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Verification of Soil Carbon Sequestration – Uncertainties of Assessment Methods

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ABSTRACT (svenska*)*

Kunskap om mängden kol som växter tar upp i från atmosfären är i dag en viktig frågeställning inom naturvetenskaplig forskning. Resultaten av sådan forskning kan bl.a. användas vid internationella konventioner som t.ex. Kyoto avtalet. I denna studie har jord prover från semi-arida agro-ekosystem i Sudan statistiskt analyserats för att se om skillnaden i organiskt kol över tid och rum kan detekteras ("minimum detectable difference" (MDD)). Proverna kom från tre olika fält. "MDD" är den minsta detekterade skillnaden mellan medelvärden när variansen, signifikansnivån, statistiska styrkan och antalet prover är kända. Inom de tre fälten varierade variansen mellan 51 000 och 212 000. Den höga variabiliteten gör en verifiering av mängden kol som jorden kan ta upp svår. Över 1000 jord prov skulle behövas för att observera en 5 % förändring i organiskt kol (motsvarande 25 g m^{-2}). En fördubbling av variansen innebär också ett fördubblat behov av antalet jordprover för att få samma "MDD". En s. k. "jackknife routine" användes för att simulera delar av det ursprungliga datasetet (de observerade jordproverna). Delarna representerade antalet jordprover och varierade mellan 2 och 99 samt simulerades 500 gånger var. Från resultaten beräknades medelvärden, variansen och deras 95 % konfidensintervall. Användning av det översta konfidensintervallet av variansen i "MDD" beräkningar kan leda till fördubblat behov av antalet jordprover. En sensitivitets analys samt framtida scenarier utfördes med ekosystem modellen CENTURY. Målet av denna analys/scenarier var att observera effekten på organiskt kol vid varierande klimat (nederbörd, temperatur), markanvändning, jordens kornstorleksfördelning, andel efterlämnad biomassa efter skörd och kväve (N) fixering. Modellen visade sig vara mest känslig för mängden N fixering av träd. Effekten av klimatförändringar var mest framträdande då mängden N fixering var hög. Möjliga framtida klimatförändringar visade ingen ökning i organiskt kol. Olika typer av odlings metoder och grödor leder till signifikanta skillnader i mängden organiskt kol i marken. Hundra år kontinuerlig odling av hirs (*Pennisetum typhoideum)* leder till en förlust av 0,3 g C m^{-2} $år^{-1}$ medan odling:träda ratio 5:10 och endast betning leder till en ökning av 0.4 g C m^{-2} $år^{-1}$ respektive 1.5 g C m^{-2} $år^{-1}$. De presenterade resultaten är simulerade helt utan N fixering. Vid närvaro av N fixerande vegetation ökar samtliga presenterade resultat.

Nyckel ord: Sequestration, Soil organic carbon (SOC), Sudan, Semi-arid, Minimum detectable difference (MDD), Jackknife routine, Modeling, Sensitivity, CENTURY

ABSTRACT

Knowing the amounts of atmospheric carbon soils can potentially sequester is gaining great interest among the scientific community. International conventions, such as the Kyoto Protocol, help promote such research. In this study, soils samples from a semi-arid agro-ecosystem of the Sudan were statistically analyzed to evaluate if changes in soil organic carbon (SOC) over time or space were cost-effectively detectable or not, given a sample size (with minimum detectable difference (MDD) method). One hundred (100) samples were taken from each of three fields. The MDD is the smallest detectable difference between treatment means once the variation, significance level, statistical power and sample size are specified. The variances of the SOC contents varied between 51 000 and 212 000. This makes short-term verification of carbon sequestration difficult as over 1000 soil samples would be required to observe a 5% change (25 g m^{-2}) in SOC over time or space. A doubling of the variance also doubles the required amount of soil samples to achieve the same MDD. A "jackknife routine" was setup to simulate alternative data sets from the available data (observed soil samples). These datasets represented sample sizes ranging from 2 to 99 and were extracted 500 times for each sample size. For the results, the mean, the variance and their 95% confidence interval were calculated. Using the upper 95% confidence interval for the variance estimates in the MDD calculations can lead to as much as a twofold increase in the sample size requirement compared with the average variance of all samples. A sensitivity analysis and future scenarios were done with the CENTURY ecosystem model to evaluate the effects of varying climates (precipitation and temperature), land management and harvest practices, soil texture and nitrogen (N) fixation by trees on SOC. The model showed to be most sensitive to N fixation by trees, and the effects of variations in climate were amplified when N fixation was allowed in the system. Probable future climate scenarios did not indicate a significant increase in SOC, whereas different land management practices did. Long fallow periods (crop:fallow ratio 5:10) and grazing showed the potential of this semi-arid area to sequester up to 0.4 g C m^{-2} yr^{-1} and 1.5 g C m^{-2} yr^{-1} respectively, while soils under continuous cultivation of millet (*Pennisetum typhoideum)* acted as a C source, losing 0.3 g C m^{-2} yr^{-1} over the next century. These numbers result in simulations without N fixation allowed from trees. The presence of N fixing legumes will increase the sequestration rates.

Keywords: Sequestration, Soil organic carbon (SOC), Sudan, Semi-arid, Minimum detectable difference (MDD), Jackknife routine, Modeling, Sensitivity, CENTURY

SUMMARY

It is well documented that atmospheric carbon dioxide (CO_2) is increasing globally. Many scientific studies also show that increased CO_2 in the atmosphere may raise the mean global temperature and disturb climates in unforeseen ways. The Kyoto Protocol is a framework aiming for an international collaboration for the reduction of atmospheric greenhouse gases (GHG), of which CO_2 is one of the most important. Within the Kyoto Protocol, there are some "mechanisms" designed to help countries reach their reduction targets as cost-effectively and efficiently as possible. One of those mechanisms is called the Clean Development Mechanism (CDM), which allows developed countries to invest in sustainable development projects in developing countries. Some studies show that improved land management practices can result in an increase of the rate at which carbon is sequestered from the atmosphere into soils, and this is one of the basis on which the CDM concept is designed. If significant investments are made to promote projects that could sequester carbon, it is important to be able to quantify as precisely as possible the changes in soil organic carbon (SOC) over time or space in order to relate the changes to the Kyoto Protocol and to justify adequate monetary sums for projects. A reason why soils should be considered as carbon "sinks" is that carbon in soils can have very long residence times (up to thousands of years) if it can reach a stable state in which is becomes protected from physical and chemical destructive processes.

SOC can be estimated though direct soil sampling. The number of soil samples over an area will determine the accuracy of the estimates. The detection of changes in SOC over time or space will also be relevant to the number of soil samples taken each time or place. Three hundred soil samples (100 samples for each of 3 fields) from a semi-arid agro-ecosystem of the Sudan, Africa were statistically analyzed to see if the detection of such changes would be possible for short-term verification. The variance is a statistical parameter explaining the variability of the samples in regards to the mean value. A number of statistical tests are designed to evaluate if two or more groups of samples are significantly different or not. If a statistical test results in fields not being significantly different, then changes in SOC cannot be detected. A method known as the "minimum detectable difference" can provide the number of soil samples required to statistically differ sampling groups, given the variability (variance) of each group. This is helpful for the design of efficient sampling schemes for the verification and monitoring of SOC. Given the variability of the samples analyzed, more than 1000 samples would be required over at least two time periods or places in order to detect a 5% increase of the SOC. Nevertheless, as the variability decreases by half, so does the number of soil samples required to detect the same change in SOC. Estimating the variance for soil properties can be difficult because many factors can influence important changes over very small ground areas. For this reason, a "jackknife routine" was used. Such a routine is used to simulate alternative data sets from the available data (observed soil samples). These datasets represented sample sizes ranging from 2 to 99 and were extracted 500 times for

each sample size. For the results, the mean, the variance and their 95% confidence interval were calculated. It is therefore possible to evaluate how representative are the overall mean and variance for each sampling group.

Computer models can be used to simulate SOC from different scenarios. One of those models, called CENTURY, was tested to evaluate its sensitivity to variations in some input parameters concerning climate, land management and harvest practices, soil texture and plant physiology regarding the modeling of SOC. A number of future scenarios were also designed to have an idea of the faith of SOC in the study area for different land management practices and climate change scenarios. Future climate scenarios did not indicate important changes in SOC, but improved land management, such as the stop of continuous cultivation and the return of long fallow periods (crop:fallow ratio 5:10 years) did show important increases in SOC. More SOC has the benefit of increasing soil fertility, crop productivity (food security), as well as helping combat other serious problems such as desertification and the decline in biodiversity. In a world where adequate food supplies and climate can cause rigorous problems, such considerations should be reflected upon. It is nevertheless important to remember that scientific proof can only be valid if socio-economic and political issued are also considered.

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1 INTRODUCTION

1.1 A Changing Climate

Billions of tones of carbon are exchanged naturally each year between the atmosphere, the oceans and terrestrial ecosystems. It appears that within the exchanges of this massive and complex system, the global carbon dioxide (CO_2) levels have varied by less than 10% during the 10 000 years before industrialization. However, in the last 200 years, this level has risen by almost 30%, and is predicted to continue rising by 10% every 20 years. The current annual emissions amount to over 7 billion tones (7 Gt CO_2) due to human activities. (UNFCCC, 2001)

Post et al. (1999) note that globally, land use changes and agricultural activities during the last 200 years have made soils act as net sources of atmospheric CO_2. However, improved land management practices can also result in a considerable increase in the rate at which carbon is sequestered into soils (Olsson and Ardö, 2002). This could also lead to higher agricultural productivity (Ringius, 1999). It is understood that these global "carbon sinks" alone are not enough for reducing the level of atmospheric CO_2 to acceptable levels, but they can contribute greatly in combating other serious problems and mitigating the greenhouse effect. Despite important reasons for criticism (mainly within the framework of the Kyoto Protocol), the use of carbon sinks in semi-arid agro-ecosystems may provide environmental and economic ways to combat major threats such as land degradation, desertification, food security and decrease of biological diversity, all of which are targeted in some United Nations Conventions.

The Kyoto Protocol contains a number of proposed "mechanisms" to help countries meet their reduction targets in a cost-efficient way, where carbon sinks could be quantified and even given economic value. In order to utilize efficiently such concepts, it is important to monitor and verify the level of carbon sequestration in soils at different scales (field level, regional, national and global). There are currently a multitude of direct and indirect methods for estimating these levels of carbon sequestration or even predicting future carbon sequestration potentials. Nevertheless, there is a pressing need to develop robust, practical and cost-efficient protocols for monitoring and verifying temporal and spatial changes in soil organic carbon (SOC). This includes examining in more detail various soil-sampling sizes conducted for baseline and verification surveys to provide quantitative values of the *uncertainties* related to different sampling methodologies. Some more indirect methods to estimate soil organic carbon include the use of computer models. Yet, model sensitivity regarding the quality and the amount of environmental input data also requires examination in more detail. Overall, this thesis will hopefully provide a good, detailed background on some *methodologies* that can be used to handle numeric data of environmental properties.

1.2 Research Objectives

This study is divided in two parts. The first part aims to study soil-sampling methodologies in order to statistically relate the number of soil samples with changes of soil organic carbon (SOC) levels over time or space. The goal is to evaluate if short-term carbon sequestration if verifiable, or not, in relation to the available data. The second part aims to investigate the sensitivity of a computer model used to estimate SOC contents. The main objectives are therefore to:

1. Quantify the number of soil samples needed to represent the soil organic carbon content (SOC) within three fields of different land-use in semi-arid Sudan, and estimate the "*minimum detectable difference*" in SOC content associated to a sample size.

2. Examine and quantify a computer model's sensitivity to a number of input data and parameters relating mainly to climate and land management practices. Also test a few probable future scenarios in order to examine future C sequestration potentials in semi-arid agro-ecosystems.

The study will focus on soil sampling extracted from three different land use classes; a cropped field, a field used for grazing and a field in the crop-fallow period. The SOC computer model is the *CENTURY Soil Organic Matter Model* (Metherell et al., 1993).

2 BACKGROUND

2.1 The UN Framework Convention on Climate Change (UNFCCC)

A vast majority of scientists now believe that economic and demographic growth over the last two centuries contributed to the rising of "greenhouse gases" in ways greater to the "natural variability", which could lead to irreversible climate change. In the wake of this problem, the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC) met for the first time in February 1991 to discuss the development of an international convention addressing this issue. The INC adopted the United Nations Framework Convention on Climate Change (UNFCCC) on May 9th 1992. The Convention was opened for signature at the UN Conference on Environment and Development (UNCED), also know as the "Earth Summit", in Rio de Janeiro on June 4th 1992, and came into force on March 21st 1994. (UNFCCC, 2001)

The ultimate objective of this new Convention was to "*stabilize atmospheric concentrations of greenhouse gases at safe level*". The Convention also states that "*such levels should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*". (UNFCCC, 2001)

All the countries involved in the convention are divided into two groups; *Annex I Parties* and *non-Annex I Parties*. The Annex I Parties are the industrialized countries that have historically contributed the most to climate change, while the non-Annex I Parties are the remaining countries, basically, the developing countries. It is recognized within the Convention that the per capita emissions of Annex I Parties are higher than those of most developing countries and they have greater financial and institutional capacity to address climate change problems. (UNFCCC, 2001)

The UNFCCC needed to contain a series of well-defined mechanisms to ensure that national commitments would be respected and achieved. Therefore, the *Kyoto Protocol* was adopted at the third Conference of the Parties (COP-3), held in Kyoto on December 11th 1997. (UNFCCC, 2001)

2.1.1 The Kyoto Protocol

The Kyoto Protocol commits Annex I Parties to individual, legally-binding targets to limit or reduce their greenhouse gas emissions, adding up to a total cut of at least 5% from 1990 levels in the "commitment period" 2008-2012. The individual targets vary from country to country and cover emissions of the six main greenhouse gases, namely *carbon dioxide* (CO_2), *methane* (CH_4), *nitrous oxide* (N_2O), *hydrofluorocarbons* (HFCs), *perfluorocarbons* (PFCs) and *sulphur hexafluoride* (SF_6). (UNFCCC, 2001)

Three "mechanisms" are established within the Protocol to help Annex I Parties reduce the costs of meeting their targets by achieving or acquiring reductions more cheaply in

countries other than their own. These mechanisms are known as *Joint Implementation (JI)*, *International Emission Trading (IET)* and the C*lean Development Mechanism (CDM)*. (UNFCCC, 2001)

The concept of *Joint Implementation* is, in brief, where a company or country part of the Annex I Parties invests in specific emission reduction projects in other developed countries (also Annex I Parties) to earn *emission reduction credits* that the investor may use in meeting its own pollution reduction targets. (UNFCCC, 2001)

The *International Emission Trading* allows Annex I Parties to exchange part of their emission commitment and, hence, to redistribute the division of allowed emission between them. In other words, this permits a country that has decreased its emissions below the target level to sell the surplus to a country with greater difficulty achieving its target. (UNFCCC, 2001)

The goal of the *Clean Development Mechanism* is to allow Annex I Parties to meet their emission reduction obligation cost-effectively by promoting and investing in sustainable development projects in developing countries. Such projects could focus on emission reductions, but the concept of terrestrial biospheric carbon "sinks", through carbon sequestration in soils and biomass, could also play an important role in the CDM. This latter concept remains rather controversial although much scientific efforts are exploring their benefits. (UNFCCC, 2001)

The CDM can, in principle, result in an increase in the overall global cost-effectiveness of reducing greenhouse gases. It offers opportunity for increasing financial resource flows from the developed to the developing countries (Ringius, 1999).

The Article 3.3 of the 1997 Kyoto Protocol underlines that some specified activities in the *land-use, land-use change and forestry (*LULUCF) category that emit or remove CO_2 from the atmosphere could be covered in the calculations. Furthermore, forestry activities limited to afforestation, reforestation and deforestation that have occurred since 1990 may be included in the accounting of emissions (or reductions) and assigned amounts from the first commitment period (2008-2012) onwards. Under the Article 3.4, other activities, known as "additional human-induced activities", not dealt with under Article 3.3, may also be included, but the question to whether or not include them in the first commitment period remains under discussion. These potential additional human-induced activities could include improvements in activities such as (Lal, 2001; Smith, 2001):

- Cropland management to provide higher carbon inputs to soils
- Replenishment of soil fertility through agro-forestry management
- Erosion-control practices
- Conservation tillage
- Grazing management
- Fire management in grasslands
- Forest fire management
- Restoration of former wetlands

2.1.2 Verification Under the Kyoto Protocol's Article 3.4

Verification refers to the activities and procedures that can be followed to establish the reliability of the data. This usually means checking the data against empirical data or independently compiled estimates. This differs from *validation*, which is defined as checking that the emissions and removals data has been compiled correctly in line with reporting instructions and guidelines. (Smith, 2001)

For verification of Article 3.4 activities, estimates are required for carbon fluxes and/or changes in carbon stocks that are independent of those used in the Party's national report. This implies that for any given human-induced activity, there must be at least two independent methods for assessing the size of an emission by a source or removal by a sink. (Smith, 2001)

Generally, two types of methods are used to estimate carbon accumulation or losses on land; those that measure *stocks* of carbon and those that measure *fluxes* of carbon into and out of a given ecosystem. Differences in carbon stocks from the beginning to the end of a commitment period could simply be interpreted as the amount emitted or sequested. Alternatively, measuring the flux of carbon into or out of an ecosystem over the commitment period will also yield the net change. It is apparent that both methods will have to be combined to achieve efficient verification. Verification of carbon stocks through direct soil sampling remains rather costly and would make verification of national levels or by international review teams impossible. On the other hand, flux measurement methods are not yet sufficiently reliable to be used as the primary measurement methods. Further, because the whole ecosystem exchange is measured, it is difficult to factor out the different contributions of soils, roots and above ground vegetation. Another disadvantage is that flux measurement equipment remains very expensive and does not exist for most sites. (Smith, 2001)

Data availability and uncertainty is a problem that could slow down the implementation of activities under Article 3.4. Smith (2001) notes that very few, if any, countries perform all the measurements needed to report LULUCF activity emissions and sinks routinely. In fact, only 15 of the 27 countries which presented project proposals relating to Article 3.4 activities before the COP-6 meeting (submitted before a 1st August 2000 deadline) included quantitative estimates to back their proposals. Establishing figures for the 1990 "baseline" year will probably be even more problematic, as data relating to Article 3.4 activities does not even exist for many countries.

2.2 Soils and Organic Carbon

2.2.1 The Role of Soils in the Carbon Cycle

In the global carbon cycle, soil organic carbon (SOC) represents the largest reservoir in interaction with the atmosphere and is estimated to about 1500 Pg C to 1m depth (about 2456 Pg C to 2m depth) [P (peta) = 10^{15} g = Gt = 10^{9} metric tones] (Figure 2.1). Vegetation (650 Pg) and the atmosphere (750 Pg) store considerably less C than soils do. Some calculations estimate that emissions (release of CO_2 from the terrestrial reservoir to

the atmosphere) corresponding to change in land use (mainly deforestation and increase in pasture and cultivated lands) were around 140 Pg from 1850 to 1990 (from 0.4 Pg yr^{-1} in 1850 to 1.7 Pg yr^{-1} in 1990), with a net release to the atmosphere of 25 Pg C. (Robert, 2001)

According to IPCC (2000), historical loss from agriculture soils was 50 Pg C over the last half century, which represents 1/3 of the total loss from soil and vegetation.

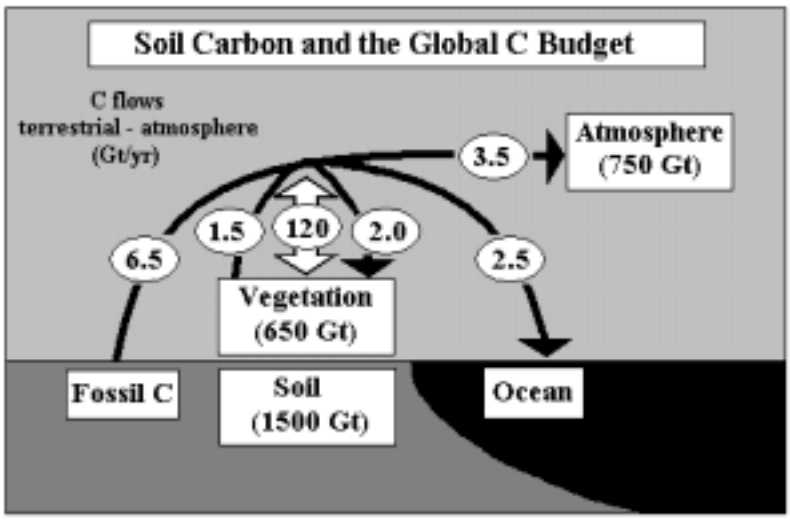


Figure 2.1: The terrestrial carbon cycle. The values represent the flows of carbon in Gt yr^{-1} between land and the atmosphere. (Modified from Robert, 2001)

In the past, the development of agriculture was the main cause of the increase of CO_2 concentration in the atmosphere, but now the combustion of fossil carbon by industry and transport (6.5 Pg yr^{-1}) represent the main contribution. It should be noted that, at present, while deforestation produces emissions estimated at about 1.5 Pg yr^{-1}, elsewhere, around 1.8 to 2 Pg yr^{-1} is accumulating in terrestrial ecosystems. This is known as the "missing sink" in the cycle, which is currently unknown. (Robert, 2001)

The main factors acting on organic matter evolution in soils concern the vegetation (residue input, plant composition), then climatic factors (temperature/moisture conditions), and the soil properties (texture, clay content and mineralogy, acidity). Other effects, relating to soil fertilisation (N, P or S) or irrigation, have an effect on the plant production and therefore on organic matter. The rate of soil organic matter (SOM) mineralization depends mainly on temperature and oxygen availability (drainage), land use, cropping system, soil and crop management. It has been noted that a given soil type exposed to a constant practice can reach near-equilibrium (steady state) in SOM content normally after 30 to 50 years. (Robert, 2001)

The total amount of carbon produced by decomposition of plant litter is mainly determined by the amount of litter present and its quality. The quality of plant litter with respect to decomposition can be defined as its relative ease of mineralization by decomposing organisms. Plant litter quality involves characteristics of plant material that

affects its assimilation by decomposers. These characteristics are both of physical and chemical nature. (Corbeels, 2001)

2.2.2 SOC and Land Degradation in Drylands

Drylands can be defined by an aridity index which represents the ratio of precipitation to potential evapotranspiration (P/PET) with values < 0.05 for hyper-arid, < 0.20 for arid and 0.20 - 0.50 for semi-arid climates (Robert, 2001). The soils of these regions can be characterized by frequent drought stress, low organic content, low nutrient reserves and especially low nitrogen content (Lal, 2001). The Office of U.S. Foreign Disaster Assistance/Center for Research on Epidemiology of Disasters (OFDA/CRED) International Disaster Database states that Sudan suffered 12 severe droughts since 1974 (CRED, 2002). Even if the term "*drought*" is very subjective and rather difficult to properly define, this data gives an idea of the frequency of the water deficiency problems encountered in the drylands of Sudan. Drought stress, as well as desertification, low germination and high seedling mortality, low water and nutrient use efficiencies are among some of the principal constraints to high biomass production (Lal, 2001). Based on the definition given by UNEP in 1977 (Nairobi conference), "*desertification"* could be defined as "the diminution or destruction of the biological potential of land which can lead ultimately to desert-like conditions". The term "*degradation"*, on the other hand, implies reduction of resource potential by one or a combination of degradative processes including erosion by water and wind and the attendant sedimentation, long-term reduction in the amount and diversity of natural vegetation and animals, and salinization (Lal, 2001).

Desertification and soil degradation impacts directly the global C cycle through its effects on land use changes and reduction in vegetation cover. This adversely affects topsoil depth and soil quality. The decline in soil quality leads in reduction in SOC pools, which at their turn increase the risk, extent and severity of desertification. These adverse effects of soil quality have been noted to be more severe in hot and dry rather than cold and moist environments. They can, furthermore, be intensified by land misuse and soil mismanagement. Desertification leads to the decline in soil structure and the reduction in soil aggregation. The decline in aggregation can, at its turn, lead to the formation of a surface crust, the reduction in water infiltration rates, the decline in available water reserves in soils and the reduction in biomass production. These crusted soils are also more prone to water runoff and erosion. (Lal, 2001)

The SOC pools are naturally very low in drylands. Previous studies in the soils of the stabilized sand dunes of northern Nigeria had SOC contents often ranging between 1 to 2 g kg^{-1} (well under 1% given a reasonable bulk density for sandy soils). Continuous cropping on these soils will lead to a decline in SOC content to an even lower level (Lal, 2001; Olsson et al, 2002). Ringius (1999) mentions that cultivation in semi-arid savannas can result in a decrease of soil carbon by as much as 40% in the first 3-5 years for sandy soils. Lal (2001) mentions that the SOC is often bound to the clay fraction, which can also be extremely low in some of the soils found in the drylands. Furthermore, the smaller clay particles are more susceptible to wind erosion than the bigger sand particles.

Lal (2001) states that a research in Niger reported that wind-blown material contained 32 times more C than the surrounding topsoil.

Figure 2.2 resumes some of the effects human activities may have on the terrestrial ecosystem.

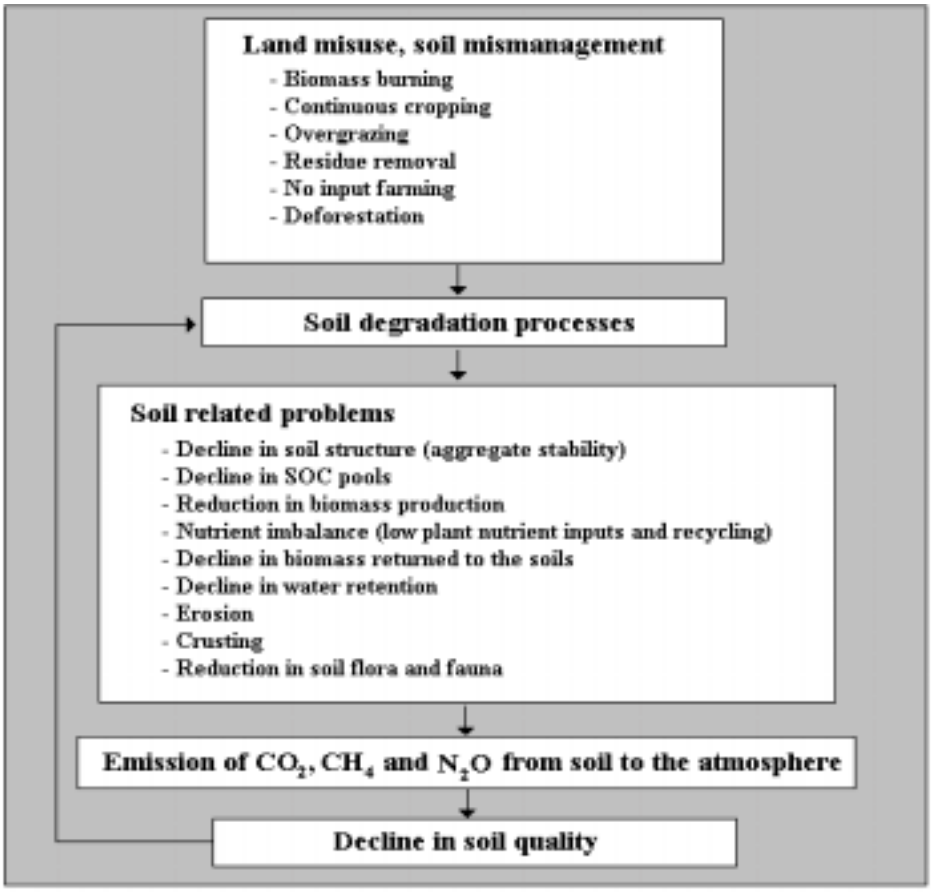


Figure 2.2: Some negative effects of human activities on the terrestrial ecosystem. (modified from Lal, 2002)

2.2.3 Dynamics of Organic Carbon in Soils

The stock of organic carbon in natural soils represents a dynamic balance between the input of dead material and loss from decomposition (Figure 2.3). In aerobic conditions, only a very small fraction (≈1%) of the carbon entering the soil ends up accumulating in the stable, humic fraction (≈0.4 Pg yr^{-1} globally) (Robert, 2001). The rest is labile. The cycling of SOM in soils has a very complex and heterogeneous structuring. SOM is generally mixed or associated with the mineral constituents. Different separation methods have been developed to quantify various SOM constituents, but one of the most common methods involves defining pools by a given turnover rate of the carbon (kinetic pools). Some physical separation methods such as particle size fractionation, density fractionation or aggregate size fractionation allows separation of kinetically meaningful

fractions. These fractions can be very sensitive to land use changes. Other methods determine the microbial biomass, which represents 1 to 5 percent of the total SOM and is a reservoir of nutrients. This fraction can fluctuate in regards with seasons and also responds rapidly to soil management changes. Isotopic methods, such as Carbon-14 dating or Carbon-13 natural abundance are other very powerful methods, which allow estimation of residence times of SOM and its fractions. (Robert, 2001)

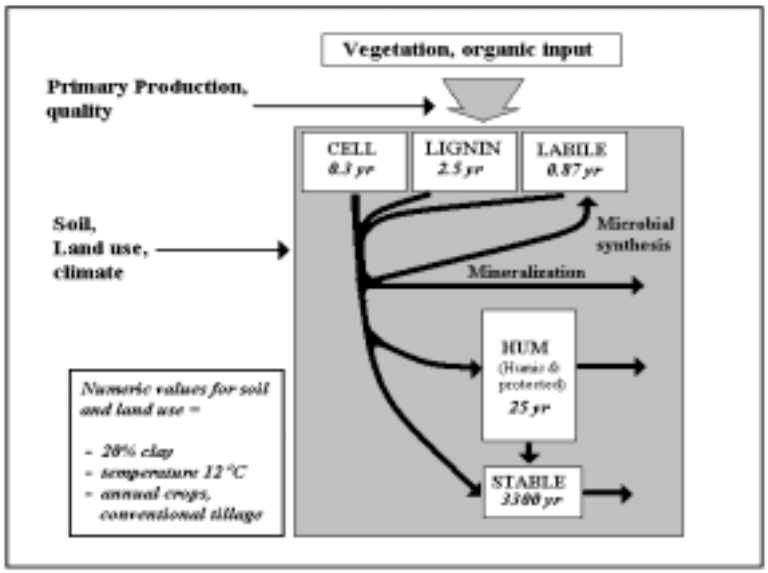


Figure 2.3: Model of soil carbon dynamics. The numeric values represent the results of experiments performed under a specific soil and land use. (Modified from Robert, 2001)

The different C pools found in a soil have different mean residence times, which can range from one year (to a few years, depending on the biochemical composition) to decades or more (more than 1000 years - stable fraction). The main differentiation between these residence times is the kind of protection or the type of bonds between the organic matter and other particles. A general rule is that the residence time of soil aggregates and associated SOM increases as particle size decreases. For the stable carbon fraction, there is an important distinction between physical and chemical protection. A "*physical*" protection means an encapsulation of the organic matter by clay particles or soil micro/macro aggregates. A "*chemical*" protection refers to the specific bonds of the organic matter with other soil constituents (colloids or clays), but most often this concerns other very stable organic compounds. The general term "*sequestration*" as used in the Kyoto Protocol does not take such distinctions into consideration and is equivalent to the term "*storage"*, whatever the form of carbon. (Robert, 2001)

Different factors influence the different organic matter pools. Free organic matter particles and microbial biomass in soils are controlled by residue inputs (management of crop residues, mulching) and climate. Soil aggregation, texture and mineralogy control organic matter in macro aggregates. Therefore, tillage has a great effect on the size of pools. (Robert, 2001)

An increase in SOC can also lead to an increase in cation exchange capacity (CEC) (Robert, 2001). According to Rosen et al. (1998), Cation Exchange Capacity (CEC) quantifies the ability of a soil to provide a nutrient reserve for plant uptake. It is the sum of exchangeable cations (positively charged ions) the soil can adsorb per unit weight or volume. When dissolved in water, the nutrients are either positively charged or negatively charged. Examples of positively charged ions (cations) include: calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^{+}), sodium (Na^{+}), hydrogen (H^{+}) and ammonium (NH_4^{+}).

The establishment of suitable tree species can also have distinct benefits. Firstly, they can provide the much needed ground cover and root system for protecting the soil against erosive forces of wind and water. Secondly, they can produce biomass that can be used as fuel, and thirdly, species with deep root systems anchor the soil and protect the seedlings against drought stress. Incorporating legumes in a rotation cycle can fix nitrogen and therefore enhance the soil quality and the SOC. (Lal, 2001)

Lal (2001) discusses the potential of C sequestration in degraded lands and, although C sequestration can continue for up to 150 years, he notes that the rate and cumulative amount of C sequestration is high only for up to 50 years. Furthermore, he indicates that the peak of sequestration will be reached within the first 10 to 15 years after conversion to improved land management practices.

2.3 Study area

2.3.1 Sudan: an overview

Sudan is the largest country in Africa, area wise, and the 10th largest in the world. It covers an area of approximately 2.5 million km^2, equal to 8.3% of Africa's total surface. Its population is estimated to about 33 million, with a growth rate of 2.63% per year. The urban areas constitute of approximately 32% of the population, with the rest living in rural areas (including about 7% nomads). The population under 15 years of age represents 43% of the total population, while only 3.8% of the people are over 60 years old. The life expectancy at birth is 56 years old. (SMFA, 2002)

Agriculture employs 80 percent of the work force but only 5% of the land is really considered arable (CIA, 2001). The country extends gradually from a desert in the North, with hot, dry climate and no vegetative cover, to the African Sahel Zone in the center with light and dense savannah, and to the sub-tropical region in the South with rigorous rains and dense tree cover. This endows the country with diversity as reflected in various environments and different agriculture systems. Agriculture is the leading economic sector, contributing 48% of the GDP and providing the country with about 80% of the export earnings (SMFA, 2002). The main cultivated crops are cotton (*Gossypium spp.*), millet (*Pennisetum typhoideum*), wheat (*Triticum spp.*), sunflower (*Helianthus annuus*), sorghum (*Sorghum vulgare*), groundnut (*Arachis hypogaea*), sesame (S*esamum indicum*), karkadé (*Hibiscus sabdariffa*) and gum arabic (*Acacia senegal*). Livestock wealth was

estimated in 2000 to be 124 million head. This makes Sudan the fifth richest country in the world in livestock. The animal population is estimated to have doubled in the last decade (SMFA, 2002; SCBS, 2001). Sudan's topography is generally a broad plain, with mountains in the northeast near the Red Sea coast and near the southeastern borders (SMFA, 2002). The Nile is the dominant geographical feature, as around 70% of the area of the country is situated within the Nile river catchment (SMFA, 2002).

2.3.2 Location of the Sampling Sites

All soil samples used were taken from the province of Kordofan, in central Sudan (14ºN and 30.5ºE). The three sampling sites were situated a few hundred meters from each other, therefore covering very similar environments. The closest town is Bara. Figure 2.4 shows the location of the sampling sites on a map of Sudan.

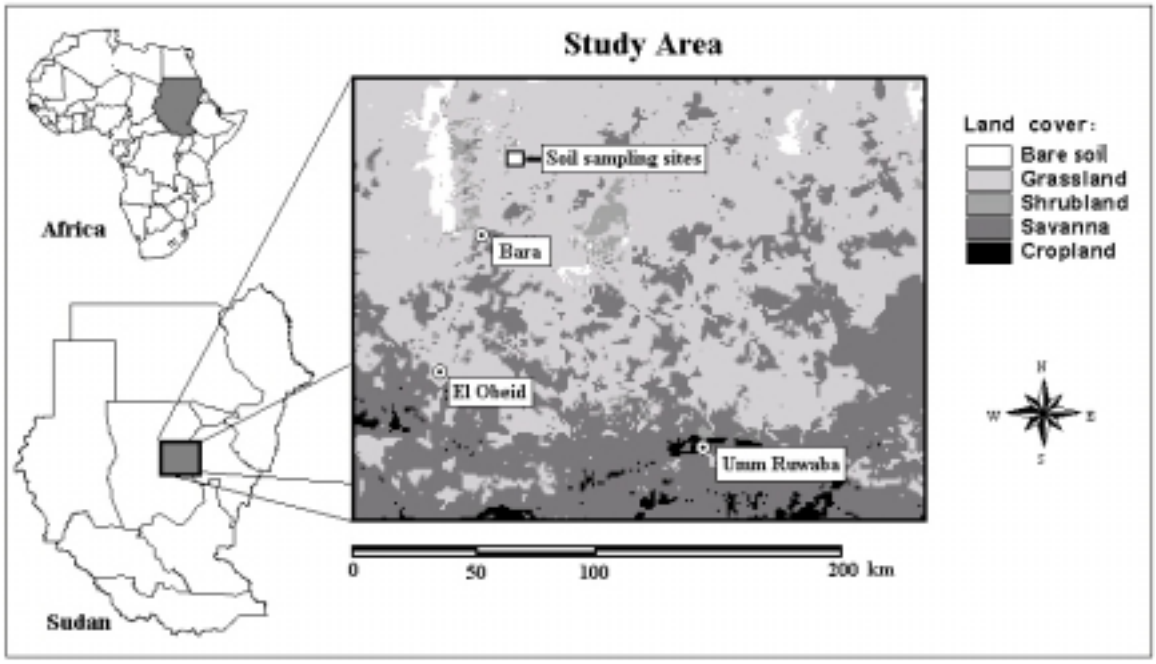


Figure 2.4: Map showing the location of the soil sampling sites in the Province of Kordofan, Sudan. The land cover classification is taken from the Africa land cover database. [1]

2.3.3 Climate

At the sampling sites, the climate is semi-arid with a mean annual rainfall of 270 mm. Precipitation is concentrated to the summer months (June to September) and often reflected with few, intensive events (Olsson, 1985) (figure 2.5). The wettest month is August with a mean monthly rainfall of 130 mm. The period of November through to

[1] The Africa land cover database is one portion of a global land cover characteristics database that is being developed on a continent-by-continent basis. The classification of land cover is based on 1-km AVHRR data spanning April 1992 through March 1993. The legend used was the "IGBP Land Cover Legend". More information can be found at http://edcdaac.usgs.gov/glcc/afdoc1_2.html

February/March does not receive any rain at all (0 mm). The wetter summer months explain the small decline in temperature during those months.

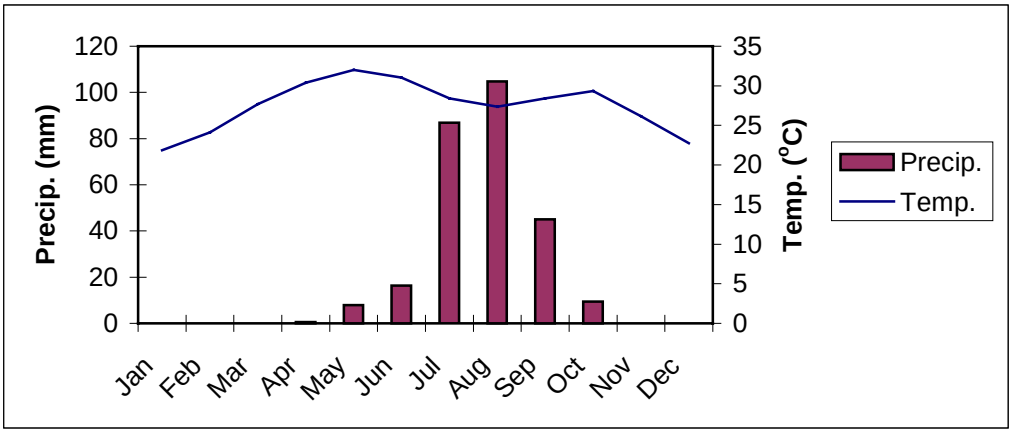


Figure 2.5: Average monthly precipitation (mm) and temperature (ºC) calculated from data from the meteorological station in Bara (closest station to the sampling sites)

2.3.4 Soils

The region is characterized by variable soil types, which are mainly reflected by the modifying effects of local factors such as topography, parent material and broad climatic zonation (Zaroug, 2000). Based on the FAO Soil Map of the World (FAO, 1995), the sampling sites are characterized by the soil type *Cambric Arenosol*.

Arenosols, also known locally as "*Qoz*", are coarse-textures sands. They are reddish in color, which becomes paler with depth, and have low cation exchange capacity (CEC). The profile is generally structureless and pH ranges from 5 to 9. The content of organic matter and mineral nutrients is naturally low, but they are characterized by high permeability to water and relatively high water availability for plants during the dry season. This is due primarily to lower bare soil evapotranspiration in sandy soils, as water penetrates deeper. (Zaroug, 2000; Breymeyer et al., 1996).

The Qoz sands are highly susceptible to erosion by wind and water, and are relatively easy to cultivate using hand tools, which explains why most of the traditional production activities are practiced on these soils. Long years of cultivation exhaust these soils causing a sharp drop in fertility and declining productivity. They are ideal for wet season grazing areas as they are free from biting insects and muddy conditions, which encourages hoof disease among livestock. (Zaroug, 2000)

Other soils of the surrounding area are haplic xerosols, chromic vertisols and chromic luvisols (FAO, 1995; Olsson et al., 2002)

2.3.5 Land Use

The land use is a blend of pastoral grazing, which is often combined with traditional rainfed cultivation, practiced as shifting cultivation. On the sandy "Qoz" soils, the most common rainfed crops are millet, sesame, sorghum and groundnuts, but sorghum is more commonly found in the more clayey soils. The "Qoz" area is where the main millet production of Sudan is obtained (figure 2.6). (Ahlcrona, 1988; Ardö et al, 2002; Olsson et al, 2002).

Figure 2.6: A cultivated field of millet (Pennisetum typhoideum). A soil sample has been taken in the lower part of the picture.

Free grazing of rangelands is the most common feeding system for livestock (Zaroug, 2000). During the short wet season, grasses can grow and mature rapidly producing abundant biomass. Mainly camels and goats graze the area, but cattle and sheep are also found (figure 2.7).

Figure 2.7: Livestock grazing the fields. To the left are sheep and to the right a camel standing next to an Acacia senegal.

Olsson et al. (2002) state that from interviews with local farmers, it is evident that the land use practices have changed noticeably during the last few decades. Rotation systems with long fallow periods (15-20 years) interspersed with short periods of cultivation (4-5 years) have been replaced to what is more or less continuous cropping today. This is due mainly to an increased demand for food due to population increase combined with decreasing yields, which leads farmers to extend their cultivated areas.

2.3.6 Fires

Natural and anthropogenic fires occur frequently in the area. It is common practice to burn the cropland annually prior to planting, which occurs in June or July. Previous studies observed natural fire return intervals for this and similar environments to range from 1 to 12 years (Sitch, 2000). Le Houérou (1989, pages 86-89) states that in the North Kordofan Province of Sudan, wildfires can sweep across the country burning 15-20% of the land area each year. He also mentions that official documents of the Republic of Sudan dating from 1977 state that some 30% of the range resources are burned annually by wildfires in the province of Kordofan. [2]

2.4 The CENTURY Model

The CENTURY model (version 4) is a general process model of plant-soil nutrient cycling, which can be used to simulate carbon and nutrient dynamics for different types of ecosystems including grasslands, agriculture lands, forests and savannas (Metherell et al. 1993). CENTURY consists of several major submodels: a soil organic matter (SOM)/decomposition submodel, a water budget submodel, a grassland/crop submodel, a forest production submodel, and management and events scheduling functions. The water budget and plant production submodels calculate the majority of the direct environmental controllers (for example, soil temperature, soil moisture levels, plant nutrient uptake and the quantity and quality of plant residue production) that are required for the organic matter/decomposition submodel (Pennock et al., 2001). The model computes the flow of carbon, nitrogen, phosphorus and sulfur through the model's compartments. The minimum configuration of elements is C and N for all the model's compartments. The model runs using a monthly time step, functions at the scale of a square meter (i.e. point basis), simulates the 0-20 cm surface layer and requires the following driving variables (Metherell et al. 1993):

- Monthly average maximum and minimum air temperature
- Monthly precipitation
- Soil texture
- Plant nitrogen, phosphorus, and sulfur content
- Lignin content of plant material
- Atmospheric and soil nitrogen inputs
- Initial soil carbon, nitrogen (phosphorus and sulfur optional) levels

The SOM dynamics submodel tracks *active*, *slow* and *passive* organic matter pools. The active pool represents microbial biomass and microbial products, and has a short turnover time of 1-5 years. The slow pool contains a fraction of the SOM that is physically protected and/or in chemical forms with more biological resistance to decomposition, with an intermediate turnover time of 20-50 years. The passive pool represents the

[2] It is also interesting to note that the European Space Agency (ESA) produces monthly databases of global active fire detection and burnt area detection. These are, at the moment, free of charge and can be a great tool to investigate fire frequency and distribution. More details can be found at http://shark1.esrin.esa.it/ionia/FIRE/ (May 2002).

fraction that may be both physically and chemically protected and has turnover times between 400-2000 years. (Mikhailova et al., 2000; Dawidson et al., 2000).

The model uses first order equations to simulate all SOM pools, and the soil moisture and temperature modify transformation rates. The turnover of active SOM and the formation of passive SOM are mediated by soil texture and clay content respectively (higher in clay soils). (Mikhailova et al., 2000)

In agro-ecosystems simulations using CENTURY, management-related driving variables are added to the ecological driving variables. Information can be specified for crop rotations, dates of planting and harvesting, fertilizer and organic amendment addition, herbicide use, grazing, irrigation, fire, tillage practices and erosion. (Pennock et al., 2001)

Within the water budget submodel, the potential evapotranspiration is calculated as a function of the average maximum and minimum air temperature. The monthly precipitation is used to calculate bare soil water loss, interception water loss and transpiration water loss. The field capacity and wilting point for different soil layers are calculated as a function of the bulk density, soil texture, and organic matter content. The average soil temperature near the surface is estimated from the data of the maximum and minimum air temperature and canopy biomass. (Metherell et al., 1993)

The grassland/crop submodel simulates plant production for different herbaceous crops and plant communities (for example, warm and cool season grasslands, wheat and corn) and can even include the impact of grazing and fire on plant production. Grazing removes vegetation, returns nutrients to the soil, alters the root/shoot ratio and increases the nitrogen content of living shoots and roots. On the other hand, the impact of fire is to increase the root/shoot ratio, increase the C:N ratio of live shoots, remove vegetation and return inorganic nutrients to the soils. (Metherell et al., 1993)

The decomposition of the soil organic matter is controlled primarily by the soil temperature and moisture (figure 2.8). Average monthly soil temperature at the soil surface controls the temperature function and the ratio of stored water. The monthly precipitation to the potential evapotranspiration (PET) is the input for the soil moisture function. Microbial respiration occurs for each of the decomposition flows. The partitioning of decomposition between stabilized SOM and CO_2 flux is a function of soil texture for the stabilization of active C into slow C. Plant residues (the shoots and roots) are partitioned into structural (resistant to decomposition) and metabolic (readily decomposable) plant material as a function of the initial residue lignin to nitrogen ratio.

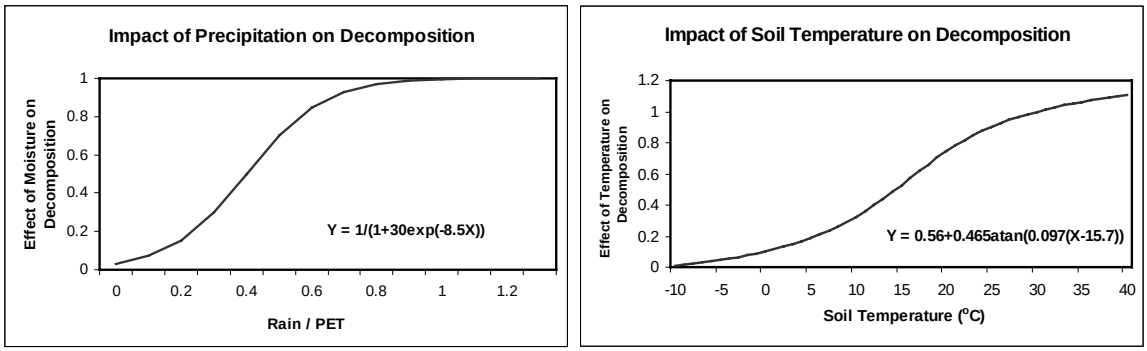


Figure 2.8: The effects of soil moisture and temperature on decomposition in the CENTURY model. (modified from Metherell et al., 1993)

Pennock et al. (2001) mentions that much research are carried out focusing primarily on field-based observational studies. Extrapolations beyond these specific research sites are required if process-based models, such as CENTURY, are to be applied at successively smaller scales. CENTURY is point-based but has several driving variables that are sensitive to landscape transfers and position (for example, soil erosion). This should be carefully considered because although the output of the model is point based, the position of the point in the landscape determines the appropriate soil erosion input values for a given model run. Nonetheless, because the main purpose of this study is to investigate model sensitivity to some parameters and input data, such technicalities are not considered. Also, the landscape surrounding the study plots is relatively flat, reducing the effects of erosion on the position of the point-based modeling.

3 METHODS

3.1 Soil Sampling

Systematic soil sampling was done in three fields of different land-use (cropped, grazed and fallowed) in semi-arid Sudan, in February 2001. One hundred (100) samples were taken from each field making the total number of samples for this project three hundred (300). Each sample was taken with a 5 x 5 meter interval, covering an area of 50 x 50 meters. The samples were taken with a one-litre soil auger at a depth of 0-20 cm.

3.2 Selection of the Experimental Fields

The requirements for the sampling sites were as follows: The cultivated field was ideally continuously cropped for at least 10 years, the field in fallow had not been cultivated for at least 10 years and the grazing field had been untouched for at least 10 years. Interviews with the locals provided the following information on the fields sampled (Jonas Ardö, personal communication, April 2002).

Cultivated field: Was cultivated from 1996 to 2000 with millet/sesame. In 2001, it was not cultivated but weeds were removed. Eight (8) trees were growing within the 50 m x 50 m sampling field. An additional 8 trees were noted within a 20 m buffer around the field.

Field in fallow period: Was not cultivated for over 20 years. In the near future, nothing will be done on this field except some grazing and gum collection (from *Acacia senegal*) from 2002 and forward. Eighteen (18) trees grew within the sampling field, with an additional 28 trees in the 20 m buffer around the field. The total of trees was therefore 46 for a 70 m x 70 m area.

Grazing field: Was not cultivated since 1983. It was grazed, as it was never fenced. The field was, nevertheless, fenced in March 2002, using some thorny bushes. This means that no grazing and no cultivation will occur on this site in the near future. Ten (10) and 13 trees were noted within the boundaries of the field and the 20 m buffer respectively. A total of 23 trees therefore grew within the 70 m x 70 m area.

The trees/bushes noted were either *Acacia senegal* (52), *Acacia tortilis* (10), *Leptadenia pyrotechnica* (18), *Ziziphus spina-cristy* (4) or *Faidherbia albida* (1). [3]

3.3 Measurement of the Soil Organic Carbon (SOC) Content

A quantitative value of the soil organic and inorganic carbon (non-metallic) was measured in laboratory for each soil sample to provide a value of the total carbon content. The analyses were made using the *Carbon Determinator LECO CR-12*. The

[3] In brackets are the total numbers of trees (for all fields).

methodology includes the burning of the samples (at 1300 ºC), which consequently oxidizes the carbon into carbon dioxide (CO_2). The water content, as well as some small particles, are channelled to two filters and the amount of carbon dioxide is detected with a built-in infrared detector. A microcomputer, thereafter, converts this amount of carbon dioxide to a percentage of carbon (given the weight of the original sample analysed). The instruments capability of detection ranges between 0.01 to 100% carbon. The uncertainty of the *CR-12* is ±1% of the carbon content of the samples. The machine's calibration was done using $CaCO_3$ containing precisely 12% carbon. For this study, both the organic and inorganic carbon were considered as *soil organic carbon* because of the extreme low percentages of inorganic carbon. Knowing the bulk density of the sample, the percentage value was subsequently transformed to a value representing the amount of carbon in grams (g) per square metre (m^2) for the upper 20 centimetres (cm) of soil. It is important to note that in the context of this thesis, 1 m^2 equals *1m x 1m x 20 cm deep* (200 liters).

$$SOC\,(g\,m^{-2}) = \frac{\%C}{100} \times (Bulk\ density \times 200) \qquad (3.1)$$

3.4 Bulk Density

The bulk density can be determined with the ratio of the dry weight of a soil sample by its volume. Once the weight is known, the bulk density is calculated with the following equation:

$$Bulk\ density = \frac{Weight}{Volume} \qquad (3.2)$$

3.5 Soil Texture

The soil texture was determined by both sieving and hydrometer analysis. The dried samples were sieved to weight the fraction with particles < 2 mm. To dissolve aggregates, the samples were mixed in solution with 0.5-liter 0.05 M tetra sodium diphosphate decahydrate ($Na_4O_7P_2$*10 H_2O). The sand fraction was calculated by sieving a wet sample through a 0.063 mm net. The following equation describes how the percentage was calculated:

$$Sand\ fraction\ (\%) = \frac{Weight\ of\ sand}{Total\ weight\ of\ sample} \qquad (3.3)$$

The silt and clay fractions (0.06 – 0.002 mm) were determined by sedimentation analysis, i.e. hydrometer analysis, using a Sartorial Portable Pt 2100.

The table 3.1 below describes the classification of different particle sizes defining the overall soil texture.

Table 3.1: Classification of particle sizes.

	Sand	**Silt**	**Clay**
Particle size (mm)	0.06 – 2	0.002 – 0.06	< 0.002

source: SGU, 1990.

3.6 Theoretical Background on some Applied Statistics

3.6.1 Test of Hypothesis (test of significance) – Power Analysis

A commonly used tool in statistical analysis of data is the test of a hypothesis (or test of significance) (Zar, 1984). The hypothesis under test is usually referred to as the *null hypothesis* (H_0), and is tested against the *alternative hypothesis* (H_1). Frequently, the null hypothesis is that no change has occurred in the monitored resource, while the alternative hypothesis is that a change has occurred.

Two types of errors are associated with any statistical test. The Type-I error (α) is the probability of rejecting the null hypothesis when the null hypothesis is true. The Type-II error (β) is the probability of failing to reject the null hypothesis when, in fact, it is false. The value $1-\beta$ is known as the statistical *power* and, in a monitoring perspective, it is the probability that a change will be detected when a change has really occurred. Table 3.2 resumes these concepts in relation to a statistical decision.

Table 3.2: Statistical decision and the error probability

Statistical Decision	**No change has taken place**	**There has been a real change**
Test detects a change (reject H_0)	Type-I error (α)	No error Power ($1-\beta$)
Test detects no change (fail to reject H_0)	No error ($1-\alpha$)	Type-II error (β)

3.6.2 Analysis of Variance (ANOVA)

An analysis of variance (ANOVA) can be used to test whether differences in means ($\mu_1, \mu_2, \mu_3, \ldots, \mu_n$) of three or more sample groups are statistically significant in order to conclude if they were taken from the same population or not. The null hypothesis (H_0) of an ANOVA is always that the sample means show *no* statistical differences and can be generalized as being equal.

$$Ho: \ \mu_1 = \mu_2 = \mu_3 \ \ldots = \mu_n$$

An ANOVA is accomplished by analysing the variability *within* and *between* each treatment group (in this case, the variation of SOC content *within* one particular field and the variation *between* each field). This variability is expressed as the *sum of squares* (*SS*). The *total sum of squares* (*TSS*) is the sum of the squared deviations of all observations from the overall mean. This total sum of squares may be partitioned into the *within sum of squares (WSS)* and the *between sum of squares* (*BSS*). These are thereafter divided by their appropriate *degree of freedom* (v) to give the *mean square* (*MS*). The

ratio of $MS_{between}/MS_{within}$ is then tested for significance using the F-distribution to know if the null hypothesis should be rejected or not. If the absolute F-value from this ratio is greater than the critical value of F (taken from an F distribution table), the null hypothesis (H_0) of no differences between means is rejected, and the alternative hypothesis (H_1) that the means (in the population) are different to each other is accepted.

From the example table below (table 3.3), the partitioning of the sum of squares is as follows: (Note that the "pluses" in the table indicate means, so that X_{+1} designates the mean of column 1, and X_{++} denotes the mean of all the observations.)

Table 3.3. Example of data arrangement for analysis of variance (ANOVA).

	Category 1	Category 2	… Category *k*
Sample 1	X_{11}	X_{12}	X_{1k}
Sample 2	X_{21}	X_{22}	X_{2k}
Sample 3	X_{31}	X_{32}	X_{3k}
:			
Sample *I*	X_{i1}	X_{i2}	X_{ik}
No. of samples	n_1	n_2	n_k
Mean	X_{+1}	X_{+2}	X_{+k}
Standard deviation	s_1	s_2	s_k
Overall mean: X_{++}			

source: Rogerson, 2001

$$TSS = \sum_i \sum_j (X_{ij} - X_{++})^2 \qquad (3.4)$$

$$BSS = \sum_j n_j (X_{+j} - X_{++})^2 \qquad (3.5)$$

$$WSS = \sum_i \sum_j (X_{ij} - X_{+j})^2 = \sum (n_j - 1) s_j^2 \qquad (3.6)$$

The F-value for the ANOVA is:

$$F = \frac{BSS/(k-1)}{WSS/(N-k)} = \frac{MS_{Between}}{MS_{Within}} \qquad (3.7)$$

where: k = the number of treatment groups
N = the total number of samples in all the treatment groups

3.6.3 Nonparametric Multiple Comparisons

In a situation where the sample data does not follow a normal distribution, an analysis of variance (ANOVA), like described above, should not be used to test for significant differences. As an alternative, *nonparametric* (or *distribution-free*) tests should be applied. One of those tests is known as the *Mann-Whitney Test*, which, instead of using

the actual measurements for comparisons, uses the *ranks* of the measurements. It can be employed to test between only two sample groups. To test between more than two sample groups, the nonparametric analysis of variance is done by the *Kruskal-Wallis Test*. Similar to the Mann-Whitney Test, the Kruskal-Wallis Test ranks the observations. Unlike an ANOVA, nonparametric tests are used to test for significant differences between medians and not means. Further details on nonparametric multiple comparisons can be found in Zar (1984).

3.7 Applied Statistics

3.7.1 Descriptive Statistics

A first step in analysing the data sets was to generate general descriptive statistics for each field part of the study. This was done to get an initial idea about the variability of the data within and between the data sets. The variance (s^2), was calculated as follows:

$$s^2 = \frac{\sum (X_i - \mu)^2}{n-1} \qquad (3.8)$$

where: X_i = the sample value
μ = the mean of all samples
n = the number of samples

3.7.2 Testing for Normality and Differences in the Data

The three data sets were then tested for normality with the *Anderson-Darling Normality Test*. The data was, thereafter, analysed using a one-way analysis of variance (ANOVA) and the Kruskal-Wallis test to test for significant differences between the different land cover types. All the combinations of fields were tested two-by-two (cultivated/fallow; cultivated/grazing; fallow/grazing), as well as the three fields together. At this point, the acceptance of the null hypothesis of no difference between means would raise questions regarding the likelihood and the limits of detecting a difference in SOC, given that one exists between different land cover types. Whether or not the data is normally distributed, both ANOVAs and nonparametric testing was performed to provide a base for comparisons and discussion.

3.7.3 Calculation of the Minimum Detectable Differences (MDD)

The temporal and spatial variability of the amounts of soil organic carbon contribute to the variability of their estimates at all scales. In long-term field studies, it is often of interest to detect specific changes in soil properties in order to monitor or verify theories and projects. The "*minimum detectable difference*" is a concept that can be used to study the relation between the number of soil samples required to statistically detect these changes (spatially or temporarily), with a specified confidence level, given the variability of the soil property. The concept can be applied in a number of ways, depending if it is related to *one-sample, two-sample* or *multi-sample hypotheses* (Zar, 1984). Nonetheless, it can be specified as follows (Garten et al. 1999):

> "*The smallest detectable difference between treatment means once the variation, significance level, statistical power and sample size are specified*"

The result of the minimum detectable difference, associated with a sample size, represents the minimum change required to reject the null hypothesis (of no change between treatment means). The concept should, nonetheless, be applied to normally distributed data.

3.7.3.1 MDD for One-Sample Hypotheses

A one-sample hypothesis testing denotes performing statistical analysis on observations taken from only one source or at one particular time – for example, SOC contents taken from one location on a specific date. In such a case, the *Student's t-test* can be used to evaluate the hypotheses and judge whether the sample mean (μ) equals the mean specified in the null hypotheses (μ_0) or not. Commonly specified hypotheses are:

$$H_0: \mu = \mu_0 \qquad \text{and} \qquad H_1: \mu \neq \mu_0$$

If an estimate, s^2, of a population variance, σ^2, is known, it is possible to estimate the minimum sample size required to detect a difference between μ and μ_0 by performing a *t-test* with the probability of α of committing a Type-I error and a probability of β of committing a Type-II error. To test at the α significant level (one or two tailed) with $1-\beta$ power, this minimum sample size required to detect δ and possibly reject the null hypotheses is (Zar, 1984):

$$n = \frac{s^2}{\delta^2}\left(t_{\alpha(1or2),v} + t_{\beta(1),v}\right)^2 \tag{3.9}$$

where: s^2 = the sample variance
δ = the minimum detectable difference
v = degree of freedom (n- 1)
t = value from a *t-table*

By rearranging equation 3.9, it is possible to estimate how small δ (the difference between μ and μ_0) can be detected by the *t-test* with $1-\beta$ power, at the α level of significance, using a sample of specified size n:

$$\delta = \sqrt{\frac{s^2}{n}}\left(t_{\alpha(1or2),v} + t_{\beta(1),v}\right) \tag{3.10}$$

3.7.3.2 MDD for Two-Sample Hypotheses

A two-sample hypothesis is used to test the significance between two treatment means, each representing a group of samples taken from a population (either with spatial or temporal variability). The most commonly used hypotheses are:

$$H_0: \mu_1 = \mu_2 \quad \text{and} \quad H_1: \mu_1 \neq \mu_2$$

The MDD between these two means, given the *within* population variability (estimated with s_p^2) is (Zar, 1984):

$$\delta = \sqrt{\frac{2s_p^2}{n}}(t_{\alpha(1or2),v} + t_{\beta(1),v}) \tag{3.11}$$

The *within* population variability can be estimated with the *pooled variance*, s_p^2, which can be calculated with (Zar, 1984):

$$s_p^2 = \frac{SS_1 + SS_2}{v_1 + v_2} = \frac{v_1 s_1^2 + v_2 s_2^2}{v_1 + v_2} \tag{3.12}$$

where:
SS_1 = sum of squares of group 1
SS_2 = sum of squares of group 2
s_1^2 = variance of group 1
s_2^2 = variance of group 2
v_1 = degree of freedom of group 1 (n_1-1)
v_2 = degree of freedom of group 2 (n_2-1)

3.7.3.3 MDD for Multi-Sample Hypotheses

A multi-sample hypothesis is used when dealing with three or more means[4]. In this case, the MDD value represents the smallest difference detectable between the *two most different means*. An ANOVA must be performed from the three or more (k) treatment groups in order to get an estimate of the within group variability (s^2) which can be estimated by the error MS. Knowing this variability, the MDD is (Zar, 1984):

[4] The case where k = 2: If $k = 2$, then $H_0: \mu_1 = \mu_2$, and either the two-sample *t-test* or the single factor ANOVA may be applied. The conclusions obtained from these two procedures will be identical. The error MS will, in fact, be identical to the pooled variance in the *t-test*. Nevertheless, if $k = 2$, and a one-tailed test between means is required, or if the hypothesis $H_0: \mu_1 - \mu_2 = \mu_0$ is desired for a μ_0 *not* equal to zero, then the t-test is applicable, whereas the ANOVA is not. (Zar, 1984)

$$\delta = \sqrt{\frac{2ks^2\phi^2}{n}} \tag{3.13}$$

where: k = number of treatment groups
s^2 = variance (or $MS_{within,}$ also known as error MS)
ϕ = tabulated critical value related to the noncentrality parameter
n = sample size (from each treatment group)

If, while having or assuming a normal distribution, an ANOVA has not rejected the null hypothesis, it may be interesting to know to what *power* the ANOVA has been tested. This can be calculated with (Zar, 1984):

$$\phi = \frac{(k-1)(groups\,MS - s^2)}{ks^2} \tag{3.14}$$

where: s^2 = the error MS from the ANOVA

This critical value, ϕ, can be converted to the power of the ANOVA by consulting a reference chart which will give the probability of having committed a Type-II error in the analysis (Zar, 1984).

3.8 "Jackknife" Analysis of Statistical Parameters

The calculations of the minimum detectable difference depend primarily on the variance (or the error mean square of an ANOVA). Therefore, it is of interest to estimate this parameter as accurately as possible. If there is a rather high variability within a data set, estimates of variances could be highly variable if estimated with random sample sizes smaller than the total amount of samples available. For example, the variance estimated with all the samples available for one field (in this case, 100) could be very different than variances estimated with only 25, 50, or any other number of samples smaller than 100, randomly chosen samples. To analyze this problem, a program in MATLAB (The MathWorks, Inc, 2000) was written to perform what is called a "jackknife" routine. The purpose of a jackknife routine is to evaluate the variability of statistical parameters (means, standard deviations, variances, confidence limits, and others) in relation to the number of randomly extracted samples used to calculate the parameters in question. For this study, each jackknife routine was executed 500 times, calculating each time several statistical parameters of the randomly extracted samples. By doing this, it is possible to evaluate the distributional properties of the mean, the standard deviation, the variance and their confidence intervals (in this case 95%) for every possible sample size ranging from 2 to 99 during each jackknife set. The 100 sample values were reclassified before each extracted sample subsets to assure full randomness. An overall mean of all the results, as well as the 95% confidence limit of all the results, were calculated once the procedure was executed the requested number of times (500). The 95% confidence limit was estimated by multiplying the standard deviation by 1.96, assuming that the 500

jackknifed results followed a normal distribution. An alternative method for estimating the confidence intervals is presented in the discussion (percentiles).

A first step, using the jackknife procedure, was to analyse variations in the means as well as the 95% confidence limit of the means for the distinct fields. Hypothetically, all sample values from the cultivated field were thereafter increased by 50, 100 and 250 g m^{-2} to simulate a homogeneous increase of carbon sequestration, assuming that such an increase would require detection during a verification scheme. This was done to see if such increases were sufficient to *differ* the fields (the normal cultivated field and the field with simulated sequestration increase) from each other with a reasonable sample size. By plotting both simulations on the same graph, it is possible to visually see if the distributions greatly overlap each other or not, and at which sample size they stop overlapping.

Comparable routines were performed to evaluate variations of the variance, to be used in the minimum detectable difference calculations. For each sample size extracted with the program, the variance was calculated. If this data was used in a pilot study to prepare a verification scheme, it should be considered that future sampling programs *could* encounter larger variances than the variances of the pilot study. If this is the case, the sampling program designed to detect a certain level of change would not be capable of detecting such a change, and the program could be a failure. Because of this, the 95% confidence limit was also estimated from the 500 variances calculated for each sample size (done by multiplying the standard deviation by 1.96). The minimum detectable difference was calculated with the average variance and the upper 95% confidence limit of the variance to evaluate differences in samples sizes. The minimum detectable difference based on the upper 95% confidence limit could represent a "conservative" value in sample size determination.

Jackknife routines were also executed on the sample sets once the top (highest) 10% of the SOC values were removed from the data sets. The reason why the top 10% of the SOC values were excluded instead of the top and bottom 5% of all SOC values is simply because the data showed a number of extreme high values with basically no extreme low values. Jackknife routines of this manipulated data enables comparisons between MDD calculations for the real variances and "somewhat realistic" possible lower variances. SOC levels can easily have very high values due to factors such as rotting branches in the soils or animal excrement.

3.9 Limit of Accuracy about the Mean

The limit of accuracy (LA) is a theoretical concept providing the desired confidence interval of the mean, for a specified number of samples. The sample mean (μ) ± the LA gives a value range for a given confidence level. It is defined as follows:
(Lal et al, 2001b)

$$Limite\,of\ accuracy\,(LA) = SE \times t \qquad (3.15)$$

where: SE = Standard Error
t = t distribution for desired confidence level
(example: t = 2.26 for n = 10 at 95% level)

The standard error (SE) is calculated as follows:

$$SE = SD \div \sqrt{n} \qquad (3.16)$$

where: SD = Standard Deviation
n = number of samples

This LA was calculated for the three fields at a confidence level of 95% (two-tailed), and sample sizes ranging from 2 to 100.

3.10 Simulations with the CENTURY Model

The CENTURY model (version 4) obtains input parameters through twelve ASCII data files. Ten of those twelve files contain subsets of variables, corresponding to information on land management practices. More specifically, these files control the options for:

- Crops
- Cultivation
- Fertilization
- Fires
- Grazing
- Harvest
- Irrigation
- Organic matter addition
- Trees
- Tree removal

The timing variables and schedule of when events are to occur during the simulation is maintained in a schedule file. The site-specific parameters, such as precipitation, temperature, soil texture, and the initial conditions for soil organic matter are described in another separate file. All files are required in order to run the model.

Climate data from the meteorological station in Bara (13º42'N, 30º30'E) were used for the simulations, as this is the closest station to the sampling sites. The data available ranged from 1908 to 1988. For missing data within the observation period or for simulations outside the time span of the data, mean values of all observations available for the related month were used.

The soil texture used during modeling of the base scenario was equal to the average of the sand, silt and clay fractions calculated from some soil samples analyzed (n = 3).

The initial amounts of soil C were established by running the model to equilibrium using long-term climate averages from the available climate data. Parameterization of the model was done by using default parameters included in CENTURY and consultation of previous modeling studies in the same area (Ardö et al, 2002).

3.10.1 Sensitivity Analysis

In order to perform a sensitivity analysis, a general base scenario was designed (schedule file). This scenario represents land management practices known to have happened, or typical for the area (Ardö et al., 2002). All simulations were run using this same scenario. As mentioned above, equilibrium of the SOC was established by running the model for a very long time (starting date: 3000 B.C.) and simulated the carbon flows up to year 2002. The table 3.4 below resumes the events incorporated for the modeling.

Table 3.4: Summary of the modeling scenario (land use history) used as the basis for the sensitivity analysis.

Modeled Land Use History		
Time Period	**Management**	**Crop:Fallow ratio**
-1890	Annual low intensity grazing October fire every ninth year	–
1890-1915 1916-1935 1936-1950	Cultivation of millet Trees (*Acacia*) during fallow Grazing in Nov. and Dec. after harvest Low intensity grazing during fallow	5:20 5:15 5:10
1951-1974	Cultivation of millet No trees during fallow Grazing in Nov. and Dec after harvest Low intensity grazing during fallow	5:6
1975-2002	Continuous cultivation – millet Grazing in Nov. and Dec after harvest	27:0

The main differences found in the modeling scenario are between events taking place during *cropping* years and years of *crop-fallow* period. The two tables 3.5 & 3.6 resume the annual timing of some parameters (management practices) typical for the cropping and fallow years respectively.

Table 3.5: Generalization of the annual timing of certain parameters used during the simulations with CENTURY for a typical "cropping year".

	Cropping Year											
Management	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tree removal [1]					X							
Fire [2]						X						
Crops planted [3]						X						
Crop growth						X	X	X	X	X		
Harvest [4]										X		
Grazing [5]											X	X

1. Clear cut tree removal (100% aboveground) – only the first year of cropping
2. Medium
3. Millet (hand-weed cultivation)
4. Grain with 85% straw removal
5. Winter grazing – low intensity (Winter grazing – high intensity between 1975 and 2000)

Table 3.6: Annual timing of certain parameters used during the simulations with CENTURY for a typical year in "crop-fallow period".

	Fallow Year											
Management	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trees [1]	X	X	X	X	X	X	X	X	X	X	X	X
Crops [2]	X	X	X	X	X	X	X	X	X	X	X	X
Grazing [3]						X	X	X	X	X	X	X
Fire [4]		X										

1. Acacia/savanna allowed growing (not between 1951 and 1974)
2. C4 tropical grasses allowed growing
3. Low intensity (slightly modified from CENTURY's version)
4. Every fifth year of fallow (except from 2000 to 2100 – no fires at all)

The sensitivity analysis of the model was primarily to evaluate the impacts of variations of input parameters or values on the resulting simulated SOC. The model calculates SOC for three organic matter pools (active, slow and passive), but the output variable investigated for the sensitivity analysis was the sum of these three pools (therefore making no distinction between pools) – output variable in CENTURY [SOMSC]. The table below, table 3.7, describes the parameters tested, as well as the methodology used for each simulation.

Table 3.7: The parameters tested in the sensitivity analysis of the CENTURY model and the methodologies used for the simulations of each parameter.

Parameter(s) [Codes in CENTURY]	**Simulations**
Precipitation *[PRECIP(1-12)]*	Direct changes were made to the monthly averages. This was done to test the long-term effects of precipitation changes on the SOC and evaluate if these changes are proportional to the simulated SOC. In Sudan, less rain can represent areas more North, while more rain can be found more South of the study area (Bara) (Ardö et al., 2002). From the mean values, increases and decreases of up to 25% were tested, running a simulation for every 5% difference Simulations (precipitation): -25%, -20%, -15%, -10%, -5%, +5%, +10%, +15%, +20% and +25% of monthly averages.
Temperature *[TMN2M(1-12), TMX2M(1-12)]*	Direct changes were made to the monthly averages. From the mean values, increases and decreases of up to 3.0ºC were evaluated, simulating every 0.5ºC difference. Nevertheless, the *range* of the temperature values did not change. Simulations (temperature): -3.0ºC, -2.5ºC, -2.0ºC, -1.5ºC, -1.0ºC, -0.5ºC, +0.5ºC, +1.0ºC, +1.5ºC, +2.0ºC, +2.5ºC and +3.0ºC of monthly averages.
Soil Texture *[SAND, SILT, CLAY]*	Ten different combinations of soil textures were simulated. Simulations (% sand : % silt : % clay): 85:15:0, 85:7.5:7.5, 85:0:15, 90:10:0, 90:5:5, 90:0:10, 95:5:0, 95:2.5:2.5, 95:0:5 and 100:0:0
Management (harvest) *[RMVSTR, REMWSD]*	The harvest management in the base scenario was set to simulate "grains with 85% straw removal" (aboveground residue removed). Simulations were made changing the percentage of straw removal and remaining residue left standing. Simulations (% straw removal): 0%, 70%, 75%, 80%, 85%, 90%, 95% and 100%
N fixation used in tree file (for Acacia spp. trees growing during fallow periods) *[SNFXMX(2)]*	The default value for the N fixation (maximum g N fixed per g C NPP (Net Primary Production)) of the *Acacia spp*. tree was set to 0.0 (for all the simulations described above). Simulations were performed increasing this value up to 0.1. Simulations (N fixation): 0.0001, 0.001, 0.01, 0.05 and 0.1 maximum g N fixed per g C NPP
N fixation and Precipiation *[SNFXMX(2), PRECIP(1-12)]*	With N fixation set to 0.01 g N fixed per g C NPP, the same precipitation changes as described above were tested. Simulations (Precipitation with N fixation = 0.01): -25%, -20%, -15%, -10%, -5%, +5%, +10%, +15%, +20% and +25% of monthly averages.
N fixation and Temperature *[SNFXMX(2), TMN2M(1-12), TMX2M(1-12)]*	With N fixation set to 0.01 g N fixed per g C NPP, the same temperature changes as described above were tested. Simulations (temperature with N fixation = 0.01): -3.0ºC, -2.5ºC, -2.0ºC, -1.5ºC, -1.0ºC, -0.5ºC, +0.5ºC, +1.0ºC, +1.5ºC, +2.0ºC, +2.5ºC and +3.0ºC of monthly averages.

3.10.2 Future Scenarios

Three land management practices were simulated with three possible future climate scenarios for the years of 2002 up to 2100. The climate scenarios used were inspired from a special report written by the Intergovernmental Panel on Climate Change on regional impacts (IPCC, 1998). The projections with respect to temperature represent a rate of warming of about 0.2 ºC per decade. In respect to precipitation, models for the Sahel illustrate extended differences, with some predicting an increase and others a decrease in precipitation. Consequently, both an increase and a decrease of 15% (from the 1908-1988 averages from Bara) until 2100 were tested in combination with the temperature warming (table 3.8). These changes in precipitation followed a simple linear transformation, with 0% change in 2002 and 15% in 2100 – equal to a 1% change every 6½ years. For all future scenarios, the N fixation rate from the trees was set to zero.

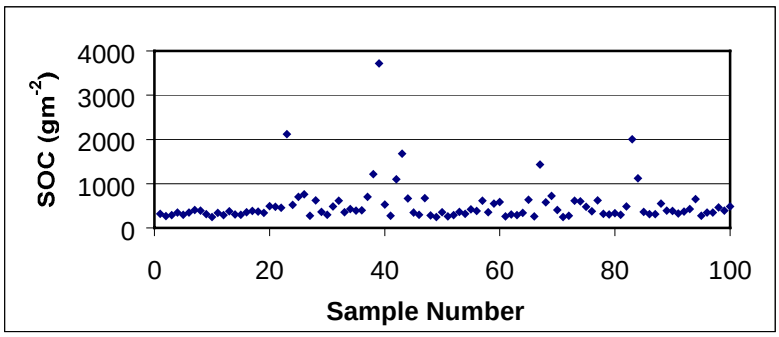
Table 3.8: Future climate scenarios tested on three land management practices for the years 2002 to 2100.

Land management	Climate Scenarios
Continuous cropping	1) "no change" (mean values used)
Crop:fallow 5:10 (years)	2) Temp. +0.2 ºC per decade and precip. +15% over 98 years
Grazing only	3) Temp. +0.2 ºC per decade and precip. - 15% over 98 years

4 RESULTS

4.1 Descriptive Statistics of the SOC

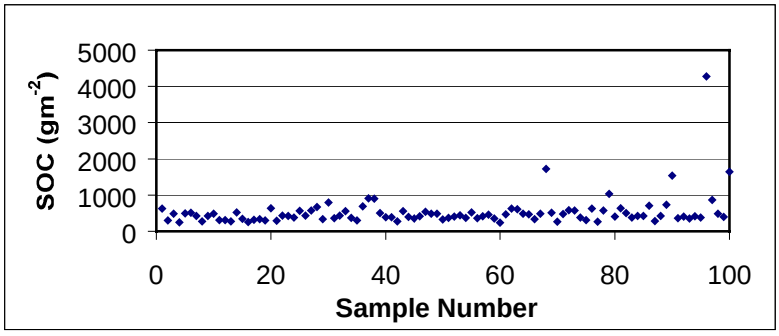
The soil organic carbon (SOC) contents measured per square meter to a depth of up to 20 cm deep varied between ≈ 200 to ≈ 4000 g m^{-2} (figures 4.1, 4.2 & 4.3). The overall average was ≈ 500 g m^{-2} with the grazing field almost 100 g m^{-2} lower than the other two fields. The high-extremes are rather limited (<8) when compared to the overall number of samples (100) for each field, and are most frequent in the cultivated field.



Cultivated Field:

No. of samples: 100
Minimum: 242.9
Maximum: 3716.3
Mean: 519.2
Median: 374.7
Variance: 212952
St. deviation: 461.5
St. error: 46.2

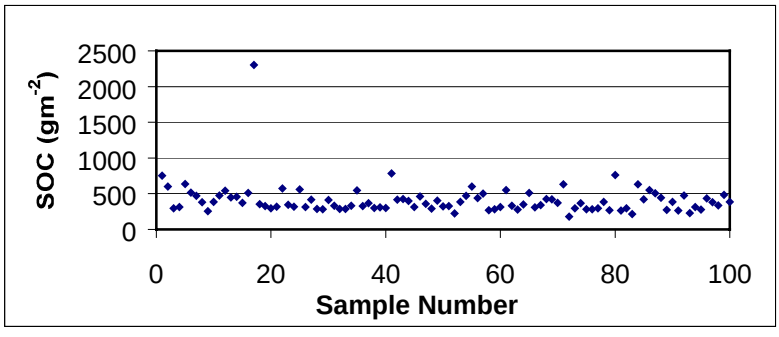
Figure 4.1: Soil organic carbon (SOC) levels and descriptive statistics of 100 soil samples taken from a cultivated field.



Field in Fallow:

No. of samples: 100
Min: 239.5
Max: 4277.5
Mean: 532.3
Median: 426.0
Variance: 207043
St. deviation: 455.0
St. error: 45.5

Figure 4.2: Soil organic carbon (SOC) levels and descriptive statistics of 100 soil samples taken from a field in crop-fallow period.



Grazing Field:

No. of samples: 100
Minimum: 181.4
Maximum: 2303.0
Mean: 411.0
Median: 367.9
Variance: 51425
St. deviation: 226.8
St. error: 22.7

Figure 4.3: Soil organic carbon (SOC) levels and descriptive statistics of 100 soil samples taken from a grazing field.

4.2 Bulk Density

Ten (10) soil samples were weighted for a known volume. The weight varied between 1625 g l^{-1} and 1829 g l^{-1}, with an average of 1711 g l^{-1} (1.71 Kg l^{-1}). From the average, the variations were ±7%.

4.3 Soil Texture

The soil distributions of the three sampling sites were extremely similar (figure 4.4). The sand fractions represented more than 93% in all sites, corresponding to 93.7% for the cultivated field, 93.6% for the field in fallow period and 95.1% for the grazing field. The silt and clay fractions were comparable, but with the clay fraction slightly inferior. The silt fraction ranged between 3% and 3.6%, while the clay fraction varied between 1.9% and 3.3%. All sites can be considered as having the same soil and soil texture.

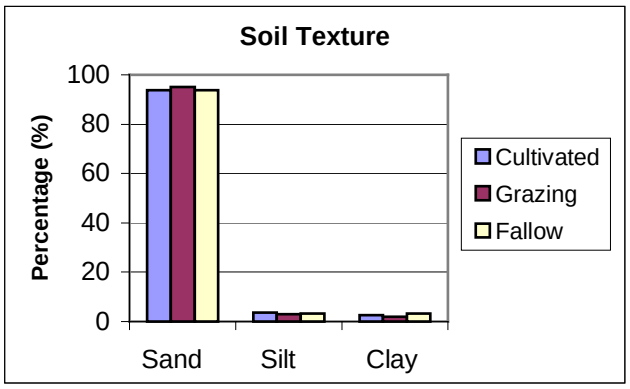


Figure 4.4: Soil distribution of the three sampling sites; the cultivated field, the grazing field and the field in crop-fallow period.

4.4 Testing for Normality

All three data sets (cultivated, fallow and grazing fields) were tested for normality. They all failed to respect a normal distribution, the cause being a long tail towards the high end of the distribution (positive skewness). In such cases, Shaw et al. (1996) propose transforming the data by taking the logarithms of all observed values instead. This can be done to reduce some of the skewness characterizing the raw data and to minimize the distance between the mean and the median. The results of such transformations still failed to all fully respect normality. Thus, the raw data, and *not the logarithms*, were used for the calculations performed in the context of this thesis.

4.5 Testing for Significance Differences

Because the data sets failed to respect normality, the appropriate way to test for significant differences should be with a nonparametric test. These test for significant differences between medians. Below are comparisons of both a nonparametric test and

an analysis of variance (ANOVA). The assumption of normality is used to extract an estimate of the error mean square, which can be valid in the calculations of the minimum detectable differences between many treatment groups.

4.5.1 Analysis of Variance (ANOVA)

Analyses of variances were performed to test for significant differences between means of the different land cover types. Tables 4.1 and 4.2 show the results of these ANOVAs for all three fields tested together, as well as all two-by-two combinations respectively.

Table 4.1: Results of an ANOVA for the SOC levels of all the soil samples taken from the three distinct fields (cultivated, fallow and grazing) analyzed in the pilot study. Significance level α=0.05

Source of Variation	***Sum of Squares (SS)***	***Degree of Freedom (v)***	***Mean Squares (MS)***
Total	47557211.729	299	
Between (groups)	886529.787	2	443264.9
Within (error)	46670681.942	297	157140.3

F_{ANOVA} = (between MS / within MS) = 2.821
$F_{0.05(1),\ 2,\ 297}$ = 3.03
2.81 < 3.03 ; therefore, do not reject H_0

From the equation 3.14, the *power* of the ANOVA performed above with all the data of the pilot study is evaluated to:

$$\phi = \frac{(k-1)(groups_MS - s^2)}{ks^2} = \frac{(3-1)(443264.9 - 157140.3)}{(3)(157140.3)} = 1.82$$

Consulting a reference chart with $v_1 = 2$, $v_2 = 297$ and $\phi = 1.82$, the power of the ANOVA is estimated to be 0.81. This means that there was a *19% chance of having committed a Type-II error* in the analysis.

Table 4.2: Results of ANOVAs for the SOC levels of all the soil samples taken from the fields (cultivated, fallow and grazing) analyzed in the pilot study. The ANOVAs were performed for each combination of fields at a significance level of α=0.05.

Fields tested	***Results of ANOVA***
Cultivated / Fallow	F_{ANOVA} = 0.04 ; Do not reject H_o
Cultivated / Grazing	F_{ANOVA} = 4.43 ; Reject H_o
Fallow / Grazing	F_{ANOVA} = 5.89 ; Reject H_o
$F_{0.05(1),\ 1,198}$ = 3.89	

4.5.2 *Nonparametric Tests*

Table 4.3 shows the results of Kruskal-Wallis/Mann Withney tests, used to test for significant differences between sample groups (when normal distribution is not encountered). The null hypothesis is of equal median between the groups.

Table 4.3: Results of nonparametric tests (Kruskal-Wallis and Mann-Withney) for the SOC levels of all the soil samples taken from the fields (cultivated, fallow and grazing) analyzed in the pilot study. The tests were performed for each combination of fields at a significance level of α=0.05.

Fields tested	***Results of test***
Cultivated / Fallow / Grazing *	Reject H_o
Cultivated / Fallow	Reject H_o
Cultivated / Grazing	Do not reject H_o
Fallow / Grazing	Reject H_o

** Kruskal-Wallis Test*

All the combinations showed significant differences except the combination of the cultivated/grazing fields. This means that the differences in SOC were detectable by a nonparametric test for the other combinations (cultivated/fallow/grazing, cultivated/fallow and fallow grazing).

4.6 Jackknife Analysis

Figure 4.5 (A) shows the results of a jackknife routine executed on the cultivated field. The parameter analysed was the mean and its 95% confidence interval. This interval clearly decreases as the sample size increases. At a sample size of 10, the confidence interval is $\approx \pm 300$ g m^{-2}, while it decreases to $\approx \pm 200$ g m^{-2} at a sample size of 20 and $\approx \pm 150$ g m^{-2} with a sample size of 30. The mean, nevertheless, remains stable at all sample sizes over 5, with a value of $\approx$ 520 g m^{-2}. There is no confidence interval at a sample size of 100, which illustrates the difference between a jackknife routine and a bootstrap routine. In the latter, the same sample can be read multiple times, making it possible to have variations even when 100 samples are extracted. The simulated increases of SOC contents were done on all the samples. This explains the similarity of the 95% confidence intervals of all the curves. Over 90 samples are required to differ the two scenarios for an increase of 50 g m^{-2} (B). The sample size decreases as the required detectable difference increases. For the scenario of the 100 g m^{-2} increase (C), 80 samples are required, and for the 250 g m^{-2} increase (D), 35 samples are needed. The rather large confidence intervals reflect the high variability of the SOC contents.

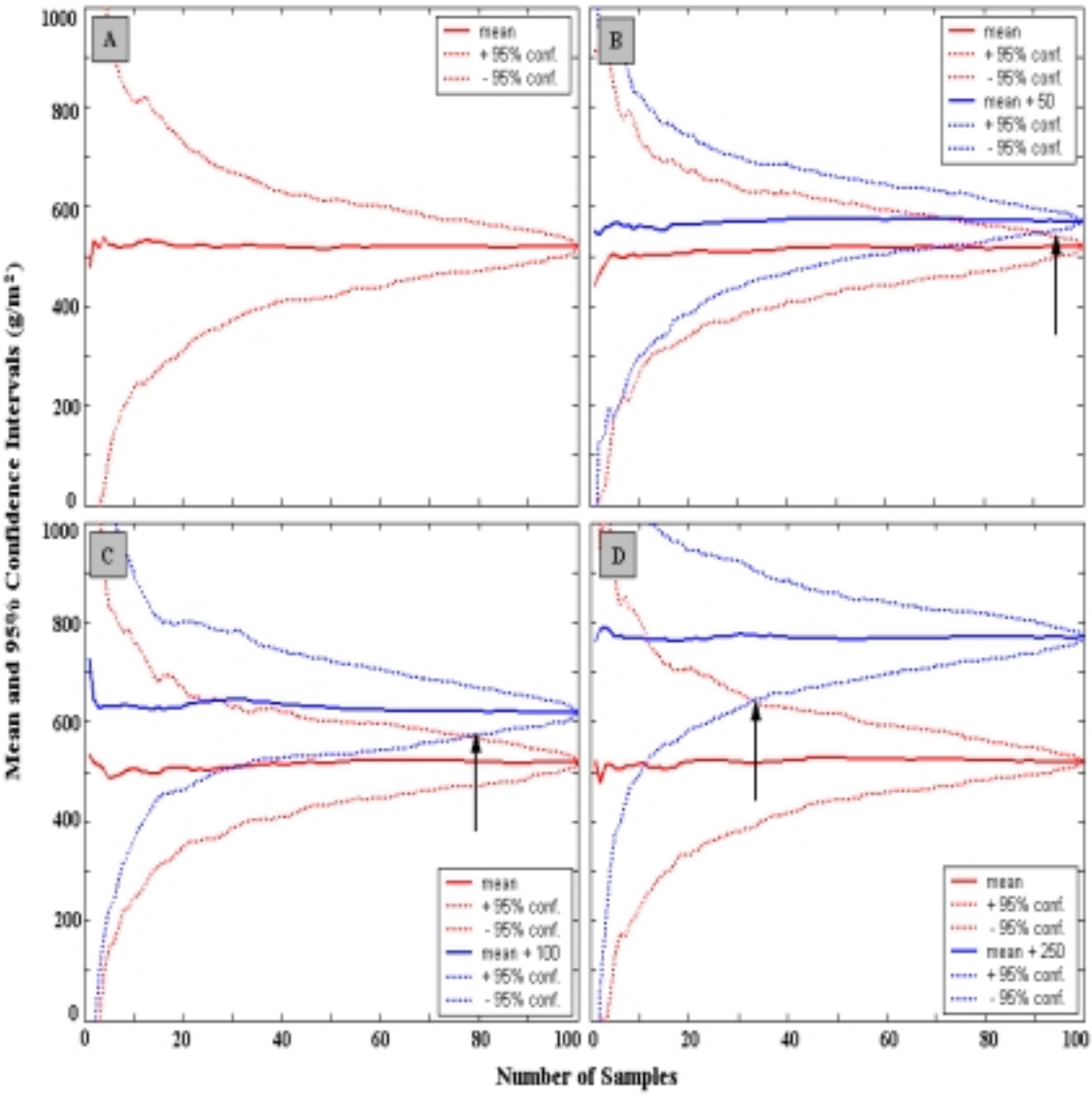


Figure 4.5: The results of the jackknife routine (500 times) simulating homogeneous SOC increases on the data from the cultivated field. The full line represents the mean of the 500 simulations for each sample size, while the dotted lines represent the upper and lower 95% confidence intervals of the mean. A) cultivated field with no increase, B) cultivated field plus a 50 g m^{-2} increase, C) cultivated field plus a 100 g m^{-2} increase and D) cultivated field plus a 250 g m^{-2} increase.

4.7 Calculation of the Minimum Detectable Difference (MDD)

The MDD calculations depend mainly of the variability (variance) within the samples and the number of samples extracted. Below, figure 4.6 illustrates six MDD curves calculated for six possible variances. Note the logarithmic scale on the *x*-axis representing the sample size. A variance of ≈ 200000 was calculated for both the cultivated and fallow fields, while the grazing field's variance was closer to 51000.

The MDD with the variance of 15000 represents approximately the fields without their top 10% highest values (the few high-extremes found in each field).

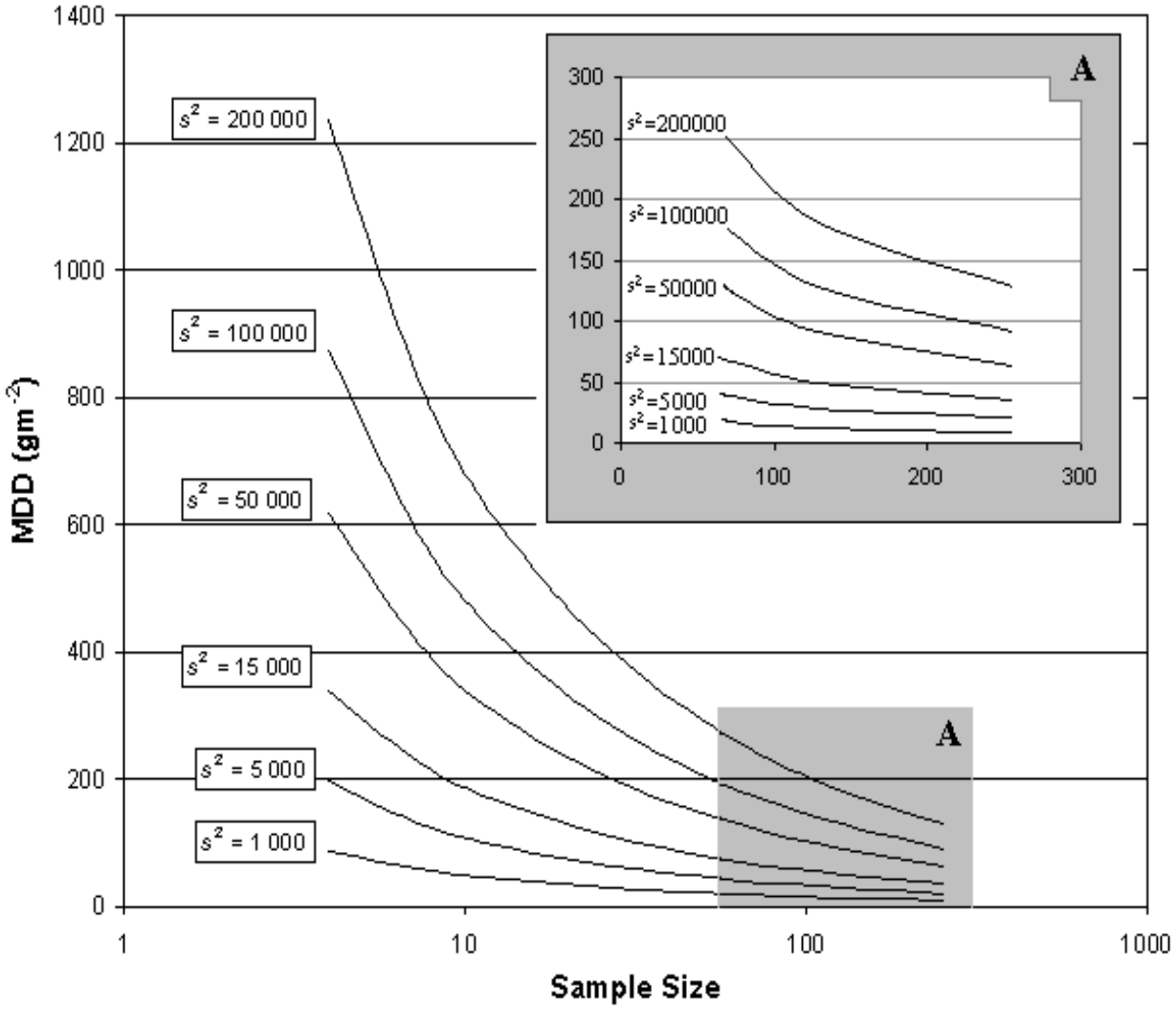


Figure 4.6: Calculated minimum detectable difference (MDD) in SOC inventory as a function of variance and sample size. The MDD is the smallest difference that can be detected (α = 0.05) between two mean SOC inventories with 90% confidence (1 – β) given the average variance (or error mean square from ANOVA) and the sample size.

Table 4.4 gives numeric values of the MDD calculations of figure 4.6 (above) for some sample sizes. One can see that in some cases, a doubling of the variance also doubles the required amount of samples to achieve the same MDD. For example, a MDD of 128 g m^{-2} can be detected with 256 samples if the variance is 200000, 128 samples for a variance of 100000 and 64 samples for a variance of 50000. The detectable change decreases approximately as a function of [1/SQRT(n)] (Johnson et al. 1990), consequently, as the sample size increases, collecting one more sample is less efficient in reducing the detectable change. For example, with a variance of 5000, the MDD decreases by 40 g m^{-2} (from 123 to 83 g m^{-2}) as the sample size increases from 8 to 16,

but decreases only by 30 g m^{-2} (from 83 to 53 g m^{-2}) as the sample size increases from 16 to 32. As a result, there may be a trade-off between achieving a desired detection capability and an unreasonably large sample size.

Table 4.4: Some numeric values of the MDD calculations (gm^{-2})showed of figure 4.6 (above) for some sample sizes.

	Variance (s^2)					
Samples	***200 000***	***100 000***	***50 000***	***15 000***	***5 000***	***1 000***
4	1235	872	617	338	195	87
8	777	550	388	213	123	55
16	529	374	264	145	83	37
32	366	259	183	100	58	25
64	256	181	128	70	40	18
128	181	128	90	49	28	12
256	128	90	64	35	20	9

The figure 4.7 shows more specifically the MDD for each field based on their calculated variance. Also shown is the MDD calculated from the eMS (error mean square) of an ANOVA. This latter curve would represent the most realistic MDD calculations for change detection over time or space in the study area.

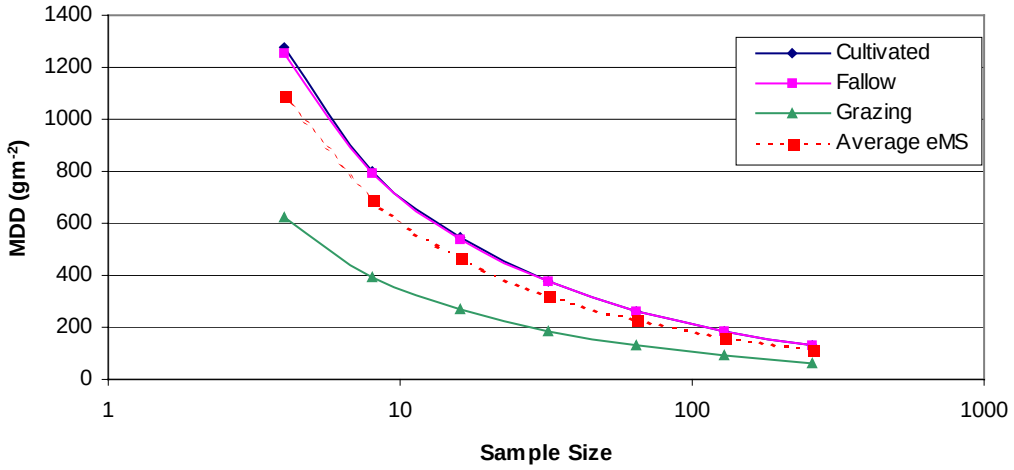


Figure 4.7: Calculated minimum detectable difference (MDD) in SOC inventories as a function of the average variance of each distinct land cover type. The MDD for the average variance of all three fields (estimated with the error mean square of the ANOVA – Average eMS in graph) is also shown.

4.8 Effect of Jackknife Results on MDD

If estimated from all the samples, the variance of the grazing field is ≈ 51000. The jackknife routine (figure 4.8) shows that this value overestimates the variances calculated from less than 40 samples. Nonetheless, the upper 95% confidence interval was also calculated, and, for sample sizes under 40, can be between 10000 and 20000 higher than the average variance. The variance stabilized with sample sizes over 40. Sample size

requirements (in MDD calculations) using this upper 95% confidence interval can increase as much as a twofold compared with the average variance. For example, ≈ 20 samples would be required to detect a 50% change based on the average variance (51000), while it would require over 40 samples to detect the same change based on a variance representing the upper 95% confidence limit.

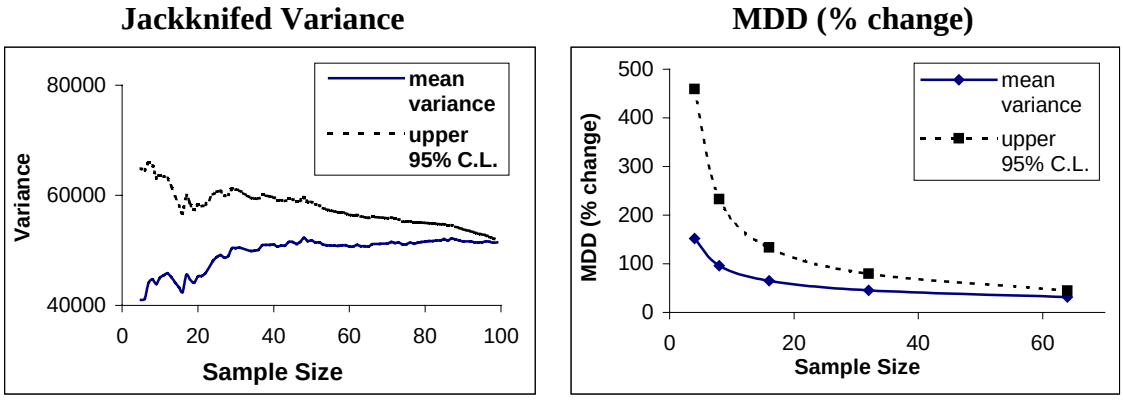


Figure 4.8: (left) The mean and the upper 95% confidence limit for the variance of the grazing field after jackknifing 500 data sets for each value of n (sample size). (right) The minimum detectable change (MDD) in percent calculated from the average variance (s^2 = 51 425) and the jackknifed upper 95% confidence limit for the variance of the grazing field.

MDD calculations were also performed on variance estimates of the fields once the top 10% (highest values) of SOC contents were removed from the data sets. The results are a clear indication of the influence of such high values on the variance estimates and the MDD calculations (table 4.5). The detection of a 5% change requires less than half the samples when those few high-extremes are removed. As the percentage of change required increases, so does the gap between samples sizes based on both scenarios. Sample size requirements calculated with the upper 95% confidence intervals are also shown in the table.

Table 4.5: Sample size (n) required to detect 5%, 10%, 25%, 50% and 100% changes in the average soil organic carbon level from the three tested fields. For each case, the MDD is calculated based on the average error mean square of the ANOVA (mean) and the upper 95% confidence limit of the error mean square calculated from the bootstrap routine (U95%). The first two columns show the results using all the samples of the three fields for the ANOVAs, while in the last two columns, the top 10% of the values for each field was removed.

Change (*from mean = 488 g m^{-2}*)		**All samples**		**Change** (*from mean = 399 g m^{-2}*)		**- top 10%**	
%	**g m^{-2}**	**Mean**	**U95%**	**%**	**g m^{-2}**	**Mean**	**U95%**
5	25	>1000	>1000	5	20	500	700
10	50	>1000	>1000	10	40	125	190
25	122	250	250	25	100	20	39
50	244	66	75	50	200	6	14
100	488	17	23	100	400	-	5

4.9 Limit of Accuracy of the Mean

The standard errors (SE) for each field, based on all samples (100 per field) were calculated to be:

	Cultivated	Fallow	Grazing
Standard error (SE):	46.2	45.5	22.7

The cultivated and fallow fields were considered to have the same SE (≈ 46). Figure 4.9 shows the theoretical limit of accuracy of the mean values for the sampling fields, calculated for a confidence level of 95%.

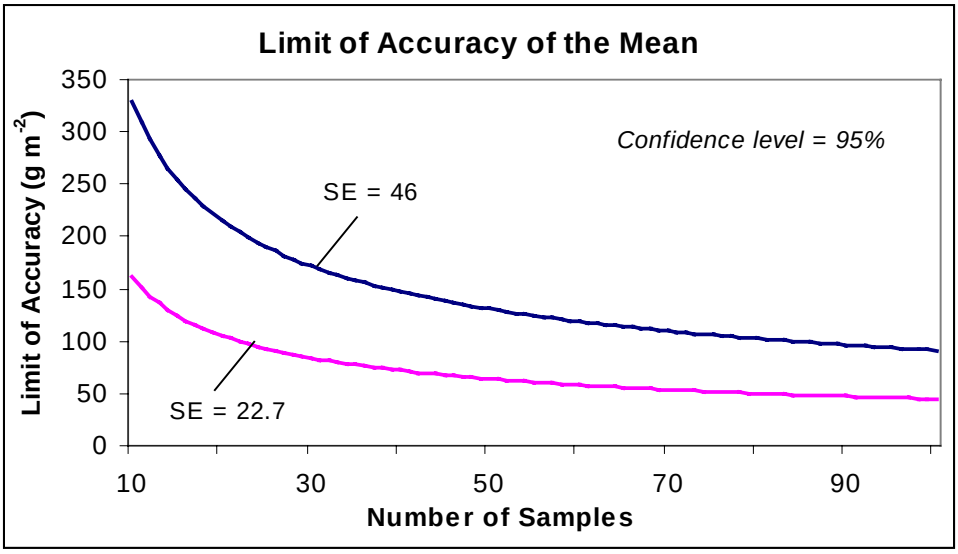


Figure 4.9: The limit of accuracy (LA) of the mean value for the three fields sampled. The LA represents the value range of the confidence interval for the mean, given a sample size and confidence level, and is based on the standard error (SE). The curves presented were calculated at the 95% confidence level.

4.10 Sensitivity of the CENTURY model Regarding SOC

Precipitation: The impact of increased precipitation can be directly linked to a decrease in SOC (figure 4.10). The effects of a decline in precipitation are, nevertheless, more important than the adverse effects of a precipitation increase. The SOC, at model equilibrium, varies from 280 g m^{-2} to 329 g m^{-2}, and as the introduction of millet cultivation starts in 1890, the decline in SOC is proportional for all precipitation levels.

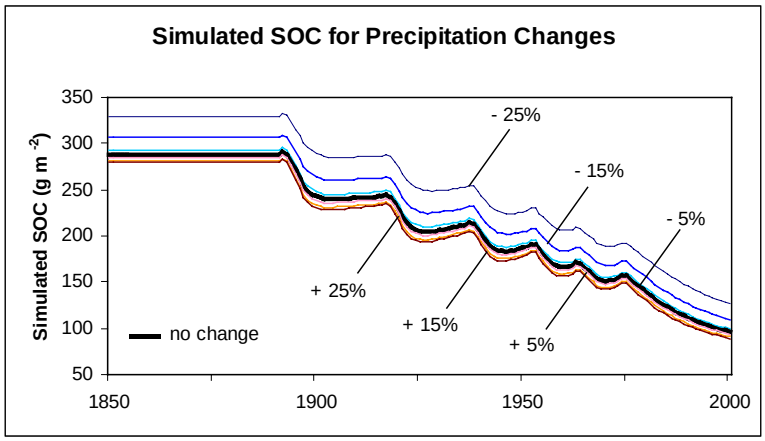


Figure 4.10: Simulated SOC resulting from variations in average monthly precipitation values. Variations from –25% to +25% of the precipitation averages were tested. The graph shows the results of the simulations from 1850 to 2002.

Figure 4.11 shows the results of the same simulations as presented in figure 4.9, but for year 2002 only. A decrease of 25% in precipitation increases the SOC by 30 g m^{-2} for the base scenario, while an increase of the same percentage decreases the SOC by 7 g m^{-2}. The effects of more precipitation seem to level off, whereas the effects of less precipitation indicate that SOC levels continue to increase for precipitation values less than –25% of the monthly averages.

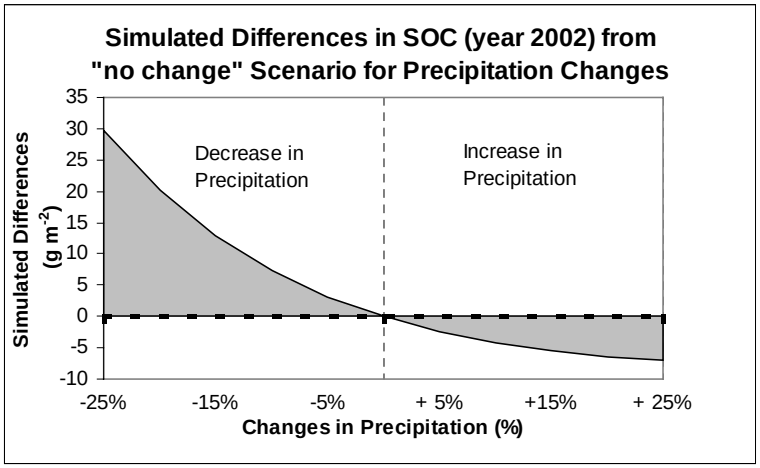


Figure 4.11: Simulated SOC in year 2002 for precipitation differences varying from –25% to +25% of the mean monthly averages. The results represent the differences between each simulation and the simulation with the real monthly averages (no change).

Temperature: The equilibrium for the simulations of the temperature variations ranges from 277 g m^{-2} to 325 g m^{-2} (figure 4.12). The effects of direct temperature differences are somewhat linear with the stronger impacts associated with colder temperatures. Again, the introduction of millet cultivation in 1890 is clearly visible and corresponds to the beginning of the SOC decline.

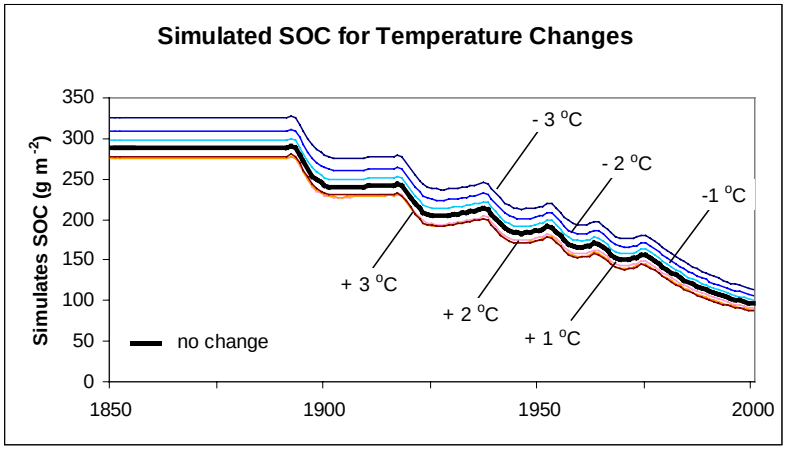


Figure 4.12: Simulated SOC resulting from variations in average monthly temperature averages. Variations from –3.0 ºC to +3.0 ºC of the averages were tested. The graph shows the results of the simulations from 1850 to 2002.

The simulation for year 2002 are shown in figure 4.13. An equilibrium seems to occur for temperature increases of more than 2.5 ºC. For a decrease of temperature, SOC levels appear to continue to increase. The final simulated SOC ranges approximately ± 15 g m^{-2} from the scenario with real monthly averages.

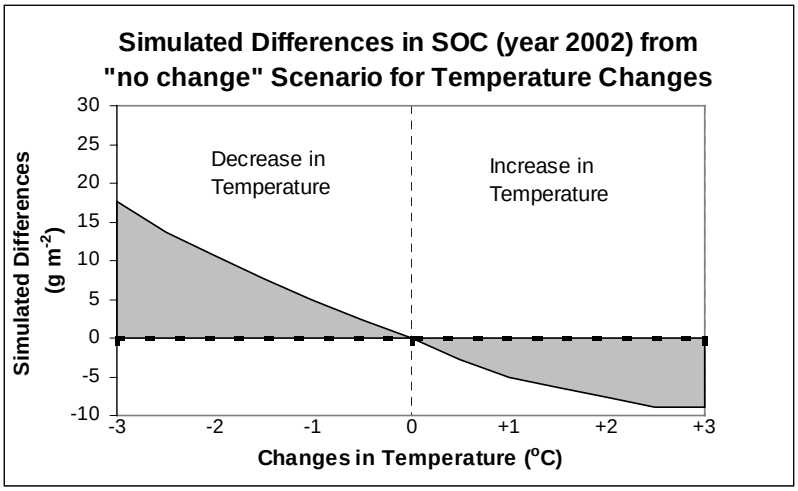


Figure 4.13: Simulated SOC in year 2002 for temperature differences varying from –3.0 ºC to +3.0 ºC of the mean monthly averages. The results represent the differences between each simulation and the simulation for the real monthly averages (no change).

Soil texture: The simulations show that SOC increases with increasing clay and silt contents (figures 4.14 & 4.15). The equilibrium level with 15% clay was one and a half time the equilibrium with no clay (ranging from 380 g m^{-2} to 250 g m^{-2} respectively). The pattern of decomposition is once again proportional throughout the simulations.

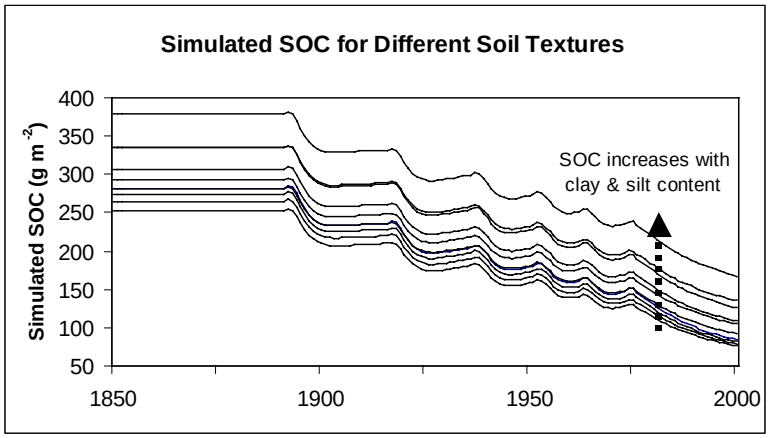


Figure 4.14: Simulated SOC from 1850 to 2002 for 10 different soil texture combinations. The sand fraction was always set to at least 85%, while the silt and clay fractions varied in value for the remaining 15%.

From figure 4.15, showing the simulations for year 2002, it becomes apparent that SOC content increases with the increase of smaller particles (SOC clay > SOC silt > SOC sand). The highest simulated SOC content is when clay equals 15% (maximum clay fraction tested). SOC slightly decreases as the clay fraction declines from 15% to 10%, 7.5%, 5%, 2.5% and 0%. SOC does not change importantly with varying sand fractions, as it is nearly equal with sand fractions ranging from 85 to 100%. SOC simulated with 15% clay (85% sand) is more than the double of the SOC simulation with 100% sand (166 g m^{-2} and 75 g m^{-2} respectively).

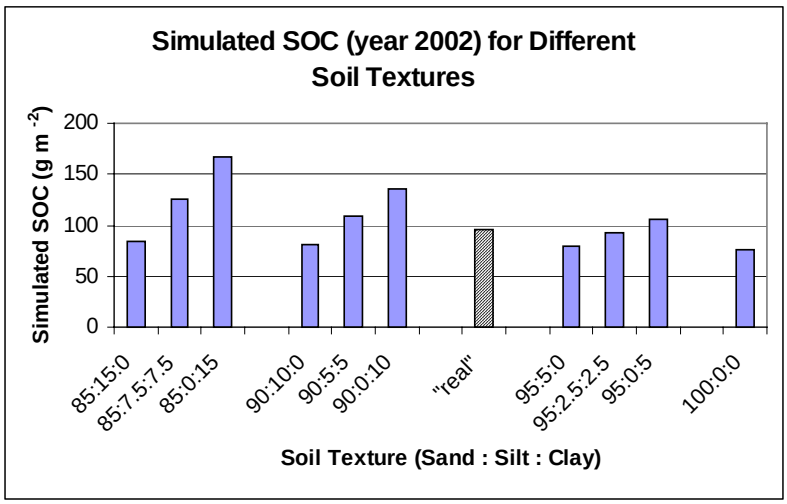


Figure 4.15: The results, in year 2002, for simulations testing varying soil textures. All simulations had a minimum of 85% sand. The result of a simulation with the "real" soil texture (93:4:3) is also shown for comparisons.

Management (havest): The sensitivity of the model regarding the harvest management practices tested is minimal (figure 4.16). Different aboveground residue (straw) removal percentages, varying from 70% and up, are not at all influential for the modeled SOC. In year 2002, SOC ranged by only 4 g m^{-2}. Those curves overlap each other, making them practically inseparable when plotted on the same graph. With 0% straw removal, the simulated SOC in 2002 is equal to 117 g m^{-2}, whereas the other simulations range between 93 and 97 g m^{-2}.

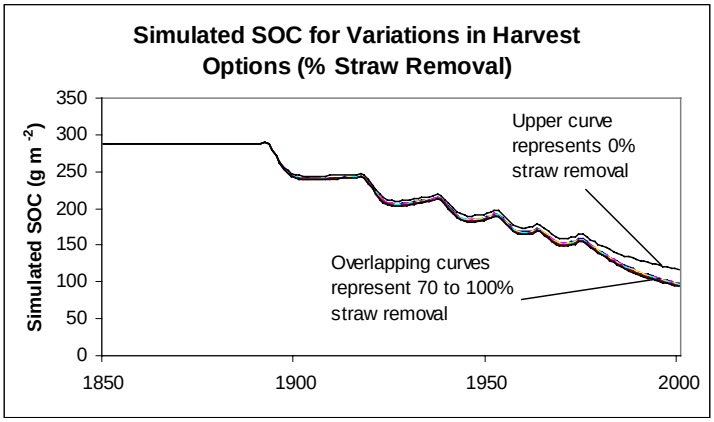


Figure 4.16: Results from simulations of the base scenario, with variations of the percentage of aboveground residue (straw)removal during harvest. Simulations from 70% straw removal to 100% straw removal were tested, with a simulation every 5% difference.

N fixation of trees: The model showed to be very sensitive to varying N fixation rates (figure 4.17). The equilibrium value for N fixation values set at 0.01 g N fixed per g C NPP or more is almost five times higher than simulations with no N fixation. In 2002, simulated values range from 95 g m^{-2} to 413 g m^{-2}. The maximum effects of N fixation are reached at 0.01 g N g^{-1} C NPP, as the rates superior of this value (0.05 and 0.1 g N g^{-1} C NPP) simulate the exact same SOC content (saturation). The higher N fixation rates cause the rate of decline of SOC to be amplified during the first half century after the introduction of cultivation (1890).

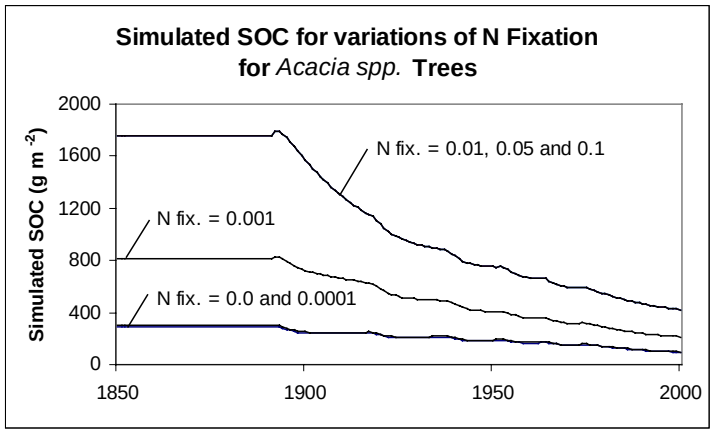


Figure 4.17: Six (6) simulations of SOC associated to different rates of N fixation by trees. The N fixation represents the maximum symbiotic N fixation (g N fixed per g C produced (net primary production – NPP))

Precipitation with N fixation rate of 0.01 g N g^{-1} C NPP: When the model is run with N fixation through trees, the effects of precipitation do not fallow the same pattern as when no N fixation is modeled. Whereas before less precipitation was always equal to more SOC, this generalization is no longer valid (figures 4.18 & 4.19). The range of SOC contents modeled for year 2002 is, nevertheless, not much bigger than with no N fixation.

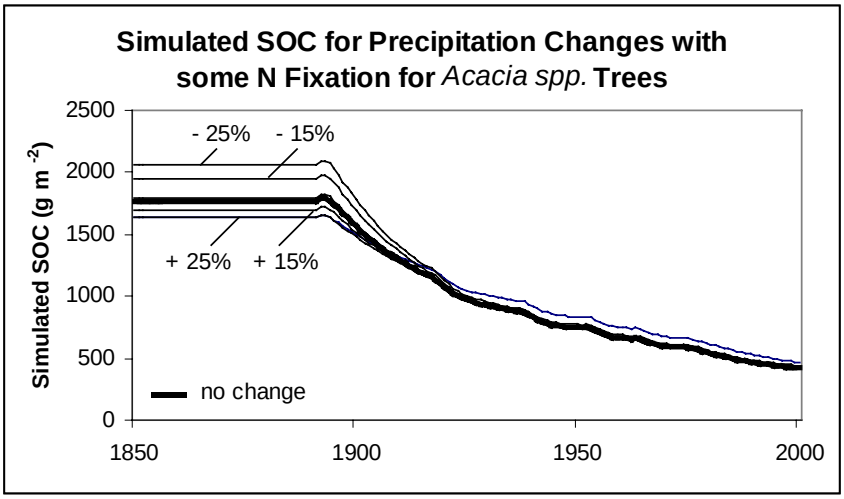


Figure 4.18: Effects of precipitation variations (from monthly mean averages) on SOC, with N fixation set at 0.01 g N fixed per g C NPP.

Figure 4.19, below, shows the impacts of precipitation variations for year 2002, when the model is run allowing N fixation from the trees - *Acacia spp*. - which grow during crop-fallow periods. Interestingly, the effects of more precipitation now increase SOC content, whereas with no N fixation, they decreased the SOC content.

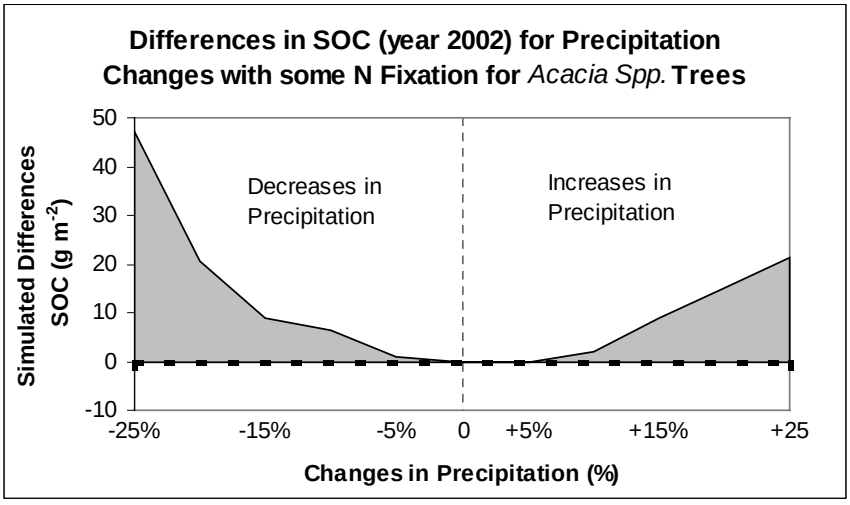


Figure 4.19: Simulated SOC in year 2002 for precipitation differences varying from –25% to +25% of the mean monthly values, with N fixation from trees (g N fixed per g C NPP) set to 0.01. The results presented represent the differences between each simulation and the simulation for the real monthly averages (no change).

Temperature with N fixation rate of 0.01 g N g^{-1} C NPP: The model shows extreme sensitivity for temperature variations, when N fixation is allowed in the system (figure 4.20). For 2002, SOC ranges from 176 g m^{-2} to 882 g m^{-2}. The equilibrium values range from less than 1000 g m^{-2} up to approximately 4000 g m^{-2}.

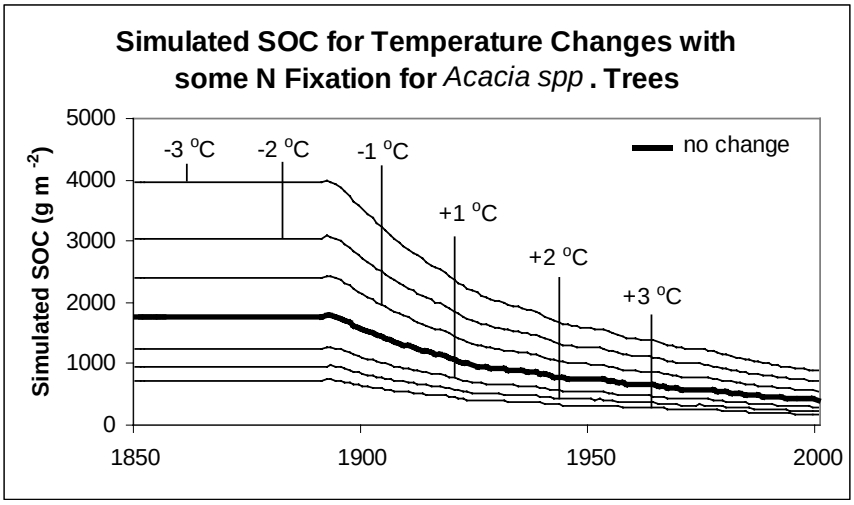


Figure 4.20: The effects of temperature on SOC modeled with N fixation set at 0.01 g N fixed per g C NPP.

The generality of less SOC for warmer temperatures remains the same, but with rates greatly amplified compared with "no N fixation" simulations. For 2002, a decrease of 3.0 ºC caused the SOC to be 17 g m^{-2} greater with no N fixation, while with N fixation set to 0.01 g N g^{-1} C NPP, 3.0 ºC cooler increases the SOC approximately by 500 g m^{-2} (29 times more) (figure 4.21). For the temperature variations tested, the range of SOC for 2002 varies by almost 750 g m^{-2}.

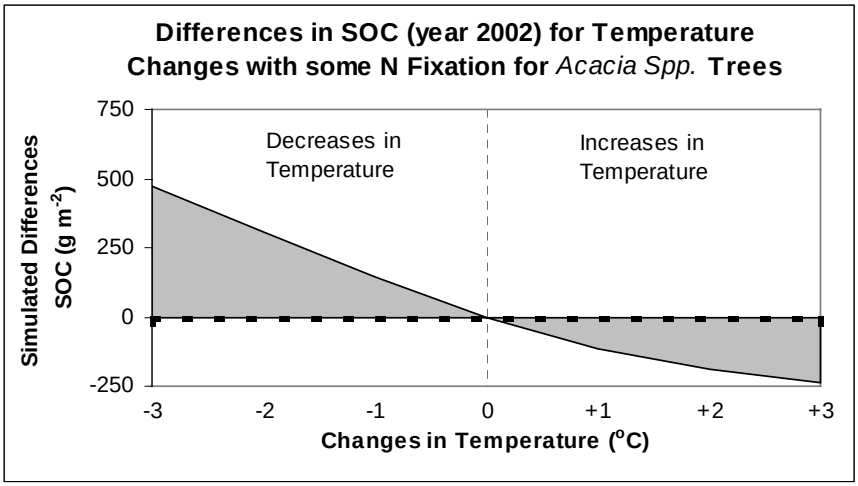


Figure 4.21: Simulated SOC in year 2002 for temperature differences varying from –3.0 ºC to +3.0 ºC of the mean monthly averages, with N fixation from trees (g N fixed per g C NPP) set to 0.01. The results represent the differences between each simulation and the simulation for the real monthly averages.

The range, in g m^{-2}, for the tested parameters, simulated for the year 2002 are presented in figures 4.22 & 4.23.

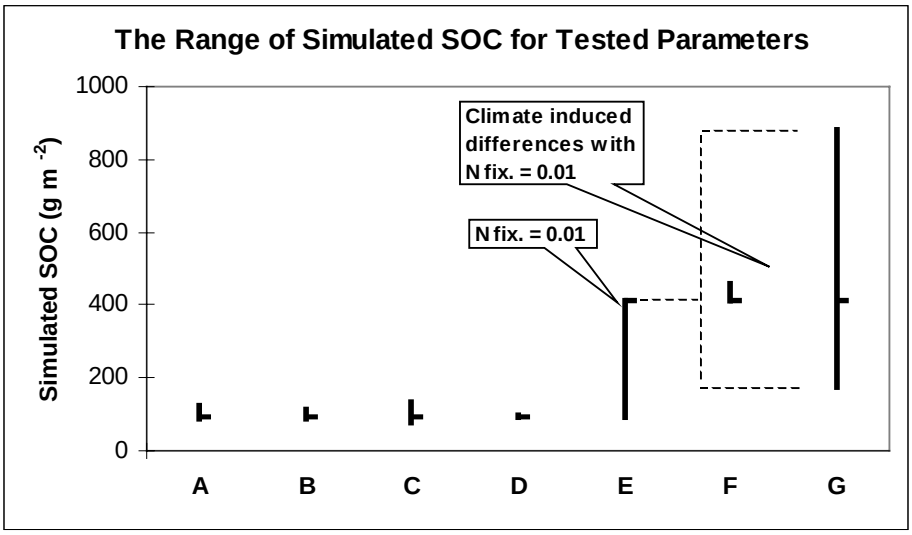


Figure 4.22: The range of simulated SOC for the parameters tested in the sensitivity analysis. A) Precipitation, B) Temperature, C) Soil texture, D) Harvest practices, E) N fixation, F) Precipitation with N fixation set to 0.01 g N fixed per g C NPP and G) Temperature with N fixation set to 0.01 g N fixed per g C NPP. The small horizontal bars represent the base scenario for A, B, C and D with actual mean values and N fixation set to 0.0, while for E, F and G, they represent the base scenario with actual mean values and N fixation set to 0.01 g N fixed per g C NPP.

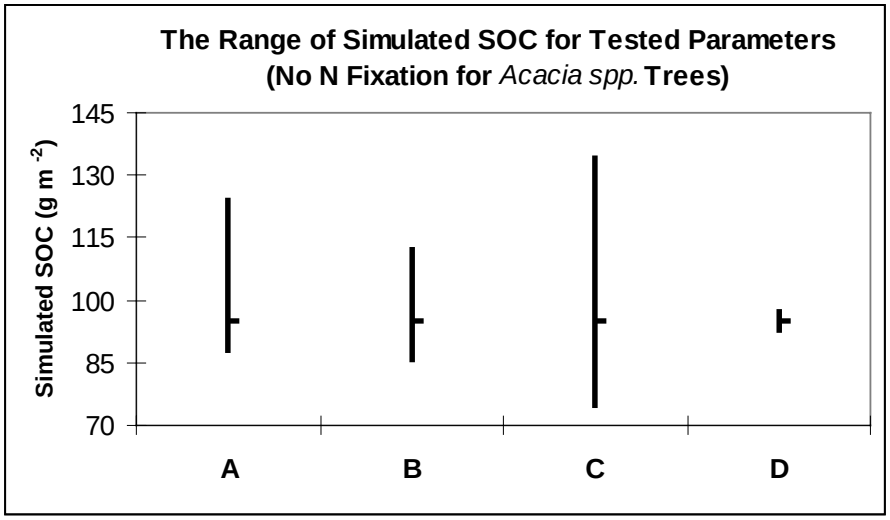


Figure 4.23: The range of simulated SOC for 4 of the parameters tested in the sensitivity analysis for year 2002. A) Precipitation B) Temperature, C) Soil texture and D) Harvest practices. The small horizontal bars represent the base scenario with actual mean values..

Future Scenarios: Figure 4.24 illustrates future simulations for three possible management practices. The climate scenarios used were simply an extrapolation of the mean values from the data available for Bara. Continuous cultivation continues to decrease SOC, while rather rapid recovery of SOC is associated with long fallow periods or grazing only.

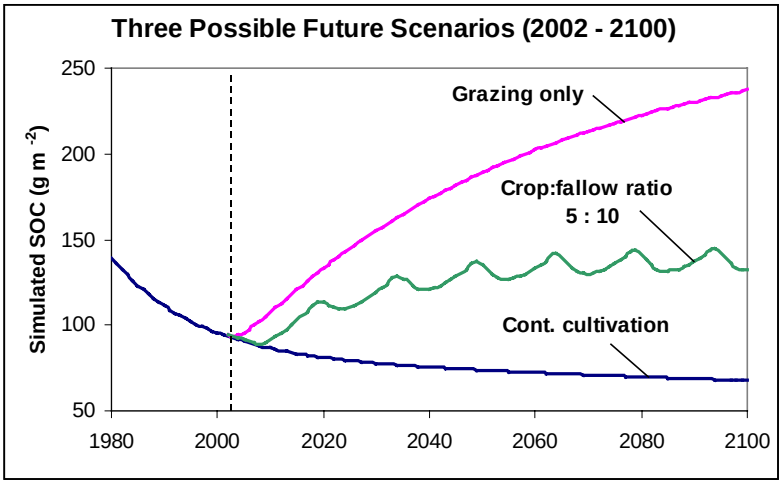


Figure 4.24: Modeling of SOC for three future management scenarios. Mean temperature and precipitation values from available data for Bara were used.

Figure 4.25 shows the modeling of SOC in 2100 associated to three management practices, based on three probable climate scenarios. The results clearly reveal that SOC is much more sensitive to land management practices than future climate change. The effects of the modeled climate variations are almost negligible, whereas the discontinuation of cultivation can increase SOC as much as 3½ times.

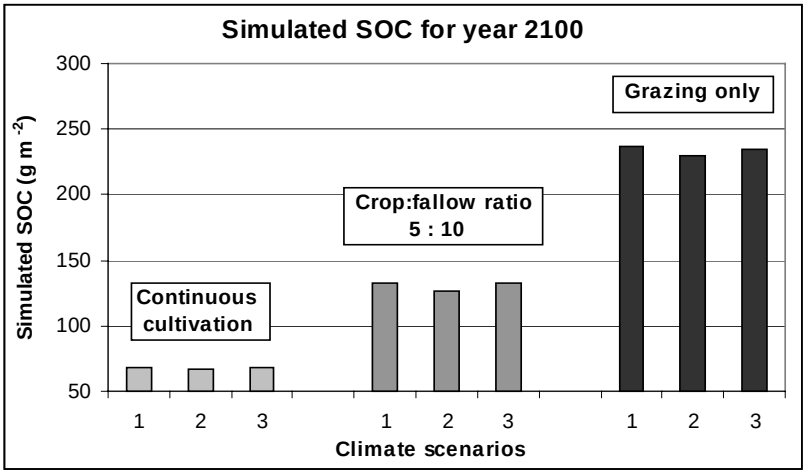


Figure 4.25: The effects of climate change on SOC in 2100. Three climate scenarios were tested: 1) no change, 2) an increase in temperature of 0.2 ºC per decade and a gradual increase of precipitation of 15% in 2100, and 3) an increase in temperature of 0.2 ºC per decade and a gradual decrease of precipitation of 15% in 2100.

5 DISCUSSION

5.1 Potential of Carbon Sequestration

Many international policy efforts directed at reducing the rate of increase of atmospheric CO_2 are now considering the potential for additional soil carbon storage (UNFCCC, 2001; Smith, 2001). One argument backing up carbon sequestration in soils instead of in vegetation can be that it is assumed that carbon has a much longer residence time in the soils (Lal, 2001). It can also help fight other problems such as land degradation, soil erosion and food security. Deforestation might release important amounts of carbon back in the atmosphere. Many studies indicate that improved land management practices can lead to an increase of carbon sequestration in soils (Lal, 2001; Olsson et al., 2001; Olsson et al., 2002). Within the Kyoto Protocol, it is proposed, through the Clean Development Mechanism (CDM) - Article 3.4 (UNFCCC, 2001) - that these carbon sinks could be quantified and given an economic value, with the intention of promoting sustainable development projects in developing countries. The economic, social and political consequences related to such projects could be significant and it is clear that the actors involved would be in urgent need of reliable verification schemes to support these economic or political decisions. There is presently much of attention given to these matters, most importantly, towards to likelihood of judging if global carbon sink verification is possible or not, given today's knowledge, capabilities and technology. Naturally, a main argument against the CDM is the lack of reliable data for baseline estimations and future, ongoing monitoring. However, in the first part of this research, the focus was more to evaluate verification possibilities given much data. With 100 soil samples for each of three fields of distinct landuse covering ground areas of 50 x 50 meters, the data used for this study could be considered of high quality when compared with other proposed verification schemes (Lal et al, 2001b). The key questions relating to estimating below-ground organic carbon storage were:

- *What are the limits to measuring or detecting significant differences in SOC inventories over time or space?*

- *Would verification over the study plots be cost-efficiently possible or not?*

Computer models can be the only practical way to test and simulate impacts of different and future land management practices on SOC over long periods of time. Ideally, the models should respond adequately to changes in the input data and parameters. They should be sensitive enough to recognize small changes, but without being over-sensitive. The purpose of the modeling with CENTURY was therefore to:

- *Evaluate changes in the model's output values due to variations in some of the model's input parameters.*

- *Simulate the effects of possible climate changes on SOC.*

5.2 The Study Fields

Basic descriptive statistics of the study fields show that there is a rather high variability in SOC contents. Even if the means of the fields are relatively similar (519.2 , 532.3 and 411 g m^{-2} for the cultivated, field in fallow and grazing fields respectively), the overall variances are very high (ranging from 51 425 to 212 952). The cultivated and the fallow fields are very similar statistically, whereas the grazing field shows a mean ≈ 20% lower and a variance ≈ 75% lower than the other two fields. A reason might be that the grazing field has about half the amount of trees found in the field in fallow period, and SOC has been noted to increase under tree cover (Buresh et al., 1998). But for the cropped field, the tree cover is similar to the one on the grazing field, stating that differences in SOC could most probably be better explained with land management history. Well-documented land use history is difficult to obtain, primarily because written documentation most often lacks and the historical land management practices can easily be forgotten over time. The use of reliable remote sensing (i.e. aerial photography) can also be limited due to the amount of data. Nevertheless, it is known that the grazing field used in this study had not been cultivated since 1983 (Jonas Ardö, personal communication, May 2002). Results from previous modeling with CENTURY over the study area show that grazing only should be a management practice capable of sequesting important amounts of carbon back into the soils (Olsson et al., 2002). Their study also indicates that, compared with cultivation practices, grazing should sequester more carbon. In this study, the grazing field was the site with the lowest SOC. In practice, generalizations of management practices are difficult to determine for this area. A reason for this is that the fields can cover vast areas, which are not fenced, making it difficult to know the intensity, or even presence, of grazing livestock. Fields left in fallow can also theoretically be grazed, as they are often not fenced either. For modeling purposes, the intensity of grazing can be determined quite accurately, but such management practices are difficult to estimate when interpretating SOC contents of soil samples. Therefore, direct comparison of soil samples extracted in such fields (for example, grazing or fallow fields) and their simulated results should be interpretated with care. Also, it should be noted that a number of samples from the cultivated and fallow fields had extreme high values, which affect importantly relevant statistics. It would be, nonetheless, of interest to model more fields of well-known landuse history to eventually be able to understand better the carbon flows related to various management practices.

Small uncertainties could result while measuring SOC contents in laboratory. The *Carbon Determinator LECO CR*-12 can have uncertainties of up to ±1% of the sample C. As a verification procedure, 25 samples were tested twice to estimate the mean error between the two measurements. The results deviated by an average of 0.096%. Also, errors in the estimation of the bulk density can have important effects on the SOC measurements when extrapolating point-based results to square meters. The bulk density estimates from fields in the area deviated by ±7% from the mean (1711g l^{-1}). For the average SOC content and bulk density of all samples (0.15% SOC), this results in uncertainties of ±36 g m^{-2}.

An ANOVA shows that there was no significant difference in SOC inventories between the three land cover types. Nevertheless, fields compared two-by-two with the grazing field did show significant differences. On the contrary, the nonparametric tests showed almost opposite results. The null hypothesis was rejected for the comparison of all three fields, the cultivated and fallow fields together and the fallow and grazing field together. In this case, the results from the nonparametric tests are more significant than the results from the ANOVA because normality of the data was not fully respected. Whichever the test, not rejecting the null hypothesis indicates that a specific land cover can sometimes not reflect SOC levels. In the cases where no difference is presently detectable, how many samples would be required to differentiate the fields if sequestration was to occur? MDD calculations, as they were done in this thesis, assume normality, therefore, sample sizes corresponding to non-normal data would not entirely be relevant. However, the concepts discussed in this thesis provide a good background on a *methodology* that can be used to monitor environmental properties, and argues some important theories regarding statistical analysis.

5.3 The Minimum Detectable Difference (MDD)

Based on the average variance estimate of the three tested fields (the error mean square of the ANOVA), a change of as low as 5 to 10% from the present mean ($\approx$ 490 g m^{-2}) would be practically unverifiable, because over 1000 samples from each time period would be required to detect these differences (table 4.5). Only changes of at least 50% ($\approx$ 250 g m^{-2}) could be monitored with a somewhat reasonable sampling program (<66 samples). This really raises questions about detection limits. Section 5.4 discusses simulated C sequestration potentials and the rates of C sequestration or losses per year.

The method used in this thesis for calculating the MDD takes into account both types of errors related to hypotheses testing; the Type-I error and the Type-II error. Johnson et al. (1990) used a slightly different approach for calculating what they refer to as the "mean detectable change", which corresponds to a 50% chance of actually detecting the change, with a specified sample size. The key parameter for their calculation is the standard error and only the Type-I error is considered. They note that considering only the Type-I error decreases the sample size compared with a method considering both types of errors. If lower probabilities of committing Type-I errors (α) are required, then the sample size will increase (Zar, 1984). The same conclusion can be made with an increase of the power of the test ($1 - \beta$). As the probability of committing a Type-II error decreases, larger sample sizes are required. A fewer number of treatment groups (k) compared also tends to increase the critical value, ϕ, which is associated to greater power (Zar, 1984)

The estimations of the MDD are based on the assumption of normally distributed data. In fact, values from the *t* distribution are required for the calculations. In this study, the data did not fully respect normality and using critical values from the *t* distribution can induce uncertainties in the calculations. Nevertheless, like Johnson et al. (1990) mention, normality tests are generally not very powerful and the hypothesis of normally distributed data may be tenable in spite of non-normality in the data. They also argue that the *t-test* is robust in the presence in substantial non-normality.

The sample size calculated from the MDD calculations represent the amount of samples that should be taken during *each* sampling period or from *each* location. However, there are occasions when equal sample sizes are impossible or impractical. Zar (1984) discusses the possibility and consequences of such difficulties. Interestingly, unequal sample sizes can result in an increase of the total amount of samples for a desired power, compared to equal sampling. For example, 90 (45 + 45) samples would be required to detect a particular change with equal sampling, while 118 (30 + 88) samples would be required to detect the same change, at the same power, for unequal sampling of two treatment groups. (Zar, 1984)

Also, in many studies, a number of soil samples extracted for a small ground area are mixed together to create one sample representing the area. When such methods are applied, the probability of having samples with extreme high or low SOC values are limited. In fact, this method could lead to a much lower variability of SOC contents, as the carbon is more equally distributed within the new "mixed" samples. The elimination of the few extreme values that may occur during the sampling scheme can reduce the variance importantly. As an example, removing the 8 high-extreme values from the 100 samples taken in the cultivated field reduces the variance from 212000 to 17000, equal to approximately one twelfth of the original variance. It is clear that such a difference in variances has great implications in the calculations of the MDD.

At the time of the study, the laboratory measurement of organic carbon of one soil sample cost 70 SEK (approximately $7 US) at Lund University. This indicates the magnitude of sampling budgets when a great number of samples are required. It should also be noted that this cost only cover the laboratory work, and does not include any other procedure (traveling, man-power, equipment, energy).

5.4 Previous Model Simulations and Data for Estimating C Sequestration

Some modeling simulations have recently been executed by Olsson et al. (2001) with the CENTURY model over the same study area. The purpose was to estimate sequestration potentials due to improved land management. More specifically, simulations were made based on a scenario that a field was used strictly as grazing land until 1950, when it was then put under permanent cultivation from 1950 to 2000, and reverted to rangeland with the same grazing intensity as before 1950 from year 2000 onwards to 2100. Their results clearly show a drastic drop in soil organic carbon between 1950 and 2000, during the permanent cultivation period ($\approx$ 820 g m^{-2} in 1950 to $\approx$ 340 g m^{-2} in 2000). They show an increase of over 200 g m^{-2} within the first 50 years of reverted rangeland (340 g m^{-2} in 2000 to 550 g m^{-2} in 2050), and an increase of 310 g m^{-2} by the end of the century (650 g m^{-2} in 2100). Such a sequestration rate is equal to 4.2 g m^{-2} yr^{-1} for the first 50 years, or 3.1 g m^{-2} yr^{-1} over the 100 years. Is that enough to be verifiable? The answer is relevant to the variability of the SOC inventories estimated during a sampling scheme, and of course, the time period for the verification. If, for example, such an increase would require detection between the Kyoto Protocol's proposed baseline year of 1990 and 2010, then the minimum amount of soil samples, taken from each time period,

required to statistically differ the two treatment means would be approximately as follows, given different variances:

Variance (s^2)	Samples (n)
1 000	4
5 000	16
15 000	48
50 000	120
> 100 000	> 250

Table 5.1: The minimum number of soil samples required to detect simulated soil carbon sequestration of 4.2 g m^{-2} yr^{-1} (Olsson et al. 2001) between 1990 and 2010 over a similar study area. Method by Zar (1984).

With rather low variances, such an increase is very well verifiable. Nonetheless, the question is, are such low variances realistic for the area? Variances of other projects were observed to compare their values (Johnson et al., 1990; Ardö et al, 2002; Jakubaschk, 2002)

Firstly, Ardö et al. (personal communication, April 2002) had an average variance of $\approx$ 4000 for soil sampling extracted in similar land covers. However, this mean variance is based on only 4 samples per field, which raises questions on the reliability of this sampling procedure. With $n = 4$ samples and a variance $s^2 = 4000$, the minimum detectable difference based on a one-sample hypothesis ($\alpha = 0.05$ and $1 - \beta = 0.90$) is equal to 152 g m^{-2}. Put differently, this indicates that the estimate of the overall mean of a field, based on 4 samples having a variance of 4000, could be offset by up to ±152 g m^{-2} before a *t-test* would reject the null hypothesis for that mean estimate (with the significance level α and the power $1 - \beta$ of the test stated above). With the same variance and sample size, at least 60 samples would be required to have a 90% probability that the 95% confidence interval is between ±25g m^{-2} of the mean (5% of a mean of 500 g m^{-2} for example).

It should be noted that similar testing could also be made to calculate the confidence limits for the population variance. But the sampling distribution of variances is not symmetrical, and neither the normal nor the *t* distribution may be employed to set confidence limits around a variance or to test hypotheses about a variance. Instead, the chi-square (χ^2) distribution can be used to define an interval within which there is a $1 - \alpha$ chance of including the variance (s^2), given a sample size. From the example above, the 95% confidence interval of the variance of 4000 taken from 4 samples would be from 1284 to 55555. With 60 samples ($s^2 = 4000$), the interval of the same confidence is between 2874 and 5950. Zar (1984) reviews this concept and discusses a method to calculate the sample size required to achieve a wanted confidence in tests concerning the variance.

Secondly, very recent soil sampling was undertaken by Caren Jakubaschk (2002, in progress) in the framework of the investigation of the possible impact of *Acacia senegal* on SOC and N contents. Her sampling was done in the Umm Ruwaba District, in Sudan, during February 2002. Samples from fields in fallow period with/without *Acacia senegal*, crop fields continuously cultivated for 10 to 30 years, and undisturbed fields for at least 30 years with/without *Acacia senegal* trees were taken. Her variances vary

between 4600 and 115000 for sampling sizes from 6 to 18 samples of the top 20 cm of soil. This makes the detection of a change of around 100 g m^{-2} possible with roughly 10 samples ($s^2 \approx 5000$) to over 100 samples ($s^2 \approx 100000$).

Thirdly, Johnson et al. (1990) collected 60 soil samples from an experimental forest in New Hampshire, USA, in the purpose of presenting a method for computing sample size requirements for long-term studies of multiple soil properties. Even though the environment of their study is totally different to the environment of this research, their results can give another viewpoint on the variability of soil organic carbon. They calculated a standard deviation for the total carbon content of 5910. The standard deviation being the square root of the variance, this implies that the variance was approximately 36 million. Realistically, such an extreme variance would make it totally impossible to monitor changes, base on those samples.

5.5 Jackknife Analysis, Confidence Intervals and Limit of Accuracy

Jackkniffing (or bootstrapping) can be viewed as a means of simulating alternative sample sets. As Johnson et al. (1990) mention, such simulations can be very useful as it is often difficult to adequately determine analytically some statistical properties and because one usually has only one set of samples to work with.

By using a jackknife routine, the samples extracted *cannot* be extracted a second time. This makes the difference between a jackknife routine and what is called a "*bootstrap*" routine. In the latter, the resampling technique is done "with replacement", which means that a particular data value may be included multiple times in the bootstrap data set.

The 95% confidence interval used in the jackknife routine was calculated by multiplying the standard deviation by 1.96. The normal distribution could be justified because of the large number of jackknifed data sets (500). Nevertheless, to be totally free of parametric assumptions, the 0.025 and 0.975 quantiles of the results could be used as the confidence interval values (if a 95% confidence is wanted). With a total of 100 values, these quantiles would represent the midpoint between the 2nd and 3rd smallest values and the 2nd and 3rd largest values (0.025 x 100 = 2,5; 0.975 x 100 = 97.5). Jackknifing 500 times, these values would be midpoints between the 12th and 13th smallest and largest values. A jackknifed or bootstrapped *median* of the variance or standard error could also be used in the calculations of the MDD, instead of the *mean* of this statistic (personal communication, Chris E. Johnson, April 2002). The median can be representative when normal distribution is not encountered (Johnson et al., 1990).

The limit of accuracy can be a useful way to know if a given number of samples represents the mean value of a field with satisfying precision. A problem is that the standard error is calculated only once based on all the available samples and then used to explain the accuracy associated to all the different sample sizes afterwards. As seen from the jackknife routine, the variance (consequently the standard deviation and standard error) can vary importantly if calculated with subsets of the available data. Therefore, the *one* standard error value for a field should be interpretated with care. The LA calculated

for the study sites nonetheless show that the high variability of the data can cause difficulties to accurately estimate the mean. With 100 samples, the cultivated and grazing field's mean value range by ± 91 g m^{-2}, while the grazing field's mean value can range by ± 45 g m^{-2}.

5.6 Spatial Heterogeneity of SOC and Aggregate Stability

The vegetative distribution is visibly more heterogeneous in rangelands than in many other ecosystems. The patchy spatial and temporal distribution of resources in many rangelands make it challenging to both increase and monitor carbon sequestration in such soils. Previous carbon-13 studies in US rangelands indicate that vegetation shifts can frequently result in SOC being out of equilibrium with new plant communities. To cost-effectively monitor and manage carbon sequestration in these ecosystems, the spatial distribution of soil carbon at different spatial scales and how soil structure interacts with SOC for its different fractions must be better understood and taken into consideration. (Bird et al., 2002)

A recent study was conducted by Bird et al. (2002) in the rangelands of New Mexico, USA, to characterize the spatial distribution of aggregate stability and SOC under different land cover types. More specifically, sampling was done under mesquite shrubs (*Prosopis spp.*), black grama grasses (*Bouteloua eriopoda*) and in interspaces between plants on a number of research plots. Their results indicate that both aggregate stability and C distribution demonstrated great heterogeneity at the patch scale and between study plots (landscape scale) under the different land cover types. They state that to reliably measure total soil C across semi-arid landscapes, one must use caution when extrapolating C values generated from soil samples to broader land areas. For C sequestration management, this multi-scale variability has important implications. For example, different landscape areas will respond differently to organic inputs from vegetation and soil structure and stability.

Lal (2001) also discusses variability of some soil properties found in the soils of the drylands. In fact, he states that differences in ground cover in these areas can be reflected in different SOC contents within meters of each other.

5.7 Sensitivity Analysis of the CENTURY Model Regarding SOC

Predicting management strategies and climate effects on ecosystems is very difficult through field experimentation alone. Most experiments are done over relatively short periods compared to the period of environmental processes. Thus, environmental models offer an alternative to study process dynamics, they can be used repeatedly at various scales and they do not cause any disturbance to the study area. It is however of interest to evaluate model's responses to input variations in order to judge its utility regarding the modeling of the area under study in respect to the available data.

5.7.1 N Fixation

The model showed to be most sensitive to N fixation rates from the trees. Climatic variations also had a much greater impact on the resulting SOC when N fixation from trees was allowed in the system. The sensitivity of the model to climatic variations therefore increases in relation to the already sensitive N fixation parameter. This should be reflected upon and considered when modeling SOC in semi-arid environments.

In CENTURY, the maximum amount of N fixation that can occur from a tree is based on the amount of production (net primary production; NPP). The demand of N from the tree is computed as:

$$N\,demand = C\,produced \times \max.\, N/C\ ratio\ of\ the\ whole\ plant \quad (5.1)$$

The maximum N/C ratio of the whole plant is computed by summing the C allocation fractions of new production for juvenile and mature trees and the initial C/E ratios for forest compartments (E = elements; N, P or S). The maximum N fixation value is then used to compute the C/N ratio of the tree parts based on the amount of N available.

If the amount of N fixed plus the amount of N available are greater than the demand for N, then the C/N ratio is set to the maximum amount based on preset values in the file for tree options. If the amount of N fixed plus the amount of N available is less than the demand for N, then the C/N ratio for the tree components will be adjusted accordingly. Setting a high N fixation value will prevent the system from becoming N limited. (personal communication, Cindy Keough, Natural Resource Ecology Lab., Colorado State University, May 2002)

The model can also simulate atmospheric N fixation amounts based on precipitation. This amount depends on the intercept and the slope values determining the effects of annual precipitation on atmospheric N fixation (wet and dry deposition), set in the site-specific file. A reason why increased precipitation starts to increase SOC when N fixation from trees is allowed (wet deposition) (figure 4.19) may be due to the amount of atmospheric N fixation crossing a critical threshold, making the system no longer N limited due to atmospheric fixation amounts. (personal communication, Cindy Keough, Natural Resource Ecology Lab., Colorado State University, May 2002)

5.7.2 Climate

In general, it has been observed that temperature seems to influence more decomposition than net primary production (NPP), while precipitation seems to influence more NPP than decomposition. An increase in precipitation will result in an increase of NPP. (Breymeyer et al., 1996).

The results of this study indicate that SOC accumulation is controlled more by output (decomposition) than input (NPP). Even if more precipitation increases NPP, the SOC content associated to this increase in precipitation follows a declining trend. Over the yearly time-span, this means that decomposition caused by a precipitation increase is more important than the carbon sequestered from the newly produced C input in the

system. A reason may be that decomposition occurs over a longer period over one year than NPP, which takes place only during the growing season (June-October). However, regarding NPP, Breymeyer et al. (1996) interestingly note that in arid regions, more water can be available for plant growth in sandy soils with low water-holding capacities than soils with higher water-holding capacities. This is due primarily to lower bare soil evapotranspiration in sandy soils, as water penetrates deeper. They also state that the opposite effect occur in humid regions.

The effects of temperature and soil moisture on decomposition increase as soil temperature and higher rain/PET ratios increase (figure 2.8). This partly explains why increases of these parameters (precipitation and temperature) lower SOC content, as decomposition factors are greater. For the direct effects of precipitation, lower rainfall averages had a slightly larger impact on SOC than equivalent precipitation increases. From the yearly total precipitation amount at Bara, a 1% change represents a difference of 2.7 mm. The maximum precipitation change tested was 25%, which represents a deviation of 68 mm from the total yearly average. The SOC in 2002 ranged by approximately 37 g m^{-2} for these maximum deviations.

Modeling with constant mean values for precipitation could be seen as somewhat unrealistic considering that central Sudan experienced important variations in annual precipitation totals during the last century (Ahlcrona, 1988). CENTURY can also run simulations by stochastically generating climate variables based on the long-term averages, standard deviations and skewness of monthly data values. This climate setup could provide a more flexible method to test long-term climate change scenarios by inducing differences in the "variability" (standard deviation and skewness) associated to the mean values, instead of running the model with the same climate values year after year (Mitchell et al., 2001). Nevertheless, modeling with mean values can be used to simulate outside the time-range of the available data or to bring the model simulation to equilibrium. For this reason, knowing the direct impact on SOC of different mean values can be useful. Ahlcrona (1988) studied climate data from 1900 to 1986 for climate stations in central Sudan and annual standardized precipitation totals varied from plus 200% to minus 200% from the mean, with many years varying by at least 50% (both above and below the mean). This shows that constant long-term monthly averages can easily over or underestimate climate values in this region. Mitchell et al. (2001) also tested the effects of climate variability on grassland productivity in Saskatchewan, Canada using the CENTURY model. They conclude that changes in the variability of monthly precipitation had a greater impact on uncertainties when simulating NPP than constant variations in precipitation across time, not altering the variability of the monthly values. Similar tests could be performed for SOC.

The effects of temperature variations on SOC were comparable to the effects due to precipitation variations. The higher temperatures increased decomposition, but the outcome seemed to level off at + 2.5 ºC or more. This could be because average temperatures are already very high, which decreases the effects of extra degrees. The range of simulated SOC for year 2002 varied by approximately 25 g m^{-2} for variations of 6 ºC.

When modeling with no N fixation from the trees, the SOC levels are much lower compared to the SOC from the soil samples analyzed. Just before the introduction of continuous cultivation in 1975, the modeled SOC was estimated to approximately 150 g m^{-2}. The average SOC from the soil samples was approximately 488 g m^{-2}, meaning that the model underestimated SOC by more than a three fold. When introducing some N fixation from the trees (0.01 g N fixed g^{-1} C NPP or more), the modeled base scenario becomes more representative, with a SOC content modeled for 2002 of 417 g m^{-2}. As discussed above, the climate variations are greatly amplified when N fixation is allowed. The modeled SOC in 2002 for the climate scenarios tested with N fixation set to 0.01 g N fixed per g C NPP now varied by 700 g m^{-2}, whereas it varied only by 37 g m^{-2} when no N fixation was allowed.

5.7.3 Soil Texture

Regarding the soil texture, it is apparent that the clay fraction is the leading parameter for carbon sequestration potential. The SOC reflected the clay content in a linear matter with SOC in 2002 of 167.5, 135.4, 105 and 75 g m^{-2} for clay fractions of 15, 10, 5 and 0% respectively. This indicates that 1% clay sequestered about 6 g m^{-2}, given the base scenario. Variations in sand fractions did not all influence SOC, as the results from 85 to 100% sand were the same. Even if the quantification of the sand fraction is precise, differences in how the remaining fraction (silt & clay) is divided can greatly impact the resulting SOC (figure 4.15). Even at 95% sand, variations in silt and clay for the remaining 5% result in SOC, for year 2002, of 79 to 105 g m^{-2} (a difference of 26 g m^{-2}). For a sand fraction of 85%, such variations equal SOC varying from 84 to 167 g m^{-2} (a difference of 83 g m^{-2}). Today's laboratory techniques make it possible to quantify each fraction with relatively high accuracy, but when modeling over large areas, or applying a distributed CENTURY model to a GIS (Ardö et al., 2002), the differences in soil texture should be seriously considered. Further studies testing CENTURY's sensitivity to bulk density in semi-arid environments should also be studied.

5.7.4 Harvest Practices

The variations in harvest practices, in respect to the amount of above ground residue removal, did not impact the final SOC in important ways. In fact, the simulations with 70% straw removal and 100% straw removal were almost identical (figure 4.16). The SOC varied by maximum of 4 g m^{-2} for the entire simulated time period. This is another indication that SOC in semi-arid environments can be mainly influenced by output processes (decomposition) instead of input (litter). The simulation with 0% straw removal was done mainly to know the range of output results influenced by this parameter, but logically, harvest practices will always remove a great portion of the above-ground biomass, especially as straw is a important building material in the region.

5.7.5 Future Scenarios

Future simulated scenarios show that differences between land management practices are much more influential on SOC than climate change. While the responses to climatic variations are minimal, the simulations for different land management practices showed to be greatly influenced by the discontinuation of nonstop cultivation. By the end of the

first decade (2012), the modeled grazing scenario was already 20 g m^{-2} higher than the modeled cultivation scheme. At the end of the simulations (2100), the grazing and 5:10 crop:fallow scenarios showed SOC to be three and a half (3½) and twice (2) the amounts simulated for continuous cultivation.

Gill et al. (2002) analyzed the impact of varying atmospheric CO_2 levels on a grassland in Texas, U.S.A. Both C_3 (*Solanum dimidiatum* and *Ratibida columnaris*) and C_4 (*Bothriochloa iscaemum*) plant species were studied in regards to their responses to atmospheric CO_2 levels ranging from historical (last Inter-glacial period) to probable future concentrations - using enclosed chambers. More specifically, these levels ranged from 200 μmol mol^{-1} to 550 μmol mol^{-1}. Carbon sequestration in soil organic matter and N cycling were also examined. They observed that the soil carbon storage and the N cycling were much more responsive to increases in past CO_2 than those forecast for the coming century. Increases in atmospheric CO_2 caused the increase in soil organic matter, but production and soil carbon storage basically saturated above 400 μmol mol^{-1}, a CO_2 concentration very close to today's global one. This states that we could very well soon be at a threshold where the benefits of extra CO_2 may not be all that great. Furthermore, much of the increased C was partitioned to rapidly cycling pools (labile fractions), which makes long-term C sequestration negligible because of their high turnover rates. In regards to N, their measurements showed that soil N decreased about threefold in a nonlinear way, as CO_2 went up, with again the largest changes occurring at historical concentrations. This caused a fundamental nutrient limitation in the system, and the decrease in N availability apparently constrained the ability of the plants to use extra CO_2. Their conclusions are that to correctly assess the impacts of rising CO_2 on carbon sequestration patterns and nutrient dynamics, knowledge of potential threshold responses is required and soils under grasslands that may have played a important rrole in sequestering C in the past could soon lose this ability due to a lack in nutrient availability.

5.7.6 Comments on Sensitivity Analysis and Modeling of SOC

The sensitivity tests performed in this study were all relatively simple in the sense that few parameters were changed each time a simulation was executed. The other parameters remained constant. The impact of one parameter can be very different when combined with variations in other parameters during the same simulation. This was seen with climate variability combined with increased N fixation in the present study. Mitchell et al. (2001) also showed in their sensitivity analysis of the CENTURY model that increased CO_2 concentration over the next century had relatively little effect on average annual productivity of C_3 and C_4 plants unless precipitation was increased as well. Models such as CENTURY simulate complex processes. They can be excellent tools for testing hypothesis and to answer questions that require detailed treatment of different physiological responses, but extra detail in modeling normally increases the number of parameters. Many default values have to be used with CENTURY and many other parameters have to be estimated from experiments in similar environments and literature. This fact can stimulate further studies involving model sensitivity, or the effects of climate change, where more parameters could be tested in combination.

The modeling of the SOC content with CENTURY showed to be rather difficult for this environment. When no N fixation is allowed in the system, CENTURY clearly underestimates SOC, with amounts at least half of the observed data. Of course, the land use history modeled is only an assumption of what may have happened on the actual fields, which could partly explain the variations between model and reality. The simulations for future scenarios showed that land use is a driving parameter determining the faith of SOC in the environment. Detailed land use history can be difficult to obtain, and when modeling over long time periods, generalizations must be made. The base scenario used in the sensitivity analysis was compiled with information typical for the area and contained only a few events such as fires, regular harvest practices, cultivation of millet, the growth of trees during fallow period and low intensity grazing. It would be easily possible to try modeling the sampling fields as accurately as possible, but this would imply making changes in the base scenario mostly for the last quarter of the century (1975 – 2002), where land use history is known or can be well estimated. But even though, the SOC, modeled with CENTURY, for 1975 was very low (158 g m^{-2}). Simulations executed with a precise land use history would still not reach the observed SOC of 400 – 500 g m^{-2} by 2002. If N fixation is allowed in the system, the simulated results can be much closer to the observed data, but knowing the amount of N fixation is difficult to estimate, and different values have showed to result in very different SOC contents. Also, because CENTURY is point-based (1 m^2), it is difficult to set the appropriate parameters for trees for the reason that trees do not grow in a homogeneous matter and are often spread out over an area.

6 CONCLUSIONS

Much of the African semi-arid ecosystems are degraded in some way, and increasing soil fertility should be a priority in these areas. Increased soil fertility can initiate a chain reaction of many positive effects crucial to overcome some of the serious problems encountered in such ecosystems and elsewhere. Low food security, decreasing crop yields, desertification, decline of biodiversity and erosion problems are only some of the reasons why the quality of the soils found in semi-arid agro-ecosystems should be carefully managed. It is obvious that controlling global warning is not a key priority in this part of Africa when locals are threatened daily by the problems mentioned above, which for them, are naturally much more significant. With concepts, such as the Clean Development Mechanism, it is now possible that foreign investments target soil sequestration projects. Such projects can, nonetheless, only be successful if the local's needs, socio-economic and political situation are taken into consideration. As Tschakert (2001) mentions, sometimes, political situations, or other reasons, may prevent improved land management practices, even with the full willingness of the local farmers themselves. In her study of the situation in Senegal, she noticed that a law on land tenure ("La Loi sur le Domaine National") states that traditional land management systems, such as longer fallow period, were officially limited to a duration of no longer than two years.

The verification of carbon sequestration is no obvious task in this area. The SOC is naturally very low and has an important variability over space. A very precise verification scheme would require considerable soil samples. If all the samples used in this study are considered, more than 1000 samples would be necessary to observe a 5% increase in SOC over time. The decrease of the variability in SOC samples will in return decrease importantly the required amount of soil samples needed to statistically differ two or more sampling groups. The mixing of soil samples could perhaps lower the variance within a treatment group? More studies regarding this issue should be undertaken for this study area. A doubling of the variance also doubles the required amount of soil samples to achieve the same detectable change (MDD), which means that the number of samples can quickly decrease based on different sampling schemes. This thesis presents a *methodology*, resuming some statistical concepts relevant to the verification of changes over time or space of environmental properties. Thus, the minimum detectable difference (MDD) calculations are based on a normal distribution of data. Using methods such as "jackknife" or "bootstrap" routines enables the estimation of statistical parameters and their confidence intervals, and can be designed to respect non-normality in the data. Knowing the confidence intervals of the variability can be very valuable when designing sampling schemes. It should be to no ones interest to overlook spatial variability when aiming to verify differences over time or space of soil properties. Neglecting such variability can lead to substantial simplifications, which can consequently reduce the value and purpose of the study itself. There is a fine line between accuracy and feasibility, and if the aim of a study is strictly to verify changes in SOC, efforts to not over-simplify the data should be seriously considered.

Computer models are important tools to test hypothesis and further the understanding of process dynamics for different scenarios. CENTURY has often been used in research projects and has been validated for several ecosystems on Earth. However, it requires a large number of input parameters. Knowing the accurate value for many of these parameters can be challenging and truthful land use history over long periods of time is often difficult to approximate. The SOC in the study area of the semi-arid region of the Sudan is naturally very low, and changes over time or space are, to a certain extent, minor. Simulations showed that different land management practices could sequester or lose approximately 1-2 g m^{-2} yr^{-1} over the next century. With CENTURY, the range of simulated SOC in 2002 for the different scenarios reached at least 30 g m^{-2} for most of the parameters tested in the sensitivity analysis. This indicates that the use to the computer model as the primary tool for verification of SOC is limited. Variability in the rate of nitrogen (N) fixation by trees could double and triple modeled SOC. It makes it difficult to estimate the proper N fixation value, because small variations of this parameter result in very different SOC contents. No N fixation could be seen as a "conservative" option, but if N fixing legumes are present in the landscape, they should also be included in the simulations. This is part of the dilemma scientists are faced with when modeling the environment. The "patchiness" of the vegetation found in the study area make it even more difficult to simulate SOC, as CENTURY is a point-based model.

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8 APPENDIX

8.1 Some Useful Definitions

The following are useful definitions of terms used in the context of this thesis.

Afforestation: Activities that lead to the establishment of forest on lands that previously did not carry forest within living memory (X number of years).

Jackknife routine: A jackknife routine is a type of statistical methods which typically use repeated resampling (without replacement) from a set of data to assess variability of parameter estimates.

Carbon sequestration: The uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon (for example, in soils).

Deforestation: Refers to change of land cover with depletion of tree crown cover to less than 10%. Changes within the forest class (e.g., from closed to open forest) that negatively affect the stand or site - and, in particular, lower the production capacity - are termed forest *degradation.*

Dryland: Drylands can be defined by an aridity index which represents the ratio of precipitation to potential evapotranspiration (P/PET) with values < 0.05 for hyper-arid, < 0.20 for arid and 0.20 - 0.50 for semi-arid climates

Fallow period: Refers to the period when an agricultural field is left unseeded during a (or many) growing seasons.

Labile: Readily or continually undergoing chemical, physical, or biological change or breakdown; unstable.

Lignin: Lignin is an amorphous polymer related to cellulose that provides rigidity and together with cellulose forms the woody cell walls of plants and the cementing material between them.

Nonparametric: Nonparametric implies that there is no assumption of a specific distribution for the population.

Rangeland:	Area of land that is occupied by native herbaceous or shrubby vegetation which is grazed by domestic or wild herbivores. The vegetation of rangelands may include tallgrass prairies, steppes (shortgrass prairies), desert shrublands, shrub woodlands, savannas, chaparrals, and tundras.
Reforestation:	Planting of forests on lands that have previously contained forests, but that have been converted to some other use.
Type I error (α):	The probability of rejecting the null hypothesis when the null hypothesis is true.
Type II error (β):	The probability of failing to reject the null hypothesis when the null hypothesis is false.

8.2 Jackknife Routine in Matlab

Example of program used to make jackknife routine in Matlab.

The first part of the program calculates the mean (or standard deviation, variance) once for each sample size ranging from 2 to "all" samples (in this case 100 samples). Before doing so, all the values are randomly reclassified. The data file should be a simple text file with one value per row. The results are thereafter plotted on a graph.

```
function out=jord(infil)
close all

%  Specify the name of text file, which should be saved in same folder as this program
%  itself (same path).

A=load('*.txt');

% To reclassify randomly all the values of the "in" file:

lgt=length(A);
r=rand(lgt,1);
Tr=[A,r];
Trs=sortrows(Tr,2);
Ts=Trs(1:lgt,1:1);

% Calculation of the mean value as a function of number of samples:

[r,k]=size(A);
for k=1:r,
   medel(k,1)=mean(Ts(1:k,:));
end

out=medel;

% [Can replace mean by std for standard deviation or var for variance]

plot(medel,'*:k')
xlabel('No of measurements')
ylabel('mean')
title('Mean value as a function of the number of samples')
grid on
```

A second part of the program executes the first part a required amount of times (example 500 times), therefore, creating a loop. The mean and the 95% confidence interval (multiplication the standard deviation by 1.96) of the statistical parameter calculated in the first part is afterwards calculated for each sample size ranging from 2 to "all".

For example, if the first part calculates the variance once for each sample size, the second part of the program calculates the mean of the 500 variances calculated for each sample size and its 95% confidence interval. The results are also plotted on a graph.

```
close all
D=[];

% Set the number of times the jackknife routine is to be executed:
NbrOfRand=500;

for k=1:NbrOfRand
   D(k,:)=jord('*.txt')';
end

sigma=1.96*std(D)';
meanval=mean(D)';
P=[meanval,sigma];

plot(meanval,'--')
hold on
plot(meanval+sigma,'--')
plot(meanval-sigma,'--')
axis([0 100 0 1000])
grid on
```

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