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Soil Organic Carbon in Upper East Region, Ghana

– Measurements and Modelling

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This study has been carried out within the framework of the Minor Field Study (MFS) Scholarship Programme, funded by the Swedish International Development Co-operation Agency (Sida).

The MFS Scholarship Programme gives Swedish university students the opportunity to carry out fieldwork in a Third World country. The extent of the work corresponds to BA or Master's dissertations, or similar in-depth studies. The studies focuses on areas and issues of relevance for development problems, and are conducted in countries supported by Swedish development assistance.

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The Department of Social and Economic Geography at Lund University is one of the departments that administer MFS Programme funds. Studies conducted by student granted scholarships by this department, focuses on spatial aspects of different development issues.

ABSTRACT

As a response to the enhanced greenhouse effect International Emissions Trading and Clean Development Mechanism were proposed as countermeasures at the Kyoto climate conference, in 1997. The observed raise in levels of atmospheric carbon dioxide has increased attention on the carbon cycle and claimed the need of more knowledge and understanding of the global carbon cycle. This can be obtained by the use of ecological models. One of these is the CENTURY soil organic matter model.

In this study, we evaluate the CENTURY model and investigate what effect different land use and cultivation intensity has on carbon content in soil. The field study was performed in the semi-arid Upper East Region of Ghana, since savannas have large potentials for carbon sequestration. Soil samples were taken in February of 2000, at the surface and at 20 cm depth in uncultivated areas, continuously cultivated fields and in fields with fallow periods. Data regarding climate, soil management and soil properties were gathered and entered into the model. Simulated carbon content was compared with observed carbon content to evaluate the usefulness of the model.

The highest carbon content existed in uncultivated areas, whereas cultivation was found to have a decreasing effect on the carbon content. Fields with fallow periods had lower carbon content than continuously cultivated fields. Manure increased carbon levels, and exerted an important influence over soil organic carbon. The finer soil fractions were correlated with the carbon content in continuously cultivated fields and in uncultivated areas. A significant correlation between observed and simulated carbon content did only exist on fields with fallow periods, where CENTURY overestimated the carbon content with 10%. The conclusion of our results is that simulations with CENTURY, using available data, are not suitable for estimations of carbon content in an environment with this high application of manure, since the model only could estimate true content in one of the three land use classes. The credibility of the correlation between observed and simulated carbon content is reflected by gathered information, by the structure of the model or by a combination of them both.

Keywords: Carbon, CENTURY, simulation, land use, soil texture, savanna, the Kyoto Protocol

SAMMANFATTNING

Som ett svar på den förstärkta växthuseffekten föreslogs vid Kyotokonferensen 1997 en handel med utsläppsrättigheter och åtgärder som reducerar koldioxidhalten i atmosfären. De påvisat ökade halterna av koldioxid i atmosfären har uppmärksammat kolcykeln och visat på behovet av en ökad kunskap om den globala kolcykeln. Detta kan uppnås med hjälp av ekologiska modeller. En av dem är "CENTURY soil organic matter model".

I denna studie utvärderas CENTURY, och påverkan av olika markanvändning och odlingsintensitet på kolinnehållet i jorden undersöks. Fältstudien har utförts i det semiarida Upper East Region i Ghana, emedan savanner har en stor potential för upptag av kol. Jordprover togs i februari år 2000, vid markytan och på 20 cm djup, i obrukade områden, kontinuerligt odlade fält och i fält med trädesperioder. Klimatdata, jordbruksdata och data om jordegenskaper samlades in och användes i modellen. Det simulerade kolinnehållet jämfördes med det observerade för att utvärdera hur användbar modellen är.

Högst kolinnehåll uppvisade obrukade områden, medan odling visade sig ha en minskande effekt på kolinnehållet. Fält med trädesperioder hade ett lägre kolinnehåll än kontinuerligt odlade fält. Gödsel ökade kolhalterna och utövade ett viktigt inflytande över kolinnehållet. De finare kornstorleksfraktionerna var korrelerade med kolinnehållet i kontinuerligt odlade fält och i obrukade områden. En signifikant korrelation mellan observerat och simulerat kolinnehåll påvisades endast i fält med trädesperioder, där det simulerade kolinnehållet var 10% högre än det observerade. Slutsatsen av våra resultat är att CENTURY, med tillgänglig data, inte är tillräckligt bra för uppskattning av kolinnehållet i jorden i denna miljö, där tillförseln av gödsel är hög. Endast en utav de tre markanvändningsklasserna erhöll signifikanta simulerade kolvärden vid jämförelse med observerade kolvärden. Trovärdheten i korrelationen mellan dessa avspeglas i insamlad data, modellens struktur eller en kombination av de båda.

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Medasi!

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1 INTRODUCTION

1.1 Savannas and the Global Carbon Cycle

It is no longer a question whether the global climate will change; rather when, where, and by how much. The 1990's was the warmest decade during the 20th century. Many parts of the world have suffered major heat waves, floods, droughts, and extreme meteorological events. This has led to significant economic losses and loss of life. The incidence of this kind of natural catastrophe is expected to increase in a warmer world, and will severely undermine the goal of sustainable development. Developing countries are the most vulnerable to this trend (Watson, 1999).

At the climate conference in Kyoto, in 1997, 180 governments decided that action was needed to limit greenhouse gas emissions from industrialised countries (Watson, 1999). The observed increase in levels of atmospheric carbon dioxide (~280 ppm in 1800, ~315 ppm in 1957, ~358 ppm in 1994) and the Framework Convention on Climate Change (FCCC) have increased attention on the carbon cycle (Schimel *et al.*, 1996).

Through photosynthesis, plants extract carbon dioxide from the atmosphere. During burning or decomposition most of this carbon dioxide is released to the atmosphere, but some of the carbon compounds are sequestered in the soil. Grassland ecosystems store most of their carbon in soils, where turnover times are relatively long (100-10,000 years). Thus changes in grassland carbon storage have significant and long-term effect on the global carbon cycle (Parton *et al.*, 1995). The net annual flux of carbon from tropical grasslands and savannas is assumed to have been zero before 1800, when European colonisation began. Since that time, carbon flux to the atmosphere has increased due to woodland clearing and cultivation (Scholes & Hall, 1996).

Savannas cover about 11.5% of the earth's land surface. The proportion of savannas makes them a significant repository of the earth's element budget and in the fluxes of atmospheric gaseous. The biodiversity of savannas is high, the perennially dry climate causes extensive annual biomass burning, and the proportion of trees and grass is inherently unstable. Therefore, small changes in climate or land use can have a large impact on biomass and soil properties (Scholes & Hall, 1996). Thus, large losses of topsoil constitute a threat to agriculture. The loss of topsoil has both biophysical and socio-economic causes. Land degradation has accelerated with increasing demographic pressure, land misuse and soil mismanagement, followed by a decline in soil quality, a reduction in above- and belowground biomass production, disruption of the carbon cycle and a reduction in the soil organic carbon pool (Folly, 1997). Savannas lie mostly within the developing world, where population pressure and land use changes will be highest in the next few decades (Scholes & Hall, 1996).

Two of the most discussed methods for limitation of carbon dioxide in the Kyoto Protocol are the International Emissions Trading and the Clean Development Mechanism. Severely eroded lands and overexploited ecosystems, mainly in developing countries, receive a chance to recover ecological balance by selling emission quotas. With help of this income a sustainable land management can be achieved. In order to implement the Protocol definitions, an accounting system, a monitoring system, a reporting system, and inventory guidelines will have to be defined (Watson, 1999). It is necessary to develop cost-effective and accurate methods for measurement and supervision of the soil carbon. The slow turnover of the soil organic carbon (SOC) sink makes it a more secure carbon sequestration mechanism than plant biomass (Lugo & Brown, 1992). Soil organic matter and ecosystem models will play an important role in understanding land management and soil organic carbon sequestration relationships (Post *et al*., 1999).

In recent years, a variety of models have been developed to simulate soil organic matter development. However, there have been few attempts to model dynamics of elemental interaction. Parton *et al*. (1993) developed a model, CENTURY, which simulates the changes in composition of organic matter, availability, and interactions among carbon, nitrogen, sulphur, and phosphorus in soils under different land use systems.

1.2 Aim

The general aims of this study are to assess the usefulness of the CENTURY global carbon model to estimate the actual carbon content in a semi-arid area and to evaluate the variability in carbon content as a function of land use. The objective is to evaluate the value of the model as a tool for estimating carbon sequestration in soil. The study consists of the following examinations:

- Determination of carbon content in field-measured samples
- Simulation of carbon content by use of land management information and data concerning climate and soil properties
- Determination of impact of soil texture and bulk density on observed and simulated carbon content
- Evaluation of the variability in carbon content as a function of cultivation intensity

We will focus on the carbon content in three different land use classes, fields that are continuously cultivated, fields with crop-fallow periods, and uncultivated areas, all at a small scale region. Soil samples were collected over a period of two weeks in February of 2000, which coincided with the dry season.

2 THEORETICAL BACKGROUND

2.1 The Carbon Cycle

2.1.1 The Global Carbon Cycle

The earth contains about 10^{23} g of carbon (C). Most of this carbon is buried in sedimentary rocks, where it is found in organic compounds and carbonates. At times during earth's history when the production of organic carbon by photosynthesis has exceeded its decomposition, organic carbon has accumulated in sediments. Through geologic time, these deposits of organic carbon have accounted for the accumulation of oxygen in the atmosphere. The sum of the active pools near the earth's surface is about 40×10^{18} g C (fig. 2.1) (Schlesinger, 1997).

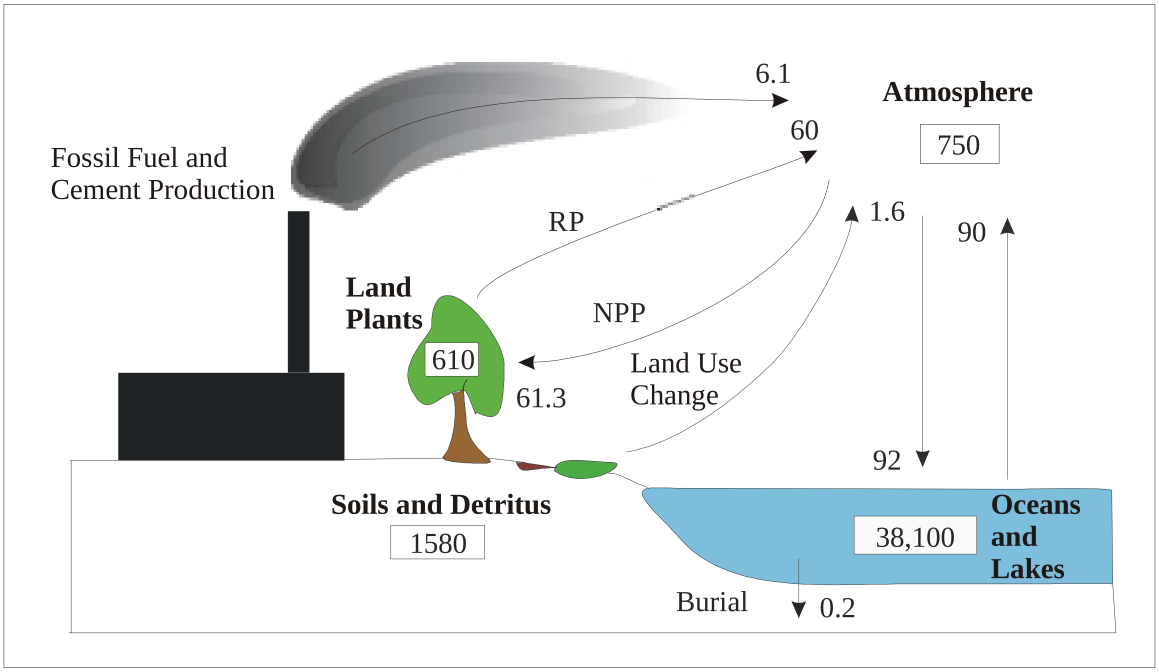

Figure 2.1. *A simplified representation of the global carbon cycle, showing the major pools and fluxes. The numbers in boxes indicate carbon stored in major pools. The numbers by the arrows show the amount of carbon annually flowing by various pathways between the pools. All pools are expressed in units of 10^{15} g C and all annual fluxes in units of 10^{15} g C/year, averaged for the period 1980 to 1989 (values from Ciais et al., 1995; Schimel et al., 1996 & Schlesinger, 1997).*

Dissolved inorganic carbon, which is the largest near-surface pool of carbon, has enormous capacity to buffer changes in the atmosphere. Land ecosystems of the earth contain about 2.2×10^{18} g C, an estimated 0.6×10^{18} g C in vegetation and 1.6×10^{18} g C in soils. The soils of the world contain about three times more organic carbon than is contained in vegetation. However, tropical forests contain more carbon in their vegetation than in their soil (Houghton, 1991). These land carbon stocks are changing in response to changes in area of agricultural land, age structure of forests, climate, and chemistry of the atmosphere and precipitation (Melillo *et al.*, 1996). The current exchange of carbon dioxide (CO_2) between the atmosphere and the biosphere is about 150×10^{15} g C yr^{-1}, so the biosphere is more likely to buffer the rise of carbon dioxide as a result of human activities (Schlesinger, 1997). The annual fossil fuel emission 1992 and 1993 was about 6.1×10^{15} g C (Ciais *et al*., 1995). From this, it can be concluded that the terrestrial biosphere is currently playing a major role in the carbon cycle.

The largest fluxes of the global carbon cycle are those that link atmospheric carbon dioxide to land vegetation and to the sea. At equilibrium, the sea contains about 56 times as much carbon as the atmosphere. The flux of carbon dioxide in each direction between the seas and the atmosphere is in the order of 90×10^{15} g C yr^{-1} (Denman *et al*., 1996). Although terrestrial ecosystems comprise a carbon pool less than a tenth the size of the seas, carbon flux between the earth's land area and the atmosphere is slightly greater than between the seas and the atmosphere (Winjum *et al*., 1992).

Relatively small changes in large pools of carbon can have a dramatic impact on the carbon dioxide content of the atmosphere, especially if they are not balanced by simultaneous changes in other components of the carbon cycle. A 1% increase in the rate of decomposition on land would release nearly 0.6×10^{15} g C yr^{-1} to the atmosphere. Schimel *et al.* (1994) estimate that the soil carbon pool can loose 0.7% of its content (11×10^{15} g C) for every degree of global warming during the 21st century. On the other hand, a 0.2% per year-increment to the biomass of carbon on land, as a result of a greater storage of net primary production, could balance the carbon dioxide budget of the atmosphere (Schlesinger, 1997).

2.1.2 Ecosystem Metabolism

The carbon cycle is of central interest to biogeochemistry. Living tissue is composed primarily of carbon, making estimates of the global production and destruction of organic carbon an overall index of the health of the biosphere, both past and present. The balance between primary production and decomposition determines the overall storage of carbon on land (Schlesinger, 1997).

Each year, about 5% of the land's total carbon stock is exchanged with the atmosphere as a result of plant and soil metabolic activities (Melillo *et al.*, 1996). Green plants and algae use the sun's energy to convert carbon dioxide (and water) into carbohydrates in the process, the photosynthesis:

$$6\,CO_2 + 6\,H_2O \Rightarrow C_6H_{12}O_6 + 6\,O_2 \qquad (1)$$

Through photosynthesis, land plants absorb approximately 120×10^{15} g C yr^{-1} in the form of CO_2 from the atmosphere. Plant tissue typically contains about 45 to 50% carbon. This carbon uptake is approximately balanced by plant and soil respiration, which release carbon as carbon dioxide to the atmosphere (Melillo *et al.*, 1996). The rate of photosynthesis is analogous to the rate of net primary production (NPP). For plants in nature,

$$NPP = GPP - RP \quad (2)$$

where *NPP* is the net primary production in a year. *GPP* is the gross primary production, the amount of carbon absorbed through the process of photosynthesis by the ecosystem's green plants in a year. *RP* is the plant respiration, the amount of carbon released to the atmosphere as CO_2 by the ecosystem (green plants, animals, and micro-organisms) in a year (Schlesinger, 1997; Melillo *et al.*, 1996). NPP, GPP and RP are all measured in g C yr^{-1}.

NPP is a measure of the annual accumulation of organic matter per unit of land. Global NPP on land is estimated to 60×10^{15} g C yr^{-1}. Allocation of NPP varies with vegetation type and age. In grassland communities, essentially all aboveground NPP is found in photosynthetic tissue (Schlesinger, 1997). Water and nutrient availability, vegetation structure, particularly the tree-grass ratio, the plant density and cover, and the amount of standing dead material control the primary production (Scholes & Hall, 1996).

The conversion of forests to agricultural land releases carbon to the atmosphere through burning at the time of deforestation and through decay in the years following. Cleared lands may hold 20-50 times less carbon per unit area than forests (Houghton, 1991). Conversely, the regrowth of forests on abandoned lands withdraws carbon from the atmosphere and stores it again in trees and soil. Carbon is accumulated in young and middle-aged forests, while little if any carbon is accumulated in old-growth forests. Changes in the frequency of fires, insect outbreaks and other disturbances can also alter the age structure of forests and affect their capacity to store carbon. Warming and drought can cause these disturbances (Melillo *et al.*, 1996). The net flux of carbon to the atmosphere from tropical deforestation in 1980 has been estimated to between 0.6 and 2.5 $\times 10^{15}$ g C (Houghton, 1991). Continued forest clearing for agriculture to meet the food needs of a growing human population combined with an expansion and intensification of air-pollution stress on terrestrial ecosystems could further reduce carbon storage on land (Melillo *et al.*, 1996).

2.1.3 Decomposition

Most of the NPP is derived to the soil as dead organic matter (Scholes & Hall, 1996). Soil organic matter contains approximately 58% carbon (Post *et al.*, 1999). In grassland ecosystems, where little of the aboveground production is contained in perennial tissues, the annual litterfall is nearly equal to annual NPP. Most detritus is delivered to the upper layers of the soil where it is decomposed by micro-fauna, bacteria, and fungi (Schlesinger, 1997).

Microbial activity increases exponentially with increasing temperature. Decomposition leads to the release of carbon dioxide, water, and nutrient elements, and to the microbial production of highly resistant organic compounds known as humus (fig. 2.2) (Schlesinger, 1997). Humus compounds accumulate in the lower soil profile and compose the bulk of soil organic matter. The general term soil organic matter (SOM) refers to all the organic components in the soil. These include:

1) Living biomass (intact plant and animal tissues and micro-organisms)
2) Dead roots and other recognisable plant residues
3) A large amorphous and colloidal mixture of complex organic substances no longer identifiable as tissues

Only the third category of organic matter is referred to as humus (Brady & Weil, 1996).

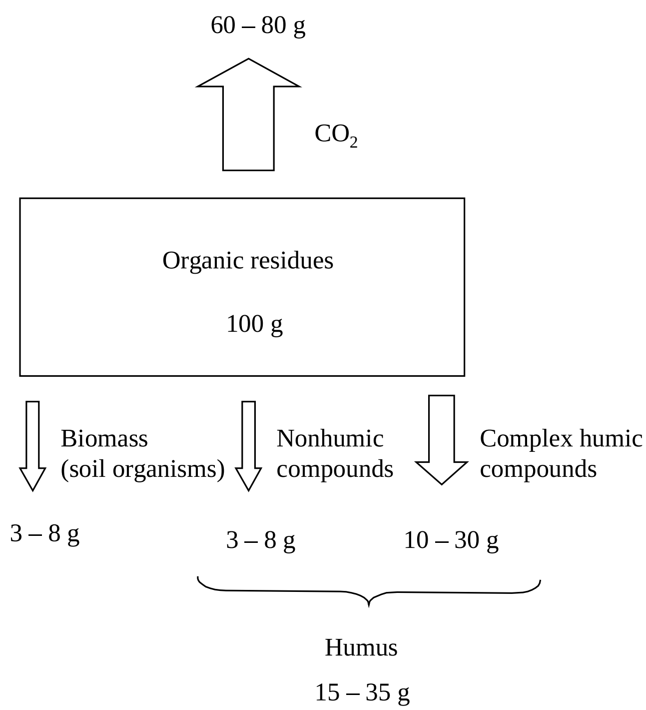

Figure 2.2. *Disposition of 100 g of organic residues one year after they were incorporated into the soil. 60-80 g of the organic residues has been oxidized to carbon dioxide. Less than one-third remains in the soil, some in the cells of soil organisms, but most in humus material. The proportion remaining from root residues (complex humic compounds) tends to be somewhat higher than that remaining from incorporated leaf litter (nonhumic compounds) (Brady & Weil, 1996).*

The structure of humus is poorly understood, but humus contains numerous aromatic rings with phenolic (-OH) and organic acid (-COOH) groups. These radicals offer a major source of cation exchange capacity in many soils (Schlesinger, 1997), the ability to absorb and exchange negative charges on their surface. Humus is capable of absorbing large quantities of water, thus increasing the water holding capacity of the soil, and is therefore important in crop production (Fitzpatrick, 1986). Carbonation weathering occurs in the lower soil profile and is the result of accumulated carbon dioxide in the soil pore space (Schlesinger, 1997).

A global estimate of soil organic matter suggests a mean residence time of about 30 years for the total pool of organic carbon in soils. However, the mean residence time varies between the surface litter and the various humus fractions. The respiration of living roots makes it difficult to use estimates of carbon dioxide flux in calculations of turnover of the soil organic pool (Schlesinger, 1997).

2.1.4 Soil Organic Matter in Savanna Soils

By definition, savannas have 10-50% coverage of woody plants and, in the native state, a well-developed grass layer. Grasslands are defined to have less than 10% tree cover (Scholes & Hall, 1996). The soil carbon stored in savannas and grasslands is an important pool, since it represents a significant proportion of the total system carbon and is stabilised for hundreds to thousands of years (Ojima *et al*., 1993). The range of carbon found in Ghana by Greenland & Nye (1959) was 1680 g C m^{-2} for the drier savanna zones to 5600 g C m^{-2} for the humid savanna zone. For a comparison, tropical rainforests have shown carbon contents ranges from 390 g C m^{-2} to 540 g C m^{-2} (Greenland & Nye, 1959).

Climate and vegetation usually act together to influence the soil content of organic carbon. Primary production in many savannas is low, due to low rainfall and soil fertility, which leads to a low soil organic matter content (Scholes & Hall, 1996). In climate zones where the natural vegetation includes forests and grasslands, the total organic matter is higher in soils developed under grasslands than under forests. The relatively high content of root matter in grasslands decomposes more slowly and contributes more efficiently to soil humus formation than does forest leaf litter. The organic carbon content also decreases less abruptly with depth in grasslands than in forested ones, because of fibrous roots that extend deep into the profile. Since most organic residues are incorporated in, or deposited on the surface, organic matter tends to accumulate in the upper layers. Organic carbon contents are therefore generally much lower in subsurface horizons than those of the surface soil (Brady & Weil, 1996). In grasslands, the soil organic matter is substantially higher beneath tree canopies than between them (Scholes & Walker, 1993).

The organic matter content of comparable soils tends to be higher in cooler climates (Brady & Weil, 1996). The high maximum temperatures in savannas lead to large soil respiration losses, since respiration is exponentially related to temperature. At high soil temperatures, the mineralizing rate is accelerated, which makes nutrient release rapid, whereas residual organic matter is lower than in cooler soils (Scholes & Hall, 1996).

Moreover, soil moisture exerts a major influence on the accumulation of organic matter in soils (Brady & Weil, 1996). The alternation of wetting and drying favours decomposition over production, since soil respiration can continue at water potentials below which primary production has ceased (Scholes & Hall, 1996). The lowest natural levels of SOM are found where annual mean temperature is high and the level of rainfall is low. These relationships have large impact on productivity and conservation of soils and the difficulty of sustainable natural resource management (Brady & Weil, 1996).

While climate and natural vegetation affect SOM over broad geographic areas, soil texture and drainage often give rise to differences in SOM within a local area. The amount of organic matter in soils varies widely; from a mere trace in sandy soils and desert soils, to as high as 20 or 30% in some forested or poorly drained A horizons. The amount of organic residues returned to the soil is generally higher in more fine-textured soils, as the greater nutrient and water-holding capacities of these soils promotes greater plant production. The generally smaller pores of the fine-textured soils may restrict aeration and reduce the rate of organic matter oxidation (Brady & Weil, 1996).

More than half of the savannas and tropical grasslands in the world are situated on extremely old land surfaces. Due to old age the sandy soils are deficient in many nutrients. The small amount of clay is predominant in minerals such as kaolinite, aluminium, and iron oxides. These clays have a small surface area and are low in cation exchange capacity. In addition to the areas of old weathered acidic soils, there are significant areas of basic intrusive and extrusive geology. The basic igneous rocks weather to produce high-activity clays (Scholes & Hall, 1996), such as smectites and allophanes. These soils can store more carbon (Jones, 1973) and they tend to occur on younger land surfaces (Scholes & Hall, 1996). Clay-humus complexes protect organic matter from degradation, which favours the accumulation of organic matter in fine-textured soils (Brady & Weil, 1996).

Many savannas and grasslands experience annual fires. Fires cause a short-term loss of carbon due to direct combustion and indirectly due to changes in microclimate. For one to several years fire-ravaged soils may be warmer and wetter than in unburned state, which may increase the decomposition rate (Ågren *et al*., 1996). Depending on intensity, fire obliterates aboveground vegetation and transfers nutrient content to the soil as ash. This addition of ash leads to changes both in chemical and biological properties of the soil. The increase in available nutrients as a result of ash-fall is usually short-lived, as nutrients are taken up by vegetation or lost by leaching and erosion (Schlesinger, 1997). The long-term consequence of frequent fires may be a reduction in NPP, due to nutrient depletion. Most savanna fires are very patchy and incomplete, due to discontinuous fuel, dissected topography and the variation in temperature between day and night (Houghton, 1991). The fire consumes, even in savannas that experience fires annually, just a small fraction (<20%) of the NPP (Scholes & Walker, 1993).

2.2 Soil Management

2.2.1 Organic Matter in Cultivated Areas

In general, soils in cultivated lands contain much lower levels of organic matter than do comparable soils under natural vegetation (Brady & Weil, 1996). As in native systems, soil carbon pools and fluxes in agro-ecosystems are influenced by carbon inputs (e.g. amount and type of plant residue), climate (e.g. temperature and precipitation), and factors like soil texture, pH, drainage etc. In addition, land use and management strongly influence carbon content in agricultural soils (Cole *et al*., 1993). The balance of carbon in agro-ecosystems depends on plant residues, applied organic materials, respiration, plant removal, and erosion (Brady & Weil, 1996).

Within plant associations, biotic factors, topographic factors, and soil properties regulate the carbon accumulation. In successional ecosystems, there are additional factors that regulate the SOC pool. These include previous land use, elapsed time since abandonment (age), type of vegetation, and rates of organic matter production, both above- and belowground (Lugo & Brown, 1992).

Under natural conditions, when the soil is not disturbed by tillage, most of the organic matter produced by the vegetation is returned to the soil. In contrast, in cultivated areas much of the plant material is removed for human or animal food and relatively less returns to the land. The tillage aerates the soil and breaks up organic material, making it more accessible to microbial decomposition (Brady & Weil, 1996). Losses from many soils are typically 20 to 30% within the first decades of cultivation. The loss is greatest during the first few years of cultivation. Some of the SOM is lost in erosion, but most is probably oxidised to carbon dioxide and released to the atmosphere (Schlesinger, 1997).

The practise of shifting cultivation, in which short periods of cultivation alternate with long periods of fallow, during which forests recover, is common throughout the tropics. Deforestation for shifting cultivation releases less carbon to the atmosphere than deforestation for permanently cleared land because of the partial recovery of the forest (Houghton, 1991).

With about 10% of the world's soils under cultivation, loss of organic matter from agricultural soils has been a major component in the past increase in atmospheric carbon dioxide. The current rate of release from soils, as much as 0.8×10^{15} g C yr^{-1} is largely dependent upon the current rate at which natural ecosystems, especially in the tropics, are being converted to agriculture (Schlesinger, 1997).

2.2.2 Carbon Sequestration

Agricultural soils could be made into a net sink of carbon dioxide. As much as 0.4×10^{15}-0.8×10^{15} grams of carbon could be absorbed by agricultural soils every year through improved management practices designed to increase agricultural productivity (UNFCCC, 2000).

Low-tech strategies for carbon retention include the use of composting and low- or no-tillage practices, since carbon is more easily liberated from soil that is turned over or left bare. In semi-arid areas, the need for summer fallow could be reduced through better water management or by the introduction of perennial forage crops (which would also eliminate the need for tillage) (UNFCCC, 2000). Modern conservation tillage practises can help maintain or restore high surface SOM levels (Brady & Weil, 1996).

Compared to conventional tillage, practices such as stubble mulching and no-till leave a higher proportion of the residues on or near the soil surface. These techniques protect the soil from erosion and also discourage the rapid decomposition of crop residues (Brady & Weil, 1996).

Rotation of several crops results in a higher SOM level than continuous crop growth, because rotation produces more root residues. An addition of fertiliser or manure can help maintain much higher levels of organic matter. Application of fertilisers to previously unfertilised fields increases the organic matter levels, probably due to the production and return of larger amounts of crop residues and the addition of sufficient nitrogen to complement the carbon in humus formation (Brady & Weil, 1996).

The carbon stored in trees, vegetation, soils, and durable wood products can be maximised through "storage management". When secondary forests and degraded lands are protected, they usually regenerate naturally and start to absorb significant amounts of carbon. Their soils can hold additional carbon if they are deliberately enriched, for example with fertilisers, and new trees can be planted. Permitting the trees to both become denser and older increases both the biomass carbon store and the soil organic matter (Brady & Weil, 1996).

An increasing temperature and an increasing atmospheric CO_2 content are to a certain extent believed to have a fertilising effect on vegetation. At a higher temperature, the CO_2 becomes more accessible for the trees and respiration in the soil will accelerate, leading to a higher accessible nutrient content (Morén *et al*., 2000).

Winjum *et al.* (1992) have estimated the mean carbon storage over a 50-year period for reforestation. A reforested area in the boreal region could sequester 3.9×10^{15} g C ha^{-1}. In the temperate region, a reforested area would sequester 5.6×10^{15} g C ha^{-1}, and in the tropical region, 6.5×10^{15} g C ha^{-1} could be sequestered. Increasing forest area was found to be more significant in increasing global forest carbon sequestration than enhancing productivity in existing forest stands and plantations. In summary, promising forest and agro-forest practises could sequester between 50×10^{15} and 100×10^{15} g C over a 50-year period.

2.3 A Changing Climate

2.3.1 The Greenhouse Effect

The principal greenhouse gases are water vapour, carbon dioxide, ozone, methane, nitrous oxide, and the chlorofluorocarbons (CFC's). Apart from CFC's all of these gases occur naturally. Together, they make up less than 1% of the atmosphere. This is enough to produce a "natural greenhouse effect" that keeps the planet 32°C warmer than it would otherwise be. Levels of all key greenhouse gases (with the possible exception of water vapour) are rising as a direct result of human activity. The climate system must adjust to rising greenhouse gas levels to keep the global "energy budget" in balance. Since a thicker blanket of greenhouse gases helps to reduce energy loss to space, the climate must change somehow to restore the balance between incoming and outgoing energy. This adjustment will include a "global warming", an enhanced greenhouse effect, of the earth's surface and lower atmosphere. Even a small rise in temperature will be accompanied by many other climatic changes, in cloud cover and wind patterns (UNFCCC, 2000).

2.3.2 Atmospheric Carbon Dioxide Levels

CO_2 is currently causing over 60% of the enhanced greenhouse effect. Current annual emissions amount to over 7×10^{18} g of carbon, or almost 1% of the total mass of carbon dioxide in the atmosphere. Atmospheric carbon dioxide levels appear to have varied by less than 10% during the 10,000 years before industrialisation (UNFCCC, 2000). In the pre-industrial era, the level of CO_2 in the atmosphere was about 280 ppm, but has today reached levels above 350 ppm. About half of that increase has taken place since 1960 (Alexander, 1996). Fossil fuel burning and cement manufacture transfers carbon, mainly as carbon dioxide, to the atmosphere (Schimel *et al.*, 1996). Even with half of humanity's carbon dioxide emissions being absorbed by the seas and land vegetation, atmospheric levels continue to rise by over 10% every 20 years (UNFCCC, 2000).

2.3.3 Emissions in the Future

Climate models predict that the global average temperature will rise by about 2°C by the year 2100 if current emission trends continue. This projection uses 1990 as a baseline. It also takes into account climate feedback and the effects of sulphate aerosols, as they are presently understood. Nevertheless, there are still many uncertainties, current estimations of how much the earth will warm during the 21st century range from 1 to 3.5°C. The climate does not respond immediately to emissions. It will therefore continue to change for many years even if greenhouse gas emissions are reduced and atmospheric levels stop rising. It is still too early to predict the size and timing of climate change in specific regions. Current climate models are only able to predict patterns of change at the continental scale. Predicting how climate change will affect the weather in a particular region is much more difficult. Thus the practical consequences of “global warming” for individual countries or regions remain very uncertain (UNFCCC, 2000).

2.3.4 International Efforts to Reduce the Effects of a Climate Change

Scientists need to improve their understanding of the extent of the climate change, the timing and the impacts. However, what is already known alerts us to dramatic consequences to human health, food security, economic activity, water resources and physical infrastructure. In response to the warnings of scientists, governments launched negotiations on a global treaty to address the problem and the United Nations Framework Convention on Climate Change was adopted. The objective was to stabilise atmospheric concentrations of greenhouse gases at safe levels, achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change. The Convention was opened for signature at the Earth Summit in Rio de Janeiro, Brazil, on 4 June 1992, and came into force on 21 March 1994. Today, some 180 governments have ratified the treaty. They meet regularly at the annual Conference of the Parties (COP) to review the implementation of the Convention and continue talks on how best to tackle climate change. After two years of intense negotiations, the Kyoto Protocol was adopted on 11 December 1997 (UNFCCC, 2000).

2.3.5 The Kyoto Protocol

The Kyoto Protocol commits the industrialised countries, who have contributed the most to climate change, to individual, legally-binding targets to reduce their greenhouse gas emissions during the period 2008-2012, adding up to a total cut of at least 5% from 1990 levels. The targets cover the six main greenhouse gases, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC's), perfluorocarbons (PFC's) and sulphurhexafluoride (SF_6). In addition, the Protocol commits the signatures to changes in land use and forestry that will contribute to reduce carbon dioxide in the atmosphere (UNFCCC, 2000).

The Protocol also established International Emissions Trading and the Clean Development Mechanism, which are designed to help the industrialised countries to reduce the costs of meeting their emissions targets (UNFCCC, 2000).

The International Emissions Trading permits one country to take advantage of reductions in emissions made in another country. Before actual trading can start the Climate Convention must take decisions regarding trading regulations. The Protocol states that trading mechanisms are supposed to complement national measures, to reach cost effectiveness but not to avoid undertakings. Trading should be possible between countries with emission undertakings. This means that a country that has decreased its emissions below prescribed limits, can sell its surplus to a country with greater difficulties achieving emission reductions (MDEP, 2000).

The aim of the Clean Development Mechanism is similar to that of International Emissions Trading, but differs in the way in which projects will be implemented in developing countries. The purpose of this mechanism is to permit credit for investments in developing countries that limit emissions or increase the sequestration of greenhouse gases from year 2000 (Törnqvist, 1999). The Clean Development Mechanism will also promote sustainable development in developing countries (MDEP, 1999).

Between 16 March 1998 and 15 March 1999, 84 countries signed the Kyoto Protocol. In order to enter into force, 55 Parties (including the industrialised countries) must now ratify the Protocol. The Protocol can then enter into force around 2002. Parties must develop the framework compliance system outlined in the Protocol, and further work is needed on provisions for the land use change and forestry sector, reporting obligations, and vulnerability of developing countries to climate change and to mitigation measures (UNFCCC, 2000).

The German Advisory Council on Global Change (WBGU) has assessed the Kyoto Protocol with respect to the accounting for biological sources and sinks. The Council considers the land use changes and forestry activities, accounted in the Kyoto Protocol, to be insufficient and in need of improvement. It argues that the present approach can lead to negative impacts upon climate protection, biodiversity conservation and soil protection. Furthermore, the commitment period over five years to changes in carbon stocks, fails to comprehend the dynamics of carbon stocks and fluxes (WBGU, 1998).

Since 1998, Sweden, together with other countries and companies, has been part of a project initiated by the World Bank. The intention is to construct a prototype for an international climate fund with the aim of mitigating effects on the climate in developed as well as developing countries. One of the aims of the fund is to implement projects to serve as a basis for crediting the decisions about the Clean Development Mechanism. On 25 March 1999 the Swedish government decided to investigate the use of the Clean Development Mechanism in the Kyoto Protocol. It is urgent for Sweden to continue being a part in this work with the objective of a Swedish participation in the fund if and when it is established (Törnqvist, 1999).

3 THE CENTURY MODEL

3.1 Introduction to the CENTURY model

The CENTURY computer model was developed into its present form (Version 4.0) in 1993, as a project of the U.S. National Science Foundation Ecosystem Studies Research Project to measure grassland productivity and nutrient status. The primary purposes of the model are to provide a tool for ecosystem analysis, including grasslands, agricultural lands, forests and savannas, to test the consistency of data and to evaluate the effects of changes in management and climate on ecosystems (Metherell *et al*., 1993). The model can be downloaded at http://www.nrel.colostate.edu/PROGRAMS/MODELING/ CENTURY/CENTURY.html.

A variety of different models have been used to estimate long-term changes in soil organic nitrogen and carbon. Since 1941, when one of the first models was used, many improvements have been made. CENTURY incorporates multiple SOM variables, simulates decomposition rates that vary as a function of monthly soil temperature and precipitation, and includes both nitrogen and carbon flows. Several research groups have parameterised and successfully validated the model by comparing simulated nitrogen and carbon and aboveground plant production to mapped values (Parton *et al*., 1987).

CENTURY is composed of a SOM/decomposition submodel, a water budget model, a grassland/crop submodel, and a forest production submodel. The plant production submodels are linked to the common SOM submodel, with grasses and trees both included under CENTURY's savanna option (Parton *et al*., 1987). The model computes the flow of carbon, nitrogen, phosphorus, and sulphur through its compartments. CENTURY runs using a monthly time step 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 sulphur content
- Lignin content of plant material
- Atmospheric and soil nitrogen inputs
- Initial soil carbon, nitrogen (phosphorus and sulphur optional) levels

3.2 Input Data Used by the Submodels

3.2.1 Soil Organic Matter and Decomposition Submodel

The soil organic matter submodel contains three SOM fractions. These consist of an active fraction (active SOM) of soil carbon and nitrogen, along with soil organic matter with a short turnover time (1-5 years). The fractions also contain a pool of carbon and nitrogen (slow SOM) that is physically protected and/or in chemical forms with more biological resistance to decomposition, with an intermediate turnover time (20-40 year). The last fraction is a fraction that is chemically recalcitrant (passive SOM) and that may also be physically protected, with the longest turnover time (200-1500 year). Decomposition of each of the state variables is calculated using the following equation:

$$\frac{dC_i}{dt} = K_i \cdot M_d \cdot T_d \cdot C_i \tag{3}$$

C_i is the carbon in the state variable and i represents a value of 1 (structural soil surface litter), 2 (metabolic soil surface litter), 3 (structural soil litter), 4 (metabolic soil litter), 5 (active soil fraction), 6 (slow soil fraction), or 7 (passive soil fraction). K_i is the maximum decomposition rate parameter (per week) for the i^{th} state variable (K_i = 0.076, 0.28, 0.094, 0.35, 0.14, 0.0038, and 0.00013). M_d is the effect of the ratio of monthly precipitation to potential evapotranspiration rate on decomposition. T_d is the effect of monthly average soil temperature on decomposition (Parton *et al*., 1993).

The model assumes that all carbon decomposition flows are associated with microbial activity and that microbial respiration occurs for each of these flows. The formation of passive SOM is a function of clay content (higher for clay soils) and is primarily controlled by the stabilisation of active SOM in micro-aggregates. Some passive SOM is also created by the decomposition of slow SOM, and includes a similar effect of clay. The active SOM decay rate changes as a function of the soil silt plus clay content (low values for high silt and clay soils) (Parton *et al*., 1989). Leaching of soluble organic matter of the soil is calculated as a function of the decay rate for active SOM, the sand content, and water flow (Parton *et al*., 1993).

3.2.2 Biophysical Submodels

The CENTURY model includes a simplified water budget model. The potential evapotranspiration rate is calculated as a function of the average maximum and minimum air temperature. Monthly precipitation is used for calculations of bare soil water loss, interception water loss, and transpiration water loss. The field capacity and wilting point for different soil layers is calculated as a function of the bulk density, soil texture, and organic matter content. Average monthly soil temperature near the soil surface uses the information about maximum and minimum air temperature and canopy biomass (Parton *et al*., 1993).

3.2.3 Plant Production Submodel

The grassland submodel simulates grass growth and includes the impact of grazing and fire on plant production. The impact of fire is to increase the root/shoot ratio, and to increase the C:N ratio of live shoots, removing vegetation and returning inorganic nutrients. Grazing removes vegetation, returns nutrients to the soil (by urination and defecation), alters the root/shoot ratio and increases the nitrogen content of live shoots and roots (Parton *et al*., 1993).

3.3 Description of the CENTURY Environment

The CENTURY model obtains input values through different data files, with each containing a certain subset of variables; for example values related to cultivation, fertilisation, fire, grazing, harvest and irrigation (fig. 3.1). Within these files there may be multiple options in which the variables are defined for multiple variations of the event. For example, within the grazing file, there may be several grazing options defined, such as fraction of standing dead removed by a grazing event or effect of grazing on production. For each option, the variables are defined to simulate that particular option. The data input file for each site can be updated with site-specific parameters such as precipitation, soil texture, and the initial conditions for soil organic matter. The timing variables and schedule of when events are to occur during the simulations are maintained in the schedule file (Metherell *et al*., 1993).

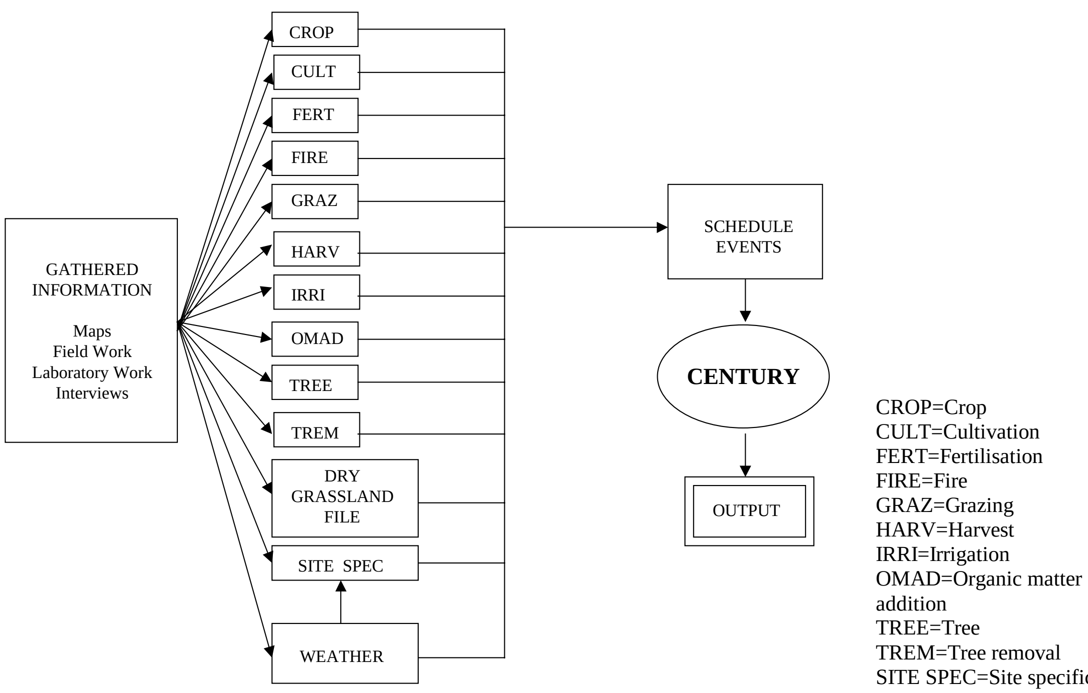

Figure 3.1. *The CENTURY model environment (simplified) showing the relationship between gathered information, files and the CENTURY program. Parameters in OMAD and TREM were not used in the simulations of this study (modified from Metherell et al., 1993).*

4 METHOD

4.1 Study Area

The fieldwork for this study took place in Ghana, a West African state, bordering Ivory Coast, Burkina Faso, Togo and the Atlantic Ocean (fig. 4.1). The actual study area is part of the Upper East Region, in the north-eastern corner of Ghana, at about 11°00’N and 00°15’E. The regional capital in the Upper East Region is Bolgatanga. The biggest town in the region, Bawku, with a population of about 34,000 inhabitants is located east of Bolgatanga. During colonial times the British built up Bawku, and made it a major trading centre. Bawku is located at a major cross road, close to the borders of Burkina Faso and Togo (Dickson & Benneh, 1988). In Manga, a small village close to Bawku, SARI (Savanna Agricultural Research Institute) has one of its offices. SARI serves as an educational institution for the farmers and teaches about measures to improve the productivity, keep up the soil quality and about different cultivation methods.

Figure 4.1. *Upper East Region is located in the northeastern Ghana. The inserted map shows Ghana’s location in Africa (modified from Africa Maps).*

4.1.1 Climate

The climate in Ghana is controlled primary by the tropical continental air mass and the tropical maritime air mass (Dickson & Benneh, 1988). The distinct seasons are results of the movement of the Inter-Tropical Convergence Zone (ITCZ) separating these two air masses (Folly, 1997). Dominating from November to February, when ITCZ is at its southern position, is the tropical continental air mass, with dry and cool winds. This air mass carries a significant volume of sand particles from the Sahara Desert. This desert wind, the Harmattan, which is especially noticeable in the north, makes the sky hazy and has a decreasing effect on the temperature. The dryness of the air prevents the formation of clouds, making the day temperatures high and the night temperature low, thereby creating a large temperature range (Dickson & Benneh, 1988).

ITCZ moves towards the north by the end of February and reaches its northernmost position by the end of August. This is accompanied by a period dominated by the tropical maritime air mass (Folly, 1997). The tropical maritime air mass has a higher temperature, but contains more water. As a consequence of more cloud formations, the days are cooler and the nights warmer, creating a smaller temperature range. This air mass has a larger influence on the climate from March to October and the south is more affected than the north (Dickson & Benneh, 1988).

The Upper East Region has a tropical continental or interior savanna climate, mostly influenced by the tropical continental air mass. The movement of the ITCZ results in two rainy seasons in the southern part of the country but only one in the north, lasting from May to October. As a result the north receives less rain than the south. The study area receives about 1000 millimetres a year (Dickson & Benneh, 1988) Precipitation, in monthly totals, gradually increases during the rainy season and then falls sharply (fig. 4.2). Considerable variations exist between successive rainy seasons in time of onset, duration and amount of precipitation (Adu, 1969). The humidity is high during the rainy season but very low, about 20%, during the dry season (Dickson & Benneh, 1988).

Since Ghana is situated near the equator and affected by warm air masses, the mean annual temperature is rather high, approximately 25°C. Local temperature is dependent on distance to the sea, where a larger distance equals a larger temperature range (Dickson & Benneh, 1988). Mean annual temperatures vary little from year to year (Adu, 1969). In Manga, situated in the Upper East Region, the highest average temperatures occur in March to April (fig. 4.2).

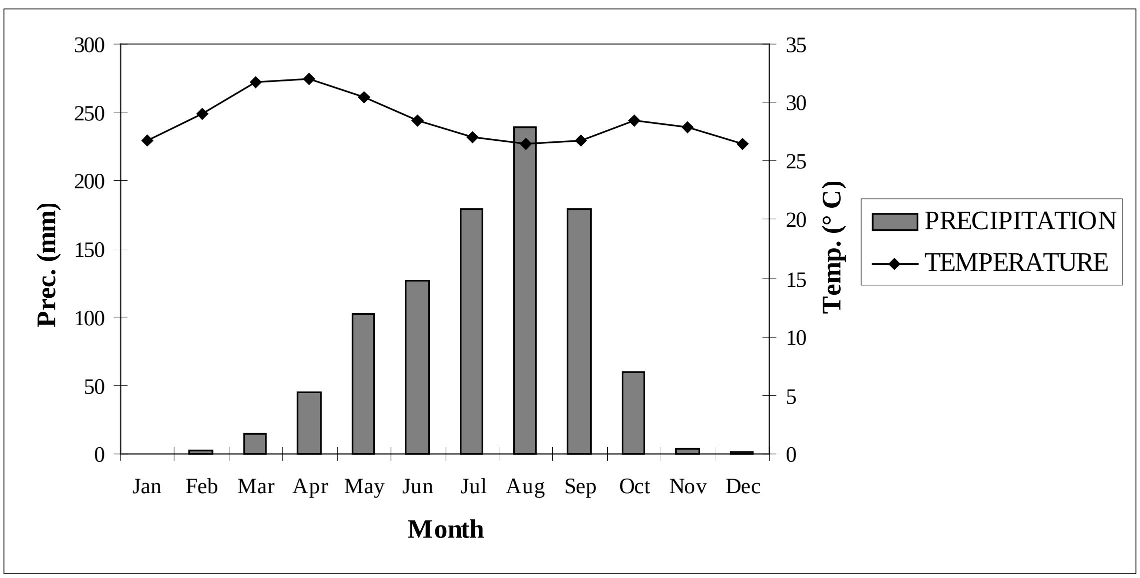

Figure 4.2. *Precipitation and temperature, in mean monthly values, measured at Manga climate station, 1961-1999 (GMSD, 2000).*

4.1.2 Geomorphology and Geology

The Upper East Region belongs to the savanna high plains consisting mostly of granites and Birrimian rocks. The land surface has levelled into erosion-plateaux or tropical pediplains through chemical and physical weathering (Olsson, 1992). The surface is today quite flat with slopes less than 2%. The whole study area lies about 300 meters above sea level. Only a few hills exist, rising 100 to 150 meters above the plateaux (Folly, 1997).

Ghana has a few large rivers, with the Volta river dominating in the north. The Volta river comes from Burkina Faso and flows to the Atlantic Ocean. All the streams in the study area are tributaries of the Volta system. The rivers are flooded during the rainy season. Only the main river is permanent throughout the year (Dickson & Benneh, 1988).

4.1.3 Soils

The type of soil in an area depends on the age of the soil, the underlying rock type, relief, slope, climate and vegetation. High temperatures and much precipitation increase the amount of weathering and thereby the depth of weathered material. These climatic conditions also affect the decay rate of vegetation, affecting the soil by being a source of minerals, and replacing nutrients lost by leaching. Vegetation also prevents or at least reduces much of the soil erosion (Dickson & Benneh, 1988).

General Characteristics of the Soils in the Upper East Region

The soils of the Upper East Region are generally coarse textured and have a low accumulation of organic matter and low fertility, due to the rapid decomposition and frequent burning of the lands. The soils also have low nitrogen content (Folly, 1997). The extreme shifts between dry and wet conditions in the Upper East Region cause intense leaching of nutrients out of the topsoils. The lower nutrient status and the lack of water decrease potential productivity. The moisture can also lead to a hardening of the subsoils resulting in the development of iron-pan, also known as laterite (Adu, 1969). When soil is exposed to the sun, this can be a permanent condition. Laterite is prone to weathering and is a non-productive soil that quickly becomes incapable of sustaining plant growth if vegetation is removed or burned (Plummer & McGeary, 1996).

The Effect of the Harmattan

Much of the topsoil in the study area consists of aeolic deposits, caused by the Harmattan. Some positive effects are higher base-saturation, increased cation exchange capacity, higher pH-values and higher content of organic matter and plant-available phosphorous. The most negative effect due to the high content of fine material (fine silt) is a reduced infiltration capacity. According to Olsson (1992) the positive effects outweigh the negative and this phenomenon is an advantage to crop production. Figure 4.3 shows the effect of Harmattan.

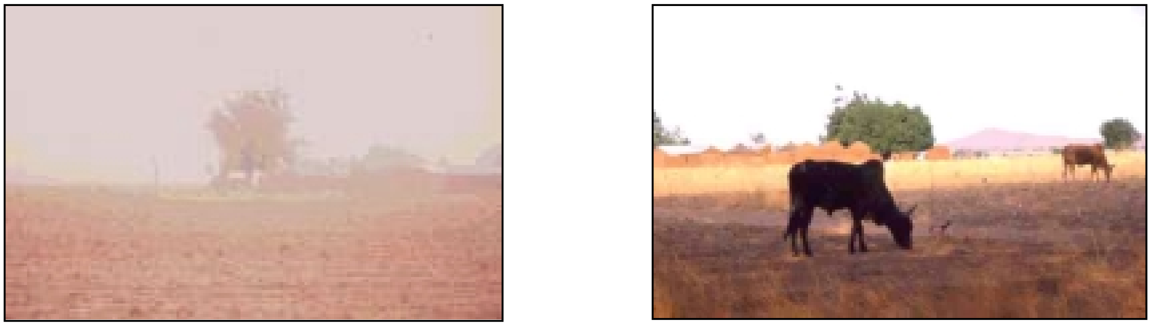

Figure 4.3. *The Harmattan makes the sky hazy during December, January and February and brings fine particles from deserts in the North (the photo to the left). The photo to the right was taken on a clear day during the dry season.*

Soil Erosion Problems

Due to the population pressure and intense cultivation, the Upper East Region suffers from enormous rates of soil erosion. Increased cultivation has contributed to less vegetation cover, which, without proper management, increases the risk of erosion. The precipitation pattern, with heavy rains on a very dry and unprotected soil, makes the situation worse. The intensity in the rains increases the sheet and gully erosion. Another danger is the increasing use of tractors (Dickson & Benneh, 1988), although this was not yet a problem in the study area at the time of the study. A significant reduction in soil depth has been observed. This reduction varies between the soil types but is especially high for the Tanchera soil series. These soils have a low suitability for agriculture due to their low capacity to retain moisture and low nutrient content (Folly, 1997). The amount of organic matter present in the soil probably has an effect on aggregate stability, for aggregates smaller than 2 mm. Because of their low organic matter content, all the soil types in the area are considered to be sensitive for erosion (Folly, 1993).

Through soil erosion, nutrients and organic matter are removed, thereby affecting soil fertility and agricultural production capacity. Both physical and socio-economic factors affect the soil erosion rate. An example is the increased population pressure, with outcome such as increased need for grazing areas and fuel wood. Other factors affecting soil erosion are traditions, perception, land ownership, profit-maximisation and legislation. Physical factors affecting soil erosion are conservation measures, type and magnitude of the vegetation cover and the soil's susceptibility to erosion. The soil's susceptibility to erosion is dependent on physical and chemical characteristics of the soil, which are influenced by the farming practices. A few attempts have been made to limit erosion in the Upper East Region but measures to prevent erosion are not widespread in the region (Folly, 1997).

Varempere-tafali, Tanchera and Dorimon-pu Soil Type

In the study area the main soil type was, according to the Ghanaian classification system, Varempere-tafali. The Varempere association is developed over biotite granites, which are weathered to great depths. The sub-strata usually consist of fine incompletely weathered black mica and feldspar (Adu, 1969). Varempere association consists of shallow soils in the summits and moderately deep soils with a colluvial accumulation on the middle slopes. Since the study area is very flat this soil is here relatively deep with colluvial accumulation of several centimetres of decomposed parent material. The Tafali topsoil consists of sandy loam or loamy sand surface soil to an average depth of 5.5 m and is grey brown or brown in colour. The layer below contains more clay and is more reddish. While the mean clay content in the A-horizon is 6 to 10% (to a depth of 3.7 to 5.5 m), it increases greatly in the B-horizon, where it is about 20 to 40% clay. This means that the B-horizon has a comparatively high water retention capacity. The Tafali soil is underlain by quartz gravel and stones, iron concretions and iron-pans (FAO, 1967). The Tafali soil has normally been used for cultivation. Since it is rather sandy the water capacity is low, but the soil is still suitable for cultivation. However, the soil is easily eroded, resulting in problems when proper conservation measures are not implemented (Adu, 1969).

Another wide spread soil type was Tanchera. The Tanchera series, like Varempere-tafali, is easily cultivated but has the same erosion problems. Other problems include a low nutrient content, lower water holding capacity and lower organic matter level, in comparison to Varempere-tafali (Adu, 1969). The Tanchera association is derived from hornblende granites and has a rather coarse textured A-horizon with concretions and quartz particles in the poorly drained B-horizon. The colour of the surface soil is dark brown or grey brown. The soil consists of coarse loamy sand with 3 to 5% clay, which increases to about 20% below 0.6 m (FAO, 1967).

Dorimon-pu differs from the other soil types by being developed over Birrimian rocks instead of granite. This soil type is unsuitable for agriculture, and these land areas are often used for grazing or planting of forest for fuel wood (Adu, 1969).

According to the American classification system (according to U.S.D.A. 7th Approximation in 1960), both Varempere-tafali and Tanchera are Oxisols, and according to FAO reddish brown lateritic soils. Dorimon-pu on the other hand belongs to the Entisols in the American classification system and rock and rock debris and Lithosols in the FAO system (Adu, 1969).

4.1.4 Land Use

Vegetation

In the Upper East Region the native vegetation was more dense than today (Dickson & Benneh, 1988). The primordial vegetation is classified as Sudanese savanna, which consists of widely spaced short deciduous trees with a ground flora composed of different species of grasses of varying height (fig. 4.4). This original form does not exist in many places. On the contrary, many areas today consist of degraded tree-savanna with fire-resistant trees. This is the result of overpopulation, long settlement and the regular fires that are part of the cultivation method practised in the area (Adu, 1969). The intensive cultivation consists of clearing and burning of land and keeping of grazing livestock. The resulting vegetation is comprised of shorter grasses and a few fire-resistant trees (Dickson

& Benneh, 1988). In our study area, trees were growing in a few areas, while the rest was cultivated with differing intensity. The land in the study area was cultivated annually through intense farming. The native areas were used for grazing by livestock.

Figure 4.4. *Sudanese savanna consists of widely spaced short deciduous tress with a ground flora composed of different species of grasses of varying height.*

Cultivation

In the Upper East Region about 90% of the population are engaged in cattle rearing and crop farming. All land possible is used for cultivation (Dickson & Benneh, 1988). Most farmers have very small fields (fig. 4.5). The average farmer has approximately 1 hectare, according to an investigation in 1992 (Ministry of Agriculture, 2000). The huge population pressure has resulted in continuous cultivation in a compound farming system (Dickson & Benneh, 1988) compared to the shifting cultivation system that used to exist.

Figure 4.5. *The most common farming system is compound farming, where the fields are situated around the compound.*

Fire is common before cultivation to prepare for new crops (Ministry of Agriculture, 2000). On the fields closest to the compound, farmers grow crops such as early and late millet (*Pennisetum americanum* (Abbiw, 1990)), sorghum (*Sorghum bicolour* (FAO, 2000)), bambara beans, cowpea (*Vigna uniguiculata* (Abbiw, 1990)) (Madsen &

Flemming, 1991) and vegetables. Intercropping is the most common cultivation system, i.e. the growing of different crops together on the same fields. Millet, sorghum and cowpea grow in the same plot in a mixture over the fields. Because of the low soil quality most of the crops need fertilisers. Early millet and sorghum need manure, while late millet and groundnut (*Arachis hypogaea* (Abbiw, 1990)) can manage with a smaller amount of manure. Early millet is harvested in July-August, late millet in October and sorghum in the period between early and late millet. Vegetables are harvested continuously when needed (Ministry of Agriculture, 2000).

Difficulties with cultivation consist of soil erosion, water supplies and remoteness from the roads (Dickson & Benneh, 1988). The erosion risk is generally high in the densely populated Upper East Region since the permanent cultivation constantly exposes the soil. Of great importance is the implementation of methods, which enables the incorporation of short fallow periods and soil conservation measures. Development of the farming system is crucial for improving the living standards in the Upper East Region since a large part of the population is rural (Olsson, 1990). Very few cash crops are cultivated. The crop is utilised almost completely for family needs (Madsen & Flemming, 1991).

Fertilisation

Essential for the yield is the use of fertilisers. Since chemical fertilisers are too expensive for a majority of farmers, the principle fertiliser is manure. The manure is mainly collected from the compound, where the animals are kept during night. During the days the animals graze large remote areas, complicating the collecting of the manure. Typically, the fields are situated around the compound and fertilised with manure and compost from the household. The fields closest to the compound generally have a higher labour and manure input. The manure is spread on the fields before sowing, but the amount of manure decreases with increasing distance to the compound (Madsen & Flemming, 1991). Shifting cultivation is still practised on the fields further away. Less manure, or none, is spread on these fields due to the larger labour input this would demand, and because of lack of manure. Instead of manure the fallow periods and the burning of the fields restore the nutrient status in these fields (Olsson, 1990).

Water Availability and Other Limiting Factors

Since there is only one rainy season the crop has to complete its lifecycle within this period of the year. This reduces the number of possible crops. Millet and guinea corn take only two to three months to mature and are therefore suitable. It may even be possible to cultivate both early and late millet, depending on the rainy season being early or late (Dickson & Benneh, 1988).

Irrigation is not common in Ghana. Since irrigation often is not an option the farmers become completely dependent on the precipitation and have to adjust their farming patterns after the rain periods (Dickson & Benneh, 1988).

The amount of available water is the primary limiting factor for food production. Effects of water deficit are drought and increased erosion problems. Another effect is psychological. The aridity is so pronounced that farmers think it is unnecessary to invest in other productivity enhancing measures like fertilisers. An investment in fertilisers is seen as a risk since lacking precipitation may prevent a high yield that year anyway (Bøgh, 1991).

Livestock
Cattle serve as the economic guarantee for the household (Madsen & Flemming, 1991). Livestock such as sheep, goat, guinea fowl, chicken and cattle exist in each village. In the non-Muslim area pigs too are held. In the north the number of livestock determines the wealth of a person. Problems associated with keeping livestock are lack of drinking water, grazing areas, food for the animals during dry season, diseases, and overstocking. People favour the quantity of animals rather than the quality. Overstocking and overgrazing increase the problem of soil erosion (Dickson & Benneh, 1988).

4.1.5 Population

According to the 1984 census, the population in Ghana was 12.2 million people (Dickson & Benneh, 1988). In 1995, the population had increased to 17.5 million people (Holmertz, 1996). The Upper East Region is one of the most densely populated areas in the country (Dickson & Benneh, 1988). The population density within the study area, excluding the mountain areas, amounts to about 200 persons per square kilometre (Ministry of Agriculture, 2000). The history of trading attracts many immigrants from neighbouring areas and countries (Dickson & Benneh, 1988). The annual population increase is approximately 3.1% (Utrikespolitiska institutet, 1996). The ratio between the number of females and males is rather constant, but the population pyramid has, like so many other developing countries, a relatively broad base, i.e. about 40% of the population is between the age of 15 and 44. The rural population is larger than the urban population. The Upper East Region is not more suitable for farming than the rest of the country, but is heavily used for cultivation because of the population pressure (Dickson & Benneh, 1988).

4.2 Field Work

4.2.1 Soil Sampling Theory

In this study, soil samples were taken within three different kinds of areas, called classes I, II, and III. Location of these classes in the Upper East Region is shown in figure 4.6. These choices were based on a population density map in Benneh & Agyepong (1990) and a map in Adu (1969) with the distribution of sheep and cattle. Digital maps of land use, elevation, geology and soil type from *Country At a Glance* CD-ROM produced by EPA (1999) were also used. The samples in class I were taken in an area with a population of 161-200 persons per square kilometre that is cultivated annually (App. I). The soil type in the area is, according to Ghana classification system, Varempere-tafali (App. I). The samples in class II were taken in forest reserves or small areas where no cultivation occurs and where trees and grasses are growing (App. I). Since there are people living in or near all sample areas, some grazing in all areas must be assumed to occur. The samples in class III were taken in areas that are cultivated but still have some fallow periods (App. I). Since such areas could not be found within the same soil type as classes I and II, due to the high population pressure in this area, these samples were taken in an area with the soil type Tanchera. This area has a lower population density, compared to the areas of classes I and II, with between 41-80 persons per square kilometre (Benneh & Agyepong (1990). Descriptions of the three classes are presented in table 4.1 and the characteristics for every site in Appendix II.

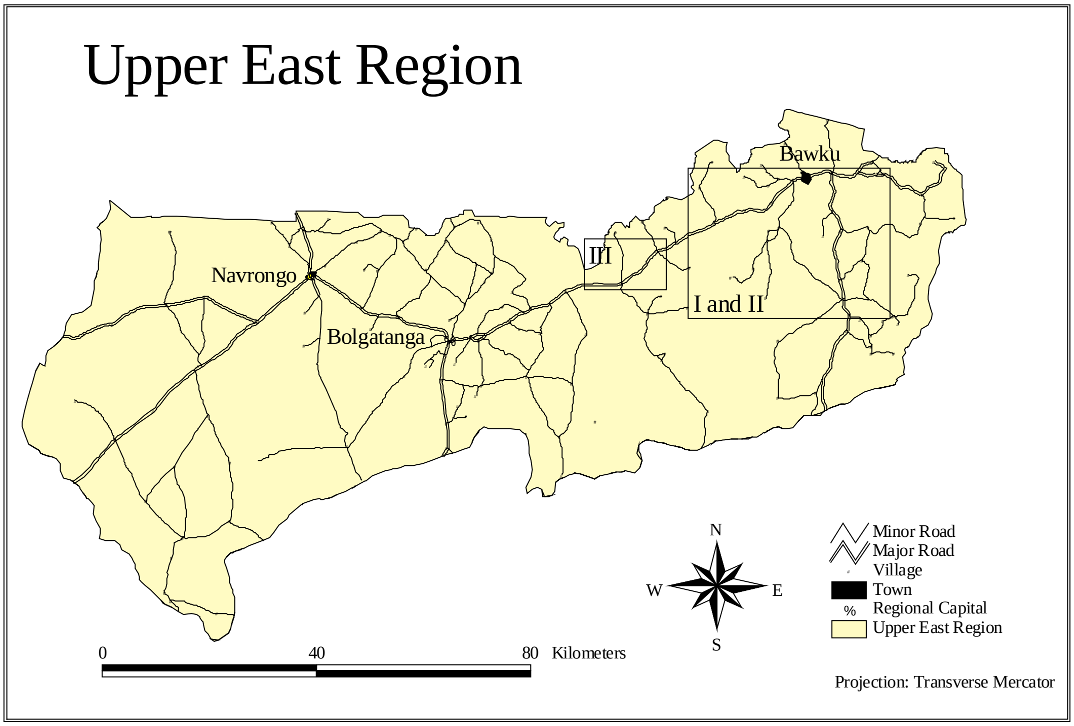

Figure 4.6. *Location of the soil sampling areas, in the Upper East Region, marked with the classes taken within each area (EPA, 1999).*

Table 4.1. *The only differing factor between classes I and II is the land use, whereas class III differ from classes I and II in land use, soil type, population and livestock density (Adu, 1969; Dickson & Benneh, 1988; EPA, 1999). (Cont.=continuous, m.a.s.=metre above sea level)*

Class	**Land use**	**Soil type**	**Geology**	**Elevation (m.a.s.)**	**Population ((100 ha)$^{-1}$)**	**Cattle ((100 ha)$^{-1}$)**	**Sheep ((100 ha)$^{-1}$)**
I	Cont. cultivation	Varempere-tafali	Granite	200-250	161-200	13	7
II	Uncultivated areas	Varempere-tafali	Granite	200-250	161-200	13	7
III	Crop-fallow	Tanchera	Granite	200-250	41-80	16	6

Within each class the parameters were as homogenous as possible. This was mainly achieved by choosing sites situated close together, making the climatic conditions more similar. The suitable areas were chosen according to all of the criteria above, and within these areas the sites were chosen randomly.

Wilding & Drees (1983), suggest an unrealistic large number of samples for estimating the mean within ±10% at the 95% confidence level. In order to detect a change of 2 to 3% in SOM, more than a hundred samples are needed, while a more limited number of samples, thirty samples, can demonstrate a minimal detectable change of about 8×10^{-6} g C m^{-2} (Garten & Wullschleger, 1999). The SOM dynamics in CENTURY is only simulated in one layer, 0-20 cm depth (Metherell *et al.*, 1993). In the study, thirty different sites were sampled in each of the three classes. This kind of carbon sampling is usually done through taking one sub-sample at the surface and one at 20 cm depth, at each site (Ardö, 2000).

In order to derive as accurate results as possible, samples for bulk density and soil texture were taken for the carbon evaluation. These soil properties, together with climatic factors, influence the soil carbon (Cole *et al.*,1993). The positions for these samples were spread to cover the different areas within each class. Bulk density is the density of undisturbed soil, which is the weight of a dry block of soil divided by the volume of the block when sampled. It takes into account the density of the soil materials themselves and their arrangement or structure. Therefore a loose porous soil will have a smaller bulk density than a compact soil even though the density of the individual particles in the two soils may be the same (Fitzpatrick, 1986). The water content was measured in all of the sample since soil moisture influence the accumulation of organic matter (Brady & Weil, 1996).

4.2.2 Soil Sampling Method

Soil samples were taken, at surface and at 20 cm depth (fig. 4.7), at different sites around Bawku during February of 2000. To prevent any effects from trees the samples were taken as far away as possible from surrounding trees, with at least a distance of two canopy radius, demanded by the CENTURY model. Before taking the surface sample, materials like grass, branches, leaves etc were removed by hand or with help of a pickaxe until the bare soil was visible. A soil sample of approximately 150 ml was taken. Both samples were placed in plastic cups and marked.

Bulk density was determined with help of the cylinder volumetric method, described in DQR (1993). According to this method, the density is determined by weighing a sample with a known volume. The steel cylinder had a diameter of 8 cm and a height of 13 cm. The bottom centimetre of the cylinder was phased to simplify the penetration into the soil and the top of the cylinder consisted of a 5.1 cm removable cylinder part to ensure the burying of the 13 cm cylinder part. In order to collect the sample a steel plate was placed beneath the cylinder. The soil surrounding the cylinder was removed, to enable the insertion of the plate and to bring up the sample (fig. 4.8). During this procedure it was important to keep the cylinder stable in order not to disturb the packing of the particles inside the cylinder. The sample was placed in a plastic bag and marked. Three to four bulk density samples were collected in each class. The number of bulk samples differs because of varying spread of the sampling areas in the classes.

Figure 4.7. *A soil sample taken at a depth of 20 cm. A part of the pickaxe is shown in the photo.*

Figure 4.8. *At the bulk density sampling a steel plate was inserted beneath the cylinder.*

Maps, field observations, and interviews with locals determined the land use. At each sampling site the following information was noted; longitude and latitude coordinates, type of vegetation, land use and grazing, fallow period, fertilisation, planting and harvest month and irrigation.

One of the sites (9) had to be abandoned due to a farmer not approving of the sampling, and seven of the sites in class II (34 to 40) were accidentally situated within the wrong soil type, Dorimon-pu.

4.3 GPS Recordings

In order to estimate the positions of the soil samples a Magellan NAV DLX-10 GPS (Global Positioning System) receiver was used. At each sampling site three position values were entered to increase the accuracy. GPS recordings were taken in order to ensure the samples were taken in the correct soil type, according to the soil map, and also to present a graphic picture of the locations of the sample sites. The positions were measured using the WGS84 map datum and the UTM projection. Comparing a mean value of recorded positions at a triangulation point with the known position controlled the precision of the GPS. The GPS was logging during 30 minutes and five positions were registered to derive a more accurate mean value. In order to make the field sample points compatible with Ghana National Grid they had to be transformed. The mean error of the discrepancy between the recorded coordinates and the "known" coordinates was 83 m in X direction and 379 m in Y direction. Thereafter, the displacement to north-east of the sampling sites could be corrected by subtracting 83 m from the X coordinate of all sample points and 379 m from the Y coordinate of all sample points. This affine transformation resulted in a better position of the sample points with respect to the true sample locations. These were verified by location of roads and land use.

4.4 Laboratory Work

4.4.1 Carbon Analyses

The carbon content was analysed on the sieved and dried samples using an apparatus called Carbon Sulphur Determination, Eltra CS500. The measuring method is based on the principle of sample combustion and analysis of the gases given off, through infrared absorption. Through combustion, the sample's carbon contents are oxidised as carbon dioxide. The combustion comes through a supply of oxygen. This oxygen is also the carrier gas. The flow amount is held constant at 180 l hr^{-1} through the means of an electronic flow regulator. The infrared cell signals correspond to the carbon dioxide concentration in the gas mixture. These signals are divided by the sample weight and the percentage of carbon is shown digitally. Since the sample weight is taken into consideration the displayed results are independent of the weight (Eltra Manual). When the temperature had been stabilised at about 1100°C calibration with calcium carbonate and CSN Chip Standard (C=0.0194% $\pm$ 0.0008) was performed. Sample weights lower than 100 mg will reduce the accuracy due to heterogeneity of the sample and due to lower weighing accuracy (Eltra Manual). Therefore, samples with a weight of between 200 and 300 mg were analysed. An Analytic AC 120S MC1 was used (d=0.0001 g) for weighing the samples. The sample was placed into a combustion boat and pushed into the Determination apparatus. The carbon content was displayed in percentage after 1-2 minutes of combustion. In order to increase the accuracy three measurement were performed for each sample.

Since CENTURY simulations result in carbon content output in grams per square metre it was necessary to transform the observed carbon content, given in percentage by the Carbon Sulphur Determination apparatus. The bulk density value (in g cm^{-3}) was multiplied with 10,000 ($1m^2=(100\times100)$ cm) to get the weight of a 1 cm layer of soil covering 1 m^2. The resulting value was multiplied with 20 since the percentage of carbon in the samples was determined for this top layer (20 cm). To calculate the amount of carbon per square metre this soil weight was multiplied with percentage rate of carbon (Young, 1976).

$$Carbon\,Content_o = (Bulk\ Density \times 10{,}000) \times 20 \times \frac{Carbon\,Content_i}{100} \qquad (4)$$

Carbon Content$_o$ is the output carbon content given in g cm^{-2}, *Carbon Content$_i$* is the carbon content input measured in percentage (%), and *Bulk Density* is given in the unit g cm^{-3}.

4.4.2 Water Content

The soil water content of the samples was analysed in the same samples as used in the carbon content analyses. Therefore, the samples were sieved through a 2 mm net (Metler TM200, maximum 210 g, d=0.001 g). The samples ≤ 2 mm were weighed before and after being dried for 24 hours in 105°C in a Gallenkamp Hotbox oven. Weight reduction represented water content, and was calculated in percentage.

$$Water\,Content = \frac{Soil\,(wet) - Soil\,(dry)}{Soil\,(wet)} \times 100 \qquad (5)$$

4.4.3 Bulk Density

The dried samples (24 hours, 105°C) were weighed on a portable advanced electronic balance, CT 1200V-03U (maximum 1210 grams, d=0.1 g (Ohaus corporation, 1995)). Since the volume was known the bulk density could be calculated with the following equation:

$$Bulk\ Density = \frac{Weight}{Volume} \qquad (6)$$

4.4.4 Soil Texture Analyses

Sieving Analyses

The same samples as used for the bulk density were used for the soil texture analyses. After drying (24 hours, 105°C) one sub-sample for sieving (>500 g) and one sub-sample (~100 g) for hydrometer analyses were drawn. The amount was chosen after expected degree of sorting and clay content (App. III). The samples (>500 g) were sieved and particles <2 mm were weighed. To dissolve aggregates 0.5-litre 0.05 M tetra sodium diphosphate decahydrate ($Na_4O_7P_2$*10 H_2O) solution was added to each sample. The samples were wet sieved through a 0.063 mm net and moved to an oven safe bowl by a water beam. After sedimentation for at least 30 seconds the samples were decanted and dried for 24 hours in 105°C. The samples were weighed and the sand fraction, as percentage of the whole sample, was determined.

$$Sand\ Fraction = \frac{Weight\,of\ Sand}{Weight\,of\ Total\ Sample} \times 100 \qquad (7)$$

Hydrometer Analyses
Soil fraction 0.07-0.001 mm was determined by sedimentation analyses, i. e. hydrometer analyses (App. III). The samples with weights (measured on a Sartorial Portable Pt 2100, d=0.1 g) between 30 and 100 g, were dispersed with 0.05 M tetra sodium diphosphate decahydrate ($Na_4O_7P_2 \times 10\ H_2O$) solution and readings were made during 24 hours. To increase the accuracy the hydrometer analyses was performed a second time during 20 minutes.

4.5 Modelling with CENTURY

Since there are many input variables in the CENTURY model, it is necessary to focus on those which have the most significant influence on the results. Standard values are used for parameters not changed by us.

4.5.1 Weather Data

The model uses for the climate data, either true weather data or monthly mean values. The weather data included are monthly mean maximum and minimum temperatures, monthly mean precipitation, standard deviation, and skewness values for the precipitation values. Since local precipitation amounts differ greatly, it is important to use weather data from a climate station as close as possible to where the samples were taken. Our model simulation uses true weather statistics for the last 39 years, from 1961 to 1999, measured at the climate station in Manga. Before and after that time period the model uses mean monthly values, calculated from the weather data 1961 to 1999, of the maximum and minimum temperature and the precipitation.

4.5.2 Vegetation Parameters

Each vegetation type in the CENTURY model is described through a number of parameters, which generally are not changed by the user.

In the uncultivated areas the vegetation was set to include acacia trees and grasses. These selections should be considered more as a type of vegetation than the actual vegetation present.

In the two cultivation classes, vegetation types were decided through interviews with farmers and observations in the field. The crops that had been growing on the fields were millet, sorghum, soybean, cowpea, guinea corn, maize (*Zea mays* (Abbiw, 1990)), groundnut, cassava (*Manihot esculenta* (Abbiw, 1990)) or combinations of these. Most of these crops were found as standard values in the CENTURY model. At a few sites (2-3, 81-83, 90-94) soybean had to be chosen instead of cowpea since cowpea did not exist in the model. Soybean was chosen because of its similarity to cowpea in nitrogen fixation. A mixture between millet and sorghum was created at site 13 since, according to the information acquired, both were growing at the location. This mixture was created as a mean values of the parameters of the crops mentioned above. On the few sites in class I cultivated during the 19th century (sites 10, 11 and 12), cassava was chosen (Shaw, 1971).

4.5.3 Influence of Animals – Grazing and Fertilisation

Animals kept at the compound influence in two ways; by grazing and fertilisation (faeces and urine) of the ground. The different ways, in which grazing occur, are described through different parameters in the same way as the different crop types. During the dry season the animals walk around freely and therefore a winter grazing, grazing on standing dead crop residues, was chosen. During the rest of the year, when the crops are growing, the animals are tied up and grazing on the fields does not take place. During fallow periods a low intensive grazing with no effect on production was chosen.

The fertilisation amount used in the model was 12.17 g nitrogen, 4.45 g phosphorous and 1.51 g sulphur per square meter. The calculations for this are shown in Appendix IV.

4.5.4 Fire

To create a somewhat realistic picture of the incidence of fires a medium hot fire type was scheduled to occur in March every five years during the period when the areas are supposed to have been natural savanna. When cultivation occurs the fields are burned every cultivation year to prepare the land for crop. In uncultivated areas fires are scheduled to occur as in natural savanna.

4.5.5 Irrigation

Only seven sites in class I were irrigated. These sites were all situated near an open water reservoir. Most irrigation takes place just after planting of the crops. We chose to use the irrigation parameter when the soil water was equal to or lower than 15% of the water holding capacity. At this stage the field was irrigated with 1 cm of water.

4.5.6 Harvest Method

In the CENTURY model, a 50% straw removal harvest method was selected, because observations in the field indicated that a large amount of straw was left on the field after harvest. Harvest was performed in October or November depending on crop type.

4.5.7 Stabilisation Period

The model was run during 6000 years to determine the length of stabilisation period, until the carbon content reaches equilibrium. The carbon content was concluded to reach equilibrium in 2500 years. Modelling was therefore set to start 4500 years ago. No initial carbon content was given. Before 1800, the carbon flux from savannas is assumed to have been zero (Scholes & Hall, 1996). The sites were simulated as natural savanna until the year 1900, except for a few sites in class I cultivated already from year 1800. Before

1800, when the European colonisation began, the annual flux of carbon from savannas is assumed to have been zero (Scholes & Hall, 1996).

4.5.8 Site-specific Data

A site-specific file, originating in this case from a file suitable for savanna climate, is changed according to the different sites. In this file the position of the site is noted. Climate parameters, bulk density and soil fractions were also changed according to our measurements.

4.5.9 Output Variables

Since the aim of the study was to study the carbon content in the soil only the output parameter "soil organic matter total carbon" was studied. This output factor includes belowground structural carbon, belowground metabolic carbon, active organic carbon, slow organic carbon, and passive organic carbon pools. A few other output parameters were, at different modelling stages of the work, studied and compared with known values like climate data to ensure the liability of the modelling.

4.6 Calculations and Statistical Tests

Pearson's correlation coefficients, with a significance level of 0.05, were used in all of the correlation tests. Analysis of variance (ANOVA), one-way, was used to determine if a significant difference could be found between the three classes. Of the different methods available, Tukey's pair wise comparisons was chosen, comparing pair wise differences between level means. For the statistical analyses MINITAB 12.1 was used.

4.6.1 Carbon Content

Differences Between Soil Depths, Classes and Sites

In order to examine possible differences between the two depths and the classes, general descriptive statistical calculations were performed, as well as variance analyses, so that significant differences between the classes could be determined.

Since some of the samples were taken on sites with different soil type, different starting time of cultivation and in varying part of the crop-fallow cycle these differences were examined to see how they affected the carbon content. The influence of the soil type was determined by comparing the soil samples in class II with samples having the same land use but a different soil type. In the same way, samples with different starting year of cultivation and samples at different stages in the crop-fallow cycle were compared.

Changes of Carbon Content Through Time
For each class, the carbon output value for every February during the modelling years was plotted against the time. In this manner, changes in carbon content could be studied, and carbon content fluctuations could be correlated to changes in land use or management practises.

Differences Among Sites
Within each class the differences between sites were examined, for both the observed and the simulated carbon contents, to find possible patterns. Correlation analysis was used to examine the connection between carbon content and parameters like bulk density and soil texture.

Evaluation of Simulated Carbon Content
One of the major aims of this study is to evaluate how well the CENTURY model predicts actual carbon content. To evaluate whether there is a connection between actual and simulated carbon content, the correlation was calculated. Since the model only gives one output carbon content for each site we compared this with a mean of our surface samples and the 20 cm samples.

4.6.2 Water Content
Mean values were calculated for the water content within each class at two different levels in the soil, at the depth of 0 and 20 cm, and as a mean between the two levels. Differences between levels in the ground were studied and the classes compared. Through correlation a possible connection between the water and the carbon content was tested, both at the level of 0 and 20 cm as well as for the mean of the two levels.

4.6.3 Bulk Density
The bulk densities for the land use classes were compared through calculation of a mean value for each class. A correlation analysis between bulk density and observed ($Carbon\ Content_i$ in formula 4) and simulated carbon content was performed.

4.6.4 Soil Texture
The soil texture was examined through calculations and comparisons of sand, silt and clay fractions for each class. The connection between carbon content and texture was determined, both for observed and simulated carbon content, by performing a correlation analysis.

5 RESULTS

The first section in this chapter describes carbon content, water content, bulk density and soil texture in the field samples. Thereafter, the results from the influence of soil type, start of cultivation and phase in crop-fallow are presented. The second section begins with a time perspective of changes in carbon content, followed by comparisons between observed and simulated carbon content. Finally, the influence of soil texture and bulk density on simulated carbon content is presented. Table 5.3 and 5.4 summarises the results of the correlation analyses.

5.1 Results from Field Sampling

5.1.1 Carbon Content

Descriptive data for all soil levels are displayed in table 5.1. At surface level, the mean of the carbon content was highest in uncultivated areas, class II (5063 g m^{-2}). Continuously cultivated fields (class I) had about half of that carbon content (2809 g m^{-2}) while fields with crop-fallow (class III) contained even less (1734 g m^{-2}). This pattern was the same for the maximum and minimum values. Class II had the highest standard deviation, followed by classes I and III. The variance analysis showed that the difference between the classes was statistically significant.

The general pattern observed was that carbon content was lower at 20 cm depth than at the surface. The relationship between the classes was the same as at the surface level. Higher values were observed in class II, followed by classes I and III. This pattern could also be observed in mean, maximum, minimum and standard deviation values. Even at this depth there was a significant difference among the different classes.

Table 5.1. *Mean, standard deviation, minimum and maximum values for carbon content at the surface, at the depth of 20 cm and as a mean between the two levels. All values are derived from 30 samples per class, and given in g C m^{-2}.*

Parameter	Class	Mean	Std.	Min.	Max.
Mean carbon value	I	2179	934	646	4739
	II	3558	2138	1339	9440
	III	1436	392	722	2246
Carbon content at 0 cm	I	2809	1456	661	8112
	II	5063	3511	1704	14428
	III	1734	633	619	3410
Carbon content at 20 cm	I	1549	634	630	2862
	II	2053	892	974	4451
	III	1138	268	546	1856

Since the model only produces a carbon output at one level (0-20 cm), the carbon content was calculated as a mean between the surface and the 20 cm samples. The pattern of the mean did not differ from the two levels described above.

Within the land use classes, the carbon content was highly fluctuating between the different sites. In class I (fig. 5.1) sites 2-7, 19 and 24 had low carbon contents while extremely high contents occurred at sites 16 and 23. The carbon content in this class varied between 646 g C m^{-2} and 4739 g C m^{-2}. The majority of the mean carbon contents for class II (fig. 5.2) were about 2000 g C m^{-2} but sites 51 to 59 had a higher carbon content, especially sites 51, 54 and 55. In class III (fig. 5.3), the contents were less variable. Sites 90 and 94 had lower values than the rest.

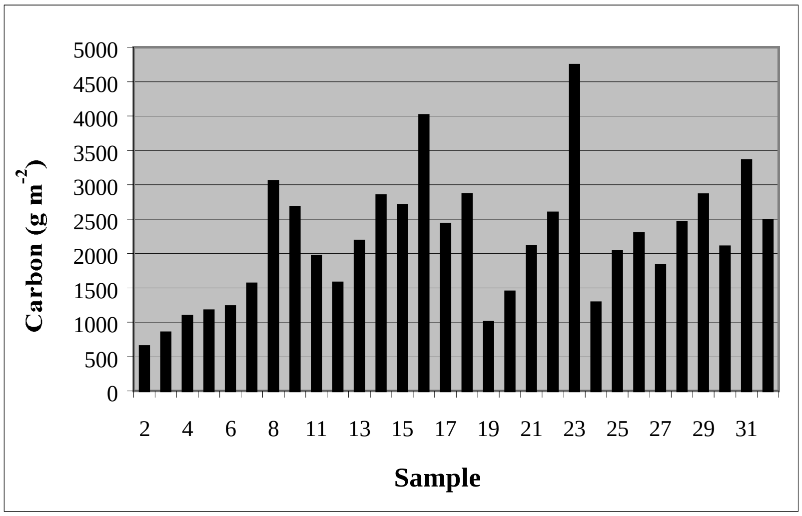

Figure 5.1. *Mean carbon content in class I, fluctuating between 645 and 4739 g C m^{-2}.*

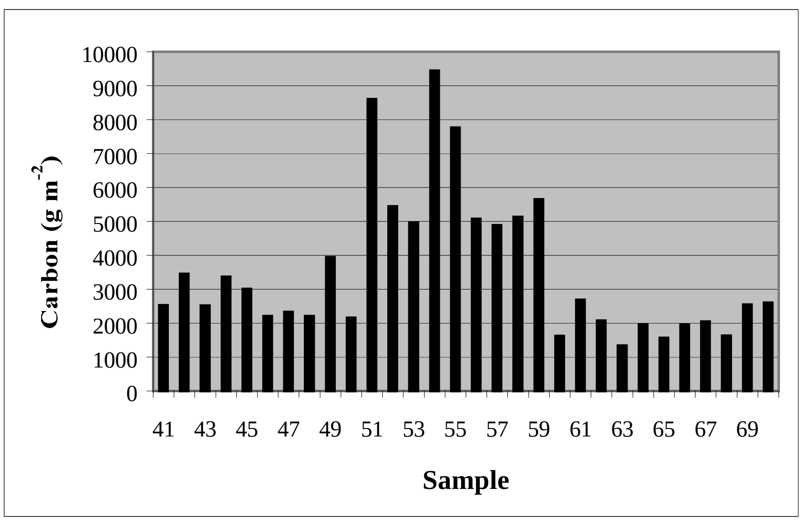

Figure 5.2. *Mean carbon content in class II, fluctuating between 1339 and 9440 g C m^{-2}.*

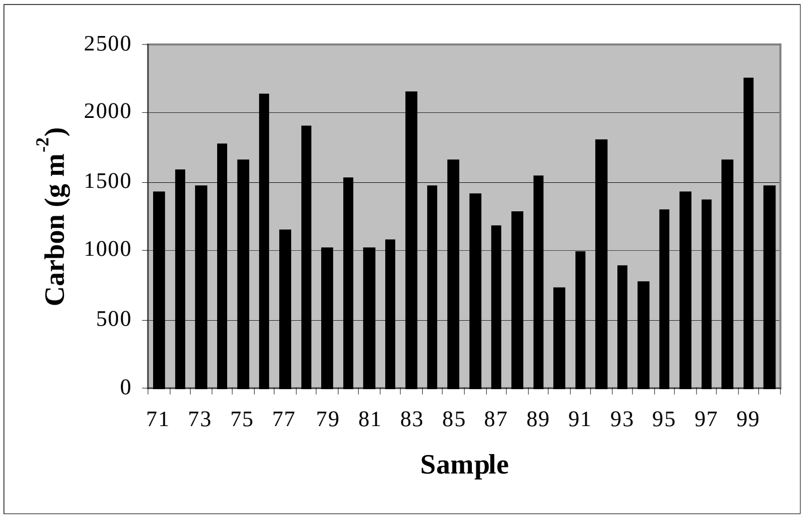

Figure 5.3. *Mean carbon content in class III, fluctuating between 722 and 2246 g C m^{-2}.*

5.1.2 Water Content

Observed water content in all of the samples was less than 0.012%. There was a statistically significant difference in water content among the different classes. The mean of the water content in the samples taken at the surface showed that class II had the highest water content (~0.005%) followed by class I (~0.003%) and class III (~0.001%). The water content in the surface samples and at 20 cm depth is presented in figure 5.4 and 5.5 respectively. Further down in the soil, at the depth of 20 cm, the water content is higher in all classes, but it still follows the same pattern, with the highest amount in uncultivated areas (~0.020%) followed by continuously cultivated fields (~0.014%) and crop-fallow areas (~0.007%).

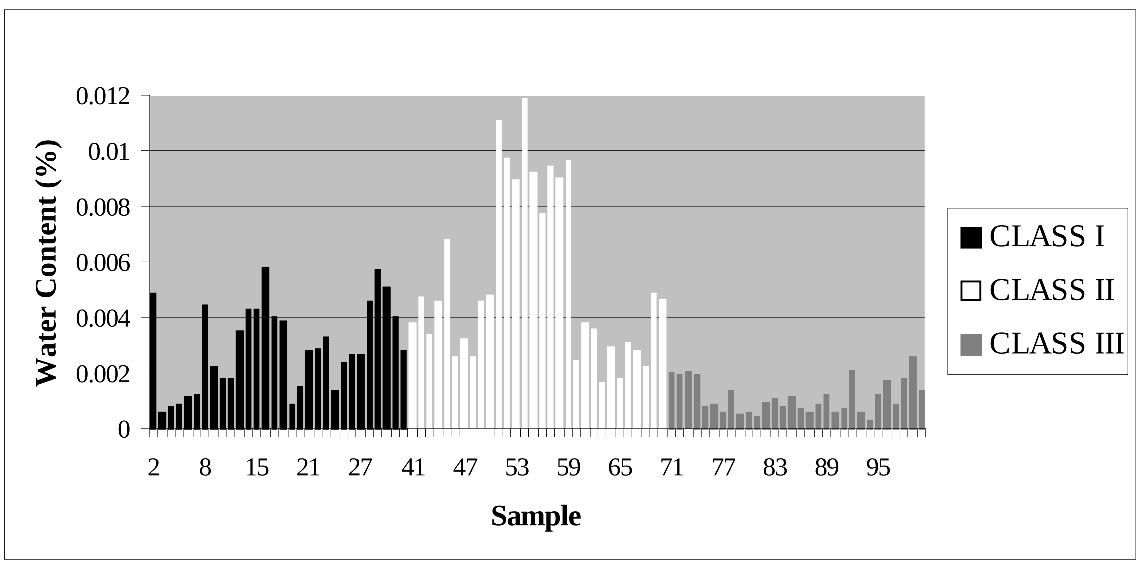

Figure 5.4. *Water content in the surface samples, with the highest content in class II and the lowest content in class III.*

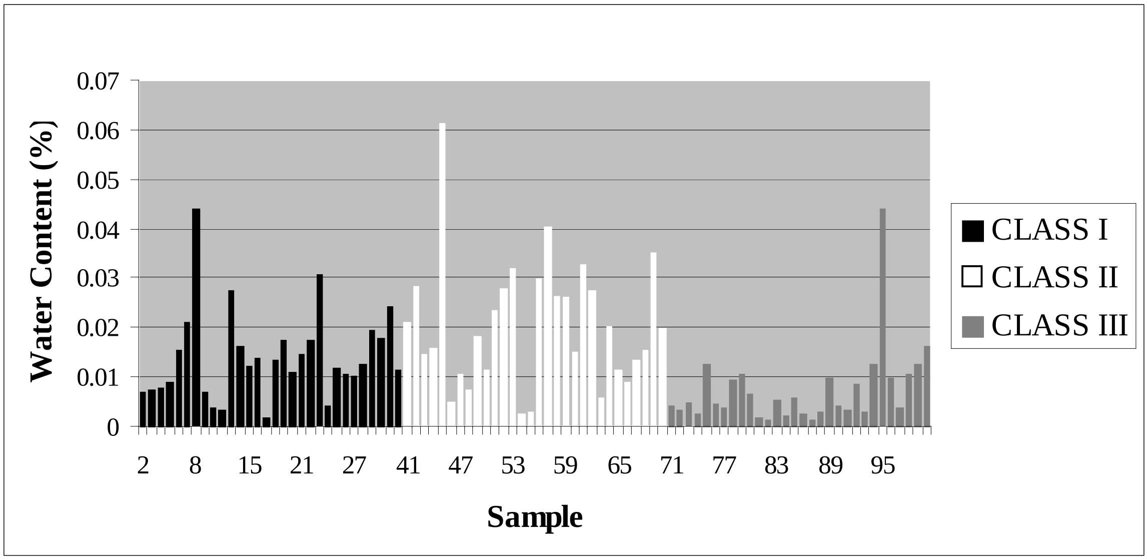

Figure 5.5. *The water content at the depth of 20 cm shows no clear pattern.*

A correlation analysis between water and carbon content at the surface level in the soil gave a significant correlation in all the classes. There was an extremely high correlation in class II. At the depth of 20 cm there was no significant correlation between water and carbon content except in class I.

Since the mean value was used in most of the calculations, it was relevant to examine the correlation between the carbon content and the water content as a mean of the two levels. The results gave no significant correlation except in class I. All correlation coefficients are shown in table 5.2.

Table 5.2. *Correlation coefficients for water content and mean carbon content for each class. Bold numbers indicate sianificant correlations.*

Class	Surface	20 cm	Mean
I	**0.629**	**0.495**	**0.564**
II	**0.930**	0.050	0.250
III	**0.613**	0.069	0.114

5.1.3 Bulk Density

The bulk density measurements showed little differences between the three different classes, when comparing the mean bulk density for each of the classes (fig. 5.6). The density was highest in class II (1.682 g cm^{-3}), followed by class I (1.650 g cm^{-3}) and class

III (1.566 g cm^{-3}). A significant correlation between bulk density and carbon (in percentage) was only present in class I.

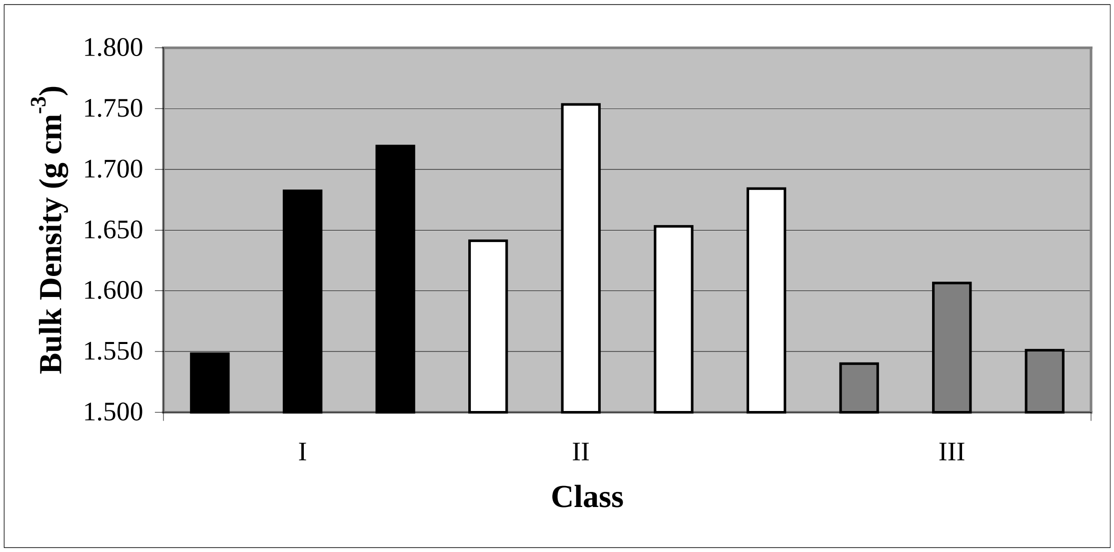

Figure 5.6. *Bulk density in classes I, II and III. Three samples were taken in classes I and III and four samples in class II.*

5.1.4 Soil Texture

The sand fraction was for all the classes between 50% and 80% (fig. 5.7) with the highest amount of sand in class III. On the other hand, silt and clay were most abundant in class I, although the clay fraction was very small in all of the classes, varying between 0.33% and 0.62%. The mean of the fractions for the different classes is shown in figure 5.7. The combined amount of sand, silt and clay was 69% in class I, 75% in class II and 90% in class III.

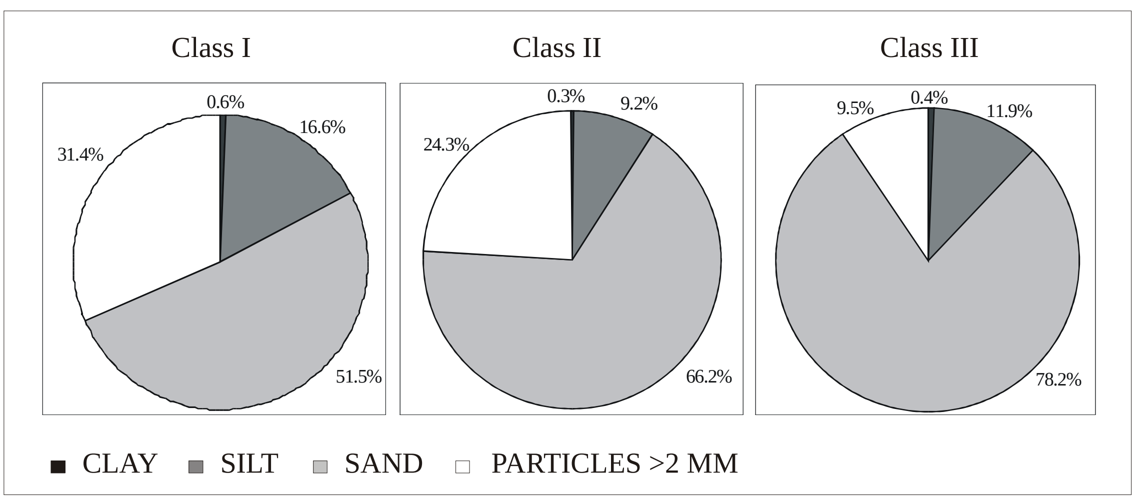

Figure 5.7. *Soil texture distribution in classes I, II and III.*

An investigation whether or not there was a connection between the different soil fractions and carbon content showed that the correlation was significant for silt and carbon contents in classes I and II, for silt plus clay and carbon content in classes I and II and for clay and carbon content in class I (tab. 5.4).

5.1.5 The Importance of Different Soil Types

A variance analysis was performed on samples taken in uncultivated areas with different soil types, in order to estimate if soil type influenced the resulting carbon content. This analysis showed no significant difference.

5.1.6 Influence of Historically Earlier Start of Cultivation

In some of the sites in class I the cultivation was estimated to have started earlier than in the other sites of this class. No significant difference in present-day carbon content in the soil was observed.

5.1.7 Different Phases in Crop-fallow

Since some of the sites in class III had had a fallow period for a few years and most of the sites were cultivated last year, after a previous longer or shorter fallow period, a test checking the separability between the two different groups was performed. This showed that no difference between the two could be determined.

5.2 Simulations With the CENTURY Model

5.2.1 Time Perspective of Changes in Carbon Content

The simulated carbon content for the three different classes can be studied in figure 5.8. The equilibrium level for class I was about 1300 g C m^{-2}. In the early 1800's the carbon content increased to around 1350 g C m^{-2}. At the end of the 20^{th} century the carbon content had dropped to a level of approximately 900 g C m^{-2}.

Class II had an equilibrium level at 1200 g C m^{-2} that did not change until 1961. Thereafter the curve fluctuated between 1150 g C m^{-2} and 1215 g C m^{-2} until today.

Class III had the lowest equilibrium level of 1100 g C m^{-2} but increased drastically at 1900 to between 1500 and 1600 g C m^{-2}.

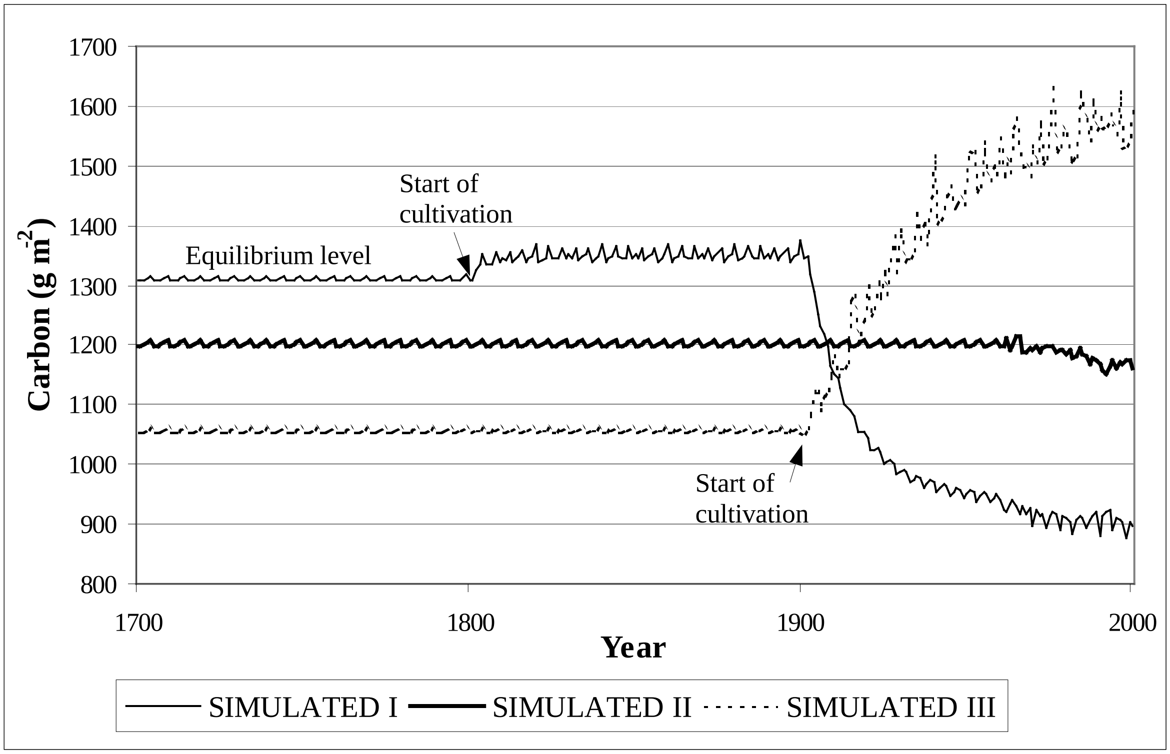

Figure 5.8. *The equilibrium level is found at about 1300 g C m^{-2} in class I, at about 1200 g C m^{-2} in class II and at about 1100 g C m^{-2} in class III. In 1800, cultivation starts in (some of the sites of) class I, causing the carbon content to increase. Cultivation does, in class III, not start until year 1900.*

5.2.2 Comparisons Between Observed and Simulated Carbon

Figures 5.9-5.11 show the result of a comparison between simulated and observed carbon content for each class and figures 5.12-5.14 show the difference between simulated and observed carbon content in each site. There were no similarities in the carbon content derived from the model compared to the observed content in class I (fig. 5.12). The simulated carbon contents fluctuated between about 600 g C m^{-2} and 1200 g C m^{-2}. This can be compared with the observed contents, which varied between 600 g C m^{-2} and 4700 g C m^{-2}. No correlation was present in class II between simulated and observed carbon contents. The simulated carbon contents in class II varied much less than the observed contents (fig. 5.13). Extremely high contents occurred at sites 51-59, up to 9500 g C m^{-2}. These extremes contributed to the low correlation. A few sites in class III (fig. 5.14) had similar contents in observed versus simulated carbon content (sites 80 and 85) whereas there were several extremely low correlated sites (sites 78, 83, 87, and 92). The correlation analysis indicated a significant relationship in class III, although it was very weak ($r=0.432$, $p=0.017$).

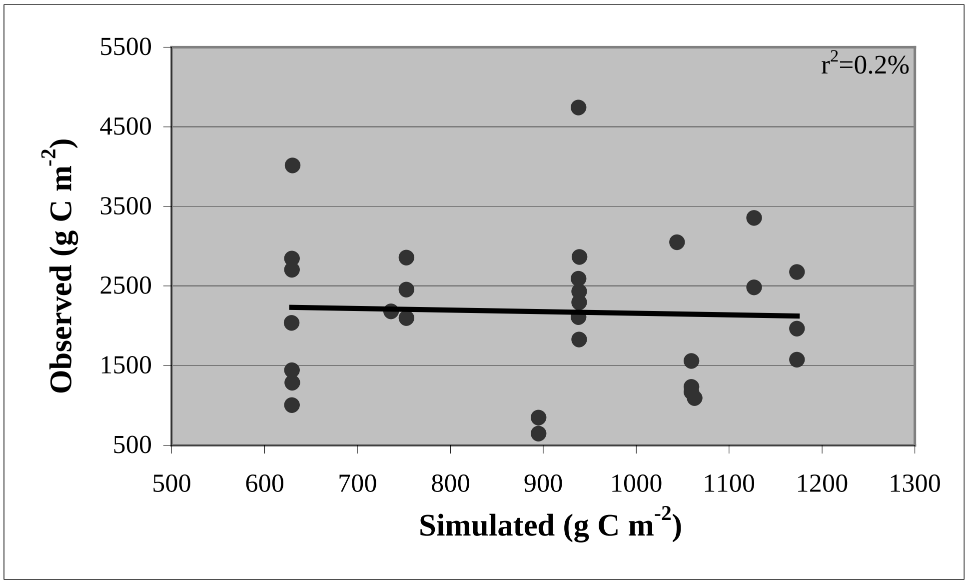

Figure 5.9. *Comparison between observed and simulated values in class I.*

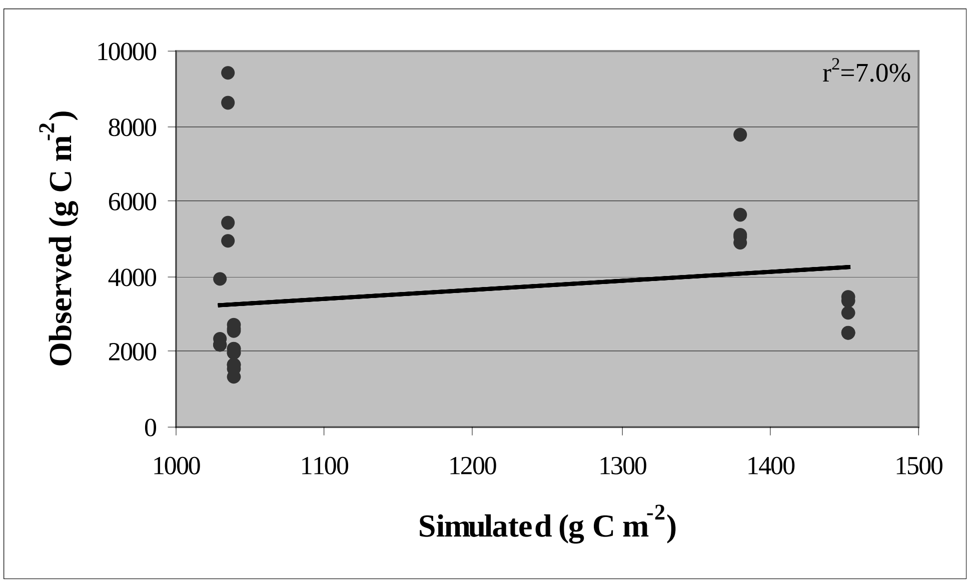

Figure 5.10. *Comparison between observed and simulated values in class II.*

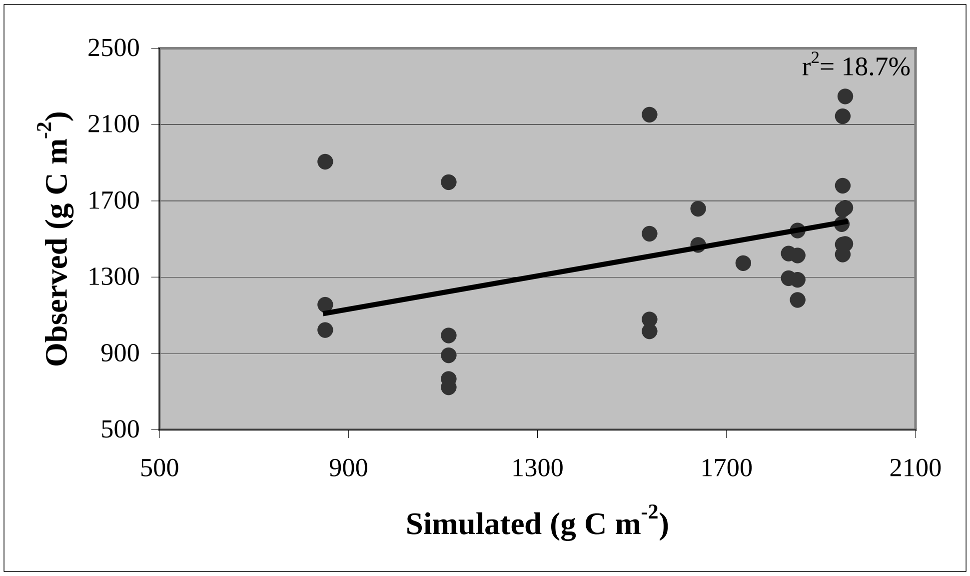

Figure 5.11. *Comparison between observed and simulated values in class III.*

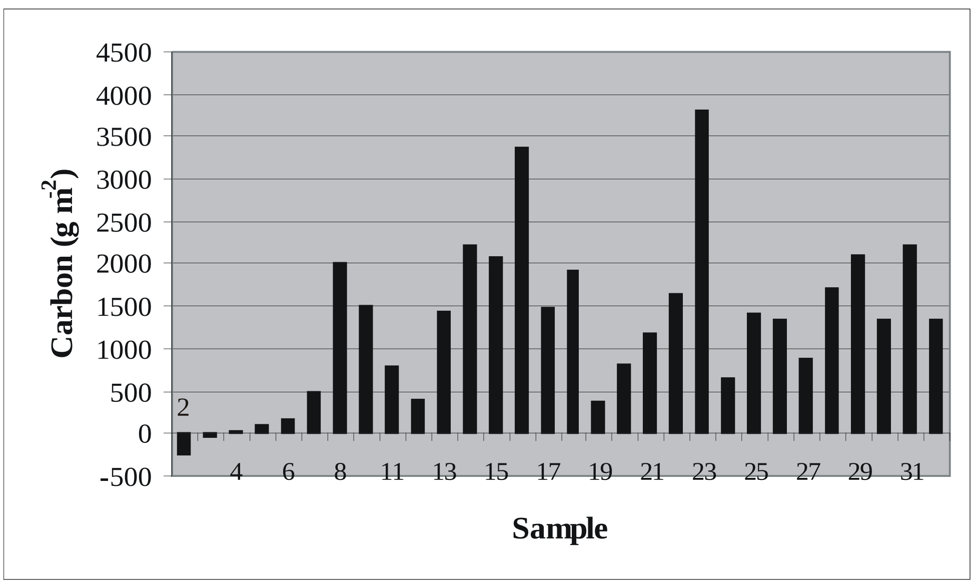

Figure 5.12. *The difference in each sample between observed and simulated carbon content in class I.*

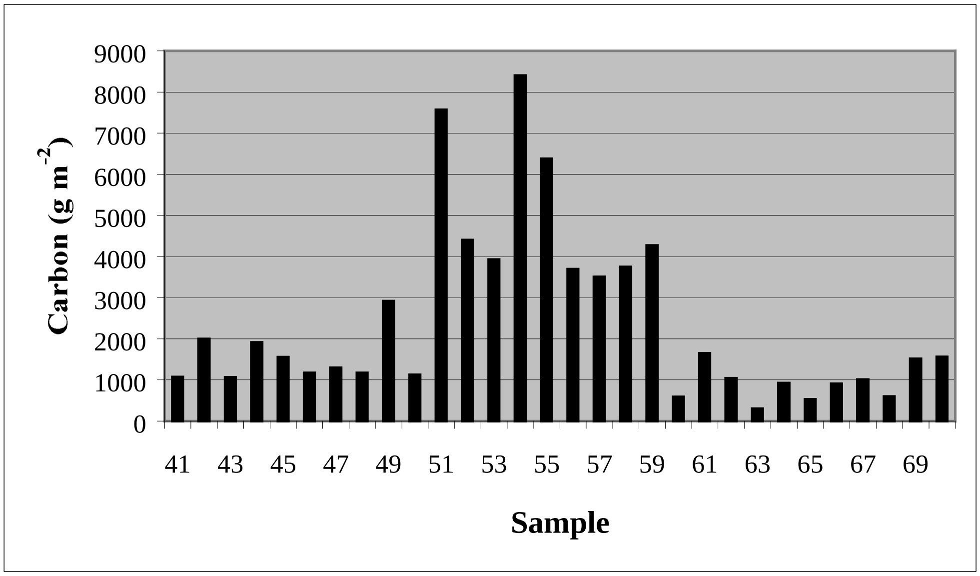

Figure 5.13. *The difference in each sample between observed and simulated carbon content in class II.*

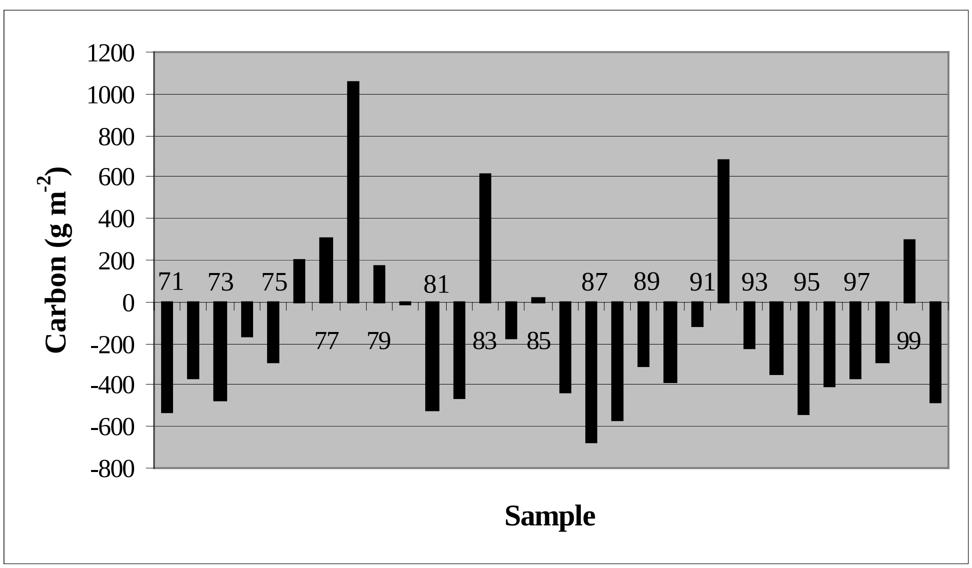

Figure 5.14. *The difference in each sample between observed and simulated carbon content in class III.*

Differences in means between the observed carbon content and the simulated content varied over a broad range in the three classes. The biggest differences were found in class II where the simulated mean content was about 1200 g C m^{-2} and the observed content about 3600 g C m^{-2}, and in class I with 900 g C m^{-2} and 2200 g C m^{-2} respectively. The simulated carbon content in class III was close to the observed content, 1400 g C m^{-2} compared to 1600 g C m^{-2} in the latter (fig. 5.15).

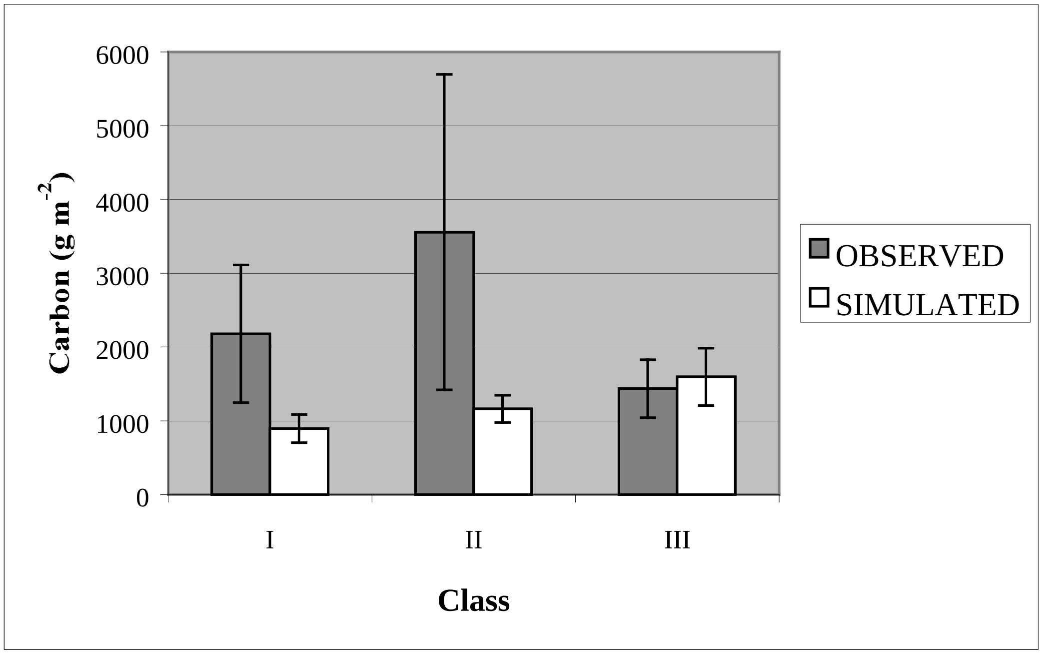

Figure 5.15. *Mean values with standard deviations for observed and simulated carbon content.*

By comparing the observed and simulated carbon content for each sample site, simulation errors were estimated. CENTURY underestimated the carbon content in class I with about 59% and with 67% in class II. In class III CENTURY overestimated the carbon content with 10%.

5.2.3 Factors Influencing the Carbon Content

The carbon content and bulk density was correlated in classes I and II, but not in class III (tab. 5.3).

One factor, which possibly could have large effects on the carbon content in the passive soil organic matter component, is the clay content. Correlation occurred in classes I and II. However, there was no significant correlation between the carbon content and the clay content in class III (tab. 5.4). The slow soil organic matter component is often correlated with the amount of silt and clay together. Significant relationships were found in classes I and II (tab. 5.4). Significant correlations were found in class I and in class II between carbon content and soil texture, for all the different soil fractions (tab. 5.4).

Table 5.3. *Correlation coefficients for observed and simulated carbon content versus water content and bulk density. Correlation between water and carbon content was only tested for observed contents. The carbon and water values are given in mean values between the two levels. Bold numbers indicate significant relationships between the parameters tested.*

Method	Class	Carbon	Water	Bulk Density
Observation	I	*	***0.564***	**-0.413**
Observation	II	*	*0.25*	0.344
Observation	III	*	*0.114*	-0.272
Simulation	I	*	*	***0.636***
Simulation	II	*	*	***0.785***
Simulation	III	*	*	-0.159
Observation and Simulation	I	-0.041	*	*
Observation and Simulation	II	0.264	*	*
Observation and Simulation	III	***0.432***	*	*

Table 5.4. *Correlation coefficients for observed and simulated carbon contents versus soil fractions. The correlation test was performed between sand, silt, clay and silt plus clay content and carbon content. Bold numbers indicate significant relationships between the parameters tested.*

Method	Class	Sand	Silt	Clay	Silt + Clay
Observation	I	0.256	***0.426***	***0.42***	***0.426***
Observation	II	-0.225	***0.498***	-0.229	***0.479***
Observation	III	0.151	-0.235	0.119	-0.229
Simulation	I	***-0.621***	***-0.659***	***-0.66***	***-0.659***
Simulation	II	***-0.716***	***0.324***	***-0.503***	***0.698***
Simulation	III	-0.154	-0.101	-0.184	-0.128

6 DISCUSSION

6.1 Evaluation of Field Observations

6.1.1 Carbon Content

The soils of our study area had a generally low soil carbon content, as a consequence of low plant productivity due to water stress, a relatively high decomposition rates due to the high mean temperature (Parton *et al*., 1989) and limited nutrient availability (Parton & Rasmussen, 1994). Another reason is that the soil was very sandy, leading to less carbon content than in fine-textured soils (Parton *et al*., 1989).

Site Differences Within the Classes

There were no clear patterns in the fluctuations of carbon in class I. On sites 2-6 and 19, which had the lowest contents, soybean/millet, sorghum/millet and millet had been cultivated. This could be interpreted as that millet keeps the carbon content down but the second highest content of all, in site 16, was also a site with millet. Most of the other millet sites had rather high carbon contents. Site 23, where sorghum had been growing, had the highest carbon content. Too few soil samples with different crop cover were taken to be able to draw any realistic conclusions about the connection between carbon content and crop type.

In class II the carbon contents within the different sites, were more similar to each other, except for sites 51-59. These sites, which had high values, could possibly have had a deviant bulk density and soil texture than the rest of the samples in class II. No bulk density was sampled close to sites 51-54 and the bulk density and soil fractions were estimated upon a mean of the nearest two known values. However, a bulk density sample taken at site 59, used as estimation for samples 55-59, did show an extremely high value. Sites 43-45 had about the same soil texture, but this similarity was not reflected in the carbon content. Site 58 lied, according to positioning by the GPS, on the border between the soil type it was supposed to be, Varempere-tafali, and another soil type, Berenyasi-kupela. Site 59 was incorrectly taken in the latter mentioned soil type.

The sites of class III differed in the number of years the soil lied fallow, but this was not reflected in the carbon content. The four sites, 90-91 and 93-94, with the lowest recorded carbon content had been cultivated with soybean, but site 92, where the same crop had been grown, had a high carbon content.

Differences Between Classes

The higher carbon content in class II, at both levels in the ground, was a result of the denser vegetation in this class. In these areas there are no annual fires and the organic matter are not removed by harvest like in the other classes, but returns to the soil and contributes to the higher organic matter content. Even though many of the areas were forest reserves some removal of organic matter for household fuel and grazing probably took place (fig. 6.1). The large amount of untouched vegetation added to the soil organic matter in the soil, and thereby increased the carbon content. The samples taken at the surface included small parts of the vegetation, which contributed to the higher carbon content compared to the 20 cm samples.

Figure 6.1. *Overpopulation and overgrazing forces the farmers to move over large distances to find grazing areas for their cattle.*

Greenland & Nye (1959) estimated the carbon content in soils under fallow. During ten years of fallow only a relatively small increase in the carbon content occurred. The rise and fall in the level of carbon with alternate fallow and crop is regarded as a fluctuation about a steady level, which is a fraction of the equilibrium level. Some time will usually be required for the natural vegetation to re-establish itself and hence for the production of fresh humified material to reach a level equivalent to that under well-developed vegetation. In the drier parts of the savanna zone the redevelopment of vegetation may take a number of years, particularly if the cultivation period is prolonged or erosion occurs. During short fallow periods of less than five years the soil carbon on average was below 50% of the equilibrium level (Greenland & Nye, 1959). Our results showed an increase in the carbon content after the beginning of cultivation, which was caused by the application of manure. The effect of fallow on soil organic matter depends as much on the initial organic matter level of the soil in relation to the equilibrium level under the fallow as on the properties of the fallow itself (Greenland & Nye, 1959).

A comparison between classes I and III showed that the carbon content was higher in class I, influenced by the more frequent application of manure. Differing between the two classes, except for the criteria that the soils of class III had fallow periods, was the soil type and the type of crop that had been grown on the fields. While it was mostly millet, sorghum or combinations including one of these crops in class I, it was groundnut, maize, soybean, cowpea, guinea corn, or combinations of these, that had been grown at the fields of class III. These two factors may have influenced the resulting carbon content of the two classes.

A transformation of the land through clearing for cultivation decreases the carbon content in the soil. The soil organic matter loss when transforming forests to cultivated areas has been studied in a few projects. According to Ihori *et al.* (1995) the climate and soil texture influence the amount of loss due to cultivation. Greatest losses tend to occur in areas with high temperature, high precipitation, coarse soil texture, and in areas susceptible to erosion. Ihori *et al.*'s study (which concentrated on large-scale and long-term influences of cultivation on total carbon budgets) showed a reduction of soil carbon of between 16 and 42%. Houghton (1991) described a loss of 20-50% due to cultivation. Variations correlate with climate and soil texture but are not explained by these variables. Management practices play a major role in determining the losses. Forest disturbance can reduce SOC due to increased erosion, faster oxidation, reduced inputs, and/or inputs of different quality (Lugo & Brown, 1992).

Problems with comparing the carbon loss due to cultivation are that it is necessary to examine the same area before and after start of cultivation. In our investigation, samples were lacking from undisturbed conditions of the cultivated areas of today. Further more, the time perspective is an important factor. The carbon content differed between land areas that had been cultivated during different number of years and uncultivated areas that had been left undisturbed during different length of time. Other problems were that in the case of transforming forests to cultivated fallow areas these areas had different soil types, which could have influenced the results.

Differing Sites

When performing the study the main aim was to study the influence of different land use. No sites with fallow periods could be found within the same soil type as the other classes, which made this aim difficult to achieve. Seven sites in class II were taken on a different soil type than the rest in the same class. These were compared to see what influence the soil type could have on the carbon content. The main reason why no significant differences could be found is that too few sites with different soil were examined. A problem with this attempt to estimate the influence of different soil types is that this estimation was made through comparison of soil samples taken in soil type Varempere-tafali and Dorimon-pu. In reality classes I and II were situated in an area with the soil type Varempere-tafali and class III in an area with the soil type Tanchera. This means that the conclusions drawn may not be accurate in this case.

6.1.2 Water Content

The low water content in all of the samples proves that the soil is extremely dry. The denser vegetation in class II prevents the water from run-off, increases the infiltration rate (Cannell & Weeks, 1979) and reduces the evaporation rate (Henderson, 1979). The higher water content in class I compared to class III can be explained by the texture of the soil. The soil texture analyses showed that the soils of class III contained more sand than class I (78% compared to 51%) and less silt and clay. Smaller particles have a higher water holding capacity than sand (Fitzpatrick, 1986).

The correlation between the water and the carbon content that existed in the soil surface can also be explained by the presence of vegetation. More vegetation results in a higher carbon content in the soil. The connection between the two factors was clearer in class II where the vegetation cover is higher. The correlation in the surface soil was less significant in classes I and III. At 20 cm soil depth, a correlation could only be seen in class I, which can be explained by the higher content of organic matter caused by the more frequent application of manure. Manure contributes to a higher water holding capacity of the soil (Brady & Weil, 1996).

6.1.3 Bulk Density

The bulk density is supposed to be correlated with carbon content. In our study, low bulk density was correlated with a larger fraction of small particles. This contributes to higher water holding capacity and therefore higher plant production (Brady & Weil, 1996). The correlation between bulk density and observed carbon content was very low in all of the classes. The bulk densities were about the same, in spite of the different soil types and land uses. Conversion of forest soils to agriculture usually increases bulk density (Lugo & Brown, 1992). The results from the measurements showed that class II had a higher bulk density than classes I and III. The reason for this may be the higher iron content in the soil. 75% of the soil in this class consists of particles <2 mm. The large particles were in many cases found to be iron concretions. This makes the soil harder to cultivate and may be a reason why these areas are uncultivated. Class III on the other hand, had a somewhat lower bulk density than the other classes, due to the fact that the soil at this location almost completely consisted of sand, silt and clay. The fraction of larger particles in this class was only 10%.

6.1.4 Soil Texture

The extremely low clay content in the soils can be a result of the rock composition. Quarts crystals and partially weathered crystals from feldspars and other minerals form sand sized grains (Plummer & McGeary, 1996). Another factor to consider is the extreme differences between dry and rain season. During the rain season when the rain falls heavily a lot of materials are removed through flooding and sheet erosion. The yearly Harmattan carries sand and silt particles from desert areas in the north. The large sand and silt fractions in the soils are a result of deposits from Harmattan.

Our study showed a significant correlation between clay and carbon in class I. Jones (1973) study of Vertisols in Nigeria also showed this significant correlation between carbon and clay content. However, this often noted positive correlation between clay and soil organic matter may however not represent the true cause-effect relationship because clay content is usually highly correlated with other factors that influence soil organic matter accumulation (Oades, 1988) like for example water content.

In a study by Ihori *et al.* (1995) the variance of total carbon was significantly related to sand content. Soils with increasing sand content had a lower carbon content, because of higher decomposition rates due to lower cohesion and aggregation, greater availability of humus to decompose and greater aeration. In our study, the correlation between the different fractions and the carbon content shows that not one specific fraction have a specifically large impact on the carbon content.

6.2 Modelling With CENTURY

6.2.1 Time Perspective

The small fluctuations during the equalisation period coincided with the occurrence of fire every five years. Simulated carbon content from year 1900 to 2000 is presented in figure 6.2, where present carbon content can be compared with simulated carbon content for year 2000.

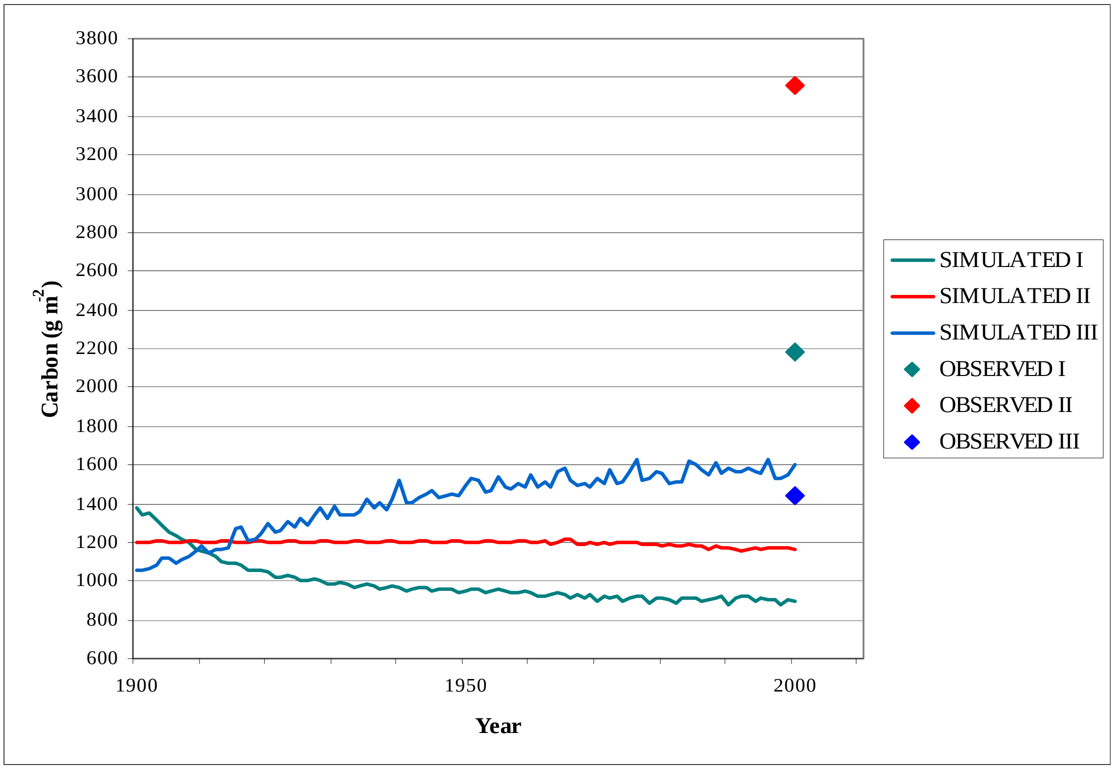

Figure 6.2. *Simulated carbon content from year 1900 to 2000 shown as lines. Present carbon contents are shown as dots. Correlation between simulated and observed carbon content was only found in class III.*

The increases in carbon content in class I soon after year 1800 corresponded with cultivation activities at some of the fields. Cassava was predicted to be growing during the 19th century, but during the 20th century it became more common with millet and sorghum (Shaw, 1971). Most of the fields in class I were not cultivated until year 1900, and the result of the more intense cultivation was a drastic decrease in the soil organic carbon content.

The carbon content in class II did not change until actual climate data was added to the model. That appeared at 1961, which caused the curve to fluctuate.

In year 1900, the cultivation began in class III. Application of fertilisers caused an augmentation in the carbon content. The end of the fallow periods are visible in the fluctuations as an increase in carbon content in the initiation of cultivation. The different crop-fallow periods varied from three to seven years. It takes a few years for the carbon to respond to the changes.

Soils initially high in carbon loose a large proportion of carbon, and soils initially low in carbon loose a smaller proportion of carbon. Increases or small losses of carbon from soils initially low in carbon indicate that the input of carbon is greater relative to losses than in soils initially high in carbon. Inputs come from decomposing vegetation and litter incorporated into the soil during initial cultivation and subsequently from crop roots, residues, and manure. Gains would most likely occur in soils containing less than 1000 g C m^{-2} in the soil at 0-30 cm depth. Interactions of bulk density, organic matter, and sample depth are important in determining the magnitude of the changes in carbon storage. Changes in carbon in most agricultural soils, where initial carbon is 3000 to 15 000 g C m^{-2} prior to cultivation, range from very little loss or slight gains in carbon to 20% (Mann, 1986).

It is generally observed that after 30 to 60 years of cultivation with a wheat-fallow system the crop production is reduced by nutrient availability. Addition of nitrogen, phosphorous, and sulphur fertiliser reduces the rate of decline of soil carbon with cultivation and suggest that a near equilibrium for soil carbon levels would occur after 150 to 200 years of cultivation (Parton *et al*., 1988).

Parton *et al*. (1988) simulated the formation of SOC during 10,000 year. The model did a reasonable job in simulating the impact of cultivation on soil carbon dynamics. The results showed that more than 80% of the final soil carbon levels were reached by year 2500 and that most of the remaining increases in soil carbon occurred from year 2500 to 5000. Simulated soil carbon levels after 10,000 years and observed soil carbon showed differences less than 15%. The comparison of the observed and simulated organic carbon levels after 90 years of cultivation suggests that the model underestimated the loss of carbon, which could be because the model assumed no erosion losses. Ihori *et al*. (1995) concluded that simulated carbon losses from 100 year of cultivation overestimated observed average carbon losses at all the sites by 11%. In our study, the simulated carbon content in class I decreased with about 30% since the beginning of cultivation (100 year).

Since CENTURY can be used to predict future SOC content, scenarios can be created to find measures to improve the soil productivity and to predict the effects of a likely development. In our study, a possible scenario would be to increase or decrease the fallow periods in class III, the only simulated carbon contents correlated with the observed carbon contents. The different scenarios included one with unchanged periods of fallow, one with a two year increase of the fallow periods, no matter what the present day fallow period in the site was, and one scenario with a two year decrease in fallow periods, also in relation to present day fallow period in that site. The results of these scenarios, over a hundred years period, were that an increased fallow period decreased the carbon content, while a decreased fallow period gave increased carbon content (fig

6.3). The reasons for this are that the addition of nutrients through manure, which takes place when the fields are cultivated, has a larger impact on the carbon content than the fallow periods, which still are relatively short.

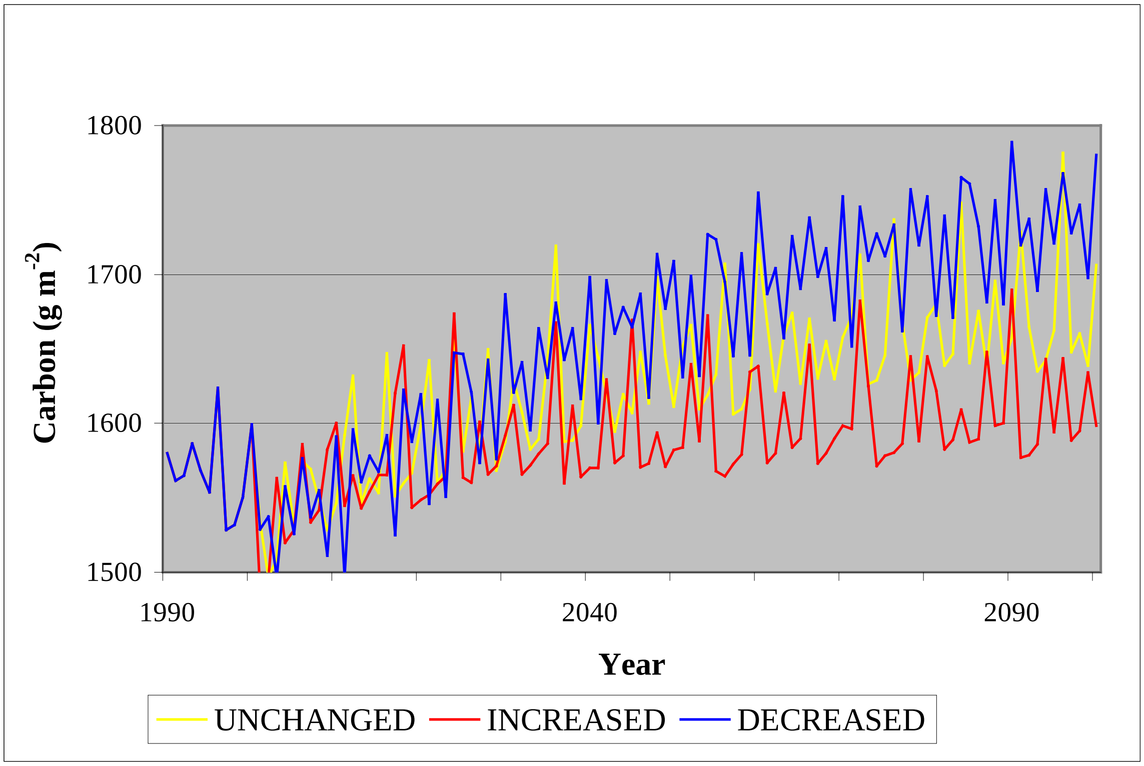

Figure 6.3. *Simulated carbon content according to three different scenarios: unchanged fallow periods, fallow periods increased with two years and fallow periods decreased with two year, from year 2000 to 2100*

Grazing intensity and nitrogen input during soil development exert important influence over contemporary organic matter levels (Parton *et al*., 1988). There are no sources of data from which one can estimate the history of pre-settlement grazing intensity or nitrogen input rate by region in Ghana. Although we used reasonable assumptions, uncertainty resulting from site history cannot be eliminated. Parton *et al*. (1988) showed that steady-state SOM, carbon, and nitrogen levels were very sensitive to grazing levels. The SOM level dropped by 40% as the simulated grazing level increased from zero to 50% of annual production.

6.2.2 Comparisons between Observed and Simulated Carbon Content

Class I

Class I showed no correlation between simulated and observed carbon contents. This can be explained by a lack of information used as input in CENTURY.

Class II

Compared to the observed values the model levelled out simulated carbon contents in class II. Bulk density and soil texture were the only input variables changed. The fluctuations in the simulated values responded to changes in these. The highest measured bulk density was taken at site 59. The low content of fine material in this sample indicated that a big fraction in this soil consisted of particles >2 mm. Sample sites 41-45 had carbon contents close to the carbon content at the sites 55-59, but a lower bulk density and a soil consisting mainly of finer particles, <2 mm in size. Therefore, there may be other factors that have bigger influence on the carbon content than soil texture. Some of these may be plant nitrogen, phosphorus, and sulphur content, lignin content of plant material, atmospheric and soil nitrogen inputs, and initial soil carbon and nitrogen levels. No available data on this was found. Thus, the response of these could not be tested.

Class II, uncultivated areas, were in most of the cases forest reserves. The lack of data of the history of these can be a significant source to the low correlated values. For our area, the only usable tree genus in CENTURY was acacia. Acacia did not seem to be common in this area, but a few other deciduous trees were growing in this class.

Class III

The only class that had correlated values in observed and simulated carbon was class III. The changes in carbon between the sites corresponded well with changes in crop, bulk density, soil texture, fallow periods, and fertilisers. There were however some extremes which contributed to the weak correlation. Information from these sites has probably been overseen and has therefore not been used as input in CENTURY. It seems though, that the high values in observed carbon are deviants in class III as a total. The same information was used at sample sites 80-83, but whereas site 80 received a very high correlated value, sites 81-83 got very low values.

At sites 77-79 cowpeas had been grown, but since these could not be used as input in CENTURY, soybean was used instead. This factor, together with overseen information could have contributed to the errors.

6.2.3 Factors Influencing the Carbon Content in CENTURY

Bulk Density

In CENTURY the bulk density has a big impact on the carbon content and highly significant correlation was found in classes I and II, but not in class III. Soil bulk density values are needed to be able to accurately assess element loss. Organic matter losses were, according to a study made by Cole *et al*. (1989), in percentage loss always greater in sandy soils and always greater under alternate wheat-fallow than under continuous cultivation in agreement with historical records.

Soil Texture

The content of clay plus silt did, in our samples, correlate with the carbon content in classes I and II. The fine silt and course clay particle-size soil fractions contain the old organic matter. The slow SOM is primarily found in the sand and coarse silt soil fractions, and the fine clay contains the active SOM fraction (Parton *et al*., 1988).

CENTURY tends, according to Parton *et al*. (1988), to overestimate the soil carbon levels for fine-textured soils, underestimate the values for sandy soils, and does perfect simulations in medium-textured soils. This correspond to our results where CENTURY overestimated the carbon content in class III and underestimated the carbon content in both class I and class II.

6.2.4 Model Validation

Comparisons between Studies Performed with the CENTURY Model

It is likely that the low correlation found between simulated and observed carbon was caused by the fact that CENTURY demands more modifications of the input values according to local conditions. This may be true at a local scale but may be different at a global scale. CENTURY was developed for predictions of long-term changes in carbon storage and productivity of U.S. soils, affected by changes in climate and management (Metherell, 1993). It has in many studies (Cole *et al.*, 1989; Cole *et al.*, 1993; Ihori *et al.*, 1995; Parton *et al.*, 1987; Parton *et al.*,1989) been validated against data for the Great Plains in the United States. There may be differences in importance of input variables between different climatic regions. Depending on land use, different amounts of driving variables are required to characterise a site (Parton *et al.*, 1988). The input modifications seemed to be sufficient in class III but not in classes I and II. The applicability of the model is limited by the data availability. The model's ability to predict SOM levels is limited by its sensibility to several factors for which data is difficult or impossible to obtain (Parton *et al*., 1988).

The low determination coefficients in our study (0.002 in class I, 0.07 in class II, and 0.187 in class III) can be compared with results from studies performed for a regional or global dataset. Comparisons between observed and simulated SOC in a central grassland region in the United States showed that the model did a reasonable job of fitting the observed data, with observed versus simulated r^2 of 0.6 for soil carbon levels (Parton *et al*., 1989). CENTURY model estimates showed, in a study for the same region performed by Ihori *et al.* (1995), no significant correlation to observed data but tended to overestimate the SOM. Losses in the fields were much more variable than simulated losses, probably because historical cultivation practices varied significantly at a local scale. The simulations represented identical management and resulted in similar losses across sites. The model has previously compared well with a large-scale, regional analysis of SOM losses in the central grasslands, which suggests that the model represents regional trends but requires accurate site-specific management information to adequately simulate variation across a smaller region.

A study performed by Parton *et al*. (1993) for a global data set of grasslands, resulted in well-simulated carbon contents (r^2=0.93). The soil carbon levels were ranging from less than 2000 g C m^{-2} in Lamto, Ivory Coast, to greater than 10,000 g C m^{-2} in Kursk, Russia. They used the assumptions that clay has an impact on passive SOM and silt plus clay have an impact on slow SOM. This assumption seemed to work across the diverse set of soil textures and soil mineralogies. All of the simulated carbon contents had errors less than ± 25% of the observed values. Lack of historical data for land use, grazing, vegetation, fires, initial carbon content and climate were large sources of error. This error can be compared with the errors in our results of 10-67%, depending on class.

6.3 Sources of Error in Method

6.3.1 Field Work

More than one triangulation point would probably have resulted in a better correction. Inaccuracies in the relationship between the global coordinate system and the Ghana National Grid could have caused this displacement towards northeast. Inaccuracies in the GPS receiver and lack of differentiation can also have been a cause. The reasons for errors in position of sites, according to road and soil maps, besides from GPS errors, might be inaccuracies in the maps.

The number of soil samples for the carbon content determination, based on the theory by Garten & Wullschleger (1999), seemed to give reasonable results. The sampling areas were rather limited why a pre-assigned randomly chosen site would have been difficult to locate with a GPS. More bulk density samples would have given more accurate values since many of the sites were assigned a value based on the nearest sampled bulk density. The bulk density is usually measured with a cylinder volumeter (DQR, 1993), but we used a simplified model. Soil packing and loss might have occurred when taking the samples. The depth of the soil samples could have varied due to irregularities of the soil surface. In the removal of the surface plant residues different amounts might have been left.

The farmers provided the information needed in the model concerning crop, irrigation, and fertilisation. Language difficulties made it sometimes hard to obtain this information and assess the accuracy. More detailed information regarding irrigation and fertilisation could have improved the accuracy of the resulting carbon content.

6.3.2 Laboratory Work

In soil texture analyses the different fractions are supposed to be separated by use of a sieve shaker, but this had to be done manually, which may have decreased the fraction of fine particles. There was no access to water in the soil lab in Manga, which complicated the wet sieving. The limited amount of water, brought there by us, could have been insufficient for removing of silt and clay. The transfer between bowls can also have caused errors in soil fractions.

In the Carbon Sulphur Determination apparatus the weight of the sample was taken into consideration and therefore affected the carbon output. It is possible that excessive air currents, vibration, temperature or humidity influenced the scale performance. The frequent calibrations minimised the errors.

6.3.3 Modelling

If the history of each field had been available, more accurate results would have been achieved. The climate data used for the modelling was present day climate and actual fluctuations during the simulation time were therefore not reflected in the results. The climate data was the same for all the classes even though there is a large spatial variability in precipitation. The frequency and intensity of fires, both those with natural and anthropogenic origin, were estimated from field observations and information from the locals. No data with this information was available for Ghana.

Since just 30 samples were taken in each class, the extremes can be representative for the class and largely affect the results.

A negative aspect with CENTURY is that references to parameterisation values are often missing in the manual, and thus complicates the usage of the model.

6.4 Future Perspectives and Research Needs

Climate related catastrophes have made climatic research highly topical. Within EU a big venture at the research about carbon and climate is going on. It will be carried out during the next three years and the national efforts are enhanced. In Sweden, more forests will be investigated to examine, for instance, the significance of the age of the forest in the carbon balance (Morén *et al*., 2000).

Improved qualification of processes where a climate change give rise to release of carbon, is a research priority (Schimel *et al*., 1996). Before ecosystem models can be confidently applied to regional and global analyses, they need to be parameterised and validated with more detailed information and with long-term field experiments (Cole *et al*., 1993). Evolution of the CENTURY model will continue as the understanding of biogeochemical processes improves. The identification of problem areas where processes are not adequately quantified is key to further developments (Metherell *et al*., 1993)

There is no direct information on the impact of the rising carbon dioxide concentrations on primary production, decomposition and herbivore in tropical grasslands and savannas (Scholes and Hall, 1996). Moreover, carbon dioxide fertilisation may result in enhanced carbon storage (Schimel *et al*., 1996). The amount of data on biomass, soil carbon and productivity is gradually improving. At the same time, uncertainties arise because changes in climate are likely to produce changes in the structure of natural and managed ecosystems (Melillo *et al*., 1996). Perhaps the largest single uncertainty in understanding and predicting the carbon budgets for tropical woodlands, savannas, and grasslands is the extent, degree and nature of land use change, along with the human processes which drive it (Scholes & Hall, 1996).

Before the Kyoto Protocol can enter into force the costs for carbon sequestration and an emission trading will have to be taken into consideration. These should include, not only costs for implementation, but also for land and crop maintenance. Availability and suitability of land for carbon sequestration is another subject for improvements. In the case of Ghana, the possibilities and economic consequences of using a carbon trading with the introduction of new land management practises would be an interesting follow-up study. Another idea is to investigate the changes in carbon content, with different types of crop on the same soil type.

7 CONCLUSIONS

Our study shows that soil organic carbon is significantly affected by land use. The carbon content is highest in uncultivated areas. However, the results shows that continuously cultivated fields have a higher carbon content than fields with fallow periods. The water content is higher in continuously cultivated fields than in the other land use classes of the study. Moreover, the carbon content is significantly correlated with water content in all classes. Continuously cultivated fields have a higher content of fine particles, and is the only class in which a significant correlation was found between carbon content and silt, clay, and silt and clay together.

The Upper East Region, like many other semi-arid African areas, suffers from over-cultivation, deforestation, overgrazing, soil degradation, and poor water conservation practices. An additional income from the Clean Development Mechanism could, with careful land use planning, contribute to a more sustainable development. If the Kyoto Protocol enter into force, it is necessary to find accurate methods for measuring carbon sequestration and to understand the global carbon dioxide- and the global carbon cycle. One approach is the use of the CENTURY model.

The results from this study demonstrate the effect of land use and the impact of known data at simulated soil organic carbon content. The model underestimated the carbon content in continuously cultivated fields and in uncultivated areas, and showed no significant correlation with observed carbon content. The carbon content in field was much more variable than simulated carbon content. The use of too many, in CENTURY standardized input parameters, and the absence of historic data, may partially explain the difference in magnitude of soil organic carbon, and within the sample sites in undisturbed areas, the similar carbon content. CENTURY overestimated the carbon content in fallow-areas with 10%, but the carbon content was significantly correlated with observed carbon. Introduction of manure increased carbon levels, and exert an important influence over soil organic carbon. Soil texture has a large impact on simulated carbon content, which is proved by the correlation between carbon content and all different soil fractions, except in fields with crop-fallow.

The conclusion of our results is that simulations with CENTURY, using available data, are not suitable for estimations of carbon content in an environment with this high application of manure, since the model only could estimate true content in one of the three land use classes. The credibility of the correlation between observed and simulated carbon content is reflected by gathered information, by the structure of the model or by a combination of them both.

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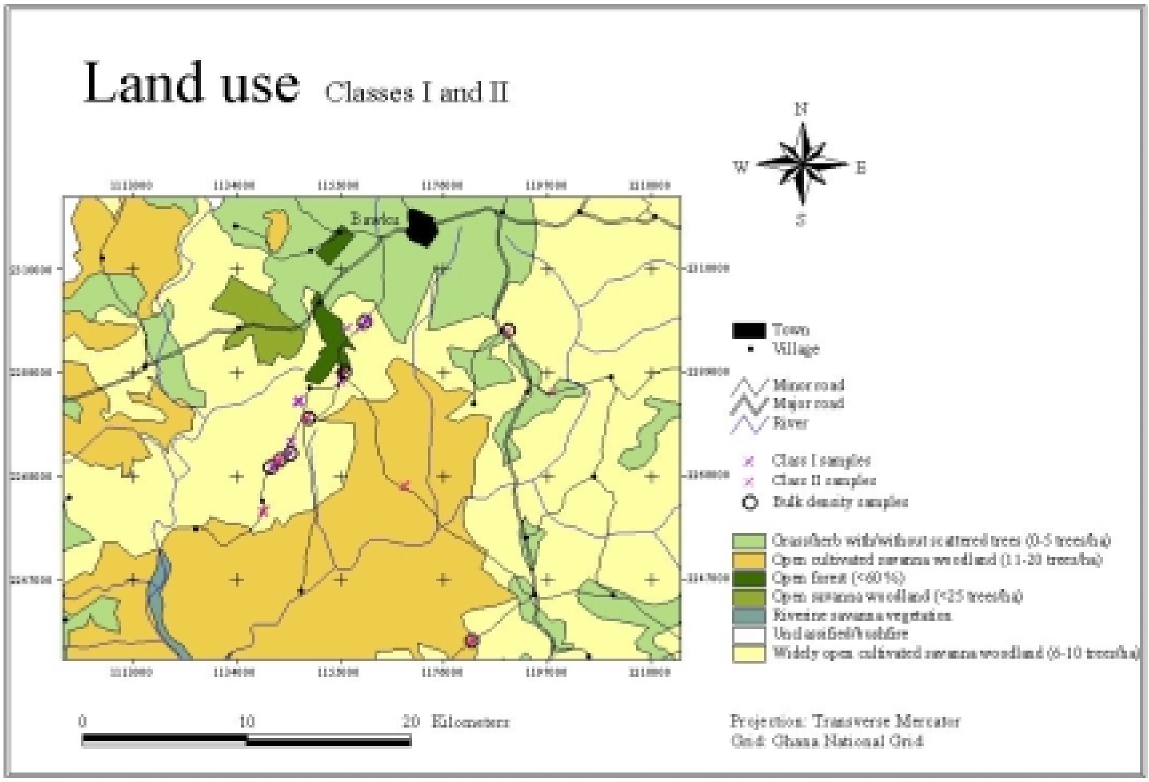
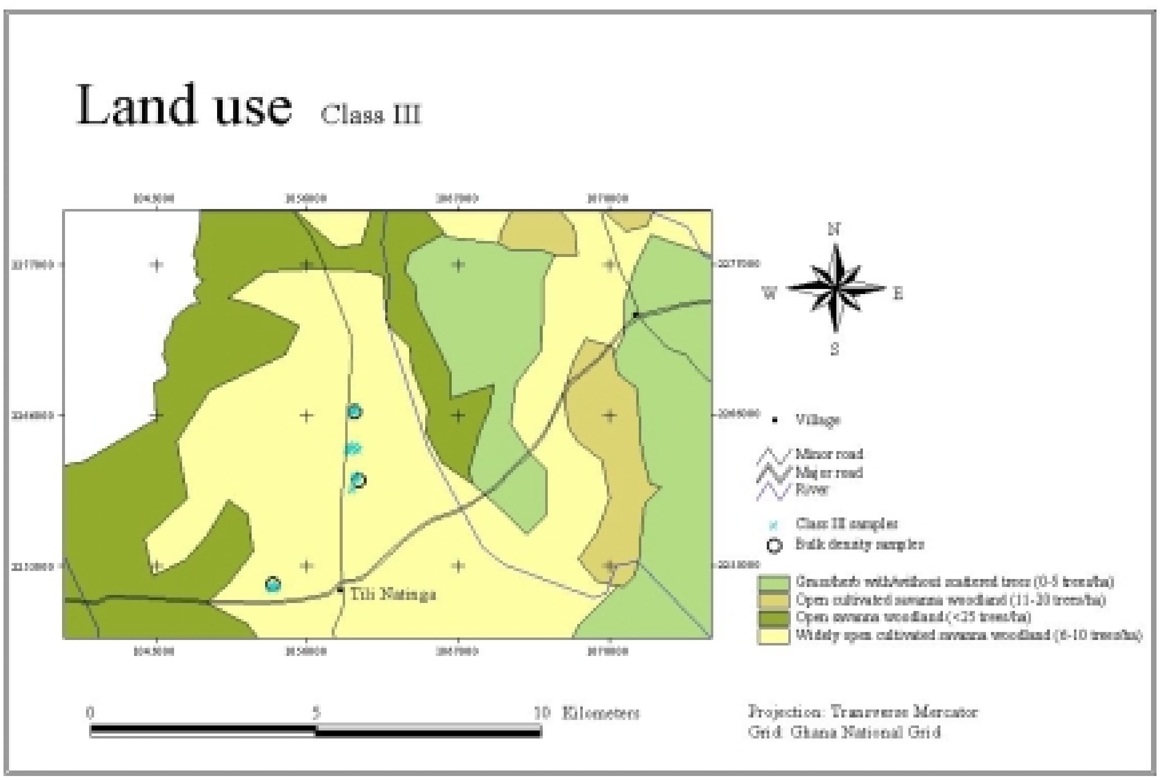
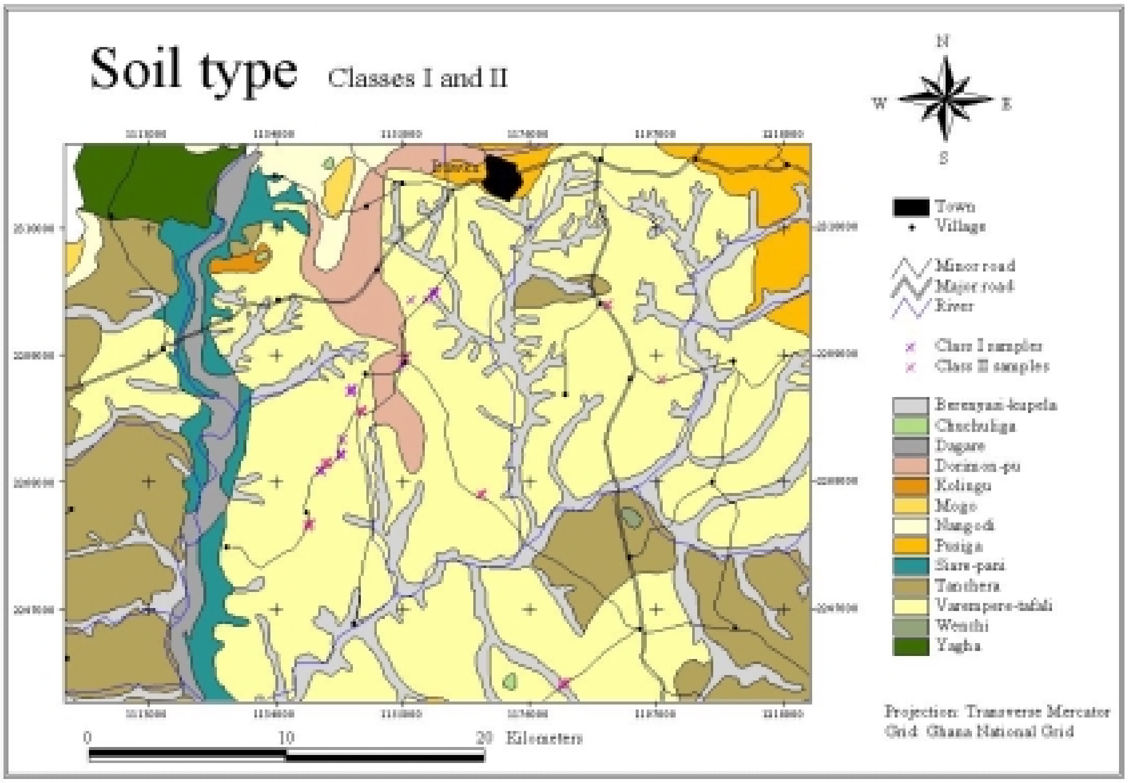
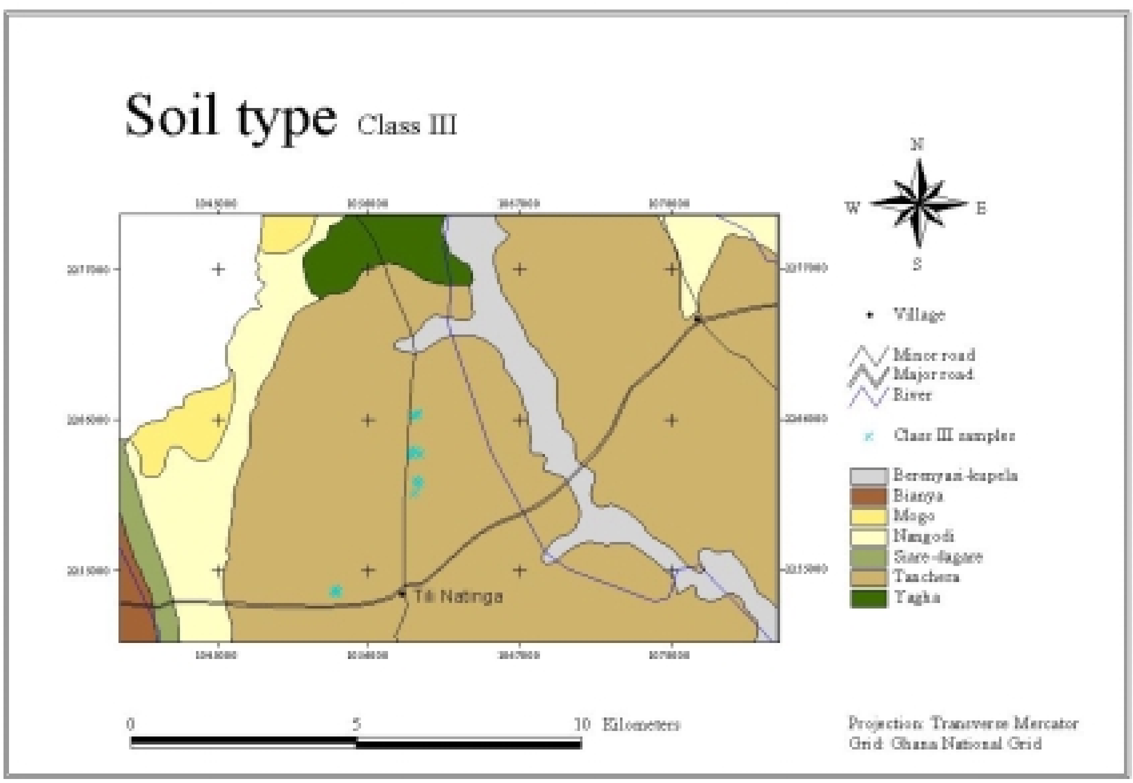
Photos:
Elisabeth Dawidson

APPENDIX I


Land use Classes I and II
N
W
E
S
Bawku
Town
Village
Minor road
Major road
River
Class I samples
Class II samples
Bulk density samples
Grass/herb with/without scattered trees (0-5 trees/ha)
Open cultivated savanna woodland (11-20 trees/ha)
Open forest (<60%)
Open savanna woodland (<25 trees/ha)
Riverine savanna vegetation
Unclassified/bushfire
Widely open cultivated savanna woodland (6-10 trees/ha)
0
10
20 Kilometers
Projection: Transverse Mercator
Grid: Ghana National Grid


Land use Class III
N
W
E
S
Village
Minor road
Major road
River
Class III samples
Bulk density samples
Tili Natinga
Grass/herb with/without scattered trees (0-5 trees/ha)
Open cultivated savanna woodland (11-20 trees/ha)
Open savanna woodland (<25 trees/ha)
Widely open cultivated savanna woodland (6-10 trees/ha)
0
5
10 Kilometers
Projection: Transverse Mercator
Grid: Ghana National Grid


Soil type Classes I and II
N
W
E
S
Town
Village
Minor road
Major road
River
Class I samples
Class II samples
Berenyasi-kupela
Chuchuliga
Dagare
Dorimon-pu
Kolingu
Mogo
Nangodi
Pusiga
Siare-pani
Tanchera
Varempere-tafali
Wenchi
Yagha
Projection: Transverse Mercator
Grid: Ghana National Grid
0
10
20 Kilometers


Soil type Class III
N
W
E
S
Village
Minor road
Major road
River
Class III samples
Berenyasi-kupela
Bianya
Mogo
Nangodi
Siare-dagare
Tanchera
Yagha
Tili Natinga
0
5
10 Kilometers
Projection: Transverse Mercator
Grid: Ghana National Grid

APPENDIX II

Gathered information, through maps and field work, for each sample site.

Class	Sample	Land Use	Crop	Fertilisation	Irri.	Soil Type	Water (%)	Density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)
I	2	Cont. Cultivation	soybean, millet	manure	no	Varempere-tafali	0.007	1.7	41.9	8.7	0.2
I	3	Cont. Cultivation	soybean, millet	manure	no	Varempere-tafali	0.007	1.7	41.9	8.7	0.2
I	4	Cont. Cultivation	sorghum, millet	manure	no	Varempere-tafali	0.008	1.7	41.9	8.7	0.2
I	5	Cont. Cultivation	sorghum, millet	manure	no	Varempere-tafali	0.009	1.7	41.9	8.7	0.2
I	6	Cont. Cultivation	sorghum, millet	manure	no	Varempere-tafali	0.015	1.7	41.9	8.7	0.2
I	7	Cont. Cultivation	sorghum, millet	manure	no	Varempere-tafali	0.021	1.7	41.9	8.7	0.2
I	8	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.044	1.7	41.9	8.7	0.2
I	10	Cont. Cultivation	sorghum, guinea corn	manure	no	Varempere-tafali	0.007	1.7	41.9	8.7	0.2
I	11	Cont. Cultivation	sorghum, guinea corn	manure	no	Varempere-tafali	0.004	1.7	41.9	8.7	0.2
I	12	Cont. Cultivation	sorghum, guinea corn	manure	no	Varempere-tafali	0.003	1.7	41.9	8.7	0.2
I	13	Cont. Cultivation	sorgum, millet	manure	yes	Varempere-tafali	0.028	1.5	60.3	21.5	0.9
I	14	Cont. Cultivation	millet	manure	yes	Varempere-tafali	0.016	1.5	60.3	21.5	0.9
I	15	Cont. Cultivation	millet	manure	yes	Varempere-tafali	0.012	1.5	60.3	21.5	0.9
I	16	Cont. Cultivation	millet	manure	no	Varempere-tafali	0.013	1.5	60.3	21.5	0.9
I	17	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.002	1.5	60.3	21.5	0.9
I	18	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.013	1.5	60.3	21.5	0.9
I	19	Cont. Cultivation	millet	manure	yes	Varempere-tafali	0.017	1.5	60.3	21.5	0.9
I	20	Cont. Cultivation	millet	manure	yes	Varempere-tafali	0.011	1.5	60.3	21.5	0.9
I	21	Cont. Cultivation	sorgum	manure	yes	Varempere-tafali	0.015	1.5	60.3	21.5	0.9
I	22	Cont. Cultivation	sorgum	manure	yes	Varempere-tafali	0.017	1.5	60.3	21.5	0.9
I	23	Cont. Cultivation	sorgum	manure	yes	Varempere-tafali	0.030	1.5	60.3	21.5	0.9
I	24	Cont. Cultivation	millet	manure	no	Varempere-tafali	0.004	1.5	60.3	21.5	0.9
I	25	Cont. Cultivation	millet	manure	no	Varempere-tafali	0.012	1.5	60.3	21.5	0.9
I	26	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.011	1.5	60.3	21.5	0.9
I	27	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.010	1.5	60.3	21.5	0.9
I	28	Cont. Cultivation	millet	manure	no	Varempere-tafali	0.012	1.7	44.0	17.5	0.6
I	29	Cont. Cultivation	millet	manure	no	Varempere-tafali	0.019	1.7	44.0	17.5	0.6
I	30	Cont. Cultivation	millet	manure	no	Varempere-tafali	0.018	1.7	44.0	17.5	0.6
I	31	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.024	1.7	44.0	17.5	0.6
I	32	Cont. Cultivation	sorghum	manure	no	Varempere-tafali	0.011	1.7	44.0	17.5	0.6

Class	Sample	Land Use	Coverage (trees are^{-1})	Soil Type	Water (%)	Density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)
*	34	uncultivated	4	Dorimon-pu	0.008	1.5	75.2	9.6	1.2
*	35	uncultivated	4	Dorimon-pu	0.005	1.5	75.2	9.6	1.2
*	36	uncultivated	4	Dorimon-pu	0.016	1.5	75.2	9.6	1.2
*	37	uncultivated	4	Dorimon-pu	0.013	1.5	75.2	9.6	1.2
*	38	uncultivated	4	Dorimon-pu	0.009	1.5	75.2	9.6	1.2
*	39	uncultivated	4	Dorimon-pu	0.005	1.5	75.2	9.6	1.2
*	40	uncultivated	4	Dorimon-pu	0.039	1.5	75.2	9.6	1.2
II	41	uncultivated	groves	Varempere-tafali	0.021	1.7	40.3	8.9	0.4
II	42	uncultivated	groves	Varempere-tafali	0.028	1.7	40.3	8.9	0.4
II	43	uncultivated	4	Varempere-tafali	0.014	1.7	40.3	8.9	0.4
II	44	uncultivated	4	Varempere-tafali	0.016	1.7	40.3	8.9	0.4
II	45	uncultivated	4	Varempere-tafali	0.061	1.7	40.3	8.9	0.4
II	46	uncultivated	6	Varempere-tafali	0.005	1.6	78.6	9.6	0.6
II	47	uncultivated	6	Varempere-tafali	0.011	1.6	78.6	9.6	0.6
II	48	uncultivated	>6	Varempere-tafali	0.007	1.6	78.6	9.6	0.6
II	49	uncultivated	>6	Varempere-tafali	0.018	1.6	78.6	9.6	0.6
II	50	uncultivated	>6	Varempere-tafali	0.011	1.6	78.6	9.6	0.6
II	51	uncultivated	7	Varempere-tafali	0.023	1.6	78.0	8.4	0.5
II	52	uncultivated	7	Varempere-tafali	0.028	1.6	78.0	8.4	0.5
II	53	uncultivated	7	Varempere-tafali	0.032	1.6	78.0	8.4	0.5
II	54	uncultivated	7	Varempere-tafali	0.002	1.6	78.0	8.4	0.5
II	55	uncultivated	5	Varempere-tafali	0.003	1.8	78.0	8.4	0.0
II	56	uncultivated	5	Varempere-tafali	0.030	1.8	78.0	8.4	0.0
II	57	uncultivated	5	Varempere-tafali	0.040	1.8	78.0	8.4	0.0
II	58	uncultivated	5	Varempere-tafali	0.026	1.8	78.0	8.4	0.0
II	59	uncultivated	5	Varempere-tafali	0.026	1.8	78.0	8.4	0.0
II	60	uncultivated	100	Varempere-tafali	0.015	1.7	77.5	7.1	0.3
II	61	uncultivated	100	Varempere-tafali	0.032	1.7	77.5	7.1	0.3
II	62	uncultivated	100	Varempere-tafali	0.027	1.7	77.5	7.1	0.3
II	63	uncultivated	100	Varempere-tafali	0.005	1.7	77.5	7.1	0.3
II	64	uncultivated	100	Varempere-tafali	0.020	1.7	77.5	7.1	0.3
II	65	uncultivated	100	Varempere-tafali	0.011	1.7	77.5	7.1	0.3
II	66	uncultivated	5	Varempere-tafali	0.009	1.7	77.5	7.1	0.3
II	67	uncultivated	5	Varempere-tafali	0.013	1.7	77.5	7.1	0.3
II	68	uncultivated	5	Varempere-tafali	0.015	1.7	77.5	7.1	0.3
II	69	uncultivated	5	Varempere-tafali	0.035	1.7	77.5	7.1	0.3
II	70	uncultivated	5	Varempere-tafali	0.020	1.7	77.5	7.1	0.3

Class	Sample	Land Use	Crop	Fallow (yrs)	Fertilisation	Irri.	Soil Type	Water (%)	(g cm^{-3})	Sand (%)	Silt (%)	Clay (%)
III	71	crop-fallow	maize, groundnut, guinea corn	4	manure	no	Tanchera	0.004	1.5	83.3	8.9	0.7
III	72	crop-fallow	maize, groundnut, guinea corn	4	manure	no	Tanchera	0.003	1.5	83.3	8.9	0.7
III	73	crop-fallow	maize, groundnut, guinea corn	4	manure	no	Tanchera	0.005	1.5	83.3	8.9	0.7
III	74	crop-fallow	maize, groundnut, guinea corn	4	manure	no	Tanchera	0.002	1.5	83.3	8.9	0.7
III	75	crop-fallow	maize, groundnut, guinea corn	4	manure	no	Tanchera	0.013	1.5	83.3	8.9	0.7
III	76	crop-fallow	maize, groundnut, guinea corn	4	manure	no	Tanchera	0.004	1.5	83.3	8.9	0.7
III	77	crop-fallow	cowpea	2	manure	no	Tanchera	0.004	1.5	83.3	8.9	0.7
III	78	crop-fallow	cowpea	2	manure	no	Tanchera	0.009	1.5	83.3	8.9	0.7
III	79	crop-fallow	cowpea	2	manure	no	Tanchera	0.010	1.5	83.3	8.9	0.7
III	80	crop-fallow	soybean, maize, groundnut	3	manure	no	Tanchera	0.006	1.6	79.3	14.9	0.6
III	81	crop-fallow	soybean, maize, groundnut	3	manure	no	Tanchera	0.002	1.6	79.3	14.9	0.6
III	82	crop-fallow	soybean, maize, groundnut	3	manure	no	Tanchera	0.001	1.6	79.3	14.9	0.6
III	83	crop-fallow	soybean, maize, groundnut	3	manure	no	Tanchera	0.005	1.6	79.3	14.9	0.6
III	84	crop-fallow	guinea corn, maize	6	manure	no	Tanchera	0.002	1.6	79.3	14.9	0.6
III	85	crop-fallow	guinea corn, maize	6	manure	no	Tanchera	0.005	1.6	79.3	14.9	0.6
III	86	crop-fallow	maize	4	manure	no	Tanchera	0.002	1.6	76.0	13.2	0.3
III	87	crop-fallow	maize	4	manure	no	Tanchera	0.001	1.6	76.0	13.2	0.3
III	88	crop-fallow	maize	4	manure	no	Tanchera	0.003	1.6	76.0	13.2	0.3
III	89	crop-fallow	maize	4	manure	no	Tanchera	0.010	1.6	76.0	13.2	0.3
III	90	crop-fallow	soybean	6	manure	no	Tanchera	0.004	1.6	76.0	13.2	0.3
III	91	crop-fallow	soybean	6	manure	no	Tanchera	0.003	1.6	76.0	13.2	0.3
III	92	crop-fallow	soybean	6	manure	no	Tanchera	0.008	1.6	76.0	13.2	0.3
III	93	crop-fallow	soybean	6	manure	no	Tanchera	0.003	1.6	76.0	13.2	0.3
III	94	crop-fallow	soybean	6	manure	no	Tanchera	0.013	1.6	76.0	13.2	0.3
III	95	crop-fallow	groundnut	4	manure	no	Tanchera	0.044	1.6	72.7	11.5	0.0
III	96	crop-fallow	groundnut	4	manure	no	Tanchera	0.010	1.6	72.7	11.5	0.0
III	97	crop-fallow	groundnut	4	manure	no	Tanchera	0.004	1.6	72.7	11.5	0.0
III	98	crop-fallow	groundnut	4	manure	no	Tanchera	0.010	1.6	72.7	11.5	0.0
III	99	crop-fallow	groundnut	4	manure	no	Tanchera	0.013	1.6	72.7	11.5	0.0
III	100	crop-fallow	groundnut	4	manure	no	Tanchera	0.016	1.6	72.7	11.5	0.0

APPENDIX III

Hydrometer analysis

Amount of soil for hydrometer analysis, chosen by expected clay content (Talme & Almén, 1975):

<10%	100 g
10-15%	75 g
15-25%	50 g
>25%	30 g

Amount of soil for sieving analysis, chosen by sorting grade (Talme & Almén, 1975):
Well sorted and mostly fine particles: 200 g
Well sorted and mostly coarse particles: 300-500 g
Unsorted: 500-800 g

Fraction of particles >2 mm are known from sieving analysis (2 mm sieve) in fields, and where calculated:

$$Particles > 2\,mm\,(\%) = \frac{Weight\ before\ Sieving - Weight\ after\ Sieving}{Weight\ before\ Sieving}$$

Therefore fraction of particles <2 mm could be calculated

$$Fractions\ of\ Particles < 2\,mm = 100 - Fractions\ of\ Particles > 2\,mm$$

as well as the weight of these particles

$$Weights\ of\ Particles < 2\,mm = Fractions\ of\ Particles < 2\,mm \times Total\ Sample\ Weight$$

Fractions of sand, silt and clay within the sample (containing only these fractions) were determined through the hydrometer analysis. The observed results were plotted in a graph were the fraction of each particle size can be determined. Through these known fractions the weight of each particle size could be determined:

$$Weight\ of\ (Sand/Silt/Clay) = Fraction\ of\ (Sand/Silt/Clay) \times Total\ Weight\ of\ (Sand + Silt + Clay)$$

These weights were compared to the total sample weight, containing all fractions of the soil, to get the fraction of sand, silt and clay in the total sample.

$$Fraction\ of\ (Sand/Silt/Clay) = \frac{Weight\ of\ (Sand/Silt/Clay)}{Weight\ of\ Total\ Sample}$$

APPENDIX IV

Calculations of manure

In the Upper East Region, 3.5 m^{-3} manure is spread at one hectare in a year (Madsen & Flemming, 1991). We assumed that all of this manure came from cattle. Assuming the density for manure is 0.8 kg l^{-1}, the amount manure spread in a year at one hectare (kg ha^{-1}) is:

$$3.5 \times 1000 \times 0.8 = 2800$$

Hence, the amount of manure per square metre (kg m^2) is:

$$\frac{2800}{10000} = 0.28$$

Excreta from 49 poultry equal the amount produced by one cow a year (Dawidson, 2000). We assumed that each farmer had 12 poultry. The total amount of manure (kg m^2) produced by these poultry is:

$$\frac{0.28}{49} \times 12 = 0.07$$

Mineral composition in excreta was calculated using data from Kirchmann & Witter (1992) (table IV.I).

Table IV.I. *Mean values of mineral composition of fresh, aerobically, and anaerobically animal dung (Kirchmann & Witter, 1992).*

Mineral composition	Cattle (mg g^{-1} dry matter)	Poultry (mg g^{-1} dry matter)
P	9.56	25.43
S	3.86	6.16
N	31.6	47.36

Amount of phosphorous (g) in cattle dung:

$$\frac{9.56}{1000} = 9.56 \times 10^{-3}$$

The calculated amount of manure from cattle, in g m^{-2}:

$$0.28 \times 1000 = 280$$

Amount of phosphorous in the manure (g m^{-2}):

$$9.56 \times 10^{-3} \times 280 = 2.68$$

The corresponding calculations were done to determine the amount of sulphur and nitrogen in the manure. In the same way the amount of phosphorous, sulphur and nitrogen in the poultry manure were calculated. Table IV.II shows the results of these calculations.

Table IV.II. *Mineral composition in manure applied on the fields in Upper East Region.*

Mineral composition	**Cattle (mg g^{-1} dry matter)**	**Poultry (mg g^{-1} dry matter)**
P	2.67	1.78
S	1.80	0.43
N	8.85	3.32

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