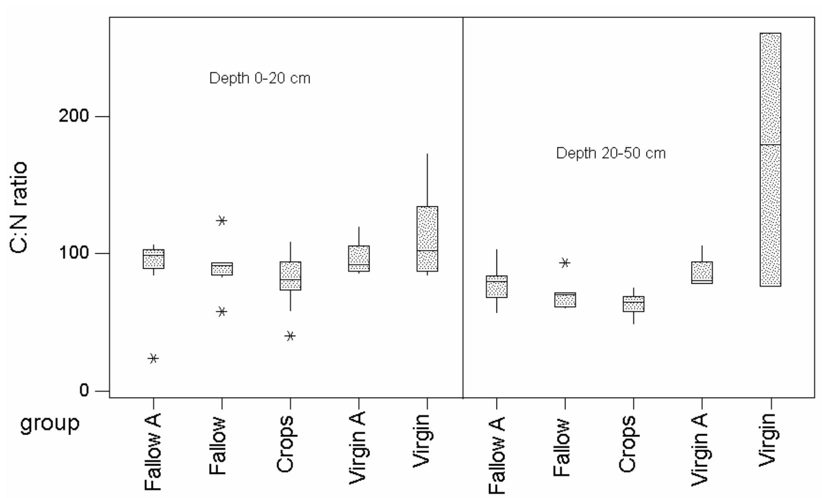

Figure 6.5: Boxplot of C:N ratio

6.3.4 Relationships between Carbon and Nitrogen

The second objective of the thesis was to find out if nitrogen content influences the carbon content in the soil beneath a special land use. I used a regression analysis and compared the carbon and nitrogen content within each land use class. Nitrogen was assumed to be the controlling variable and carbon to be the dependant variable. The resulting regression plots are listed in Appendix 5. For better understanding, the hypothesis is as follows:

H_0: There is no significant correlation between carbon and nitrogen contents within one land use class.

Table 6.7: Relationships between C and N, the shaded values are significant

Land use	No. of samples	*r* [16]	r^2 (in %)
Fallow$_A$	15 or 14	-0.24 or 0.92	5.7 or 84.5
Fallow	8	0.444	19.7
Crops	16	0.425	18.1
Virgin$_A$	6	0.786	61.8
Virgin	6	0.962	92.6

The coefficient of determination (r^2) defines the proportion of the variance of one variable "explained" by variation of the other (Shaw & Wheeler, 1996). For *Fallow$_A$* two different r^2 values were calculated because the low correlation between C and N values was due to one extreme soil sample. A regression analysis without this sample results in a significant positive correlation (r = 0.92). In the case of *Fallow$_A$*, r^2 equals 84.5, which means that 84.5% of the variance of C is accounted for the variance of N. *Fallow* and *Crops* show a low correlation while *Virgin$_A$* and *Virgin* indicate quite high correlations. For *Virgin$_A$* there is a trend towards a positive correlation and for *Virgin* the correlation is significant.

6.4 Simulations with the ICBM

6.4.1 Fallow Fields with Acacia senegal (Fallow$_A$)

Table 6.8: The input data, the modelled SOC content (SOC_M), the measured mean SOC content in 2002 (SOC_{ME}) and the difference between SOC_M and SOC_{ME}

i	k_y	k_o	*h*	r_e	Y_0	O_0	SOC_M	SOC_{ME}	*Difference*
89	0.724	0.006	0.02	1.920	35	665	557	384	196

The model was run from 1972 to 2002 in order to see if the modelled values in 2002 were comparable with the measurements taken for this study in 2002. Figure 6.6 shows a continuous decrease of total SOC contents from 1972 until today. The modelled SOC content is around one third higher than the measured SOC. The SOC content of the old carbon pool follows the dynamic of modelled total SOC while the young carbon pool contents remain at an equal low level during the 30-year period.

[16] The Pearson's correlation coefficient *r* is a measure to determine the strength of a relationship between two variables; *r* varies between –1 and +1 indicating negative or positive correlations (Shaw & Wheeler, 1996).

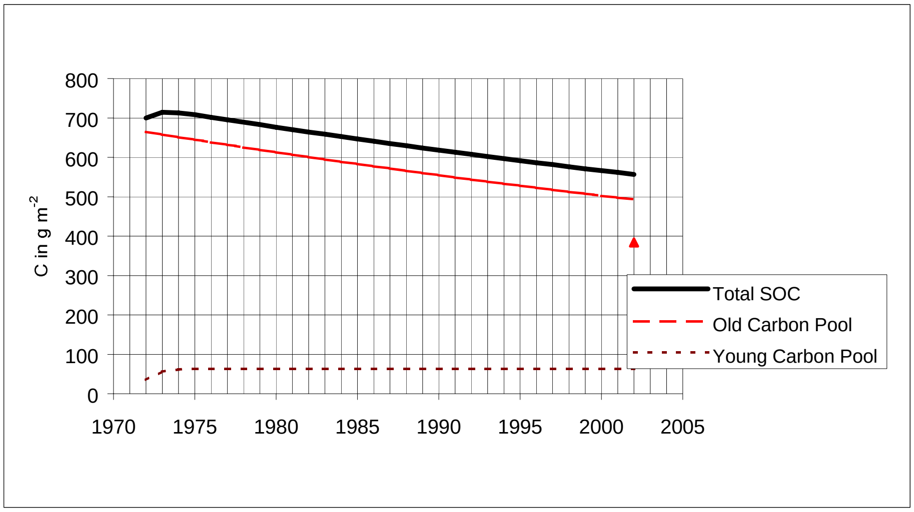

Figure 6.6: The model output for land use Fallow$_A$, the triangle indicates SOC$_{ME}$

6.4.2 Fallow Fields without Acacia senegal (Fallow)

Table 6.9: The input data, the modelled SOC content (SOC$_M$), the measured mean SOC content in 2002 (SOC$_{ME}$) and the difference between SOC$_M$ and SOC$_{ME}$

i	k_y	k_o	*h*	r_e	Y_0	O_0	SOC$_M$	SOC$_{ME}$	Difference
114	0.344	0.006	0.010	1.920	35	665	670	335	335

SOC$_M$ is twice as high as SOC$_{ME}$. The curves representing total carbon and young carbon pool increase during the 70s. Later, total carbon and the old carbon pool decrease while the young carbon pool continues at a low level.

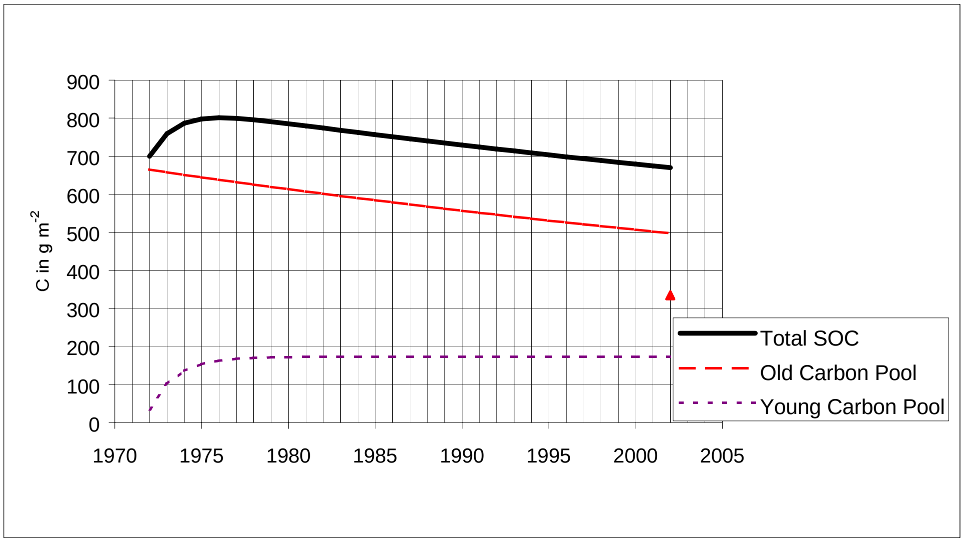

Figure 6.7: The model output for land use Fallow, the triangle indicates SOC$_{ME}$

6.4.3 Crop Fields (Crops)

Table 6.10: The input data, the modelled SOC content (SOC_M), the measured mean SOC content in 2002 (SOC_{ME}) and the difference between SOC_M and SOC_{ME}

i	k_y	k_o	h	r_e	Y_0	O_0	SOC_M	SOC_{ME}	Difference
3	0.034	0.006	0.030	1.920	35	665	517	290	230

The measured SOC content is only 60% of the modelled SOC content. The curve of total carbon falls a bit sharper compared with the other land use types. The young carbon pool stays at a very low level while the old carbon pool follows total carbon contents.

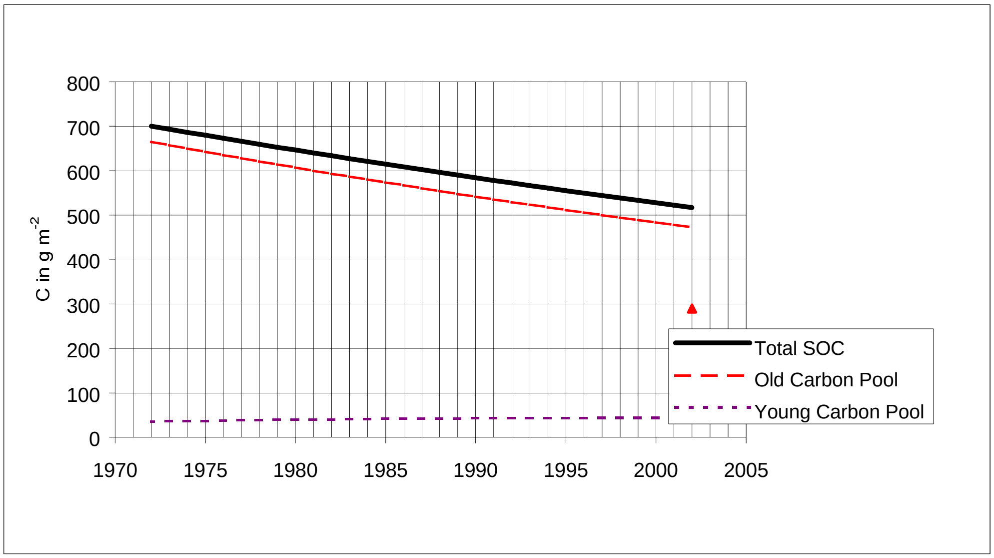

Figure 6.8: The model output for land use Crops, and the triangle indicates SOC_{ME}

6.4.4 Undisturbed Sites with Acacia senegal ($Virgin_A$)

Table 6.11: The input data, the modelled SOC content (SOC_M), the measured mean SOC content in 2002 (SOC_{ME}) and the difference between SOC_M and SOC_{ME}

i	k_y	k_o	h	r_e	Y_0	O_0	SOC_M	SOC_{ME}	Difference
63	0.724	0.006	0.010	1.920	35	665	532	416	134

The measured SOC content is around 75% as high as the model output. Again, the young pool is low during the whole time period and total and old carbon contents are decreasing slowly.

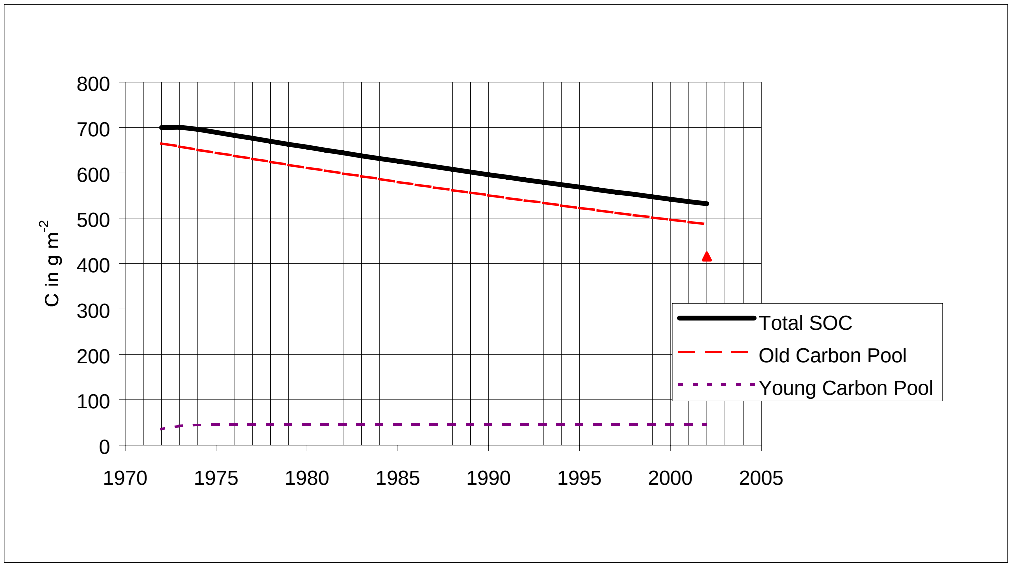

Figure 6.9: The model output for land use Virgin$_A$, the triangle indicates SOC$_{ME}$

6.4.5 Undisturbed Sites without Acacia senegal (Virgin)

Table 6.12: The input data, the modelled SOC content (SOC$_M$), the measured mean SOC content in 2002 (SOC$_{ME}$) and the difference between SOC$_M$ and SOC$_{ME}$

i	k_y	k_o	*h*	r_e	Y_0	O_0	*SOC$_M$*	*SOC$_{ME}$*	*Difference*
283	0.344	0.006	0.010	1.920	35	665	968	756	214

SOC$_{ME}$ is 20% lower than the modelled SOC content. Total carbon and the young carbon pool increase strongly in the beginning of the reference period, levelling out during time. In this case, the old carbon pool remains on a medium level of around 600 g C m^{-2}.

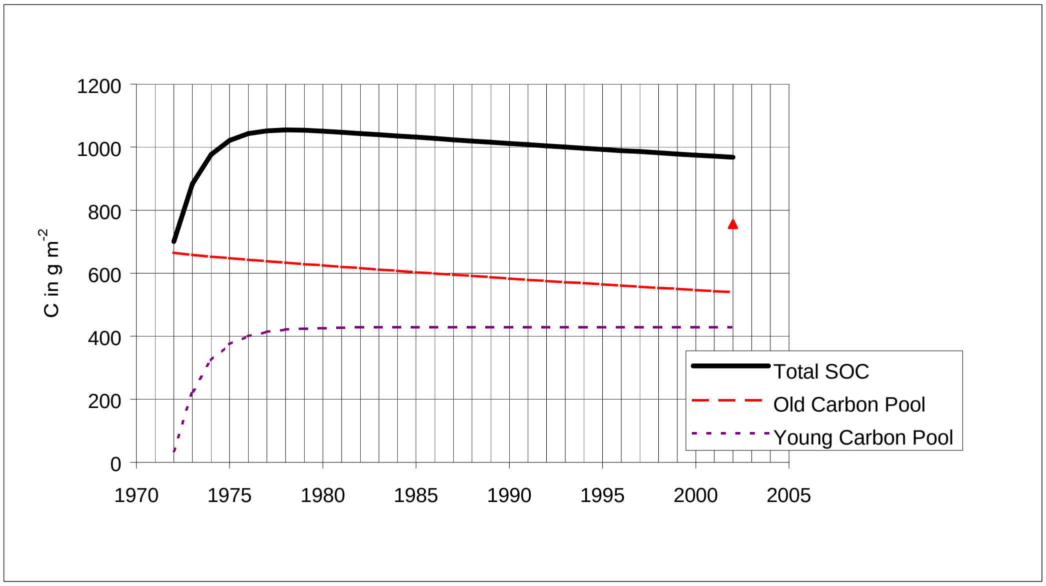

Figure 6.10: The model output for land use Virgin, the triangle indicates SOC$_{ME}$

6.4.6 Results of Sensitivity Analysis

The sensitivity of the ICBM was evaluated for the parameters i, k_y, r_e and O_o. The results of changes in different carbon inputs were then compared with the measured SOC content of $Fallow_A$ in 2002 (383 g m^{-2}). The changes in modelled SOC content for a variable carbon input i are within a range of 200 g m^{-2} (figure 6.11). Even a carbon input of 0 does not decrease the modelled SOC content to the point that it reaches the measured SOC content.

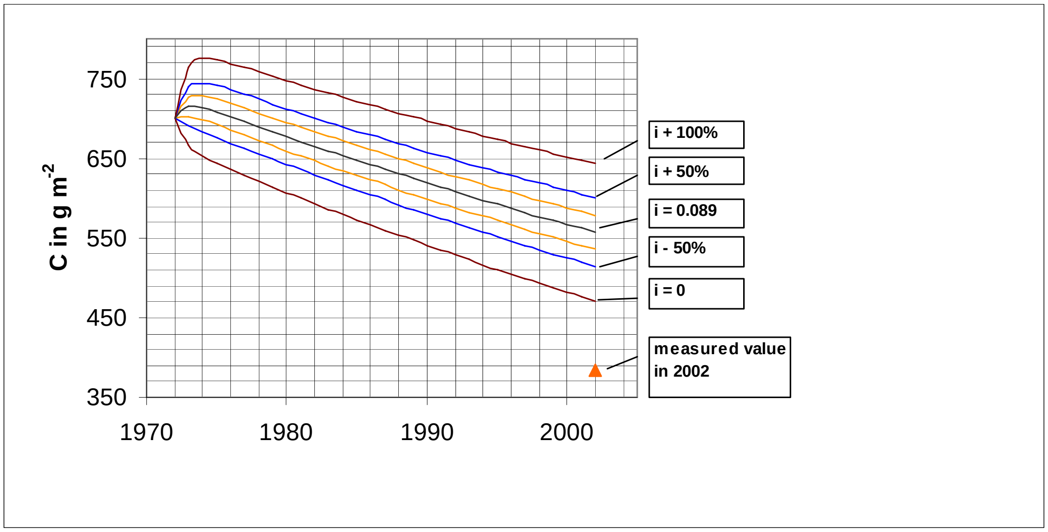

Figure 6.11: Results of sensitivity analysis for parameter i

A ± 100% change of the decay constant k_y shows a range of 100 g m^{-2} of modelled SOC contents in 2002 (figure 6.12). Thus, the range is much smaller than for parameter i. The model equation cannot be solved if k_y equals 0. The modelled SOC content in 2002 for a twice as high value of k_y is still 150 g m^{-2} higher than the measured SOC content. A decrease of k_y leads to a much stronger change in model output than an equal increase of k_y.

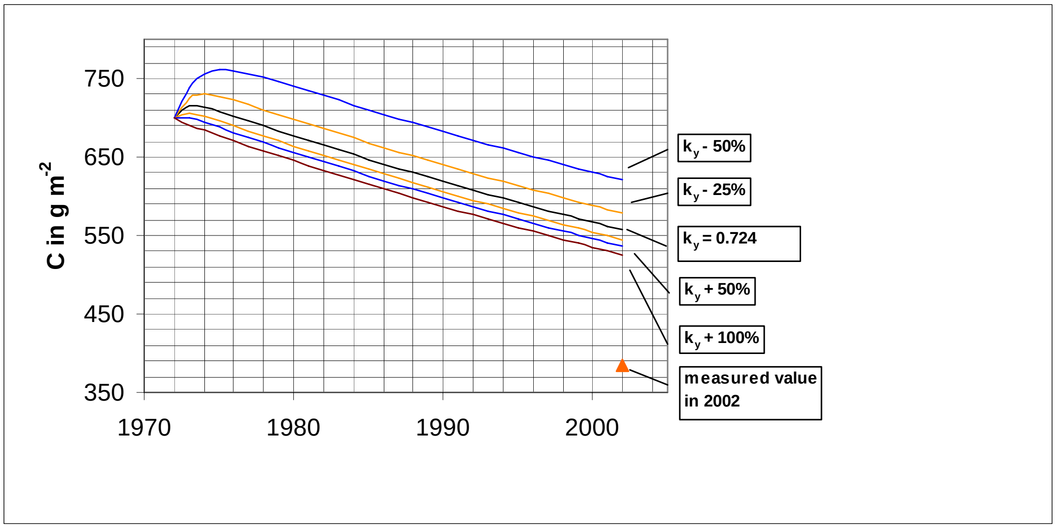

Figure 6.12: Results of sensitivity analysis for parameter k_y

Changes in r_e result in a wide range of model outputs (Figure 6.13). If the parameter is set to 0, the model equation cannot be solved. The modelled SOC content for r_e + 100% is similar to the measured SOC content in 2002.

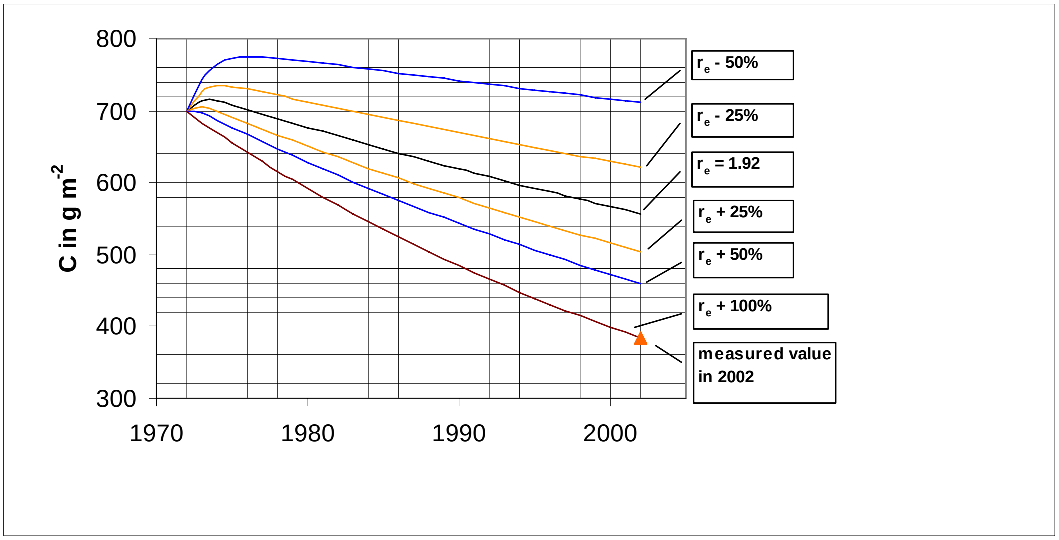

Figure 6.13: Results of sensitivity analysis for parameter r_e

The model output for a ± 50% change of the initial value of the old carbon pool O_o ranges from 260 g m^{-2} to 820 g m^{-2} (Figure 6.14). It shows the biggest changes in modelled SOC contents. The measured SOC content in 2002 could be reached with a decrease of O_o between 25 and 50%.

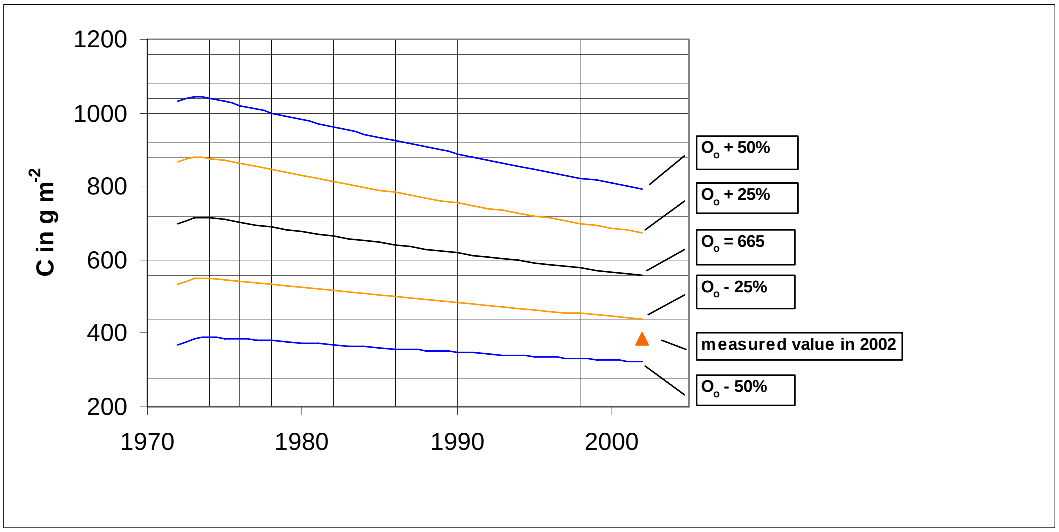

Figure 6.14: Results of sensitivity analysis for parameter O_o

7 DISCUSSION

7.1 Fieldwork

One might object that the sites of the soil samples were chosen subjectively as the study did not actually sample four symmetrically scattered samples in each plot (see figure 5.2). Former studies (Deans *et al*, 1999; Kessler & Breman, 1991, Scholes & Archer, 1997) state that the organic matter content beneath and near by trees is higher than in the surrounding area. According to Buresh & Tian (1998) the lateral roots of woody plants lead to a nutrient uptake within the root zone and thus to a redistribution of nutrients within the soil. Breman & Kessler (1995) states that on fallow fields soil fertility under woody plants improves, but if woody plants occur isolated on a large area, soil fertility on the area as a whole does not regenerate during the fallow period. Assuming the latter and being aware of the small area of my plot, samples were taken as far away from tree crowns as possible. If stands were dense, a soil sample was taken halfway between two trees. If the plot was covered with scattered trees, the sample was taken around 2 m from the tree crown. In this way, the study avoided the possibility of measuring high SOC values although the average SOC content for the plot might be much lower. One can say, that the researcher chose the worst scenario in order to avoid any misjudgment.

A further source of error is the number of soil samples taken. Conducting tests – both parametric and non-parametric tests - with an amount of 3 to 18 soil samples per group involves highly uncertain results. During interviewing farmers, it became apparent that it was extremely difficult to make farmers understand the importance of providing an accurate land use history. This resulted in difficulty distinguishing between fallow fields and undisturbed sites. As a result, the study may have included fallow fields instead of undisturbed sites and vice versa.

It was difficult to find appropriate plots for $\textit{Virgin}_A$ and *Virgin*. In the case of *Virgin*, two of the five samples were taken from a 50-year-old plantation of *Azadirachta indica* trees. Both, carbon and nitrogen contents are extremely high, obviously because the trees were around twice as high and wide as all other trees I measured. Additionally, the stands were so dense that tree crowns almost reached each other. This meant that samples had to be taken near tree stems. The standard error of *Virgin* is very high and the ranges very wide. The mean carbon content of *Virgin* at 20-50 cm depth was higher than for the topsoil. This is explained by the fact that only three samples were taken within this group at this depth of which two were on the plots with *Azadirachta indica* trees.

The equation to calculate the biomass of *Acacia senegal* proposed by Deans *et al* (1999) poses some limitations. They state themselves that natural stands, which are browsed and tapped, might not grow as fast as trees in plantations. This implies that the equations might not be a useful estimate for this study. Second, the root:shoot ratio proposed by Deans *et al* (1999) is not generally acknowledged. For example, Breman & Kessler (1995) state that the root:shoot ratio for *Acacia* trees is usually closer to 0.4 than to 0.2.

Only one tree of each species was measured and scaled up to the total amount of trees. This might be a coarse estimate but often the number of trees was too high to measure all of them. In order to treat all plots in the same way, only one tree per species was measured.

There are great differences in land use history within land use groups. The crop fields on which samples were taken have been cultivated for between 5 to 30 years, the fallow fields between 9 and 25 years and the undisturbed sites between 23 and 50 years (Appendix 4). This large variability of land use "ages" makes the measurement results less comparable.

The calculation of biomass and carbon input gave very different results for the different land uses. In all cases, the tree biomass was negligible compared to grass biomass. As the global value suggested by Jackson *et al* (1996) was too high for grass vegetation in a semi-arid region, it was divided by three to take into account the growing season. The annual grass vegetation – if not eaten by animals – is transformed to litter and decomposed during one year, but only a small percentage of the tree biomass becomes litter per year. This is why the biomass of the different land uses varies strongly, dependant on the percentage of grass cover.

7.2 Soil Sample Analysis

On average, 450 g C m^{-2} was recovered in the topsoil, which equals a quantity of around 1.3 g C kg^{-1}. Lal (2001b) discusses a study made in Nigeria in the middle nineties with similar soil conditions where 1–2 g kg^{-1} had been found. This shows that this study's results are similar to other research results.

The significant difference between mean carbon content in the topsoil of $Fallow_A$ and *Crops* is in line with former studies (Breman & Kessler, 1995; Ardö & Olsson, 2002b). In this study there is a significant difference between carbon and nitrogen contents of soils beneath *Acacia senegal* and other land uses. Although this might indicate that *Acacia senegal* is a preferable tree species in the case of carbon sequestration, one might take into account studies on other indigenous tree species. El Tahir *et al* (2002) studied chemical soil properties under *Acacia seyal*, *Acacia tortillis* and *Acacia senegal*. The results revealed higher nitrogen contents but lower carbon contents under *Acacia senegal* compared to the two other tree species. This means that other tree species might be more valuable for carbon sequestration.

The sites of *Virgin* have highest SOC contents. As mentioned above, soil samples were mainly taken within a 50-year-old *Azadirachta indica* tree plantation. Breman & Kessler (1995) refer to a study, which states that the highest SOC contents occurred under this tree species. They state that this is due to high C:N and C:P ratios of plant litter, which induces a low decomposition rate. This might be an additional reason for the large difference between *Virgin* and all other land uses.

The C:N ratio differs strongly among the different land uses. One might suppose that the C:N ratio for $Fallow_A$ is lower than e.g. for *Crops* as *Acacia senegal* is expected to fix additional nitrogen, which would lead to higher nitrogen content and thus to a lower C:N ratio. Although *Crops* overall has lower nitrogen and SOC contents, it has the lowest C:N ratio. Undisturbed sites have the highest C:N ratio, which implies that nitrogen is much more limiting in those areas than on cultivated fields. Nevertheless, it has to be taken into account, that the C:N ratios overall are very high.

There is a significant correlation between carbon and nitrogen contents within $Fallow_A$ and *Virgin*. Although, a regression analyses requires normally distributed data, which is not the case when comparing C and N contents within $Fallow_A$, *Fallow* and *Virgin*.

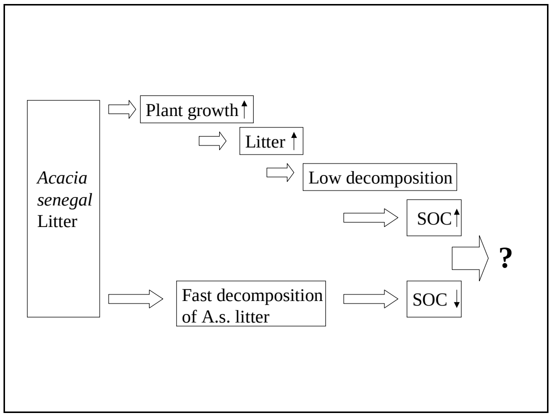

Figure 7.1: Decomposition processes

The regression analyses cannot elucidate the interweaved processes that steer C and N contents. Summarizing the information given in the former chapters, the assumption that *Acacia senegal* stands increase the soil N content (either through plant and root litter or through litter and nitrogen fixation) might result in two possible processes (figure 7.1). On the one hand, this could lead to more overall litter as additional nitrogen leads to better vegetation growth in the long run. The measured average C:N ratio of 90 indicates a low decomposition rate, which is typical for semi-arid regions. Overall, a low decomposition rate results in an increasing SOC content. On the other hand, the high nitrogen content of *Acacia senegal* litter might lead to a fast decomposition of the *Acacia* litter which would result in a decrease of SOC. Further explanation of these issues is far beyond the scope of this study.

Researchers agree that SOC is mainly concentrated in the upper 20 cm of the soil (Bernhard-Reversat, 1982). Disturbances (such as fire, animals, tillage etc) mainly influence SOC contents in the topsoil. This implies that there is great variance in SOC content of the topsoil. For example, in this study, the ranges for mean nitrogen and carbon values at 20-50 cm depth are much smaller than those between 0-20 cm depth. It is recognized that the variability of soil carbon content in the topsoil within a distance of a few meters poses a big problem for assessing mean soil carbon values (Lal, 2001a). These facts make it very difficult to estimate a mean amount of carbon in the topsoil.

In a further study, it would be interesting to investigate the spatial distribution of SOC content in North Kordofan, in respect to vegetation types, land use patterns and geographical location.

7.3 Simulations with the ICBM

The ranking of highest to lowest mean carbon content is different for modelled and measured data (figure 7.2). For measured data, the undisturbed sites have stored more carbon than the fallow sites and the crop fields range last. For modelled data, *Fallow* and $Virgin_A$ are swapped. This fact can be explained by higher model input rates (*i)* for *Fallow*, which depend on the biomass estimations. Thus, the grass fraction was much higher for *Fallow* than for $Virgin_A$.

SOC_{ME}: *Virgin* > $Virgin_A$ > $Fallow_A$ > *Fallow* > *Crop fields*
SOC_M: *Virgin* > *Fallow* > $Fallow_A$ > $Virgin_A$ > *Crop fields*

Figure 7.2: Measured (SOC_{ME}) and modelled (SOC_M) SOC contents, the order of the different land uses

The measured data shows that the grassland plots of *Virgin* have lower SOC content than the plots with *Azadirachta indica* trees. Thus, this study's biomass calculations – due to unreliable grass biomass data – resulted in much higher biomass inputs for grasslands, which imply higher SOC contents when modelling. This skews the model result, although the fit between modelled and measured SOC for *Virgin* is better than for the other land uses.

The modelled SOC contents are much higher than the measured SOC contents. There are several possible reasons for this fact. First, the decay constants may have been underestimated. Second, the external influences may have been underestimated. Third, the initial values for Y and O might be too high.

The strong increase in modelled SOC contents in the beginning of the 70s of *Fallow* and *Virgin* (figure 6.7 and 6.10) is due to the comparatively high carbon input i and a low value for k_y. The high carbon input is due to the large grass fraction of these two land use types. Even if the grass biomass is a coarse estimate, there is evidence that grasslands have high SOM contents. For example, Breman & Kessler (1995) refer to studies made on grasslands in temperate climates, suggesting that grasslands have a comparatively higher SOM content than woodlands. They state that this might be due to a higher turnover of soil nutrients in grasslands, which leads to a higher annual litter fall, in spite of a lower standing biomass.

The calculated model parameters do not mirror reality, as they should be more appropriate to the different land uses. The initial values for Y and O are estimated using data from 1963 and 2000 (Ardö & Olsson, 2002a). In 1963, a different method for SOC analysis had been used, which means that the value is more imprecise than the one from 2000 and consequently, the difference between the two values might be skewed. It would be more appropriate to use different values for the different land uses and the different land use histories. For example, in the case of a crop field that had been cultivated for 30 years the initial values should be lower as for a crop field cultivated for 5 years after a 25 year long fallow period.

For the ICBM to be used as a reliable tool for carbon assessments, one would have to develop a way to easily calculate a value that comprises land use “age” and land use history with which the parameters could be multiplied.

The parameter r_e should be adjusted to the different land management practices not only to climate data. For example, tillage influences soil properties. In the case of conservation tillage more soil carbon is kept in the soil, which is equivalent to a decrease of r_e. The soil type could be excluded in this study, as it was the same for each land use. Also, in this case it would be suitable to have a parameter for different land management practices with which r_e could be multiplied.

An improvement of the model would imply a larger set of parameters. This would make the model more difficult to understand and to run. Therefore, the model should be understood as a basic tool to assess the state of SOC and to further understanding.

The sensitivity analysis revealed that changes of parameter O_o influence model output more than parameter r_e, followed by parameters i and k_y. As the model equations are simple multiplications it is obvious that a change of the highest numbers equal the biggest change in model output.

As the initial value for O_o strongly influences model outputs, it is very important to find realistic initial values. The degree by which SOC contents decrease is different depending on initial O_o values. Low initial values lead to a smaller decrease of SOC contents than high values. The model equations reveal that an increase of the initial value O_o is directly related to a higher soil respiration, which reduces SOC contents.

Breymeyer *et al* (1996) suggest that SOC is controlled more by decomposition than by primary production and they state that rainfall is the main environmental factor affecting decomposition. Parameter r_e influences directly the decay rates k_y and k_o and includes all external influences. It is realistic that a strong change of r_e strongly influences SOC outputs. One has to be aware that a decrease of r_e affects SOC content more than an increase of r_e. This might lead to the choice of a lower r_e value as a model input as the model output is less influenced by a higher r_e value than a lower r_e value.

A decrease of parameter k_y affects model outputs much more than an increase of k_y. This is explained by the exponential decay curve. As the differences in output for de- and increased k_y values is high, it is essential to find realistic k_y values. However, an underestimation of $\mathrm{k_y}$ would have stronger effects on model outputs than an overestimation.

8 SUMMARY OF RESULTS AND CONCLUSIONS

8.1 Summary of Results

The most important results of this study can be summarized as follows:

- There is a significant difference between the carbon and nitrogen content of fallow fields with *Acacia senegal* ($Fallow_A$) and that of crop fields (*Crops*) at 0-20 cm depth. The difference between $Fallow_A$ and the three other land uses is insignificant.
- There is a significant correlation between carbon and nitrogen content under both land use $Fallow_A$ and land use *Virgin*.
- The SOC contents simulated with the ICBM do not coincide with the SOC content measured in 2002.
- On average, the SOC content under the different land use types accounts for 450 g m^{-2} or 1.3 g kg^{-1} in the topsoil.
- The average C:N ratio of all land use types is around 90.

8.2 Conclusions

The study shows that there is slight evidence that *Acacia senegal* stands have a potential to sequester carbon when compared to cultivated fields. Olsson & Ardö (2001) acknowledge these findings. According to this study, there is no evidence that *Acacia senegal* stands have a larger potential of sequestering carbon in the soil when compared to the other land use types included in the study (fallow fields without *Acacia senegal*, undisturbed sites with and without *Acacia senegal*). More research has to be done in order to assure the results of this study as the amount of samples used was small.

It was not possible to demonstrate a clear relationship between soil carbon and nitrogen contents. The processes that control C and N are too complex to be elucidated with a simple regression analysis. As both elements affect each other in both the plant and soil environment, it is much beyond the scope of this study to deal with these issues.

The ICBM did not show satisfactory results when simulating SOC in the study area. The model does not include parameters simulating land use history, grazing, erosion and occasional impacts such as droughts and fire. The authors used data series over long time periods to calibrate the ICBM to conditions in Northern Europe. In the case of Sudan, time series are not available. In this study, adjustment of parameters to the specific environmental conditions included many assumptions and estimations. If the ICBM is used in the future to assess soil carbon fluxes and pools in semi-arid areas, it should first be calibrated to these conditions using data series of a well-investigated area.

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Photographs by Caren Jakubaschk

APPENDIX 1: ARABIC GLOSSARY AND SCIENTIFIC NOTATION

Arabic	*English/ Latin*
bittikh	Watermelon
dukm	millet
dura	*Sorghum vulgare*
ful masri	Beans
ful sudani	Groundnuts
gardud	Various types of clay soil
gobbesh	*Guiera senegalensis*
goz	Sandy soil
habil	*Combretum hartmannianum*
hashab	*Acacia senegal*
haskanit	*Cenchrus biflorus*
hejlij	*Balanites aegyptiaca*
karkade	Hibiscus
kitir	*Acacia mellifera*
merrikh	*Leptadenia pyrotechnica*
nabag	*Ziziphus mauritiana*
nim	*Azadirachta indica*
samugh	Gum arabic
sayal	*Acacia tortillis*
sereh	*Maerua crassifolia*
sidir	*Ziziphus spina Christi*
simsim	Sesame
sunud	*Acacia nilotica*
talih	*Acacia seyal*
tebeldi	*Adansonia digitata*
usher	*Calotropis procera*

Units of weight and area

1 feddan	4200 m^2, 0.42 ha
1 kuntar	45 kg
1 mukhammas	7400 m^2, 0.74 ha
1 ratul	449.28 g
1 sack groundnuts	45 kg
1 sack millet/ sorghum	90 kg
1 sack sesame	73 kg

Exchange rate

1 US $ accounts for around 250 Sudanese Dinar or 2500 Sudanese Pounds

Scientific notations

Power	*Prefix*	*Abbreviation*
10^{-6} (e.g. 0.000001))	micro	µ
10^{-3}	Milli	m
10^{6} (e.g. 1 000 000)	Mega	M
10^{9}	Giga	G
10^{15}	Peta	P

APPENDIX 2: SOIL SAMPLE AND BIOMASS PROTOCOL

Soil sample protocol

Number of sample	
Date	
Depth	
GPS position	
Soil type	
Vegetation	
Land use	
Land use history	
On crop fields:	
Main crops	
Crop:fallow cycle? Last fallow period	
Planting, harvest month	
Fertilisation, irrigation	
C content	
N content	
Soil texture	
Bulk density	

Biomass protocol

Number of field	
Species composition (percentage of each species)	
Number of trees	
Measurements on average tree	
Height	
Canopy diameter	
Stem circumference at breast height	
Stem circumference at 30cm (only Acacia senegal)	
Number of stems	
Grass	
Height	
Density	
Local name	

APPENDIX 3: RESULTS FOR ALL SOIL SAMPLES

Fallow fields with *Acacia senegal* (*Fallow$_A$*)

No.	Latitude	Longitude	C in %	C in g m^{-2}	N in mg g^{-1}	N in %	C:N ratio
0-20cm depth							
7	N 12 52.0210	E 030 57.9450	0.11	390.11	118.77	0.0012	96
9	N 12 50.9440	E 030 55.0870	0.137	468.81	134.62	0.0013	102
11	N 12 51.8610	E 030 55.0290	0.129	441.44	126.96	0.0013	102
13	N 12 53.0840	E 030 53.2560	0.100	342.20	95.27	0.0010	105
16	N 12 55.4600	E 031 05.3700	0.074	253.23	130.27	0.0013	57
17	N 12 55.4600	E 031 05.3700	0.107	366.15	102.99	0.0010	104
22	N 12 56.8540	E 031 06.4750	0.093	318.25	110.76	0.0011	84
49	N 12 46.1880	E 030 46.9150	0.108	369.58	119.37	0.0012	90
55	N 12 55.8790	E 031 00.0390	0.111	379.84	108.50	0.0011	102
59	N 12 58.0980	E 031 01.0830	0.131	448.28	127.31	0.0013	103
65	N 12 54.8070	E 031 19.8600	0.079	270.34	331.98	0.0033	24
75	N 12 48.5000	E 031 01.4230	0.105	359.31	111.16	0.0011	94
86	N 12 50.0990	E 031 00.4190	0.108	369.58	111.55	0.0011	97
88	N 12 52.6550	E 031 01.6780	0.160	547.52	149.37	0.0015	107
94	N 12 51.8570	E 031 08.2170	0.088	301.14	103.05	0.0010	85
20-50cm depth							
23	N 12 56.8540	E 031 06.4750	0.067	343.91	96.13	0.0010	70
50	N 12 46.1880	E 030 46.9150	0.089	456.84	108.25	0.0011	82
56	N 12 55.8790	E 031 00.0390	0.069	354.18	88.66	0.0009	78
60	N 12 58.0980	E 031 01.0830	0.071	364.44	84.89	0.0008	84
66	N 12 54.8070	E 031 19.8600	0.075	384.98	90.65	0.0009	83
76	N 12 48.5000	E 031 01.4230	0.099	508.17	95.53	0.0010	104
87	N 12 50.0990	E 031 00.4190	0.079	405.51	105.77	0.0011	75
89	N 12 52.6550	E 031 01.6780	0.091	467.10	106.45	0.0011	85
95	N 12 51.8570	E 031 08.2170	0.042	215.59	66.26	0.0007	63

Undisturbed sites with *Acacia senegal* (*Virgin$_A$*)

No.	Latitude	Longitude	C in %	C in g m^{-2}	N in mg g^{-1}	N in %	C:N ratio
0-20cm depth							
29	N 12 54.7800	E 031 26.6320	0.112	383.26	93.47	0.0009	120
37	N 12 43.5810	E 030 49.2550	0.129	441.44	147.23	0.0015	88
39	N 12 43.5430	E 030 49.1740	0.092	314.82	107.63	0.0011	85
41	N 12 43.4640	E 030 49.1320	0.114	390.11	128.94	0.0013	88
43	N 12 43.7780	E 030 49.2110	0.134	458.55	139.15	0.0014	96
45	N 12 43.8790	E 030 49.1960	0.149	509.88	147.68	0.0015	101
20-50cm depth							
38	N 12 43.5810	E 030 49.2550	0.088	451.70	111.94	0.0011	79
40	N 12 43.5430	E 030 49.1740	0.085	436.31	104.61	0.0010	81
42	N 12 43.4640	E 030 49.1320	0.097	497.90	120.67	0.0012	80
44	N 12 43.7780	E 030 49.2110	0.086	441.44	110.54	0.0011	78
46	N 12 43.8790	E 030 49.1960	0.121	621.09	113.31	0.0011	107

Fallow fields without *Acacia senegal* (*Fallow*)

No.	Latitude	Longitude	C in %	C in g m^{-2}	N in mg g^{-1}	N in %	C:N ratio
0-20cm depth							
8	N 12 51.8280	E 030 58.4900	0.105	359.31	112.29	0.0011	94
26	N 12 56.3330	E 031 06.9480	0.087	297.71	95.44	0.0010	91
47	N 12 46.5880	E 030 47.1590	0.101	345.62	122.74	0.0012	82
57	N 12 55.4920	E 031 00.1600	0.086	294.29	93.94	0.0009	92
61	N 12 58.5150	E 031 02.0950	0.143	489.35	115.13	0.0012	124
69	N 12 56.5800	E 031 19.7650	0.064	219.01	110.20	0.0011	58
79	N 12 49.5040	E 031 02.0130	0.106	362.73	113.48	0.0011	93
84	N 12 48.6670	E 030 58.6980	0.091	311.40	100.50	0.0010	91
20-50cm depth							
27	N 12 56.3330	E 031 06.9480	0.062	318.25	88.27	0.0009	70
48	N 12 46.5880	E 030 47.1590	0.062	318.25	100.60	0.0010	62
58	N 12 55.4920	E 031 00.1600	0.061	313.11	85.41	0.0009	71
62	N 12 58.5150	E 031 02.0950	0.088	451.70	94.36	0.0009	93
70	N 12 56.5800	E 031 19.7650	0.057	292.58	94.56	0.0009	60
80	N 12 49.5040	E 031 02.0130	0.067	343.91	106.64	0.0011	63
85	N 12 48.6670	E 030 58.6980	0.066	338.78	92.56	0.0009	71

Undisturbed site without *Acacia senegal* (*Virgin*)

No.	Latitude	Longitude	C in %	C in g m^{-2}	N in mg g^{-1}	N in %	C:N ratio
0-20cm depth							
4	N 12 53.0370	E 030 59.3850	0.061	208.74	72.72	0.0007	84
12	N 12 51.6820	E 030 54.9490	0.201	687.82	115.79	0.0012	174
15	N 12 49.4350	E 030 54.6140	0.083	284.03	78.92	0.0008	105
20	N 12 55.3600	E 031 06.4440	0.091	311.40	91.50	0.0009	99
35	N 12 53.4390	E 031 13.1990	0.506	1731.53	572.96	0.0057	88
73			0.384	1314.05	316.67	0.0032	121
20-50cm depth							
21	N 12 55.3600	E 031 06.4440	0.077	395.24	100.99	0.0010	76
36	N 12 53.4390	E 031 13.1990	0.453	2325.25	173.96	0.0017	260
74			0.970	4979.01	541.12	0.0054	179

Crop fields (*Crops*)

No.	Latitude	Longitude	C in %	C in g m^{-2}	N in mg g^{-1}	N in %	C:N ratio
0-20cm depth							
3	N 12 53.8000	E 031 00.1660	0.102	349.04	120.34	0.0012	85
10	N 12 52.1270	E 030 54.8170	0.112	383.26	102.29	0.0010	109
14	N 12 53.2060	E 030 53.2580	0.089	304.56	102.33	0.0010	87
18	N 12 55.4830	E 031 05.3840	0.107	366.15	97.85	0.0010	109
24	N 12 56.7350	E 031 06.5240	0.074	253.23	93.91	0.0009	79
31	N 12 54.9920	E 031 29.5350	0.070	239.54	93.05	0.0009	75
51	N 12 46.9720	E 030 47.7560	0.071	242.96	74.81	0.0007	95
53	N 12 55.8600	E 031 00.7020	0.094	321.67	112.64	0.0011	83
63	N 12 56.4690	E 031 02.7960	0.093	318.25	101.33	0.0010	92
67	N 12 55.0410	E 031 19.9210	0.053	181.37	132.47	0.0013	40
71	N 12 53.2780	E 031 19.3480	0.090	307.98	116.96	0.0012	77
77	N 12 49.5590	E 031 01.3640	0.056	191.63	78.01	0.0008	72
81	N 12 49.0750	E 031 00.3810	0.065	222.43	83.29	0.0008	78
90	N 12 52.4380	E 031 02.1010	0.131	448.28	137.79	0.0014	95
92	N 12 54.2800	E 031 02.4210	0.069	236.12	94.02	0.0009	73
96	N 12 51.1590	E 031 09.4350	0.081	277.18	138.85	0.0014	58
32	N 12 53.4200	E 031 29.3010	0.42	1440.66	229.12	0.0023	184
34	N 12 53.5050	E 031 29.2340	0.34	1166.90	172.25	0.0017	198
20-50cm depth							
19	N 12 55.4830	E 031 05.3840	0.078	400.37	102.59	0.0010	76
25	N 12 56.7350	E 031 06.5240	0.050	256.65	103.33	0.0010	48
30	N 12 54.9920	E 031 29.5350	0.049	251.52	97.81	0.0010	50
52	N 12 46.9720	E 030 47.7560	0.049	251.52	86.84	0.0009	56
54	N 12 55.8600	E 031 00.7020	0.059	302.85	90.00	0.0009	66
68	N 12 55.0410	E 031 19.9210	0.048	246.38	79.81	0.0008	60
72	N 12 53.2780	E 031 19.3480	0.084	431.17	122.60	0.0012	69
78	N 12 49.5590	E 031 01.3640	0.060	307.98	93.58	0.0009	64
83	N 12 49.0750	E 031 00.3810	0.067	343.91	96.18	0.0010	70
91	N 12 52.4380	E 031 02.1010	0.068	349.04	96.48	0.0010	70
93	N 12 54.2800	E 031 02.4210	0.065	333.65	94.91	0.0009	68
97	N 12 51.1590	E 031 09.4350	0.072	369.58	114.27	0.0011	63
64	N 12 56.4690	E 031 02.7960	0.072	369.58	110.58	0.0011	65
Clay soil samples							
32	N 12 53.4200	E 031 29.3010	0.42	1440.66	229.12	0.0023	184
34	N 12 53.5050	E 031 29.2340	0.34	1166.90	172.25	0.0017	198

APPENDIX 4: BIOMASS CALCULATIONS

Fallow fields with *Acacia senegal (Fallow$_A$)*

Age = period during which current land use occurs on this field
d = diameter at 30 cm height, r = radius at 30 cm height
CSA = stem cross sectional area at 30cm height, T no. = No. of trees
B_T = tree biomass, B_G = grass biomass, B_{Tot} = total biomass
Above ground biomass = $y = 3.71 + 4.12 \times CSA$

Fine roots = $y = 23.4 \times CSA^{0.512}$

Coarse roots = $y = 0.0004 \times CSA^{1.737}$

No.	Age	d	r	CSA	Above	Fine roots	Coarse roots	T no.	B_T in kg m^{-2}	$B_{T\ litter}$ in kg m^{-2}	% grass	B_G in kg m^{-2}	B_G - grazing	B_{Tot} in kg m^{-2}	B_{Tot} in g m^{-2}
7	17	22	11	380.13	1569.86	489.94	12.12	3	0.0155	0.0025			0	0.002	2.49
9	25	20	10	314.16	1298.05	444.38	8.70	11.5	0.0503	0.0081	0.6	0.6798	0.3399	0.348	347.96
11	25	11.5	5.75	103.87	431.65	252.15	1.27	13	0.0223	0.0036		0	0	0.004	3.56
13	17	19.5	9.75	298.65	1234.14	433.01	7.97	15	0.0628	0.0101	0.5	0.5665	0.28325	0.293	293.30
17	18	22.5	11.25	397.61	1641.85	501.35	13.10	4	0.0216	0.0035	0.4	0.4532	0.2266	0.230	230.05
22	20	21.5	10.75	363.05	1499.48	478.54	11.19	1	0.0050	0.0008	0.2	0.2266	0.1133	0.114	114.10
49	18	12.5	6.25	122.72	509.31	274.62	1.70	2	0.0039	0.0006	0.2	0.2266	0.1133	0.114	113.93
55	30	31.5	15.75	779.31	3214.47	707.57	42.17	2	0.0198	0.0032	0.4	0.4532	0.2266	0.230	229.77
59	20	11	5.5	95.03	395.25	240.93	1.09	8	0.0127	0.0020	0.7	0.7931	0.39655	0.399	398.59
65	20	15.5	7.75	188.69	781.12	342.30	3.59	2	0.0056	0.0009	0.1	0.1133	0.05665	0.058	57.55
75	26	21.5	10.75	363.05	1499.48	478.54	11.19	8	0.0398	0.0064	0.4	0.4532	0.2266	0.233	232.97
86	24	20.2	10.1	320.47	1324.06	448.93	9.01	6	0.0267	0.0043	0.5	0.5665	0.28325	0.288	287.53
88	30	14.5	7.25	165.13	684.05	319.70	2.85	12	0.0302	0.0048	0.5	0.5665	0.28325	0.288	288.08
94	17	16	8	201.06	832.09	353.61	4.01	3.5	0.0104	0.0017	0.1	0.1133	0.05665	0.058	58.32

Fallow fields without *Acacia senegal (Fallow)*

No.	Age	d	r	CSA	Above	Fine roots	Coarse roots	T no.	B_T in kg m^{-2}	$B_{T\ litter}$ in kg m^{-2}	% grass	B_G in kg m^{-2}	B_G - grazing	B_{Tot} in kg m^{-2}	B_{Tot} in g m^{-2}
29	22	12	6	113.10	469.67	263.38	1.48	13	0.0239	0.0038			0	0.004	3.82
37	42	13	6.5	132.73	550.57	285.88	1.95	9	0.0189	0.0030	0.3	0.3399	0.16995	0.173	172.97
39	42	12.5	6.25	122.72	509.31	274.62	1.70	10	0.0196	0.0031	0.3	0.3399	0.16995	0.173	173.09
41	42	10.2	5.1	81.71	340.37	223.00	0.84	8	0.0113	0.0018	0.3	0.3399	0.16995	0.172	171.76
43	42	13	6.5	132.73	550.57	285.88	1.95	9	0.0189	0.0030	0.2	0.2266	0.1133	0.116	116.32
45	42	10	5	78.54	327.29	218.53	0.78	13.5	0.0184	0.0030	0.2	0.2266	0.1133	0.116	116.25

Crop fields (*Crops*)

No.	Age	Crop	Y in $unit_{Sud}$	Y in kg ha^{-1}	B_{tot} in kg ha^{-1}	B_R in kg ha^{-1}	B_R in g m^{-2}
3	7	M	1.5 s moh^{-1}	182.43	975.02	97.50	9.75
10	7	So	2 s 6 moh^{-1}	40.54	288.12	28.81	2.88
92	35	So	20 s 6 moh^{-1}	405.41	2881.16	288.12	28.81
71	22	So	0.5 s 4 moh^{-1}	15.20	108.04	10.80	1.08
53	10	So	5 s 3.5 moh^{-1}	173.75	1234.78	123.48	12.35
14	7	K	4 k moh^{-1}	243.24	670.71	67.07	6.71
18	20	K	5 k 0.5 moh^{-1}	608.11	1676.77	167.68	16.77
31	5	K	4 k 5 moh^{-1}	48.65	134.14	13.41	1.34
51	10	K	12 k 4 moh^{-1}	182.43	503.03	50.30	5.03
96	30	K	6 k 2 moh^{-1}	182.43	503.03	50.30	5.03
24	10	S	25 k 10 moh^{-1}	152.03	419.19	41.92	4.19
90	30	S	2 s 9.5 moh^{-1}	25.60	70.60	7.06	0.71
81	30	K, B	1 k K, 2 s B moh^{-1}	304.05	838.38	83.84	8.38
77	27	K, G	5 k K, 4 s G 7 moh^{-1}	112.93	311.40	31.14	3.11
67	30	K, S	3 k K, 2 k S 6 moh^{-1}	50.68	139.73	13.97	1.40
63	12	S, K	2 k K, 1 s S moh^{-1}	40.54	111.78	11.18	1.12
32	18	S	1 k 0.25 moh^{-1}	243.24	670.71	67.07	6.71
34	18	So	3 s moh^{-1}	364.86	2593.05	259.30	25.93

Crops: M = millet, S = sesame, K = karkade, So = sorghum, B = beans, G = groundnuts
Y in $unit_{Sud}$ = Yield in Sudanese units, B_{tot} = total biomass, B_R = root biomass

Undisturbed site with *Acacia senegal (Virgin$_A$)*

No.	Age	d_1	d_2	T no.	$Name_T$	Cd_1	log Cd_1	Cd_2	log Cd_2	log B_{T1}	B_{T1} in kg	log B_{T2}	B_{T2} in kg	B_{Tdry} in kg $400m^{-2}$	B_{Tdry} in kg m^{-2}	L B_{Tdry} in kg m^{-2}	% grass	B_G in kg m^{-2}	B_G grazing	B_{tot} in g m^{-2}
8	10	8.5	20	2	habil, usher	13.69	1.14	29.16	1.46	1.64	44.12	2.06	116.13	48.07	0.12	0.02		0.00	0.00	19.23
26	10	10		2	sereh	10.89	1.04			1.52	32.92			19.75	0.05	0.01	0.3	0.34	0.17	177.40
47	9	29.5		1	usher	18.49	1.27			1.81	64.82			19.44	0.05	0.01	0.2	0.23	0.11	120.78
57	25	26.5		1	usher	14.82	1.17			1.69	48.84			14.65	0.04	0.01	0.4	0.45	0.23	231.86
61	14	2	11.5	9 (1 U)	sereh, usher	6.76	0.83	11.56	1.06	1.25	17.88	1.55	35.53	53.57	0.13	0.02		0.00	0.00	21.43
69	13	6		3	robesh	26.52	1.42			2.01	102.86			92.57	0.23	0.04	0.15	0.17	0.08	121.78
79	18																1	1.13	0.57	565.00
84	18																1	1.13	0.57	565.00

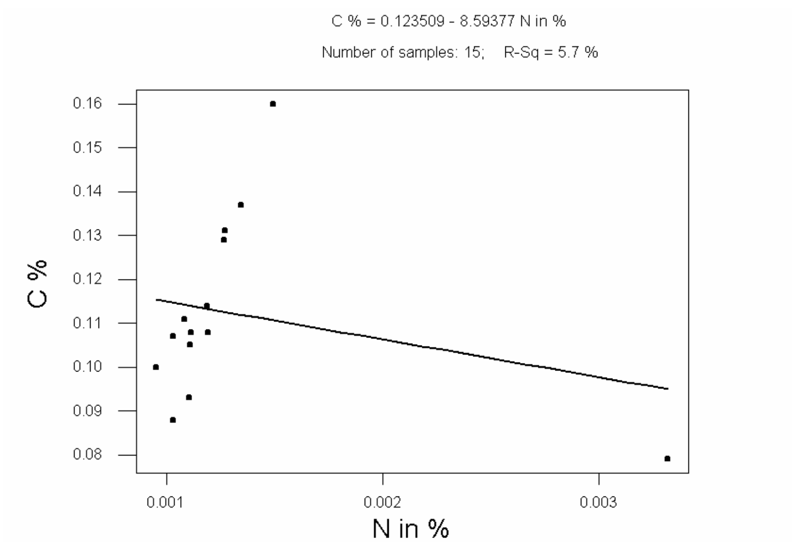
Undisturbed site without *Acacia senegal (Virgin)*

No.	Age	d_1	T no.	$Name_T$	Cd_1	log Cd_1	log B_{T1}	B_{T1} in kg	B_{Tdry} in kg $400m^{-2}$	B_{Tdry} in kg m^{-2}	L B_{Tdry} in kg m^{-2}	% grass	B_G in kg m^{-2}	B_G grazing	B_{tot} in g m^{-2}
4	30											1	1.13	0.57	565.00
12	50											1	1.13	0.57	565.00
15	31											1	1.13	0.57	565.00
20	30	8	1	robesh	12.25	1.09	1.58	38.27	11.48	0.03	0.00	0.6	0.68	0.34	343.59
35	50	24.5	7	Nim	21.16	1.33	1.89	77.03	161.76	0.40	0.06	0	0.00	0.00	64.71
73	50	38	4	Nim	57.76	1.76	2.44	278.54	334.24	0.84	0.13	0	0.00	0.00	133.70

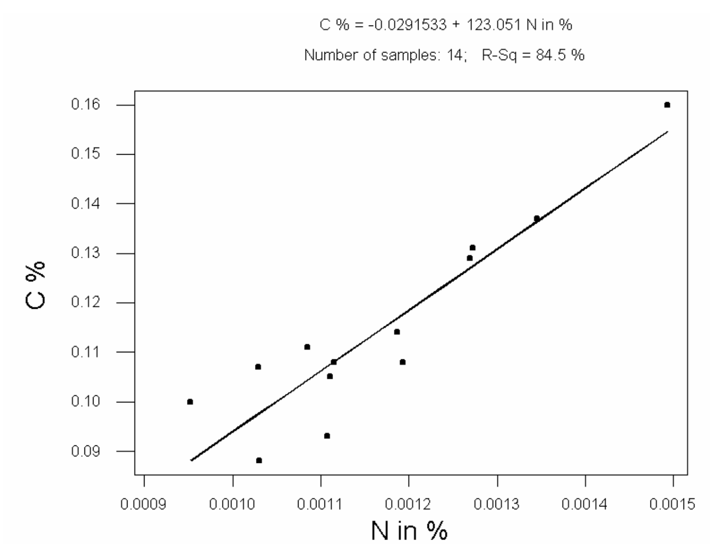
d_1 = diameter of tree 1 at 1.3 m height
Cd_1 = crown diameter of tree 1

APPENDIX 5: RESULTS OF REGRESSION ANALYSIS FOR C AND N

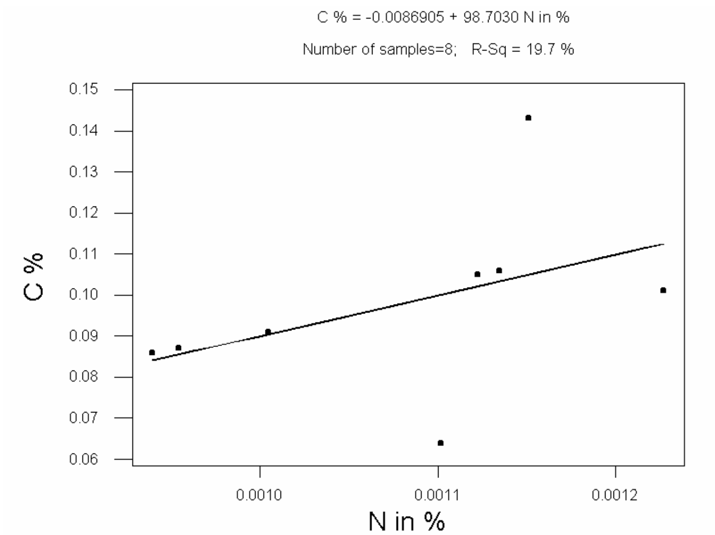
Fallow$_A$



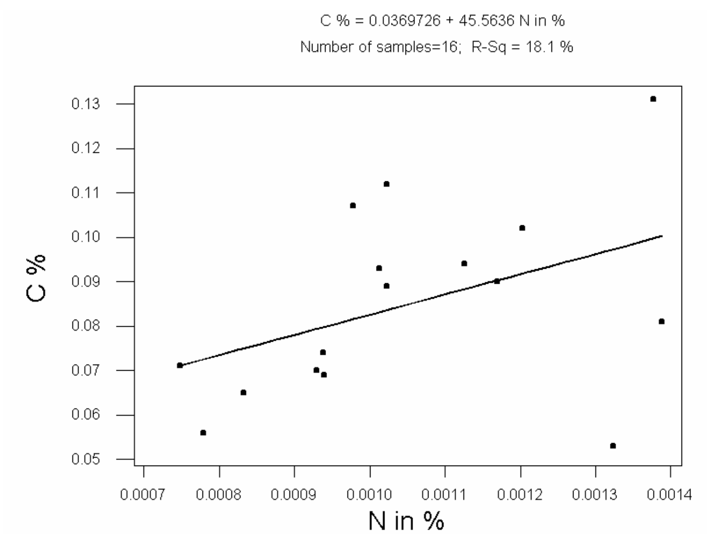
Fallow$_A$ without soil sample No. 65



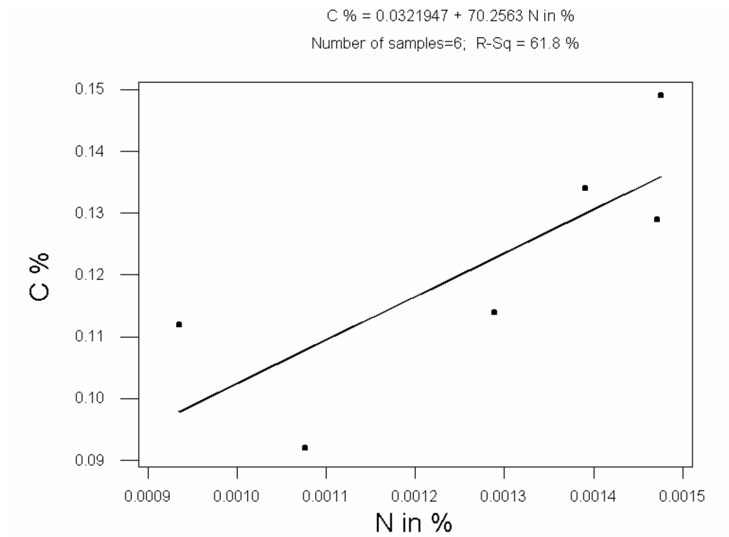
Fallow



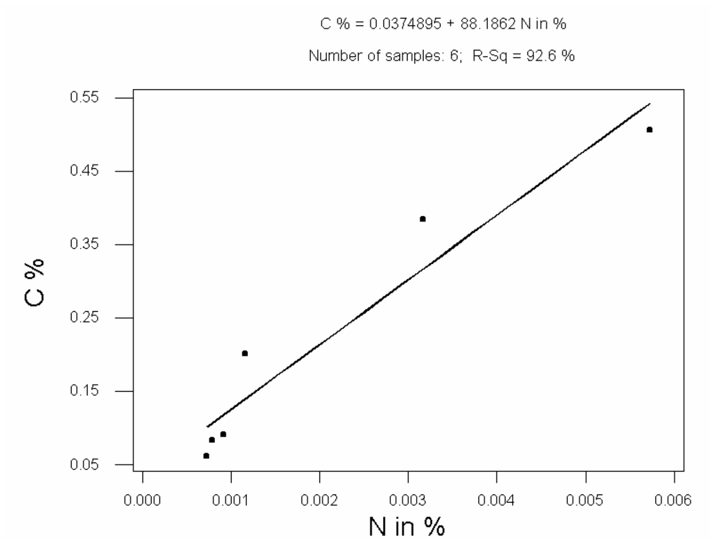
Crops



Virgin$_A$



Virgin



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