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The Status of Soil Organic Carbon under Indigenous forests, Grasslands, Wetlands and Pine Plantations in Woodbush, Limpopo Province, South Africa.

By

Hlamalani Godfrey Mongwe

Bsc. Agric (UNIN)

Submitted in partial fulfilment of the requirements for the degree of

Master of Science (Agriculture) In the

Department of Soil Science

Faculty of Agriculture and Forestry

November 2004

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Declaration

I the undersigned, hereby declare that the work contained in this thesis is my own work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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Summary

Storing soil organic carbon (SOC) is a possible way of reducing atmospheric CO_2 and potentially mitigating the effects of global warming. This study looks at soil carbon stocks, the sampling methodology and modelling of soil organic carbon in indigenous forests, wetlands, grasslands and pine plantations in Woodbush in the North-Eastern escarpment of Limpopo Province, South Africa. Dominant Pine species planted in Woodbush are *Pinus patula*, *Pinus elliotti* and *Pinus taeda*. Woodbush plantation was selected as study area because it provided easy access to all the ecosystems that were to be studied. All ecosystems in Woodbush are located in such a way that it was easy to compare them, as they existed under similar environmental and climatic conditions. The climatic conditions of Woodbush promote accumulation of SOC due to relatively higher precipitation and cooler temperatures than most parts of Limpopo Province.

Five transects were made: two in indigenous forests and three in plantations. Only the surface (0-7 cm) layer was sampled with a distance of 20 m between sampling points. Transects were not made in grasslands and wetlands because of the patchy occurrence of these ecosystems. In addition to transects, eight 1ha plots, two in each ecosystem, were sampled. Surface (0-7 cm depth) samples were collected on a grid of 20 x 20 m in each sampling plot. Two soil profile pits were sampled in each sampling plot, with samples being taken at 5, 10, 15, 20 30, 40, 50 60, 75 and 100 cm depth.

The average carbon stocks per hectare of land to a soil depth of 100 cm were as follows: 71 $t.ha^{-1}$ in wetlands, 28 $t.ha^{-1}$ in grasslands, 64 $t.ha^{-1}$in indigenous

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forests, and 46 $t.ha^{-1}$ in pine plantations. Although wetlands sequestered large amounts of SOC per hectare, their relative contribution to carbon sequestration was low because of the relatively small area (87.2 ha) they occupy in the study area (and in South Africa).

Prediction models for vertical distribution of SOC were developed using STATISTICA 6.0 for each ecosystem in order to estimate the carbon stocks to a depth of 100 cm based on SOC content and soil bulk density of the surface samples. These models were developed from observed values in soil profiles for each ecosystem.

SOC content and carbon stocks were analyzed using GIS (ARCVIEW). The GIS analysis was aimed at assessing the effect of topography, elevation, soil type, and vegetation on accumulation and distribution of SOC stocks. Most shallow Inanda soils were distributed at elevations between 1545 m and 1777 m, and on a gentle slope in the Northern aspect of the mountain. Deep Inanda soils were found mostly in the lower elevation range of 967 m and 1545 m on moderate slopes. Deep and shallow Inanda soils were found on the southern aspect.

Deep Kranskop soils are evenly distributed and mostly found at an elevation range of between 1080 and 1430 m on gentle slopes, while at an elevation range of between 1430 and 1780 m, they were found on moderate slopes. Deep soils had higher SOC stocks than shallow soils and soils in the southern aspects had higher SOC stocks than in the northern aspects.

Opsomming

Die berging van grond organiese koolstof is ‘n moontlike manier om atmosferiese koolsuurgas (CO_2) te verminder en dus om die invloed van globale verwarming te versag. In hierdie studie was die grond-koolstof voorraad bestudeer, asook die metodologie van die monsterneming en modellering van organiese grond-koolstof van inheemse woude, vleie, grasvelde en denneplantasies. Die studie was uitgevoer op Woodbush plantasie geleẻ op die Noord-Oosterlike platorand van die Limpopo Provinsie, Suid-Afrika. Die algemeenste dennespesies in Woodbush is *Pinus patula, Pinus elliotti* en *Pinus taeda.* Die Woodbush plantasie was gekies as studiegebied omdat dit oor al die ekosisteme wat bestudeer moet word, beskik. Die ekosisteme in Woodbush is naby mekaar en dus maklik vergelykbaar want die omgewings- en klimaatstoestande is eenders. Die klimaatstoestande van Woodbush bevorder die akkumulasie van grond organiese koolstof omdat die reënval hoër en die temperature laer is as in die meeste ander dele van die Limpopo Provinsie.

Vyf dwarssnitte was gemaak, twee in inheemse woude en drie in plantasies. Monsters was net uit die grondoppervlak laag geneem (7 cm) met 20 m tussen monsterpunte. Dwarssnitte was nie in grasvelde en vleie gemaak nie want hierdie sisteme is te gelokaliseerd. Monsters was ook geneem in agt 1 ha persele, twee in elke ekosisteem. Oppervlakmonsters (tot ‘n diepte van 7 cm) is op ‘n ruitnet van 20 x 20 m uit elke perseel versamel. Monsters was verder ook geneem uit twee profielgate per perseel, op dieptes 5, 10, 15, 20, 30, 40, 50, 60, 75 en 100 cm.

Die gemiddelde koolstof voorraad per hektaar, op ‘n gronddiepte van 100 cm, was as volg: 71 $t.ha^{-1}$ in vleie, 28 $t.ha^{-1}$ in grasvelde, 64 $t.ha^{-1}$ in inheemse woude en 46 $t.ha^{-1}$ in denneplantasies. Alhoewel vleie groot hoeveelhede grond organiese koolstof akkumuleer, is hulle bydrae tot koolstof akkumulasie laag want hulle beslaan ‘n klein oppervlak binne die studiegebied (87.2 ha) asook klein oppervlaktes binne Suid-Afrika.

Voorspellingsmodelle vir die vertikale verspreiding van grondkoolstof was met die gebruik van STATISTICA 6.0 ontwikkel ten einde te skat wat die koolstofvoorrraad op ‘n diepte van 100 cm was. Die skattings was gebaseer op organiese grondkoolstofinhoud en die gronddigtheid van oppervlakmonsters. Hierdie modelle was ontwikkel vanaf die waargenome waardes van grondprofiele vir elke ekosisteem.

Die organiese koolstofinhoud van die grond en die koolstofvoorraad is ontleed met behulp van GIS (ARCVIEW). Die GIS ontleding was daarop gemik om die effek van topografie, hoogte bo seespiëel, grondtipe en plantegroei, op die akkumulasie en verspreiding van organiese grondkoolstof, te beraam. Die meeste vlak Inanda grondvorms kom voor tussen 1545 m en 1777 m bo seespiëel, asook op effens steil hellings op die Noordelike berghang. Die diep Inanda grondvorms is geleë op laer hoogtes bo seespiëel, gewoonlik tussen 967 en 1545 m, op effens steil hellings. Beide diep en vlak Inanda gronde word gevind op die suidelike berghang.

Diep Kranskop gronde is eweredig versprei en word gewoonlik tussen 1080 en 1430 m bo seespiëel, op effens steil hellings, gevind. Dit kom ook voor op matig steil hellings, tussen 1430 en 1780 m bo seespiëel. Daar is meer organiese koolstof in diep grond as in vlak grond en meer in gronde teen die suidelike hang as op die noordelike hang.

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ACKNOWLEDGEMENTS

I sincerely would like to thank the following people and institutions for their help during the period of study:

Dr A. Rozanov and Prof M.V. Fey, my promoters for their guidance in project planning, experimental work and the art of scientific investigation as well as the preparation of the manuscript;

Mr W. de Clercq, for helping me with geostatistical analysis and GIS;

Mr Z.R. Nghulele and Mr A. Kunneke for helping me with GIS analysis;

SAFCOL, for allowing me to collect soil samples under their plantations area as well as the data they provided and DWAF, for allowing me to collect soil samples in the indigenous forests, grasslands and wetlands;

NRF and Eskom for the financial support for this study, and finally,

My parents, brothers and sisters for their undying love and support throughout the years I have spent at University.

Pectora roborant cultus recti

Table of content

LIST OF FIGURES

LIST OF TABLE

Pectora roborant cultus recti

List of abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
Cs	Soil organic carbon at the surface
d	Depth
Df	Degree of freedom
BD/D_b	Bulk density
ESD	Effective soil depth
GIS	Geographic information system
GCC	Global climate change
ha	Hectare
KCl	Potassium chloride
Lf	Light fraction
MS	Mean Square
NETL	National Energy Technology Laboratory
NO	Nitrogen oxide
SAFCOL	South African Forestry Company Limited
SIC	Soil inorganic carbon
SOC	Soil organic carbon

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SOM	Soil organic matter
SS	Sum of Squares
StDev	Standard deviation
t	tone
TRF	Tropical rain forest

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1. Introduction

Commercial afforestation began in South Africa at the end of the 19th century (Donald and Ellis, 1992), and plantations have over the years increased in importance. The production of industrial wood was a common goal, but planted trees are also used for domestic wood, shelter and other amenities in rural communities.

South Africa has a total land area of 122.3 million hectares (Keletwang and Semelane, 1998). About 300 000 hectares are protected forest areas of which 58% are in the state forest and 42% in other legally protected areas. About 1.48 million hectares are industrial plantations managed for sustainable production. The plantations in South Africa are located where climatic conditions are suitable for afforestation. About 41% of plantations are found in Mpumalanga, 37% in Kwazulu Natal, 11% in the Eastern Cape and 6% in the Western Cape. There are afforested areas in Limpopo Province that are small in scale and were not included by Keletwang and Semelane (1998) in their report and that make up the remaining 5%.

The South African case study by Christie and Scholes (1995) showed that new afforestation stored approximately 2.54 Tg C in 1990, and storage in forest products accounted for an additional 1.15 Tg C. Together, these two activities offset approximately 3.8% of the carbon dioxide emissions from South Africa. These estimations do not take into account the contributions made by the soils under the plantations. However, according to some estimates (Lal *et al.*, 1998), in tropical forests almost half of the total ecosystem carbon is stored in the soil and it is important to include this pool in the carbon accounting system, provided a reliable monitoring method is available. Forestry is recognized as one of the main land use options for carbon sequestration and the South African forestry industry may benefit from it through the proposed carbon budget.

Soil organic carbon stocks vary widely, depending on bioclimatic and topographic conditions and may be influenced by land use practices over time. The nature of the variation resulting from these factors at a large scale is largely reported and documented, but the precision of these estimates may be insufficient for local monitoring of SOC at forestry level.

Current maps and databases available in the South African forestry industry provide detailed information on soils. However, it might be difficult to use this information for detailed carbon estimation other than for site classification, because the estimation of SOC done in the field is guided by laboratory results from limited soil samples taken from different landscape positions and aspects. Soil classification in the South African forestry is aimed at serving as a basis for productivity prediction, nutrient management, sensitivity analysis and other various applications. The main soil properties that are used for such decisions are among others, total soil depth, effective soil depth, estimation of soil organic matter content, structure and texture.

The amount of soil organic carbon is only visually estimated in the top soil and recorded semi quantitatively as extremely high, very high, high, medium to high, medium, medium to low, and low. Limited soil samples are collected and sent to the laboratory for organic carbon analysis. As a result, the databases have insufficient information on organic carbon and its spatial distribution.

A map (Figure 1.1) of organic carbon distribution was created using SAFCOL soil database for Woodbush plantation in which the data was estimated in the field for soil organic carbon based on laboratory results.

The field estimations focus on soil colour that results from organic matter decomposition, landscape position, soil texture, the depth of organic matter and the laboratory results from collected samples. Figure 1.1 showed no spatial variation in SOC distribution over a large area. The organic matter distribution down the profile is also not possible to estimate from the data because the database contains topsoil organic carbon estimates. Therefore, SAFCOL database cannot be fully exploited in terms of its potential to become a valuable resource for carbon monitoring unless a model is developed that will use available information from the database to estimate and show spatial variation of organic carbon in some SA forest soils that have a database similar to that of SAFCOL. The total soil depth, texture and other soil properties and environmental factors that influence soil organic matter content recorded in the database need to be included in developing a model that will make a better estimation of soil organic carbon.

The North-eastern escarpment of South Africa is a timber producing area in the Limpopo Province and therefore contributing to the economy of the province. Furthermore, indigenous forests and forest plantations, occurring in the escarpment contribute to carbon sequestration, but there is no adequate documented evidence that quantifies the amounts of carbon stored and the potential storage under plantation forests and adjacent ecosystems.

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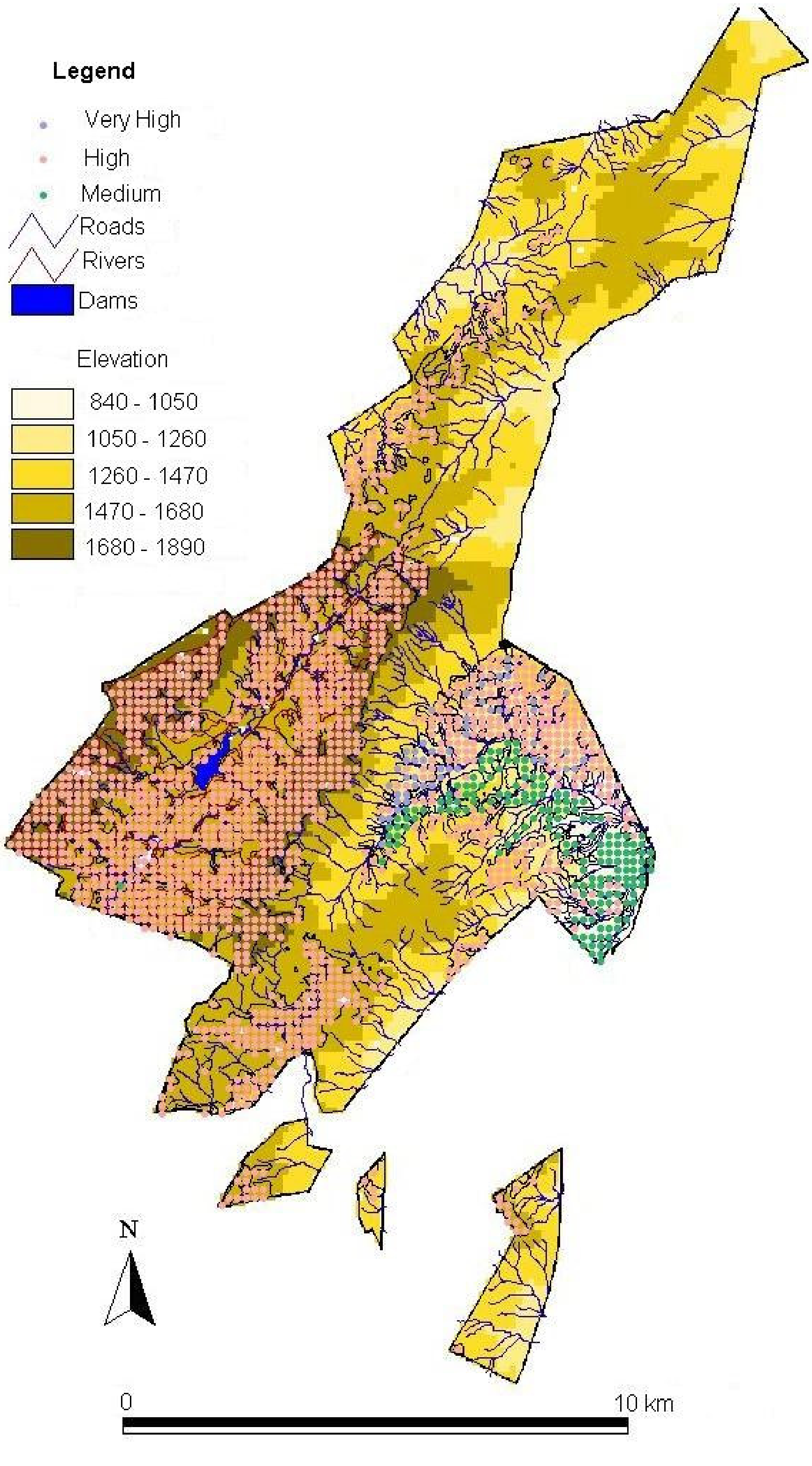

Figure 1.1. Organic carbon content distribution in Woodbush created from SAFCOL database

To clearly see the need for accurate soil carbon estimation and monitoring, which could be used in monitoring the changes in carbon status of forestry soils over time, one has to keep in mind the bigger picture of the global climate change (GCC).

The relative contribution of soils under pine plantations, indigenous forests, and on a smaller scale under wetlands and grasslands, to carbon sequestration, and the amount of the organic carbon stored in these soils is not known and this study seeks to provide answers by answering the following questions:

1. What kind of relationship exists between SOC, soil bulk density, and soil pH within each ecosystem of the Woodbush?

2. Can a model be developed that describes vertical distribution of soil organic carbon versus depth and be used to estimate carbon stocks in soil profiles?

3. Is the model applicable to an existing database to estimate carbon stocks?

4. Are geostatistical methods and GIS applicable in assessing and describing spatial variations of SOC?

The results of this study could be used to conduct soil organic carbon inventories using the approach developed and tested for the Woodbush forestry area. The accuracy of models can be tested in other areas and be validated to form part of SOC inventories in South Africa.

2. Global economy vs. global warming: Carbon emission and sequestration – A review

2.1. Environment and global warming

A growing interest in studying the organic carbon cycle was triggered by the classic works of Arrhenius (1896) at the end of the 19th century and by Callendar's vision (1938) of the anthropogenic CO_2 impact on the temperature regime of the earth.

Carbon dioxide contributes 50% of the anthropogenic greenhouse gases and with an annual rise of 0.5%, will lead to a mean temperature rise of 4°C and at least 1m eustatic sea level rise (Scharpenseel, 1997).

Carbon dioxide (CO_2) that is removed from the atmosphere and stored as carbon in a stable form like humus in the soil and $CaCO_3$ in the ocean may be considered to be sequestered in terms of the United Nation Framework Convention on Climate Change (Christie and Scholes, 1995). In general terms, therefore, carbon sequestration can be defined as the removal of carbon dioxide from the atmosphere and stored as carbon in other pools. A sink refers to any natural (soils, ocean) or artificial bodies (timber, homes, furniture) that can store carbon in a stable condition preventing or retarding its release back into the atmosphere. The removal of carbon dioxide from the atmosphere mainly occurs through the process of photosynthesis, where CO_2 is converted into other carbon compounds like starch and carbohydrates and stored in plant tissues.

Ecosystem responses to environmental factors such as water availability, temperature, and nutrient availability, have considerable spatial variability. The exertion of limitations to production and decomposition by one or more factors will depend on climate-ecosystem interrelationships (Strain, 1986; Pastor and Post, 1988; Schimel *et al*., 1989). Water and nutrient availability, reduction-oxidation conditions, soil structure, pH, and other soil factors play an important role in determining organic matter stabilization, soil flora and fauna distribution, and periods of active production or consumption of biogenic trace gases.

Land use patterns are also important factors in determining ecosystem dynamics throughout the world. Land management practices such as fire, grazing and cultivation affect ecosystem composition, cycling of nutrients and of organic matter, and other factors, which influence rates of net trace gas influx. Global change can affect land use patterns, and in turn, land use changes may be an important factor in affecting global change by modifying land surface characteristics and the net greenhouse gas emissions.

2.2. Carbon sequestration and carbon sinks

The US National Energy Technology Laboratory (NETL) defines carbon sequestration as "the removal of CO_2 from man-made emissions or the atmosphere and the safe, essentially permanent storage as CO_2 or other carbon compounds, or the reuse of CO_2 through chemical or biological conversion to value-added products" (Lee, 1999).

There are different ways to sequester carbon, including separation and capture, storage in terrestrial ecosystems, sequestration of CO_2 in geologic formations, ocean sequestration, and conversion and utilization. Separation and capture is a process to capture CO_2 from power plants and other energy systems before it is emitted to the atmosphere. However, the cost is still high. According to NETL, using currently available technology, separation and capture would increase energy costs by 50% or more. Terrestrial ecosystems, which are made up of vegetation and soils, are considered as important sinks for sequestrating CO_2.

Geologic sequestration is an approach to store CO_2 in geological formations. Three major types of geological formations have already been identified as potential long-term storage sites for CO_2: active and depleted oil and gas reservoirs, deep coal seams and coal-bed methane formations, and saline formations. Scientists have also shown that geologic sequestration in active and depleted oil and gas reservoirs and unmineable coal seams can enhance the recovery of fossil resources. Some oil fields have been injecting CO_2 for enhanced oil recovery. However, it remains uncertain how effectively and how long CO_2 can remain in geologic formations (Lee, 1999).

The ocean is another large potential sink for CO_2. Ocean sequestration includes two possible methods. The first method is to inject CO_2 into the oceans. Under this approach, CO_2 generated by power plants is injected directly into the ocean, and the injected CO_2 may become trapped in ocean sediments. The second method is to enhance the ocean's CO_2 uptake from the atmosphere through a method such as iron fertilization, which will increase phytoplankton productivity. There are also studies focusing on the biological and ecological responses and impacts from this approach.

Pectora roborant cultus recti

Conversion and utilization is to convert CO_2 into fuels, useful products, or benign solids. This approach focuses on improving the speed and energy efficiency of CO_2 conversion processes and identifying conversion processes that produce useful by-products.

2.3. Terrestrial carbon sinks

The storage of organic carbon in terrestrial sediments may be more important than previously recognized (Sarmiento and Wofsy, 1999), as more disastrous events associated with global warming continue to destroy the normal lives of humans in the form of heavy floods and drought. The terrestrial carbon sink consists of the biosphere and pedosphere. The biosphere consists of plants and animals that play a very important role in the carbon cycle within the biosphere and linking the pedosphere and atmosphere. The carbon storage in different vegetation types varies according to the type and climatic conditions that prevail. This is due to the amount of organic matter produced by different vegetation types and different decomposition rates that result from climatic conditions. The carbon storage in soil depends on the vegetation type, soil type, climate and other factors controlling the soil-forming processes.

The pedosphere (soil) lies at the interface between the lithosphere (rock) and the atmosphere (Lal *et al*., 1998), making it a very important link for the carbon cycle between the two spheres. It is a layer of about two metres deep (and is likely to be deeper in the tropics). The pedosphere supports biotic activity within the terrestrial ecosystems and interacts with the atmosphere through ion exchange processes. The interactive processes with the atmosphere through the biosphere lead to gaseous and energy exchanges between the soil and the atmosphere. Mechanisms of interaction between the lithosphere and pedosphere include leaching of nutrients and new soil formation due to weathering. Elemental cycling and pedoturbation (due to soil fauna activities) are interactive between the pedosphere and the biosphere.

The exchange of water between pedosphere and atmosphere plays a vital role in the local, regional, and global hydrological cycle (Lal *et al.*, 1998), which in the process redistributes the carbon that is dissolved. In addition to interactive linkages with the pedosphere, there are several crucial pedospheric processes linking all five predominant spheres as indicated in Figure 2.1, and in Figure 2.2.

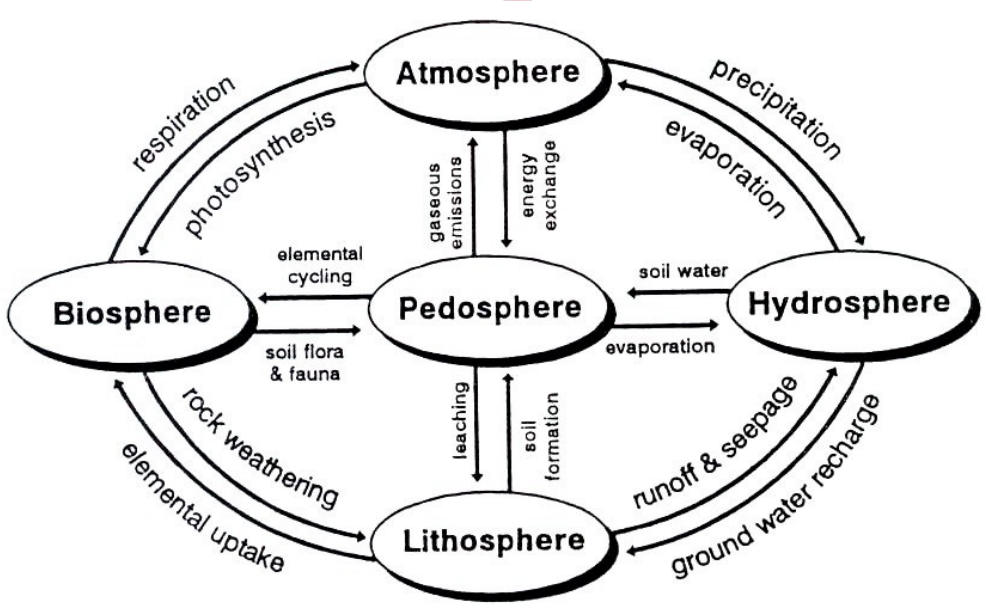

Figure 2.1 Interactive processes linking pedosphere with atmosphere, biosphere, hydrosphere and lithosphere (Source: Lal *et al.*, 1998)

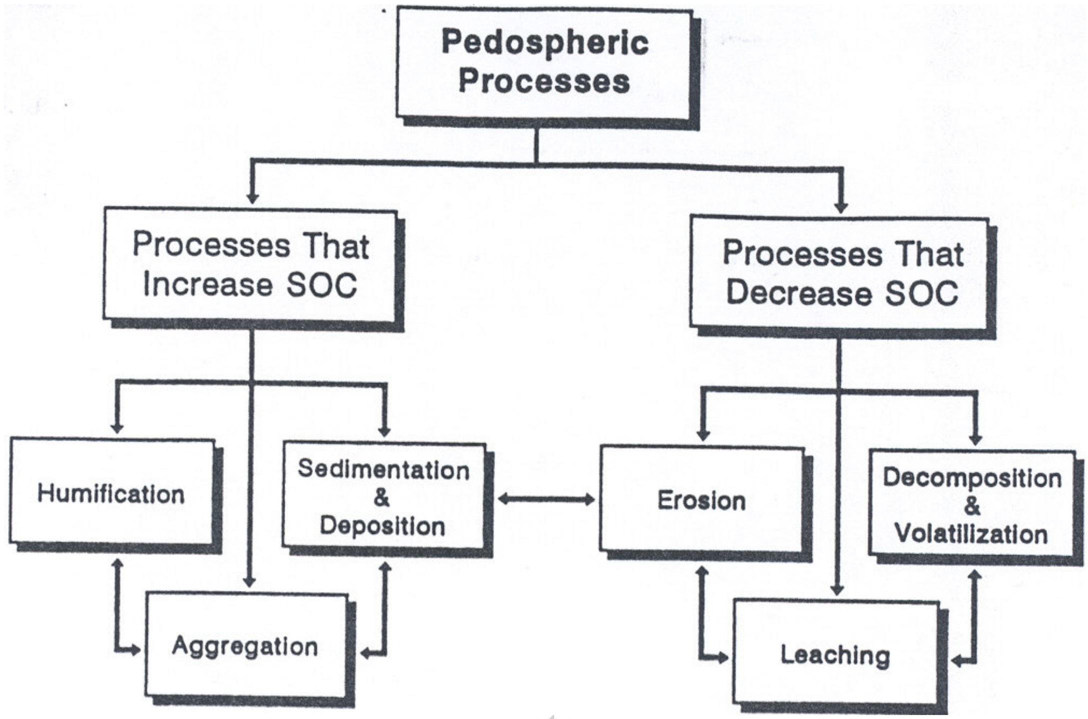

Figure 2.2 Principal pedospheric processes affecting soil organic carbon content (Source: Lal *et al*., 1998)

Carbon in the atmosphere dissolved in the hydrosphere to form H_2CO_3, interacts with the lithosphere through runoff, seepage, and ground water recharge. The hydrosphere interacts with the atmosphere through precipitation – evaporation cycle. Photosynthesis and respiration are the predominant processes linking the atmosphere and the biosphere. However, the interactive processes that play a major role in the global carbon cycle are those between the pedosphere, the atmosphere and the biosphere (Lal *et al*., 1998).

There are two types of carbon pools in the soil (pedosphere), soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC pool in the world soils was estimated to be 1500 Pg (Eswaran *et al*., 1995). The soil organic carbon pool was about 2.1 times that of the atmosphere pool and about 2.7 times that of the biotic pool comprising land plants (Lal *et al*., 1998). Estimates of the soil inorganic carbon pool are more tentative than those of the SOC pool, but may be about 12% more than those of the SOC pool (Schlesinger, 1991; Grossman *et al*., 1995). Most of the SIC pool comprises carbonates, which occur in the soils of the semi – arid regions.

The pedosphere has played a significant role in influencing the gaseous composition of the atmosphere (Lal *et al*., 1998). However, the magnitude of the total contribution to the atmospheric pool and the past and current rates of C flux between the pedosphere and the atmosphere are gradually increasing.

Little is known about the dynamics of the SIC pool in relation to land use (Lal *et al*., 1998). However, soil scientists are beginning to understand the dynamics of SOC, environmental and anthropogenic factors affecting it. Dominant pedospheric processes that affect SOC dynamics may be grouped into two categories: (¡) SOC enhancing and (ii) SOC degrading processes as illustrated in Figure 2.2. Processes that enhance SOC content are plant biomass production, humification, aggregation, and sediment deposition. Processes that degrade SOC content are soil erosion, leaching and soil organic matter decomposition. It is the net balance between these SOC aggrading and degrading processes, as influenced by land use and anthropogenic factors that determines the net SOC pool of the pedosphere (Lal *et al*., 1998). An increase in SOC, through C sequestration into the pedosphere, has two notable positive effects to the soil, the enhancement of soil quality, and the improvement in the soil's environmental regulatory capacity (Lal *et al*., 1998) (Figure 2.3).

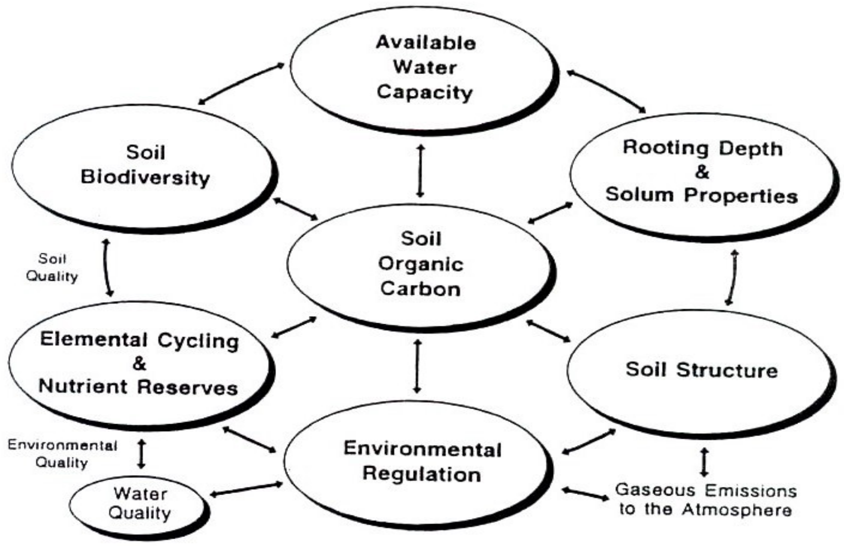

Figure 2.3. Soil organic carbon impact on soil and environmental quality (Source: Lal *et al.*, 1998)

These positive effects form the basis of strategies for sustainable management of the soil and water resources. The soil quality effects of SOC are related to several strongly interacting edaphological factors including soil structure, rooting depth and solum properties, available water capacity or least limiting water range (Thomasson, 1978; Letey, 1985; da Silva *et al.*, 1994), soil biodiversity, and elemental cycling and nutrient reserves.

The environmental effects of SOC are due to its impact on water quality and the gaseous composition of the atmosphere. The water quality effect is related to soil structure, its resistance to forces of wind and water, and transmission of water and solutes through the soil solum. The gaseous composition of the atmosphere is influenced by emissions of radioactively – active gases from the soil to the atmosphere, i.e., CO_2, CH_4, NO, etc (Lal *et al.*, 1998). The SOC and its effect on soil structure, soil moisture regime, element cycling, and transformations are important determinants of gaseous emissions from soil to the atmosphere.

The major mechanism for the terrestrial system to sequester carbon is through the process of photosynthesis. The vegetation absorbs carbon from the atmosphere in the form of CO_2 to produce organic compounds, which are later stored in the soil as organic matter after the death of plants or as parts of a plant deposited in the soil as litter. The process of transferring organic compounds from the plants into the soil involves macro and microorganisms, which are the key role players in decomposition.

Carbon storage through erosion may sequester carbon if significant amounts of eroded carbon are stored in sediments where they will decompose slowly, and if regrowth of vegetation on eroded lands replaces the lost carbon (Sarmiento and Wofsy, 1999).

The preoccupation with soils as a source of greenhouse gases rather than a sink is directly linked to the present day dramatic changes in the land use over large areas. As a result of these changes in land use, soil changes from a generally low – level CO_2 sink to a high level CO_2 source (van Breeman and Feijtel, 1990).

The land use change includes the change in vegetation cover, removal of vegetation and reducing or increasing the vegetation. Grasslands and wetlands are known to sequester organic carbon in higher volumes than forests (Scharpenseel, 1993). The soils under grass tend to store more carbon than a forest due to a growth rate that is high and because a large biomass in grass is stored below ground in the form of roots. The ^{14}C dating by Scharpenseel (1993) has shown that the C residence time in the soil organic matter of grassland commonly exceeds that of C in woodlands, where both exist in similar edaphic environments. However, the carbon is easily lost to the atmosphere if cultivation or fire destroys the vegetation.

The improvement of soil structure through the formation of organo-mineral complexes is an important mechanism of carbon sequestration in soils (Oades, 1988). Aggregation plays an important role in the global carbon cycling “the union of mineral and organic matter to form organo-mineral complexes is a synthesis as vital to the continuance of life as, and less understood than, photosynthesis” (Jacks, 1963). Microbial by-products form an important cementing material that strengthens bonds and stabilizes aggregates (Lynch and Bragg, 1985). Formation of stable aggregates provides physical protection to SOC against microbial decomposition (Powlson, 1980; Oades and Waters, 1991; Hassink *et al.*, 1993).

The wetlands of the world comprised the largest organic carbon pool of 640 Pg C (Twilley *et al.*, 1993), with about 130 million hectares of wet Riceland containing about 12 Pg of carbon (Neue *et al.*, 1991). Forests ecosystems have also been regarded as potential organic carbon sinks due to the relatively high amounts of carbon stored in the biomass rather than in the soil. However, their potential is limited by several factors like veld fires, land use change and the use of forests as a source of wood products like paper that is easily decomposed. Most studies have indicated that a large amount of organic carbon is reserved in the biomass of the forests and the organic matter addition to the soil is mainly from litter fall as leaves and twigs and die back of fine roots (Bouwman, 1990).

2.3.1. Soil Organic Carbon (SOC) Pool

The SOC content plays an important role in enhancing soil fertility (Tiessen *et al.*, 1994), and in sustainable management of tropical agro-ecosystems (Sanchez *et al.*, 1989). Similar to vegetation and soils, SOC pool is highly variable. Soils of the wet lowland tropical rainforest (TRF) regions usually contain more SOC than those of the moist or dry ecoregions (Lal, 1998). Landscape position, through its effect on soil depth and moisture regime, can also have a drastic effect on SOC. Differences in SOC content are primarily due to the total biomass pool, especially with regard to the litter fall and the root biomass. The above ground biomass production, rate of litter fall and root biomass also vary widely depending on soil and other edaphic factors.

2.3.2. Mechanisms of SOC accumulation

Soil organic carbon is composed of a heterogeneous mixture of chemical structures, often in association with soil minerals (Janzen *et al.*, 1998). These diverse forms can be broadly categorized into three groups:

Plant litter – consists of photosynthetically assimilated materials, minimally affected by decomposition, with cellular structures still recognizable. This fraction may originate from the residues and roots of vegetation grown at the site, or from organic amendments imported from elsewhere.

Inert SOC – consists of decomposition products which, because of chemical configuration or association with soil minerals, are essentially inaccessible to agents of biological decay (Hsieh, 1992, 1993). Carbon in this fraction typically has a turnover time of more than 1000 years (Campbell et al., 1967;

Harrison et al., 1993; Scharpenseel and Becker-Heidman, 1994), and is largely unaffected by management practices imposed on the soil.

Dynamic SOC – consists of photosynthetically reduced C in various stages of transition from plant litter to CO_2 (or inert SOC). This fraction includes any SOC, which is inherently decomposable. By definition, therefore, it includes C in faunal or microbial biomass, most of which originated in plant litter. Various names have been assigned to describe portions of this fraction, including 'light fraction' OM (Gregorich and Janzen, 1996), particulate OM (Cambardella and Elliott, 1992), macro-organic matter (Gregorich and Ellert, 1993), mineralizable C (Campbell, 1978), coarse OM (Tiessen *et al*., 1994), and OM in macroaggregates (Buyanovsky *et al*., 1994; Angers and Giroux, 1996). These fractions typically have a turnover time ranging from a few years to several decades. For example, light fraction OC typically has a half-life of about 10 years (e.g., Gregorich *et al*., 1995c, 1996b).

2.3.3. Changes in Inert SOC

From the standpoint of atmospheric CO_2 removal, the ideal reservoir for C gains is the inert SOC. By definition, however, the size of this pool changes only very slowly. Furthermore, the rate and magnitude of its change more likely to be influenced by inherent soil (mostly clay content) and climatic conditions than by agronomic practices (Janzen *et al*., 1998). Consequently, the potential for adopting management practices that favour significant inert SOC gains over a time scale of several years or decades may be limited. While the importance of inert C accumulation is highly significant from the perspective of soil genesis, its rate is likely to be too slow to offset atmospheric CO_2 concentration materially.

2.3.4. Changes in dynamic SOC

A more probable repository for C gains in the short term is the dynamic SOC pool. As indicated earlier, this pool includes C in transition between plant litter and CO_2 (and inert SOC). Assuming that the rate of inert SOC formation is negligible over the course of several decades, then dynamic C can be viewed simply as an intermediate in the reaction of plant litter decomposition to produce CO_2 as the end product.

The size of the dynamic SOC pool, therefore, depends on the relative rate of two processes: rate of plant litter C input (k_p) and rate of CO_2 formation (k_d). The rate of plant litter input in agro-ecosystems is closely related to crop yield or productivity. Numerous studies have shown strong correlations between crop residue inputs and SOC contents (e.g., Campbell and Zentner, 1993; Biederbeck *et al*., 1994; Nyborg *et al*., 1995; Gregorich *et al*., 1996a). Many of the SOC gains in response to improved management practices can be directly linked to higher yields arising from better crop nutrition, more efficient water utilization, and higher yielding crops (Janzen *et al*., 1998). In part, the variable response of SOC to a given management change depends on whether the new practice draws out a yield response. For example, under the semi - arid conditions of western Canada, adoption of no-tillage can maintain or enhance crop yields (Lafond *et al*., 1992) because of greater moisture retention, thereby favoring higher SOC (Campbell *et al*., 1995). Under humid conditions like those in eastern Canada, however, reduced tillage may have little yield advantage and therefore elicit only limited gains in SOC (Angers *et al*., 1995; Anger and Carter 1996).

Pectora roborant cultus recti

Plant litter input is determined not only by the crop yield, but also by the proportion returned to the soil after harvest. For example, production of corn for silage, where most of the aboveground portion is harvested, returns few residues, resulting in loss of SOC (Angers *et al*., 1995). Higher return of plant litter can also explain the benefits to SOC of straw retention (Nyborg *et al*., 1995) and use of perennial forages, which usually have a higher proportion of plant C below ground.

But amount of plant litter alone cannot explain all of the management effects on SOC storage. At least as important as the amount of C added to the soil is the rate at which it decomposes to CO_2. Any practice that suppresses the rate of decomposition lengthens the turnover time of dynamic SOC, thereby increasing its content in the soil. Suppression of decomposition rate can be achieved through one or two general mechanisms; Suppression of biological activity; and Physical protection. Because decomposition is a biological process, any practice that reduces moisture content, temperature, or aeration and low pH will favour the accumulation of dynamic SOC (Janzen *et al*., 1998). For example, frequent use of summer fallow results in SOC loss, in part because it creates moisture and temperature conditions conducive to biological activity (Janzen *et al*., 1992; Bremer *et al*., 1995; Janzen *et al*., 1997a). Similarly, application of fertilizer can retard decomposition by enhancing plant growth and desiccating the soil (Paustian *et al*., 1992). Placement of plant residue may affect decomposition by altering the physical environment. Under arid conditions, for example, no-till practices may slow decomposition by retaining residue on the soil surface where they remain desiccated (Janzen *et al*., 1998). The suppression of decomposition, by

Pectora roborant cultus recti

adoption of practices that retard biological activity, results in the accumulation of dynamic SOC which has little inherent stability against further breakdown. Consequently, it remains highly susceptible to decomposition should that practice be discontinued. For example, adoption of a fallow-wheat system in a semi - arid environment resulted in rapid depletion of light fraction C within a decade, relative to that under continuous cropping (Bremer *et al.*, 1995). Reducing biological activity, however, may not be the only way of suppressing decomposition. Accumulation of SOC may also be favoured by practices that encourage the formation of aggregates that limit accessibility to decomposition (Gregorich *et al.*, 1989; Angers and Carter, 1996; Gregorich *et al.*, 1997; Carter and Gregorich, 1996). For example, reduction in tillage intensity can increase soil aggregation and the amount of SOC stored within aggregates (Carter, 1992; Angers *et al.*, 1992, 1993c; Franzluebbers and Arshad, 1996a). Aggregation is also favoured by reduction in fallow frequency (Campbell *et al.*, 1993a, b) and by the use of perennial forages (Campbell *et al.*, 1993b), though different species may have variable effects (Carter *et al.*, 1994).

The C stored in aggregates represents a temporary storehouse of SOC, less susceptible to rapid depletion than 'free' dynamic SOC, but still subject to gradual turnover. Using ^{13}C analyses, Gregorich *et al.* (1997) found that the half-life of 'protected' light fraction OC was about 2-fold that of 'free' light fraction OC. Some findings have suggested that SOC stored within microaggregates is more effectively 'sequestered' than SOC within macroaggregates (Gregorich *et al.*, 1989; Carter, 1996). Others, however, have shown little apparent difference in SOC breakdown among aggregates of various sizes (Gregorich *et al.*, 1994).

2.3.5. Limits to SOC gain

Under relatively constant conditions, SOC eventually approaches a equilibrium-state concentration at which the rate of C input is balanced by CO_2 loss via respiration (Janzen *et al.*, 1998). An increase in SOC is prompted by adoption of a practice that disrupts this equilibrium-state, suppressing decomposition relative to C input. With the accumulation of SOC, however, rate of decomposition will eventually again converge upon C input, at which time the SOC approaches a new equilibrium-state. Thus an increase in SOC in response to a new management practice can occur only during the transition from one equilibrium-state to another, and is therefore limited to a certain duration (Janzen *et al.*, 1998). Losses of SOC upon adoption of a degradative cropping system are limited and approach zero after several decades (e.g., Bremer *et al.*, 1995). The duration of SOC gains responds to improved practices, however, has not been firmly established (Janzen *et al.*, 1998). Campbell *et al.* (1995) showed that SOC upon adoption of improved management in an arid soil approached a maximum after only six years. Angers (1992), from the study under humid conditions, also suggested a new SOC plateau within 5 years of seeding perennial forage. These studies support the view that most of the SOC gains in response to adoption of improved management or practices may occur within several years, and that gains may subside within a decade. The potential SOC gain may also vary widely among agro-ecosystems, depending on a range of factors. Among the most important, perhaps, is the potential primary production (C input), as dictated by climatic constraints. Thus, soils in areas with severe constraints on productivity (e.g., aridity) may have limited potential for SOC gains. Another variable is the SOC status prior to the adoption of a new management practice. If the dynamic SOC is already at a high level for its environment, then there may be limited potential for further gains.

The soil's capacity for 'protecting' recent C inputs, whether directly by association with minerals or within aggregates, or indirectly by suppressing biological activity, is another factor that determines the potential SOC gains.

2.3.6. Decomposition of SOM and soil aggregation

During decomposition in soil, organic residues and their decomposition products become closely associated with the mineral phase and, simultaneously, their chemical composition changes. Both processes are believed to provide recalcitrancy to further decomposition; however, their respective importance is difficult to determine (Angers and Chenu, 1998). The most direct evidence of the role of soil structure in protecting SOM from decomposition probably comes from the observation that when soil aggregates are disrupted, an increase or flush in C mineralization is observed relative to undisrupted aggregates (Rovira and Greacen, 1957; Powlson, 1980; Elliott, 1986; Gupta and Germida, 1988). Further, Beare *et al.* (1994) have shown that the level of physical protection varies with soil management practices with apparently more aggregate protection in no-till than in cultivated soils. Further support that the location of SOM in the soil matrix influences its decomposition is provided by isotopic tracer studies. In a cultivation sequence, Besnard *et al.* (1996) found that, upon cultivation, much more C was lost from the particulate organic matter (POM) fraction than from the occluded POM (located within aggregates). Physical transfers of POM from outside to inside aggregates or vice-versa, with aggregate formation or disruption could not completely account for this observation. Further, after 35 years of cultivation, the 50 to 200 μm microaggregates were relatively enriched in POM –C derived from the initial forest vegetation, as compared to macroaggregates or to nonaggregated soil. Gregorich *et al*. (1996) separated the light (<1.6 g cm^{-3}) particulate organic matter occluded within soil aggregates from the free light fraction (LF) and determined its relative age using ^{13}C natural abundance. Although LF is most often perceived as a labile SOM fraction, they found that most of free LF was of recent corn origin. These differences in relative accumulation were either due to difference in the chemical composition of SOM in different locations or to physical protection provided by the microaggregates. The fate of SOM located within aggregates will depend upon its intrinsic decomposability and on the persistence of the aggregates. The protective capacity of soil aggregates should, therefore, be related to their stability against water and other mechanical stresses, although there is as yet no direct evidence of such a relationship. On the other hand, SOM contributes to the stability of aggregates and increases their life expectancy. SOM, therefore, indirectly contributes to "self-protection" against biodegradation

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Pectora roborant cultus recti

3. Materials and methods

3.1. Site selection

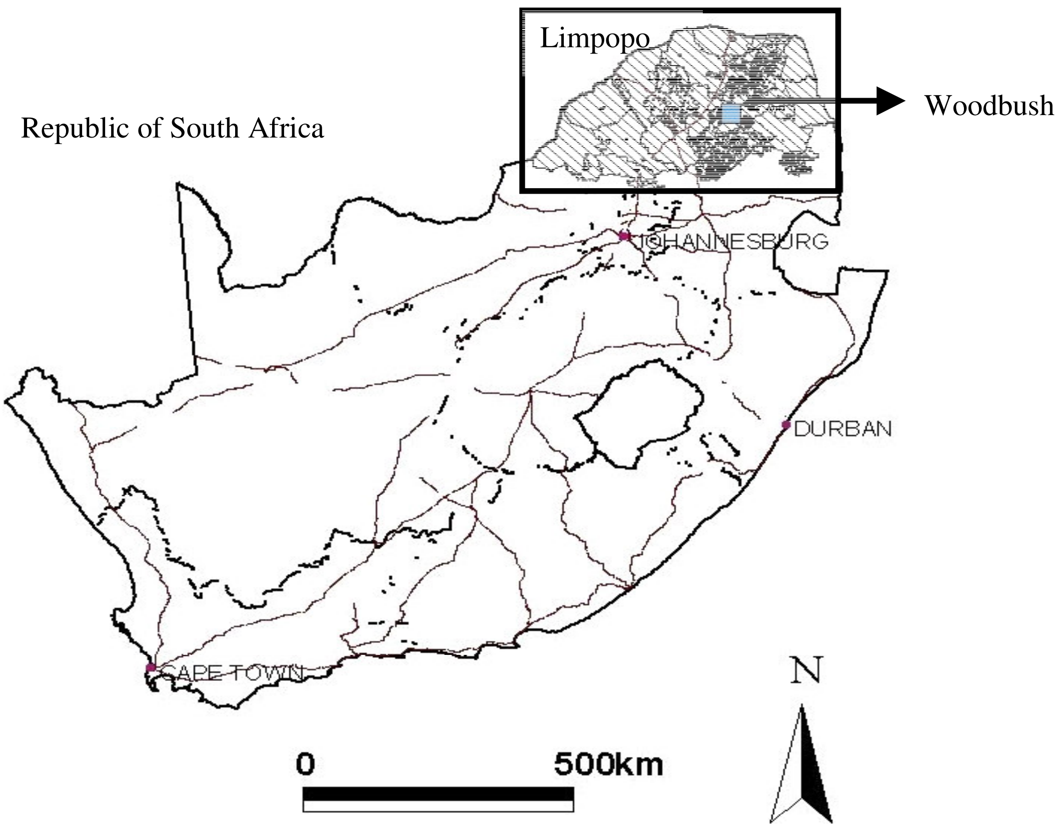

Figure 3.1. Location of Woodbush Plantation in Limpopo Province

Woodbush plantation, which occupies about 10515 ha in the Drakensberg Escarpment area in Limpopo Province, was selected as research site (Figure 3.1). The town of Tzaneen is located approximately 10 km east of the eastern boundary of Woodbush plantation.

Indigenous forests, pine plantations, grasslands and wetlands were chosen and their soil carbon stocks estimated to quantify their respective contribution to carbon sequestration. Woodbush plantation was selected as study location because it provided easy access to all the ecosystems that were to be studied. All ecosystems in Woodbush were located in such a way that it was easy to compare them, as they existed under similar environmental and climatic conditions. The afforested portion (3702 ha) of Woodbush area lies between latitudes of 23^{o}43' to 23^{o} 54' and longitudes of 29^{o}57' to 30^{o}04'.

The most prominent physiographic feature of this region is the Drakensberg Escarpment stretching in a North-South direction. The high - lying Woodbush section has an altitude range of 1400 to 1880 m (Strydom *et al*., 1997).

The Broederstroom River mostly drains the areas situated to the West of the escarpment that include Woodbush in a Southerly direction and Broederstroom River catchment was selected as the study area. This catchment was selected as the study area because it provided more data than the Koedoes River catchment. The indigenous forest, wetlands and grassland of Woodbush were not sampled by SAFCOL and there was no data on these sites. However, Broederstroom catchment is dominated by plantation compartment more than indigenous forest, while Koedoes catchment is dominated by indigenous forest. The tributaries of the Koedoes River drain a small portion in the northerly direction. More gentle slopes of approximately 35% characterize these areas.

The physiographic features of the whole area of Woodbush have a great influence on meso-climatic patterns. These climatic patterns, the topographic variation and the parent material have a great influence on soil properties such as depth, drainage and nutrient cycling.

3.2. Climate

Woodbush plantation is characterized by marked gradients in temperature and rainfall due to the variability in altitude and the physiographic nature of the area. The physiography of the area is also responsible for a prominent south easterly orographic effect in the rainfall pattern, leading to high falls on the south eastern side of prominent physiographic barriers and resultant rain shadows on the north western side (Strydom *et al.*, 1997). The areas of Woodbush plantation above 1200 m altitude are in the mist belt, where fog conditions occur during summer. The altitude, aspect variation and slope strongly influence the temperature and these complex patterns form an integral part of the site classification of Woodbush plantation (Strydom *et al.*, 1997).

The long term mean annual rainfall ranges from approximately 1050 to 1938 mm, with the highest rainfall occurring on the high-lying plateau areas. Approximately 90% of the annual rainfall occurs during the wettest half of the year, which is from October to March, resulting in a long dry season. The mean annual temperature ranges between 15.3ºC and 19.2ºC with the high temperatures at the lower lying areas and the north facing aspects. The lowest temperatures are found at the foot slopes and the valley bottoms, falling as low as 2.8ºC, because of the strong inversion of cold air during the winter months (Strydom *et al.*, 1997).

3.3. Geology and soils

The Woodbush area is underlain by a complex of granite and gneiss biotites, which are intersected by a network of diabase dykes. The boundary between the granite and gneiss biotites is not clear in the field due to the similarities in the nature of the weathering products in terms of texture, chemical properties and mixing through colluviation. The granite component makes up the dominant lithology (Strydom *et al*., 1997). The intense weathering conditions, leaching and good internal drainage have resulted in the formation of deep, red apedal soils.

The saprolite of granite is well and deeply weathered. A gradual transition from the solum to saprolite is usually a typical feature. Some deep soils are also found in some ridge top positions while soil profiles of about 3 – 4 m deep are common especially in lower lying areas of the De Hoek area of Woodbush plantation.

Soils formed from granite are usually well- to excessively drained. The topsoil horizons have a low water holding capacity. This is mainly due to the high medium to coarse sand content and a strong aggregation of clay particles into water-stable micro – aggregates resulting in a high frequency of macro pores (Strydom *et al*., 1997).

Hydromorphic soils are found in the bottomland positions on gentle slopes. The high moisture content in these positions results in the formation of non-calcareous G horizon underlying Orthic topsoil (Katspruit 1000), Westleigh mostly with luvic B1 horizon and Tukulu with unbleached A horizon and luvic/ non-luvic non-red B horizon (Soil Classification Working Group, 1991). Indigenous forests and wetlands, however, cover most of the hydromorphic soils.

The subsoils derived from granite parent material are conspicuously red, mostly with hues of 2.5YR or 5 YR. Hutton soil form with leached luvic/non-luvic B1 horizon dominates the low-lying areas. At altitudes above 1100 m, humic topsoil is often dominant, mostly in the southern aspects and along the drainage lines, resulting in the formation of Inanda and Kranskop soil forms with thin (30 cm) and thick (60 cm) humic A horizon overlying luvic B1 horizon. Magwa with thin humic A horizon over luvic B1 horizon and Sweetwater with thin and thick A horizon overlying non-red luvic B1 horizon (Strydom *et al*., 1997) are also found in small areas.

All the red soils with luvic B-horizons fall into the order of Ultisols (USDA, 1999), mainly udic and ustic suborders. The hydromorphic soils of the flood plain fall into the order of entisols (USDA, 1999). The suborder of fluvents shows the alluvial nature of the material from which they were formed.

3.4. Soils in relation to Vegetation

The vegetation of the study area (Figure 3.2), described in great detail by Scheepers (1978), represents three main types: indigenous Afromontane forest, Afromontane grasslands and scrub forest, and localized wetlands including riparian zones.

Pectora roborant cultus recti

Figure 3.2. A view of the study area where sampling sites were located

Forest plantations have mainly replaced grasslands and scrub forest areas. Considering the possible close link between vegetation type and soil organic matter content, attempts were made to analyze the soils of the area within the respective vegetation context and to conduct the comparison between different ecosystems.

3.4.1 Indigenous forests

Figure 3.3. Kranskop soil form with thin topsoil under indigenous Afromontane forest

Indigenous forests occupy the largest part of Woodbush, about 6305 ha. A sampling site was selected in the indigenous forest North of G7a compartment, which is north-East of Dap Naude dam. The litter layer, composed of dead leaves, was 5 cm thick on average, supplying reasonable amounts of organic matter to the topsoil.

Dark colours resulting from organic matter decomposition characterized the topsoil. The humic-A horizon had a crumby structure with a relatively firm consistence.

The topsoil was a thin humic A horizon, underlain by a luvic B1 horizon. The subsoils of indigenous forest sites were mainly red apedal B (Inanda Highlands) and yellow–brown apedal B (Kranskop Dargle). The red apedal B-horizon is underlain by a red saprolite derived from granitic rocks. According to field observations, the clay content increases with soil depth from an average of 26% in the A horizon to about 34% in the underlying B-horizon. The A horizon, about 27 cm deep, gradually merges into a 100 cm B horizon that has developed from granite saprolite (Table 3.1). As expected under indigenous forests, there was an abundance of roots and evidence of soil organism's activity in the topsoil, which decreased with soil depth. Profile descriptions are presented in Appendix A.4.

Table 3.1. Average soil texture and classification for the selected sites

Ecosystem	Horizon	Clay %	Silt %	Sand %	Diag. Horizon	Soil form	Soil family
Wetlands	A	20.0	25.4	54.6	Orthic A	Tukulu	2120
	B1	36.0	24.0	40.0	Neocutanic B		
	G				G		
Forests	A	26.0	29.0	45	Humic A	Kranskop	1200
	B1	34.0	15.7	50.3	Yellow Brown apedal B		
	B2	36.0	17.0	47.0	Red apedal B		
Plantations	A	18.0	23.8	48.2	Humic A	Inanda	1200
	B	34.5	17.8	47.7	Red apedal A		
	C				Unspecified material		
Grasslands	A	23.7	21.5	54.8	Humic A	Kranskop	1200
	B1	30.8	19.6	49.6	Yellow Brown apedal B		
	B2	31.0	18.0	51.0	Red apedal B		

A transect was made through indigenous forest sites, and two 1-ha plots and four profiles were also sampled (Fig. 3.4 a). The second transect through indigenous forest was made on the west of compartment F1 (Fig. 3.4b).

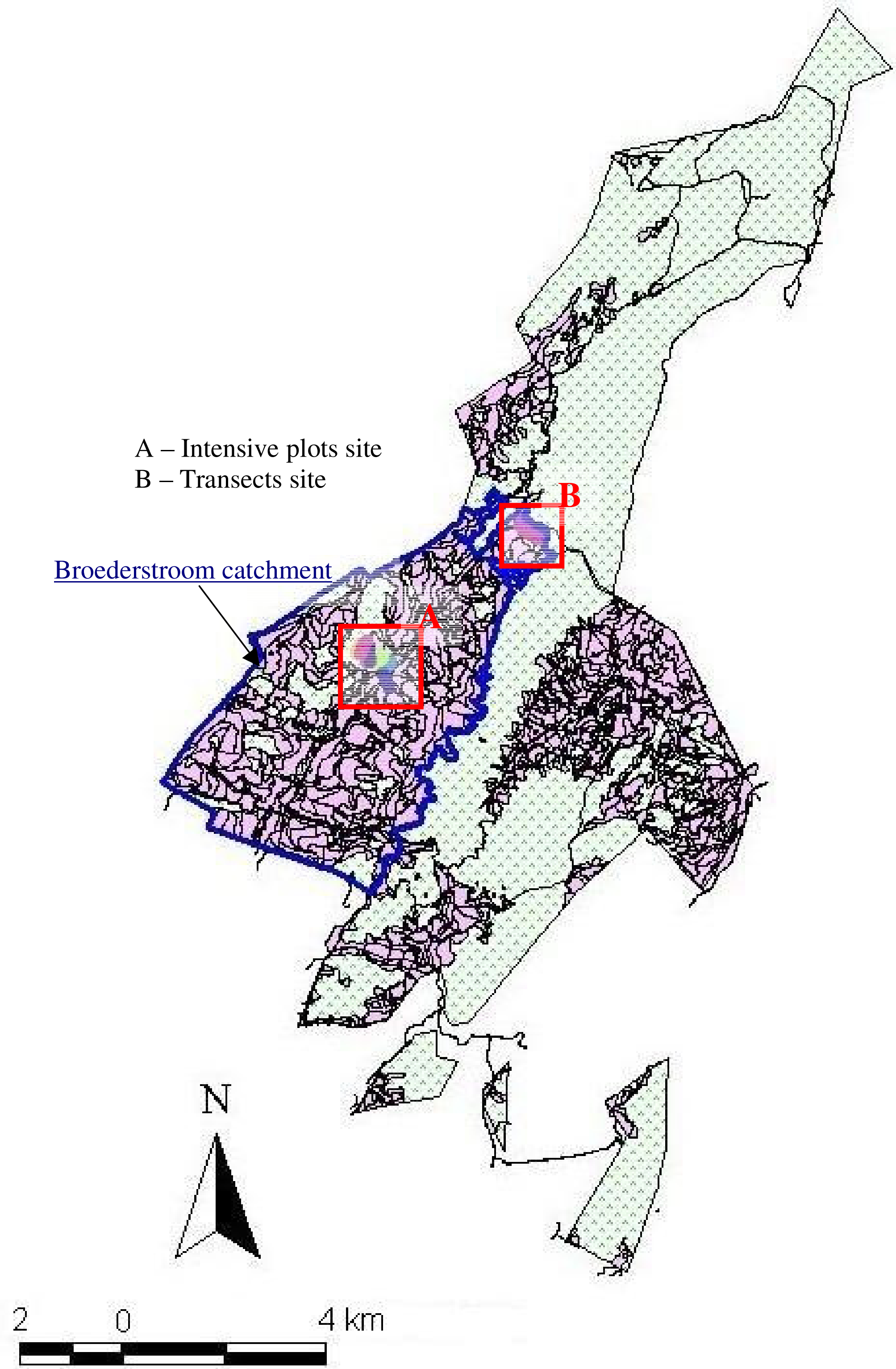

Figure 3.4 (a). Location of sampling sites and transects in Woodbush.

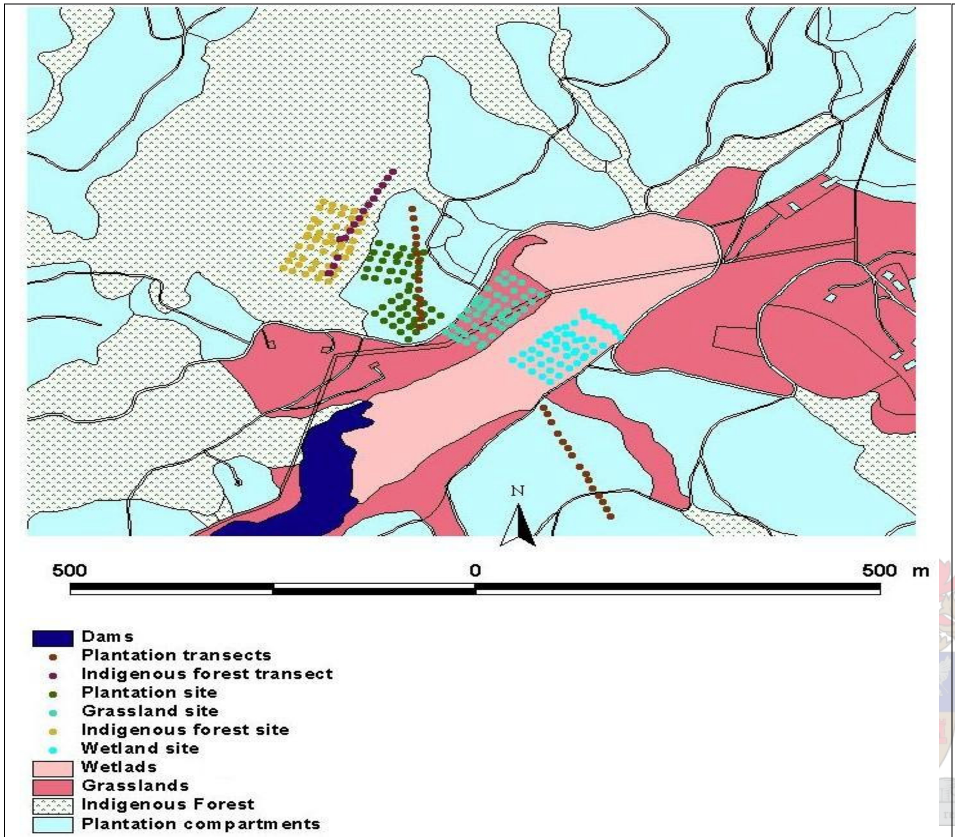

Figure 3.4 (b). Surface and transects near Dap Naude dam

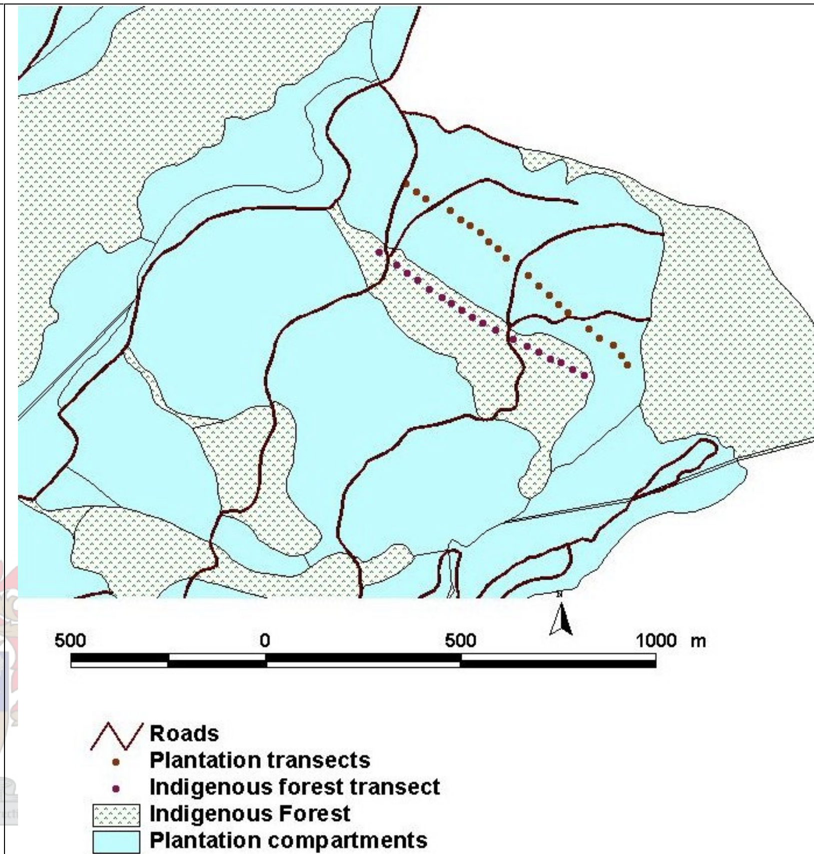

Figure 3.4 (c). Transects in F1 compartment and the adjacent indigenous forest

3.4.2. Pine plantations

Several species of pine (*P.patula, P. taeda, P. elliottii*) and eucalypt (*E. grandis*) are grown in Woodbush and cover an area of about 3582 ha. The pine trees in selected compartments were *Pinus taeda* in G7a, F1 and F21c and were 24yrs, 32yrs and 23yrs old respectively, while 23 yrs old *Pinus elliottii* were in compartment F23 at the time of sampling.

Figure 3.5. Inanda Highlands soil profile in G7a compartment

Plantations were established mainly on deep, well-drained Inanda soils. A description of all the soil profiles is presented in Appendix A4. The litter layer composed mainly of pine needles and it was about 12 cm deep at the time of sampling. The humic A overlies a relatively deep red apedal B horizon, with the clay content increasing in the B1-horizon. The Inanda Highlands soils are mostly found on southern aspects and Hutton Kelvin on northern aspects.

The Southern aspect topsoil is moister than the northern aspect topsoil and organic matter seems to be higher in the southern than in the northern aspect.

The G7a, F23, F21c and F1 compartments were sampled under pine plantations. The G7a compartment is situated approximately one kilometer North - East of the Dap Naude Dam, and covers an area of 6.3 hectares. The compartment is dominated by well-drained, deep Inanda soils. Two intensive sampling plots and one transect were made in G7a compartment. The second transect was made in the F23 compartment through to F21c compartment. Both F23 and F21c compartments are situated across the river, to the South of G7a compartment. The third transect was made in compartment F1 (Figure 3.4).

3.4.3. Afromontane grasslands

The grasslands occupy a very small portion (134.14 ha) of Woodbush Plantation. They are mostly used as annually burnt firebreaks and pastures. Grasslands are largely left unplanted on slopes above the river terrace adjacent to wetlands or riparian zones and develop temporarily in the currently unplanted compartments.

Pectora roborant cultus recti

Figure 3.6. Stony Inanda Highlands soil profile under Afromontane grasslands

The grass species vary widely because of annual burning. Some of the grasses that survive those annual fires are *Eragrostis curvula*, *Cymbopogon validus* and *Eragrostis racemosa*, (Scheepers, 1978).

The grasses grow mainly on Inanda Highlands soils, which are relatively shallow (0 – 60 cm), compared to similar soils under indigenous forests (0 – 100+ cm).

The grassland soils are similar to those of indigenous forests; however, the topsoil depth is shallower than the humic topsoils under indigenous forests. Soil profile descriptions are presented in Appendix A4. With a thin litter layer and shallow topsoil, grasslands soils are relatively low in soil organic material compared to soils under indigenous forests. The B-horizon extends down to 84cm and merges into hard rock. Grasslands within the study site were mainly found on Inanda Highlands (1200) soils.

The selected grassland site is situated South of G7a compartment, on a relatively steep slope (35 – 50%). Shallow soils and steep slopes make growing and harvesting pine trees difficult and as a result, such areas are left to native vegetation (grasslands and indigenous forests).

3.4.4. Wetlands

Wetlands occupy the smallest area of Woodbush, about 87 ha and mostly along the river terraces, in riparian zones, and around the dams and reservoirs. Wetlands are separated from grasslands by terrain change and moisture supply. The selected wetland site is situated to the South of the grassland site, and less than a kilometer east of the Dap Naude Dam (Figure 3.4). Over the years, growing trees in riparian zones has been discouraged and even prohibited for environmental reasons and due to the poor performance of most commercial species on wet sites.

Figure 3.7. Tukulu covered with 10cm layer of deposits from floods of year 2000

Soils in wetlands are formed on material transported from higher-lying areas and deposited by colluvial and alluvial processes. Description of all the soil profiles is presented in Appendix A4. The sampled topsoil was on average 40 cm deep, with a thin (3 cm) layer of organic litter on the surface (Figure 3.7). The topsoil was sandy loam; clay content increased from 20% in A to 36% in the B-horizon (Table 3.3).

The Neocutanic B horizon has yellow colours of 7.5 YR5/6. From a depth of 100 cm, the soil was saturated with water. Most roots were found in the first 20 cm of the topsoil and very few were found in B-horizon.

3.5. Sampling approach

Sampling strategy was aimed at estimating the content of organic carbon in the four ecosystems. A grid system was used when sampling topsoil so that geo-statistical analysis could be applied to assess spatial variation of SOC in the topsoil. Geo-statistical software VARIOWIN was used for spatial data analysis in two dimensions, and to develop variograms and spatial variation models. The model parameters generated with VARIOWIN were applied in the GSLIB software to produce location maps with a two-dimensional kriging procedure. Two sampling approaches were applied in this study:

Intensive plots – for micro-scale variation assessment and

Transects – a traditional method of soil reconnaissance.

Two soil profiles were opened in each plot. In each profile a maximum of 10 samples were collected, depending on the depth of the profile. Samples were taken at 5, 10, 15, 20, 30, 40, 50, 60, 75 and 100 cm depth. These sampling depths were strategically done at different depths in order to assess SOC variation pattern with an assumption that SOC variation is very high in the top 20 cm, hence 5 cm depth increments, gradually decreases between 20 cm and 60 cm (10 cm increments), and is low at depths below 60 cm (15 cm and 25 cm increments). In total four profiles were opened within each ecosystem. The profiles were aimed at assessing vertical distribution and variation of SOC. The dominant soil types and their main characteristics described in the

Pectora roborant cultus recti

field are summarized for all four ecosystems in Table 3.1. Soil texture was determined by the pipette method and results were statistically analyzed using STATISTICA 6.0

3.5.1. Intensive sampling plots

Eight 1-ha plots (two per ecosystem) were sampled in grasslands, indigenous forests, wetlands and plantations. Surface (0 – 7 cm deep) samples were collected on a 20 m grid with bulk density (D_b) core auger in each sampling plot. A total of 25 surface samples were collected in each plot. The intensive sampling approach was aimed at assessing amount, spatial variation and distribution of surface (0 – 7 cm) SOC in different ecosystems in short distances between the sampled points. Spatial analysis was done using kriging in different directions.

3.5.2. Transects

Five transects were made, two in indigenous forests and three in pine plantations. One transect was made in indigenous forests adjacent to compartment F1 and the second transect in forests adjacent to compartment G7a. Spatial analysis in transects was possible only in one direction. The first transect in pine plantations was made across compartments F23 and F21c, the second transect in compartment G7a and the third was made in compartment F1.

Only the topsoil (0 – 7 cm deep) was sampled with D_b core auger in all five transects, with 20 m distance between sampled points. Transects were sampled from the middle slopes to foot slope. The upper slopes were very steep and inaccessible for sampling. Transect sampling was aimed at assessing the effect of topography and aspect on spatial variation and distribution of SOC down the slope and to complement the intensive sampling approach by increasing the number of surface samples and the distance of sampling to estimate long-distance variation.

3.6. Model approach

Two approaches were used in generating the estimation model equations for carbon stocks. The first approach was the average model that was generated by averaging observed SOC content values of all profiles in each ecosystem. This model only estimates the average SOC content in each soil depth and as a function of soil depth (d). Because the average model only used soil depth to estimate SOC in different soil depths and the topsoil SOC is an average value throughout the ecosystem, it failed to capture the spatial variation in the topsoil. With this approach, it implies that vertical distribution of SOC throughout the ecosystem is the same.

The second approach was the normalization of averaged observed SOC content values of all profiles in each ecosystem. Normalization is done by dividing average observed SOC content values of all profiles in each soil depth by the observed SOC content value (Cs) of the topmost sample of that profile. Normalization approach was necessary to include spatial variation in the topsoil SOC in the model. This model uses both topsoil SOC and soil depth as estimating factors.

Samples were analyzed for pH in water and KCl (1:2.5); organic carbon by the colometric method (Baker, 1976) and soil bulk density using bulk density core

Pectora roborant cultus recti

auger ($389cm^3$) (Detailed methods are given in Appendix A.1, A.2 and A.3) and soil texture using the pipette method. Soil structure, consistency, litter layer thickness, moisture status, stones, roots, and soil colour were recorded in the field.

Pectora roborant cultus recti

4. Results and Discussion

4.1. Vertical distribution of SOC

Soil organic carbon content decreased with increasing soil depth in all ecosystems (Figure 4.1). The relationship was more evident under pine plantations and less evident in grasslands. The raw data for the properties plotted in this and subsequent figures are presented in appendix B.

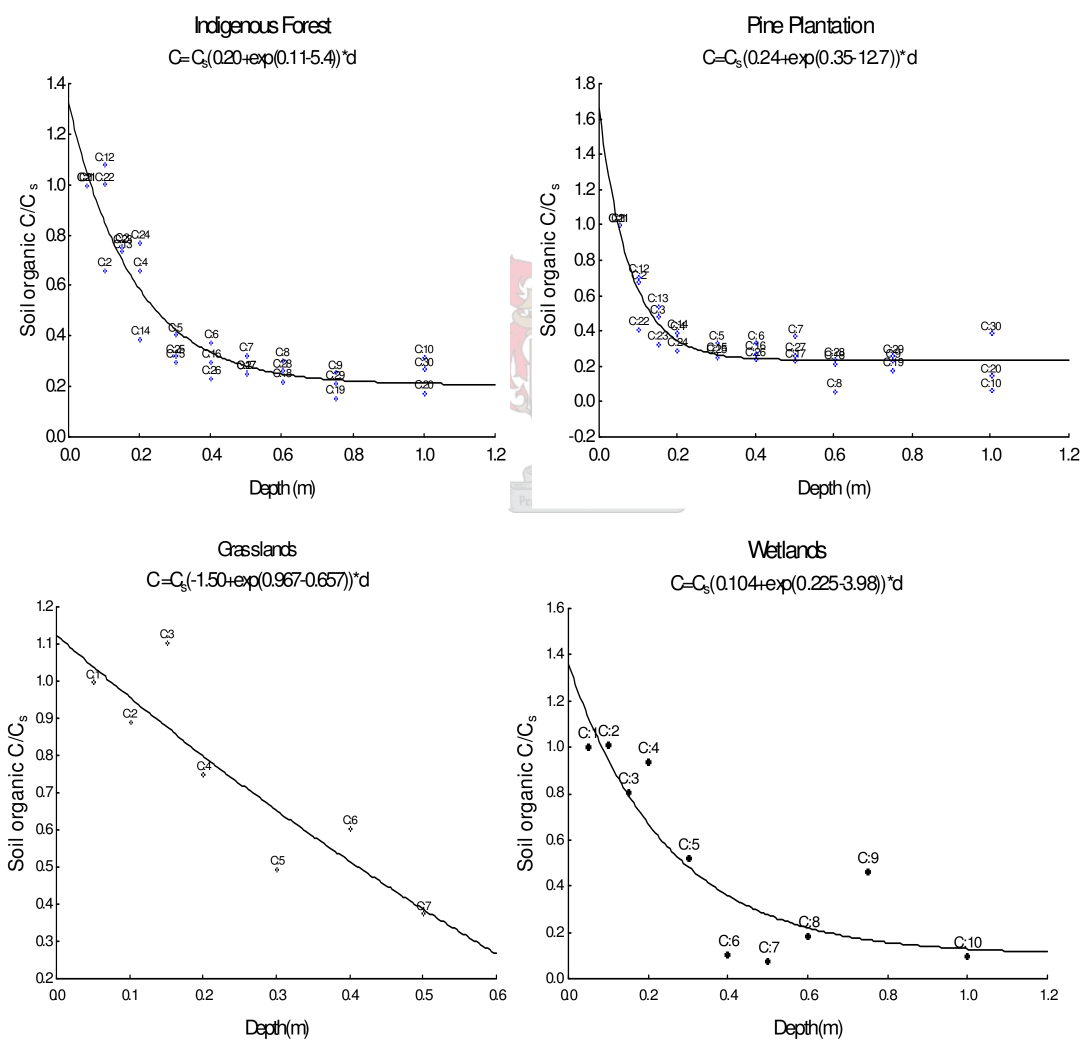

Figure 4.1. SOC relative to that in the surface as a function of soil depth for all four ecosystems

Arrouays and Pelissier (1994) found a similar relationship in humic loamy temperate forest soils of France, where SOC content declined progressively with depth over the entire profile.

The relationship between soil organic carbon content and soil depth in all ecosystems was best fitted by an exponential function. The relationship was weaker in grasslands than the other ecosystems with an r^2 value of 0.7. The graph looks like a linear function; however, the linear relationship was poorer than the exponential relationship.

Indigenous forests

Under indigenous forests profiles 1, 3 and 4, the r^2 values were equal to 0.8 and profile 2 had an r^2 of 0.25 due to low SOC in the topsoil. The SOC content distribution pattern is determined by organic carbon sources and interactive processes linking pedosphere with atmosphere, biosphere, hydrosphere and lithosphere as illustrated in Figure 2.2. SOC content distribution from the topsoil to deep layers of the pedosphere is through leaching and ground water recharge (Lal *et al.*, 1998). The two processes carry low amounts of SOC to deep soil layers especially in clayey subsoils and high SOC content is recycled by soil fauna and flora on the top layers of the soil profile. The less permeable subsoil restricts plant root penetration and limits soil fauna activities to the upper layers of the soil profile.

Profile 2 in indigenous forest had a low amount of SOC content in the topsoil (0 - 7 cm depth). No specific factor was identified or observed in the field that might have resulted in such SOC spatial variation. However, several factors such as soil compaction, pedoturbation and wind throw can be possible causes of the SOC hiatus found in profile 2. Some studies highlighted the impact of these factors on SOC vertical distribution.

Brevik *et al* (2002) found a significant decrease in SOC content in compacted soil. A compacted soil layer altered the soil carbon pool by limiting additions of organic matter to the soil, therefore limiting vegetative production. However, soil compaction in protected indigenous forests like in Woodbush, rarely occurs because of limited human activities in the forests.

Pedoturbation is possibly the most influential factor for the low amounts of SOC observed in profile 2. Wild animals like bushbuck and wild or bush pigs are found in Woodbush and have a distinct burrowing impact on soil cover as they dig for roots and in the process disturb the natural sequence of soil layers. They can dig out large quantities of low SOC subsoil and bring it to the top. A large quantity of earthworms was observed in soils under indigenous forests but they were not counted or recorded. Earthworms can significantly alter the spatial distribution of SOC where they occur in large numbers. Earthworms were found to have significantly increased average soil organic carbon content and also changed spatial distribution from uniform to patchy (Shuster *et al*., 2001). Lal *et al* (1998) found that pedoturbation played a role in redistribution of SOC and that resulted in spatial variation of SOC.

An average value of SOC content was calculated for every soil depth from a combined data set of three profiles (Appendix B5) under indigenous forests and used to develop a general estimating equation (4.1). Profile 2 was not included in the data set used to develop equation 4.1 because of the poor relationship between SOC content and soil depth. The general estimating equation (4.1) had an r^2 value of 0.92.

$$C = (1.12+\exp -2.11)*d \quad (4.1)$$

Where C is the average SOC content and d is soil depth.

The same data set was normalized (Figure 4.2) and an average value of SOC content was calculated for every soil depth and used to develop a normalized prediction equation that is a function of soil depth and SOC content in the topsoil (7 cm depth).

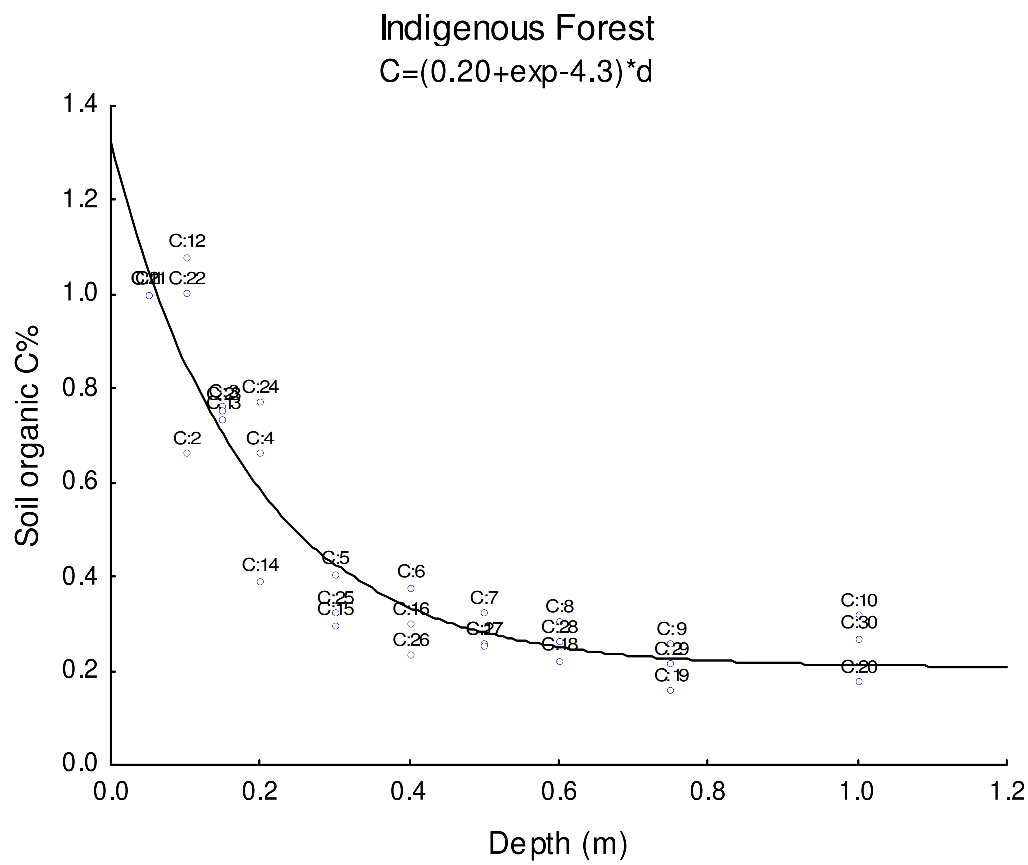

Figure 4.2. SOC distribution under indigenous forests

The general equation (4.2) had an r^2 value of 0.92.

$$C = C_s(0.20+\exp -4.3)*d \tag{4.2}$$

An analysis was done to assess the accuracy of the estimating equation for indigenous forests. A graph of residuals against depth was made. The estimation equation can be applied to a maximum depth of 100 cm. The estimated values can be high by at most 6% or low by at most 9% than the actual SOC content.

Pine plantations

An exponential relationship between SOC content and soil depth was found under pine plantations. Profiles 1, 2 and 3 had r^2 values of 0.8 and profile 4 had an r^2 value of 0.6. The SOC distribution pattern in plantation profiles is summarized in Figure 4.3.

The relationship found was attributed to the low spatial variation of SOC content in pine plantations. The low spatial variation of SOC content in plantations might have resulted from less species diversity, uniform soil type and uniform terrain slope. In each plantation compartment, only one species is planted and litter quality is likely to be the same throughout the compartment. The selected compartment (G7a) was on a convex slope and it was planted to *Pinus taeda*. Soil organic carbon distribution is a function of species diversity, species type, environment variation, moisture regime and soil type. If all factors are the same throughout the compartment, the rate of litter production and decomposition is likely to be the same. This results in a uniform spatial distribution of SOC content (Obbágy, 2000).

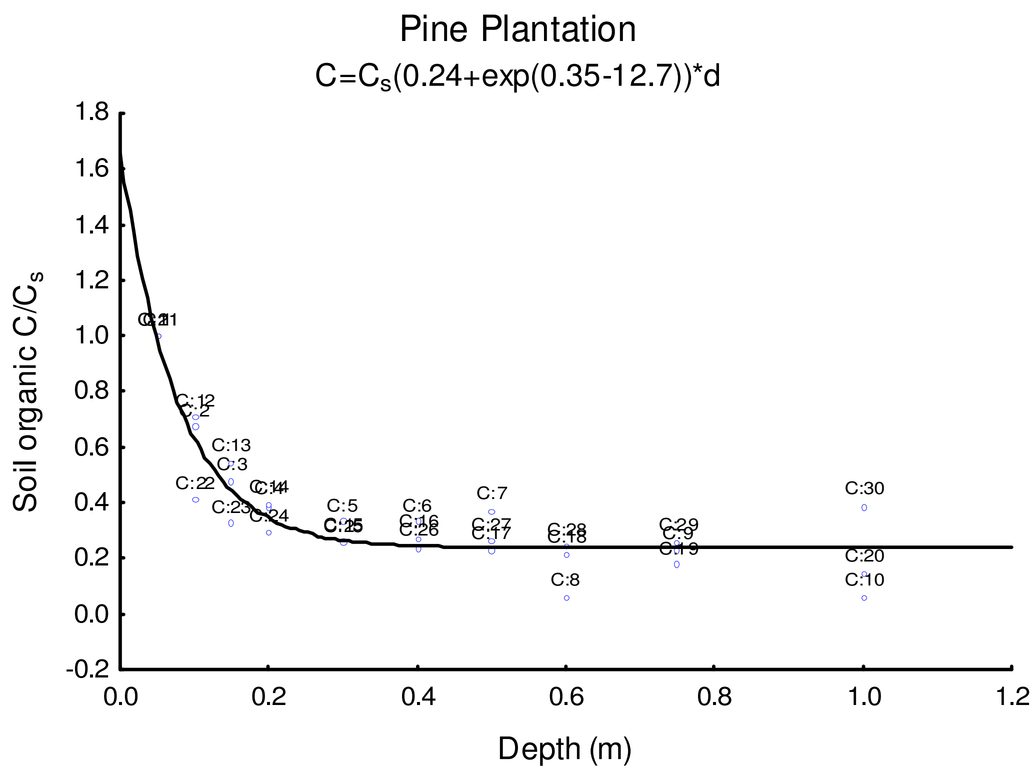

Figure 4.3. SOC distribution under pine plantations

SOC distribution variability also resulted from the ratio of above ground biomass production to below ground biomass production of species. The SOC accumulation under tree plantations is species-dependent as some species produce and accumulate more litter or roots than others. These differential rates of organic matter production eventually influence SOC stocks (Lugo and Brown, 1993). In at least for two plantation species, pines and mahogany, the rate of root production is lower, and the rate of litter production is higher than that of secondary forests of similar age growing in similar climatic and edaphic conditions at locations with similar land use history (Lugo and Brown, 1993). The amount of organic matter in the form of litter layer under pine plantations could be the larger source of SOC than roots.

The high amount of fine roots in the topsoil contributes to SOC content in the topsoil. A high level of fine roots is usually found in the top layers (0 – 10 cm) of the soil where there is a high level of plant nutrients (Gautam *et al*., 2002). Dames *et al* (2002) found large nutrient reserves within the litter layer and a predominance of feeder roots distributed within the layer. The short lifespan of fine roots, which on average is 166 days (King *at al*., 2002), contributed to the high amount of SOC found in topsoil layers (0 – 10 cm). The fine roots form the initial component of SOC, which is plant litter and when they die back, they contribute to dynamic SOC (Janzen *et al*., 1998).

There might be less mixing of organic matter with mineral soil under pine plantations compared to soil under indigenous forests. This could be due to lower root production and low soil organisms in plantations. Thus, litter accumulates on the surface and takes longer to be incorporated into mineral soil.

An average value of SOC content was calculated for every soil depth from the combined data set of three profiles under plantations and used to develop a general equation (4.3), which had an r^2 value of 0.9. Profile 4 was not included in the data set because of a poor relationship between soil organic carbon content and soil depth, compared to the other three profiles.

$$C = (0.52 + \exp -11.7) * d \qquad 4.3$$

The same data set was normalized and an average value of SOC content was calculated for every soil depth and used to develop a normalized prediction equation (4.4), which is a function of soil depth and average SOC in the topsoil (7 cm depth). The normalized estimation equation (4.4) had an r^2 value of 0.9.

$$C = C_s\,(0.24+\exp -12.35)*d \qquad (4.4)$$

The estimated values can be higher than the actual value by more than at most 7% or less than the actual value by at most 16%.

Grasslands

Under grasslands, high spatial variation was found compared to under indigenous forests, plantations and wetlands. In profile 3 and 4 an exponential function best fitted the relationship between SOC and soil depth, while in profile 1 a linear function fitted best when excluding point C3 on the basis that it is an outlier. Profiles 3 and 4 had r^2 values of 0.81 and 0.64 respectively. Profiles 2 had very few data points to draw a sound conclusion on the type of relationship that exists between SOC and soil depth due to the shallow soil depth and high volume of stones.

The high variation in organic carbon distribution in grasslands was attributed largely to terrain, stoniness, slope shape, shallow soil depth and regular disturbance of vegetation through annual burning. Pennock *et al* (2002) found that below-ground biomass in grasslands increased down the slope. The upper level and convex shoulder elements had the lowest below-ground biomass, while low elevation level and high catchments – area foot slope elements had the highest below-ground biomass. Hoa *et al* (2002) found a higher SOC pool at lower slope position than at middle and upper positions. A high volume of stones reduced aggregate stability because of the reduced

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amount of clay in the soil. Dominy *et al* (2002) attributed the high organic matter content and aggregate stability maintained in Hutton soil sites mainly to clay content that was 68% as compared to 18% in Glenrosa soil (water holding capacity). The relationship between SOC and soil depth under grasslands is shown in Figure 4.4.

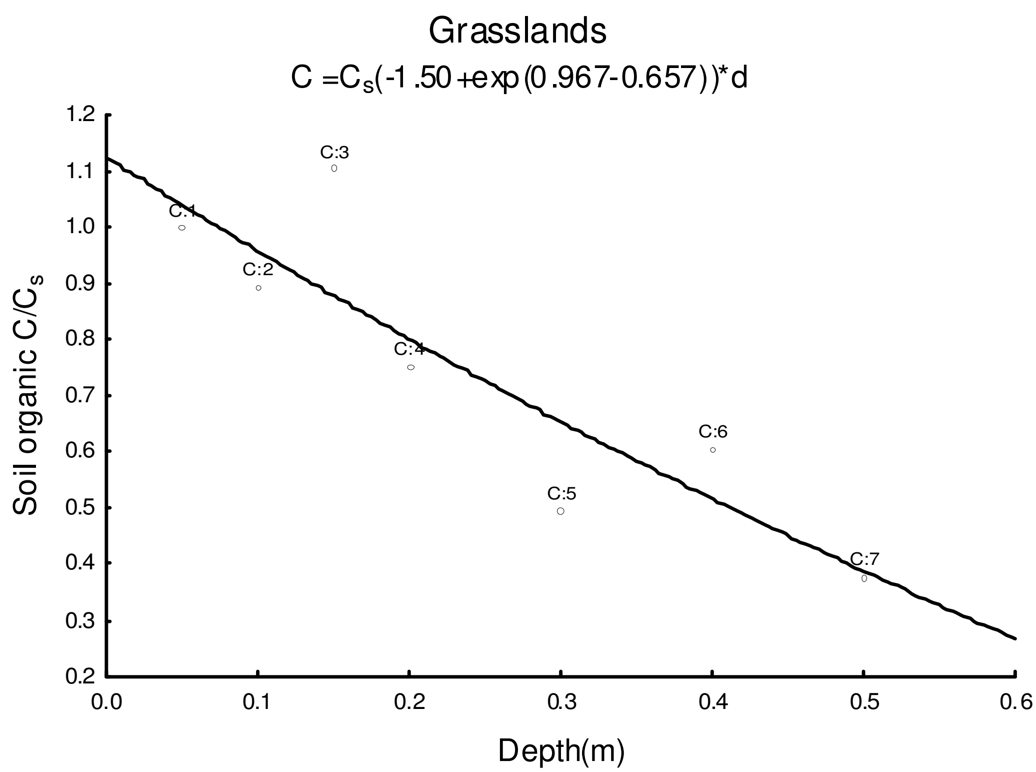

Figure 4.4. SOC distribution under grasslands

It should be noted that the grasslands in this study were not on Glenrosa soils, but the stones could have reduced water holding capacity. Annual burning of grasslands also affected amounts and distribution of SOC. Krishnaswamy and Richter (2002) found that reduced SOC was statistically associated with changes in the percentage of water–stable aggregates, which were affected by burning.

An average value of SOC content was calculated for every soil depth from combined data set of three profiles under grasslands and used to derive a general estimating equation (4.5).

$$C = (-2.28+\exp 0.72)*d \qquad 4.5$$

Profile 3 and 4 were used to develop the general equation because they showed less SOC spatial variation and the exponential relationship between SOC and soil depth in these profiles was found in both plantations and indigenous forests. The general estimating equation (4.5) in grasslands had an r^2 value of 0.77.

The same data set was normalized and an average value of SOC content was calculated for every soil depth and used to develop a normalized prediction equation that is a function of both soil depth and SOC values in the topsoil (7 cm depth). The normalized estimation equation (4.6) had an r^2 value of 0.77

$$C = C_s\,(1.50+\exp 0.31)*d \qquad (4.6)$$

Wetlands

Under wetlands, all profiles showed an exponential relationship between SOC and soil depth (Figure 4.5). All profiles had r^2 values of more than 0.8. The SOC distribution was similar to that found in indigenous forests, plantations and grasslands profiles. Brettar and Höfle (2002) found an exponential distribution of SOC in the upper Rhine floodplains of France. Several factors that influenced SOC distribution in wetlands are: water, soil fauna activities, litter decomposition rate and below-ground biomass. SOC dissolved in water is redistributed to deeper soil layers (Lal *et al.*, 1998). Soil fauna influences the rate of decomposition and is sensitive to the type of organic matter inputs.

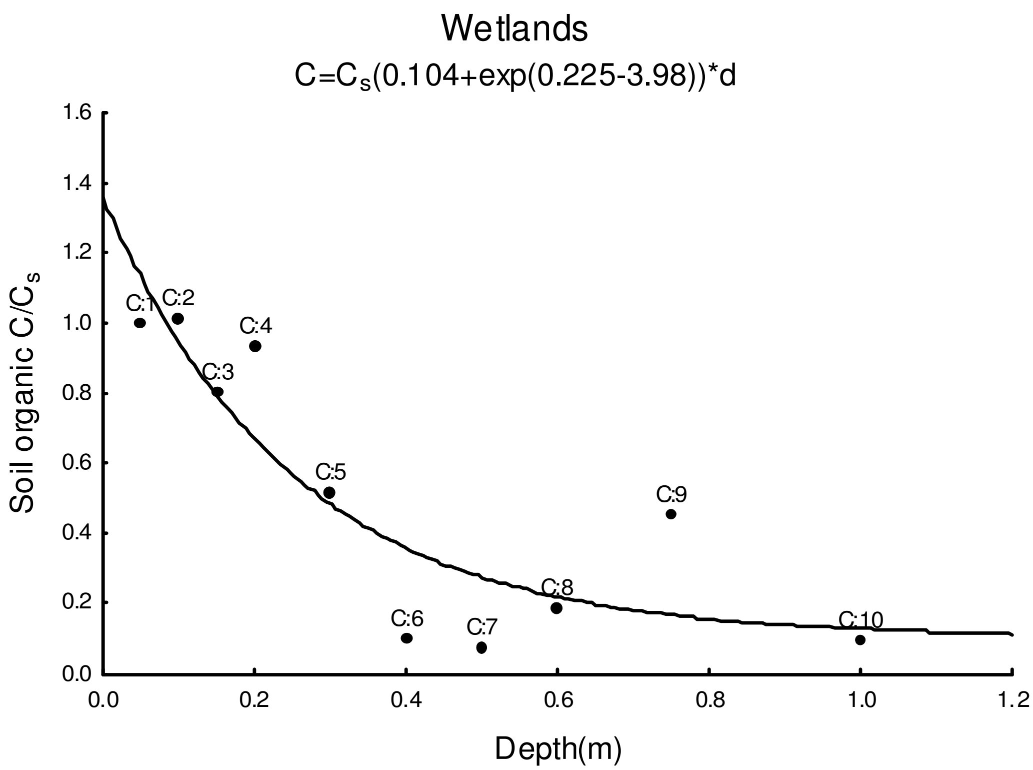

Figure 4.5. SOC distribution under wetlands

Organic matter that is less favorable to soil fauna remains undecomposed for long periods. Favorable organic material like leaves provide the most bio – available source of carbon to soil fauna, while bark may be more important as a habitat for invertebrates and other fauna (Francis and Sheldon, 2002).

A decrease in litter decomposition rate results in high level of SOC. Kelley and Jack (2002) compared decomposition rates of litter in submerged and dry sites and found that total mass and carbon declined more rapidly in fully submerged sites than in dry sites. Kelly and Jack's findings explain why there is a decrease in SOC content as the soil depth and moisture content increase. The difference in decomposition rate results in high SOC content in the drier topsoil. Contrary to Kelly and Jack's findings, Clawson *et al* (2002) found below-ground biomass is greater in the somewhat poorly drained than in the intermediate and well-drained soils.

An average value of SOC content was calculated for every soil depth from a combined data set of all four profiles under wetlands and used to develop a general equation (4.7), which had an r^2 value of 0.79.

$$C = (0.403 + \exp -2.41) * d \tag{4.7}$$

The same data set was normalized and an average value of SOC % was calculated for every soil depth and used to develop a normalized prediction equation (4.8) that is a function of both soil depth and SOC values in the topsoil. The normalized estimation equation (4.8) had an r^2 value of 0.79.

$$C = C_s (0.104 + \exp -3.75) * d \tag{4.8}$$

SOC data for all ecosystems were statistically analyzed and the SOC means of all ecosystems are tabled in Table 4.1. They were analyzed statistically for differences between ecosystems. There was no significant difference in SOC mean at 7 cm depth between plantations and grasslands. This suggest that although grasslands experience annual burning, the rate at which SOC build up is much faster than in plantations or alternatively the fire does not have a huge effect on SOC. The annual burning of grass affected the builds up of soil organic carbon in grasslands to such an extent that it was comparable to SOC under plantations. Grasslands generally store organic carbon faster than plantations due to their intensive root system, however, the annual burning interrupt normal growth.

Table 4.1. Mean SOC % in all ecosystems and standard deviations

	Indigenous Forests		Plantations		Wetlands		Grasslands	
	SOC	**StDev**	**SOC**	**StDev**	**SOC**	**StDev**	**SOC**	**StDev**
0 –5	4.47	1.37	1.82	1.21	3.85	0.69	1.95	0.51
5 – 10	4.67	1.02	1.17	0.32	3.89	1.08	1.74	0.66
10 – 15	4.53	0.57	0.87	0.27	3.08	0.39	2.16	1.23
15 – 20	3.36	0.85	0.74	0.27	3.60	0.75	1.47	0.47
20 – 30	2.36	0.40	0.62	0.27	2.00	1.04	0.97	0.29
30 – 40	1.71	0.57	0.59	0.23	0.38	0.24	1.18	0.30
40 – 50	1.94	0.48	0.54	0.27	0.27	0.11	0.74	---
50 – 60	1.62	0.42	0.44	0.33	0.71	0.93		
60 – 75	1.61	0.70	0.56	0.34	1.76	2.43		
75 – 100	1.29	0.36	0.44	0.64	0.37	0.38		

There was no significant difference in SOC mean at 0 – 7 cm depth between indigenous forests and wetlands. The reason why there is no significant difference in SOC between indigenous forests and wetlands at the surface is not known. One would suspect a difference in decomposition rate between the two ecosystems. Organic matter in wetlands always has enough moisture conducive to rapid decomposition by soil organisms than in indigenous forests, therefore restricting SOC build up in the topsoil. The means of indigenous forests and wetlands means were significantly different from those of plantations and grasslands at 0 – 7 cm soil depth. The SOC mean was significantly higher under indigenous forests than under all other ecosystems at 50 – 100 cm depth interval. This difference could be the result of higher soil fauna activity in indigenous forests than in the other three ecosystems. Their ability to carry organic material to deeper horizons and to mix soil redistributed organic carbon. The high moisture content in deep horizon in wetlands restricted the movement of soil fauna and plant roots to the top layers. Redistribution of SOC in grassland was restricted by a high volume of stones, which might have also restricted root growth to deeper horizons.

Table 4.2 gives a summary of estimating equations for SOC content using the normalized approach and r^2 in each ecosystem. SOC content is estimated as a function of soil depth (d) measured in meters and SOC content (%) in the topsoil (C_s).

Table 4.2. Exponential equations for SOC estimation and R^2 values

Ecosystem	SOC % estimation equation	R^2	Equation no.
Forests	$C = C_s*(0.25+\exp -4.3)*d$	0.92	4.2
Plantations	$C = C_s*(0.28+\exp -12.35)*d$	0.98	4.4
Grasslands	$C=C_s*(1.50+\exp 0.31)*d$	0.77	4.6
Wetlands	$C = C_s*(0.10+\exp -3.75)*d$	0.79	4.8

4.2. SOC content and Soil bulk density (D_b)

Very low soil bulk density values were measured at the soil surface in all ecosystems. This was due to the abundance of tree roots (a mat in indigenous forest) and stones that were removed before measuring the total mass. Roots were removed from the bulk sample for SOC analysis, and thus, their influence is not reflected in the SOC content values. Soil bulk density increased with soil depth in all ecosystems (Figure 4.5). Vertical distribution of bulk density was similar under indigenous forests, plantations and wetlands where soil depth was more than 100cm, while grasslands showed high variation.

The relationship between bulk density and soil depth in all ecosystems was best fitted with a logarithmic curve. Soil bulk density was affected mainly by soil texture, especially the clay content, and soil organic carbon content. Bulk density increased with clay content in all ecosystems while soil organic carbon decreased. Low bulk density is associated with high organic carbon content (Figure 4.6) and the relationship was best fitted by an exponential function. The SOC content seemed to have more influence on bulk density in the topsoil, while clay content was a major influence in the subsoil.

Under indigenous forests, soil bulk density distribution with soil depth showed very strong correlation in profiles 1 (r^2 = 0.94), 2 (r^2 = 0.91), 4 (r^2 = 0.92), and less strong in profile 3 (r^2 = 0.86). The overall logarithm function (4.9) used to estimate soil bulk density under indigenous forests had an r^2 = 0.93.

$$D_b = 0.42Ln(d) + 1.59 \tag{4.9}$$

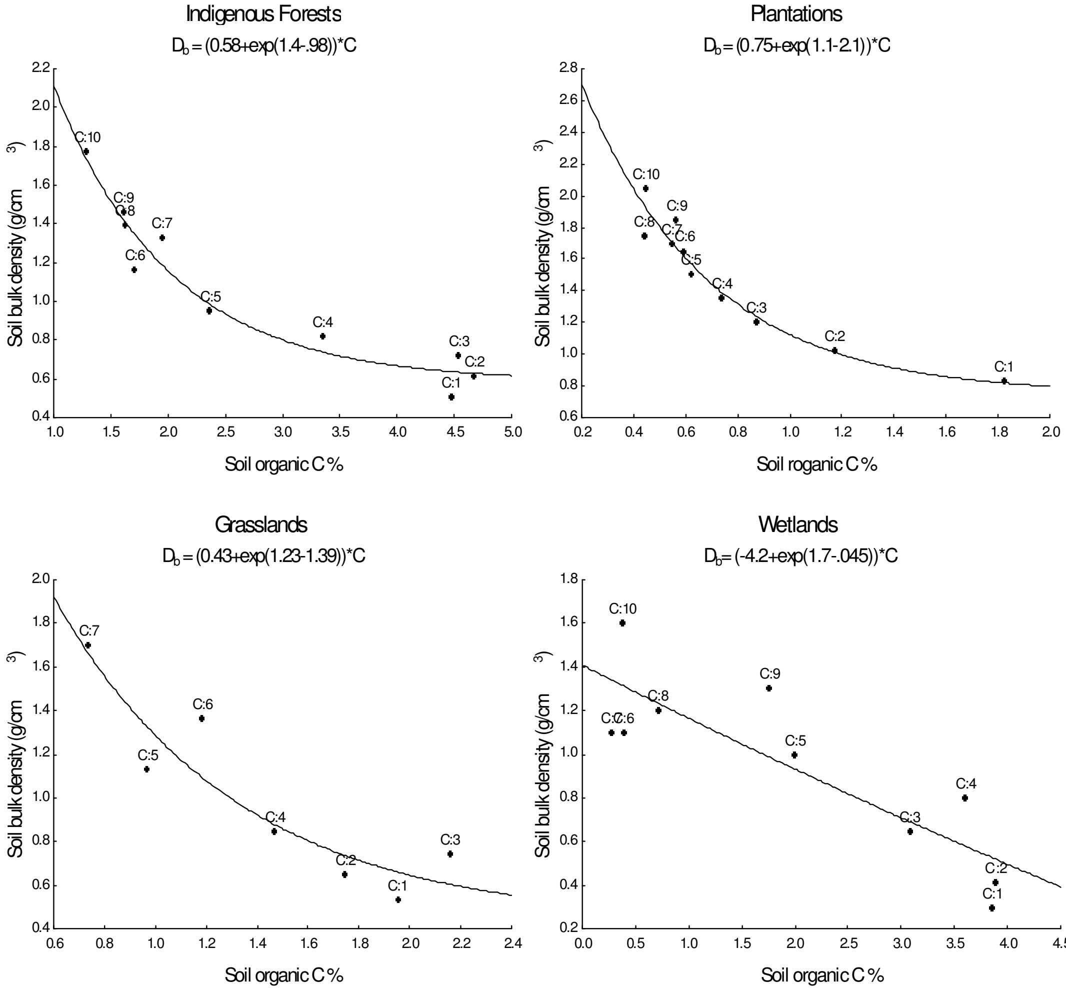

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Figure 4.6. Relationship between bulk density and soil organic carbon content

Soil bulk density had a stronger relationship with SOC content than soil pH. This relationship is shown by high regression coefficient values for the three profiles under indigenous forests except in profile 2, which was affected by pedoturbation. The relationship was best fitted by an exponential function. Regression coefficient values for the individual profiles are higher than regression coefficient values for the overall generalized prediction equation.

Soil bulk density distribution with soil depth under pine plantations showed very strong correlation in all profiles, profile 1 (r^2 = 0.97), 2 (r^2 = 0.96), 3 (r^2 = 0.98), and profile 4 (r^2 = 0.97). The overall logarithm function (4.11) used to estimate soil bulk density under pine plantations had an r^2 = 0.99.

$$D_b = 0.4Ln(d)+1.99 \tag{4.11}$$

All profiles showed a strong exponential relationship between bulk density and SOC content. Profiles 1 and 4 also showed a strong exponential relationship, with r^2 values of 0.92 and 0.7 respectively, while profile 2 and 3 had an r^2 value of 0.96. An average value of D_b was calculated for every soil depth from a combined data set of all four profiles under pine plantations and was used to develop a general equation (4.12).

$$D_b = (0.7+\exp -1.0)*C \tag{4.12}$$

Soil bulk density distribution with soil depth under grasslands showed very strong correlation in all profiles, profile 1 (r^2 = 0.99), 2 (r^2 = 0.99), 3 (r^2 = 0.86), and profile 4 (r^2 = 0.84). The overall logarithm function (equation 4.13) used to estimate soil bulk density under grasslands had an r^2 = 0.86.

$$D_b = 0.48Ln(d)+1.79 \tag{4.13}$$

There was a very poor exponential relationship between bulk density and SOC content in profile 1 and the r^2 value of 0.03, and a moderate linear relationship in profile 2 with an r^2 value of 0.65 in grasslands. A strong relationship was found in profile 3 with an r^2 value of 0.8 and a moderate one in profile 4 with an r^2 value of 0.7. An average value of D_b was calculated for every soil depth from a combined data set of all four profiles under grasslands and used to develop a general equation (4.14).

$$D_b = (0.43+\exp -0.17)*C \qquad (4.14)$$

The source of variation in estimating the D_b in grasslands was determination of soil volume (estimation of D_b in appendix A.1). Although the same D_b estimation method was applied to all ecosystems, grasslands were more affected because of large volumes of stones. It was difficult to sample properly in grasslands because the core auger could not easily cut through the stones and clods. Stones easily fell out of the core auger, which created a big error. The soil volume was determined by subtracting stone volume from total strata volume and the bulk density was estimated using soil texture. Huntington *et al* (1989) found that the greatest source of variation in estimating D_b by the pit method was in the determination of soil volume as is estimated by subtracting rock volume from total strata volume. The method of estimating D_b by subtracting rock volume from total strata volume creates high calculation error. A sensitivity analysis by Huntington *et al* (1889) demonstrated that as rock volume increased the potential error in calculation of D_b associated with errors in estimation of rock volume increased rapidly. The error that underestimated rock volume resulted in proportionately larger errors in the calculation of D_b than overestimation of the same magnitude (Huntington *et al*., 1889). Rawls (1983) showed that soil textural classes and organic carbon could be used to predict soil bulk density. The relationship among C, organic matter, D_b and soil depth were frequently used for estimating soil C pools (Huntington *et al*., 1989).

Soil bulk density distribution with soil depth under wetlands showed very strong correlation in all profiles, profile 1 (r^2 = 0.97), 2 (r^2 = 0.95), 3 (r^2 = 0.97), and profile 4 (r^2 = 0.96). The overall logarithm function (4.15) used to estimate soil bulk density under wetlands had an r^2 = 0.96.

$$Db = 0.42Ln(d)+1.46 \tag{4.15}$$

An exponential relationship between bulk density and SOC content was found in profile 1, 3 and 4 with r^2 values of 0.74, 0.7 and 0.72 respectively. In profile 2, however, a weak exponential relationship with an r^2 value of 0.2 was found. An average value of D_b was calculated for every soil depth from a combined data set of all four profiles under wetlands and used to develop a general equation (4.16).

$$D_b = (-4.2+\exp 1.7)*C \tag{4.16}$$

4.3. Soil organic C content and soil pH

SOC content increased with a decrease in soil pH in all ecosystems (Figure 4.7). In every ecosystem, there were one or two profiles that showed a strong or moderate relationship between SOC content and soil pH.

Under indigenous forests, profile 3 showed a strong linear relationship between SOC content and soil pH with an r^2 value of 0.8, while a moderate linear relationship was found in profile 4 with an r^2 value of 0.6. A very weak linear relationship was found in profile 2 and no relationship was found in profile 1.

Soil pH distribution was attributed to organic matter content, organic matter quality and the amount of organic acids released during organic matter decomposition processes. It has been found that many of the low molecular weight organic acids found in soils are intermediary products of metabolism of plants and microorganisms (Hayes, 1991). Organic acids have more effect on the topsoil layers where they are initially produced from litter than in subsoil layers. The quality of decomposed organic matter also plays an important role in determining the effectiveness of organic acids produced. Humic substances provide overwhelming abundance of acidic functional groups (Perdue, 1985), and acidic polysaccharides that can make significant contributions to the acid functional groups (Hayes, 1991).

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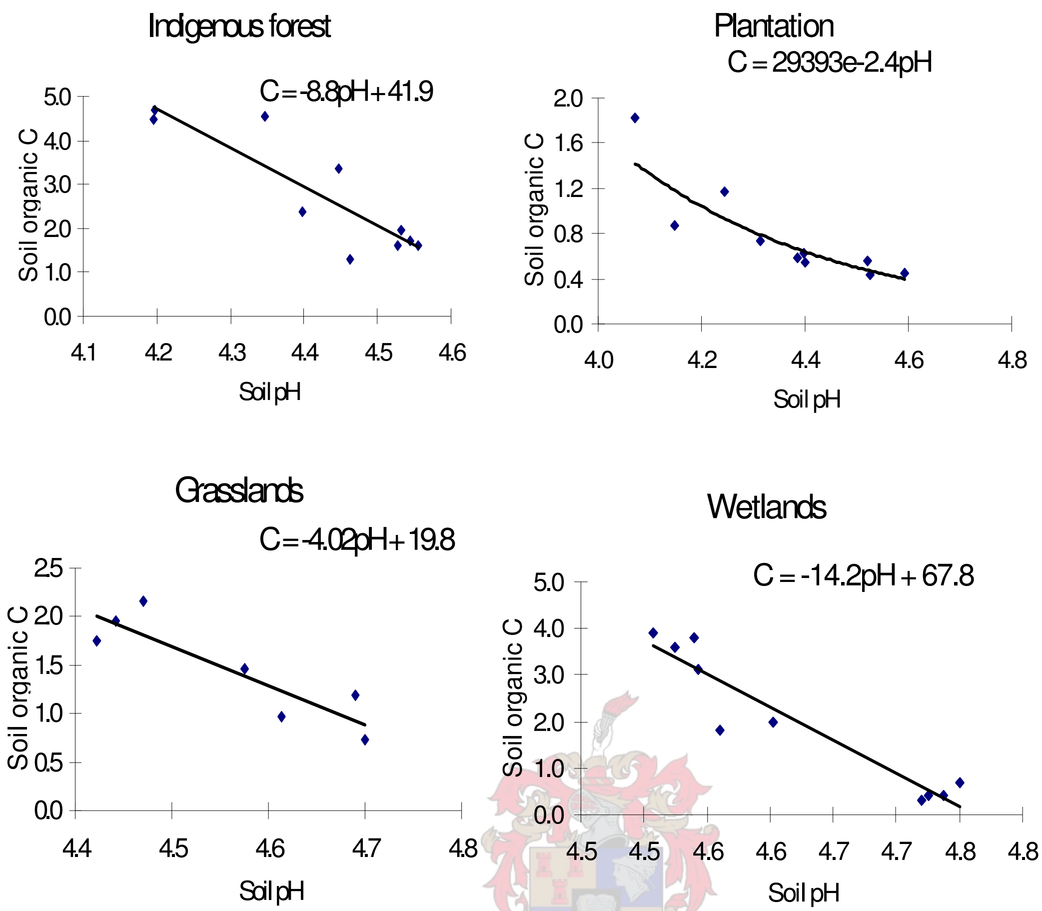

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Figure 4.7. The relationship between SOC and soil pH (KCl)

The relationship between SOC content and soil pH under plantations was best fitted by an exponential function. In profile 1 a weak relationship with an r^2 – value of 0.4 was found, while in profiles 2 and 4 a relationship with an r – value of 0.6 in both profiles was found. A strong relationship was found in profile 3, which had an r – value of 0.9. The strong relationship between SOC and soil pH found especially in profile 3 was possibly due to litter quality and decomposition products.

It has been found that organic matter from pine plantations litter (pine needles in particular) has a tendency to be acidic and produces an acidic leachate (Parfitt *et al*., 1997; Raven *et al*., 1999; Sugarman, 1999). Plantations litter was likely to have different amounts of soluble sugars and lignin content from that of indigenous forests. Pine plantations litter decomposes slowly due to lignin content, which represents a recalcitrant fraction in soil and litter (Minderman, 1968; Guggenberger *et al*., 1995). The soil buffering capacity is also enhanced by high organic matter and aluminum. It was suggested by Sugarman (1999) that the buffering mechanism in soils under pine plantations is controlled by the exchangeable Al (aluminosilicate surfaces) and hydroxo-Al compounds because of organic matter's strong affinity for cation binding especially its bonding with Al (Brady and Weil, 1999). Aluminum has a greater affinity for organic matter compared to other cations (Ross *et al*., 1991). The bonding of Al to organic matter reduces the potential of basic cations to attach to ligand groups on the organic matter (Sugarman, 1999). Because of the increased buffering capacity due to Al – organo compounds especially in the topsoil (because of high organic matter content), pH increase through an increase in basic cations is likely to be higher in subsoil than in topsoil.

Under grasslands, a negative linear relationship between SOC content and soil pH was found. In profile 1 and 4, relationship had r^2 values of 0.7 and 0.6 respectively. In profile 2, the number of data points was not enough to draw any conclusion. Profile 3 had an r^2 value of 0.4.

The distribution pattern was similar to that in indigenous forests and pine plantations, where the topsoil had lower pH than the subsoil. Although the pH

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range was not wide, possibly due to soil buffering mechanism and uniformly distributed organic carbon in the shallow profiles, the distribution pattern was well shown by the fitted curve (except in profile 2). Average soil pH in grasslands was higher than in all ecosystems. Sugarman (1999) compared soil pH under grasslands and adjacent pine plantations and found similar results where soil pH was higher under grasslands than under pine plantations.

Under wetlands, a linear relationship was found between SOC content and soil pH in profile 1. The r^2 value in profile 1 was 0.01. In profiles 2 and 3, a moderate linear relationship was found and there was an r^2 value of 0.6 for both profiles. A strong linear relationship was found in profile 4 and it had an r^2 value of 0.8. Average soil pH was lower in wetlands than in grasslands, but higher than in pine plantations and indigenous forests. Wetlands have the highest SOC per ha than the other three ecosystem and with the relationship between SOC and pH, one would expect wetland to be more acidic than the three ecosystems. This could suggest that the quality of organic matter is more influential in determining soil pH than the SOC amount.

4.4. Statistical analysis of SOC content, D_b and pH in intensive sampling plots

SOC content per ha in the topsoil (0 - 7 cm) differed significantly among the four ecosystems (Table 4.3). Wetlands had the highest SOC content, followed by indigenous forests, then grasslands and pine plantations. There was also a high variation of organic carbon content within indigenous forests and wetlands. The variation within indigenous forests was attributed to species diversity, which adds diversity of litter that has different decomposition rates. The variation in wetlands was attributed to different organic materials deposited by water and those from wetland vegetation. These organic materials have different decomposition rate due to their nature (whether it is a leaf or a bark), moisture content variation within wetland and organic matter quality (lignin content, organic acids).

There was no difference between the means of pine plantations and grasslands but the variation was fractionally higher in grasslands than in pine plantations. Soil factors such as moisture content and soil texture and vegetation type played an important role in influencing the accumulation and variation of SOC content in the topsoil.

Table 4.3. SOC content variation among the ecosystems

Ecosystems	No. Samples	Sum/ha (%)	Average (%)	Variance	Depth (cm)
Pine plantations	46	77.2	1.7	0.3	0 - 7
Indigenous forests	46	137.4	3.0	0.9	0 - 7
Grasslands	46	81.4	1.7	0.4	0 - 7
Wetlands	46	166.2	3.6	1.2	0 - 7

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Source of Variation	SS	Df	MS	F	P-value	F crit
Among Ecosystems	123.5	3	41.2	58.2	2.36E-26	2.65
Within Ecosystems	127.3	180	0.7			
Total	250.9	183				

The soil bulk density (D_b) at the surface differed significantly among the four ecosystems (Table 4.4). Pine plantations had the highest D_b, followed by grasslands and then indigenous forests, while the lowest D_b was found in wetlands. The high soil bulk density correlates well with low soil organic carbon in both pine plantations and grasslands as both ecosystems have an average SOC content of 1.7%. On other hand, low soil bulk density values in indigenous forests and wetlands correlated well with the relatively high values of soil organic carbon content in the same ecosystems.

Table 4.4. Soil bulk density (g/cm^3) variation among the ecosystems and within each ecosystem

Ecosystems	No. Samples	Sum	Average	Variance	Soil depth (cm)
Pine plantations	46.0	32.67	0.71	0.04	0 - 7
Indigenous forests	46.0	20.04	0.44	0.01	0 - 7
Grasslands	46.0	27.66	0.60	0.01	0 - 7
Wetlands	46.0	16.43	0.36	0.00	0 - 7

Source of Variation	SS	df	MS	F	P-value	F crit
Among Ecosystems	3.5	3	1.17	85.58	1.87444E-34	2.65
Within Ecosystems	2.5	180	0.01			
Total	6.0	183				

Unlike soil organic carbon content, there was little D_b variation within each ecosystem. This low variation was attributed largely to soil clay content.

There was a significant soil pH difference between the ecosystems. Grasslands had the highest soil pH followed by wetlands and pine plantations and indigenous forest had the lowest soil pH (Table 4.5). There was little soil pH variation within pine plantations due the relatively similar type of vegetation and plant litter that is deposited on the surface, which is the source of organic acids influencing soil pH at the topsoil.

Table 4.5. Soil pH (KCl) variation among the ecosystems and within each ecosystem

Ecosystems	No. Samples	Average	Variance	Soil depth (cm)
Pine Plantations	46.0	4.73	0.06	0 - 7
Indigenous Forests	46.0	4.44	0.29	0 - 7
Grasslands	46.0	5.42	0.20	0 - 7
Wetlands	46.0	5.23	0.14	0 - 7

Source of Variation	SS	Df	MS	F	P-value	F crit
Among Ecosystems	28.1	3	9.38	54.73	3.42E-25	2.65
Within Ecosystems	30.8	180	0.17			
Total	59.0	183				

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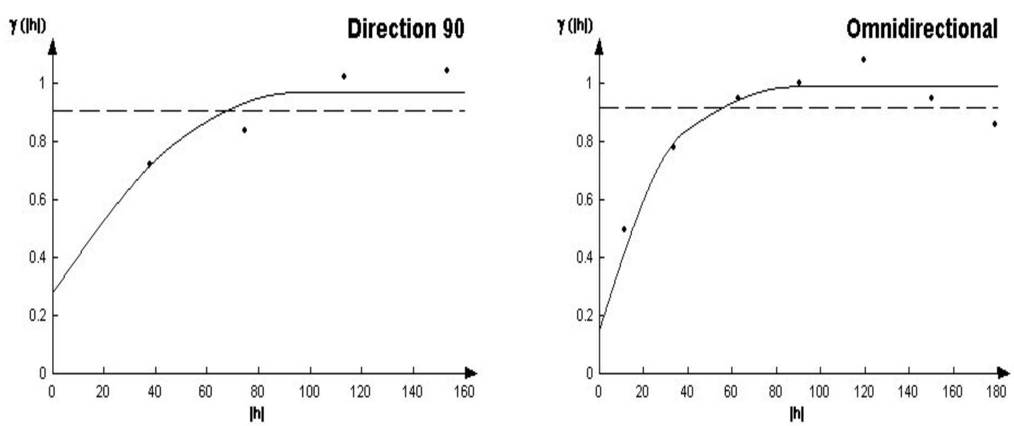
The highest soil pH variation within the ecosystem was found in indigenous forests and grasslands. This is likely to be the result of vegetation diversity within each ecosystem, which deposits litter that adds a variety of organic acids to the soil.

Organic carbon content in surface (0 - 7 cm) samples of all ecosystems showed a poor correlation with soil pH and soil bulk density. However, there was a clear correlation between ecosystem and D_b, and ecosystem and soil pH. Soils under plantations were more acidic, followed by soils under indigenous forests and grasslands and the wetlands (Table 4.5). Higher soil bulk density values were found in plantations, by followed indigenous forests and grasslands.

4.5. Geo-statistical modelling of SOC distribution on the surface (7cm)

A geo-statistical approach was applied aimed at developing spatial models to reduce the number of samples to be collected, but still providing results that can be achieved by intensive sampling strategy. Variograms were developed from the data set of carbon content in topsoil (0 – 7 cm), samples using Variowin (Yvan Pannatier, 1996).

The model used for developing variograms in all ecosystems was spherical. The indigenous forests model was derived from omni directional variograms (angular tolerance = 90º) illustrated in Figure 4.8.



(a). Direction 90° (b). Direction 0°

Figure 4.8. Indigenous forests variograms

The model range was about 74 m along the drainage line or stream (East-West, 0º direction) and 46 m across the drainage line (North-South, 90°). This meant that two sampled points that were more than 74 m apart along the stream were spatially independent and there was high variation, such that SOC from the two sampled points was likely to be significantly different, while two sampled points within the range had a relatively low variation such that the difference was likely to be insignificant. In simple terms, when collecting samples along the stream (0º direction) in indigenous forests, it was necessary to collect a sample in every 74 m at most. In indigenous forests, there was a very strong directional distribution pattern of SOC.

The model range for pine plantations was 65 m at direction 75º with an angular tolerance of 25º, and 47 m at direction 165º with angular tolerance of 50º (Figure 4.9).

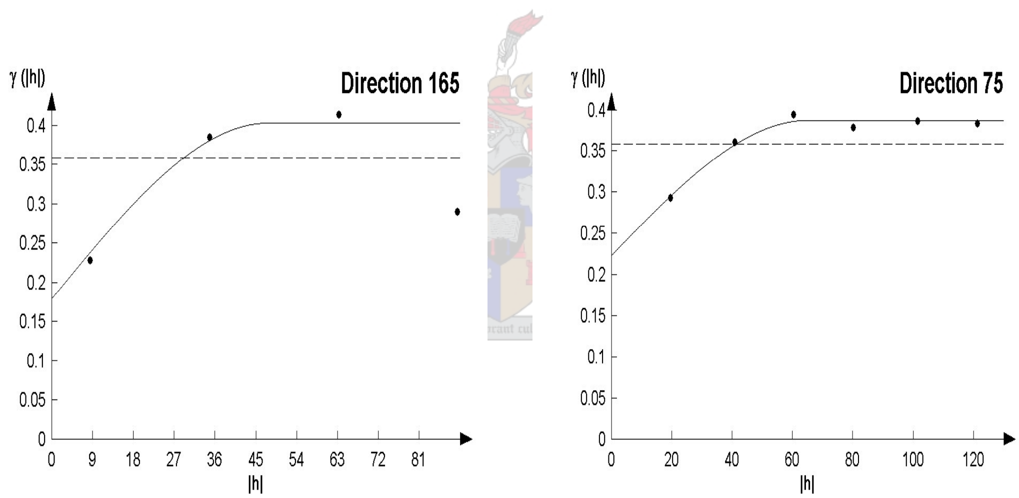
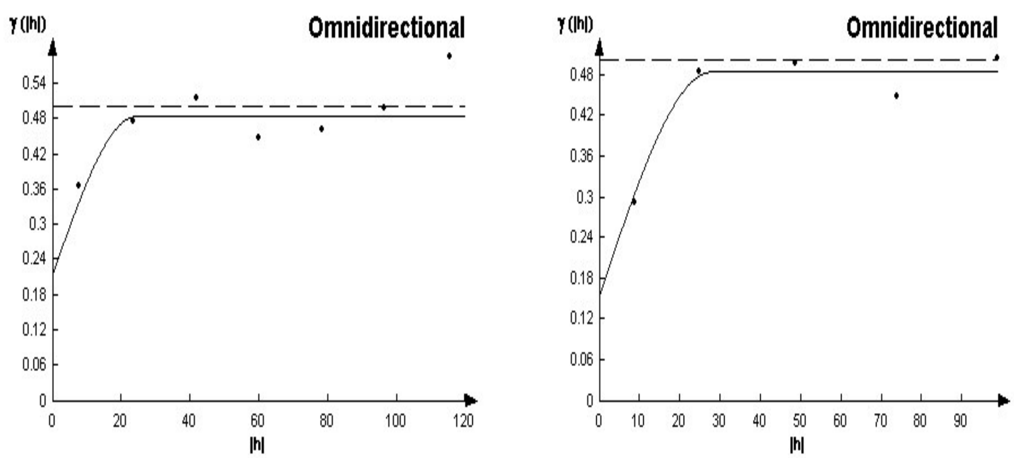


Figure 4.9. Pine plantations variograms

This meant that under plantations SOC content of two samples that are more than 65 m apart in the 75º direction and more than 47 m apart in the direction perpendicular to 75º were likely to be significantly different.

The grasslands had a much lower range than indigenous forests and pine plantations. With a model range of 31 m at direction 0º, and 24 m at direction 140º (Figure 4.10), grasslands showed a higher spatial variation than any other ecosystem. When sampling in grasslands, it was necessary to collect a sample every 31 m in the direction parallel to the stream and 24 m in the direction crossing the stream. This implies that more samples will be required in grasslands than in plantations and indigenous forests per ha to get a good representative batch of samples for SOC estimation purposes.



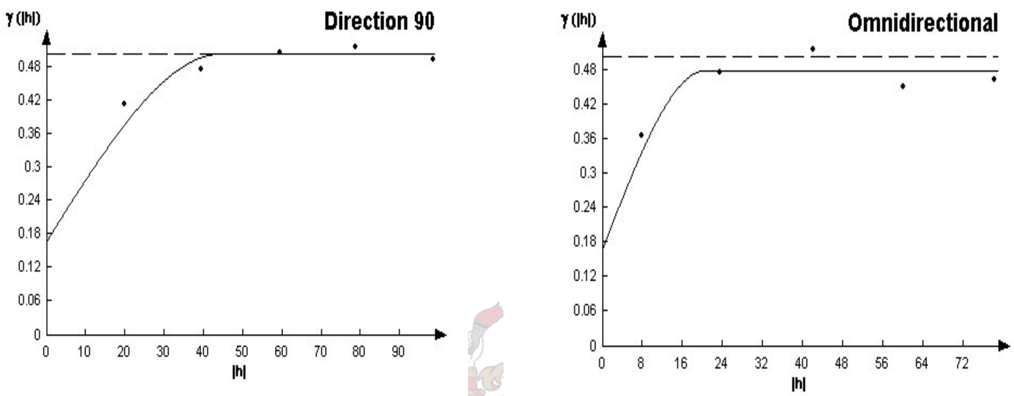
(a). Direction 0°

(b) Direction 140°

Figure 4.10. Grasslands variograms

The wetlands had a model range of 45 m along the river (at direction 90º) and a range of 38 m across the river at direction 0º (Figure 4.11). There was, however, a slight directional impact towards the river because of increasing moisture content.

The model range (distance between two sampling points) can only be applied in one direction. A change in direction will require a different model range because the slope changes and that will result in a different SOC distribution pattern.



(a). Direction 90°

(b). Direction 0°

Figure 4.11. Wetlands variograms

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The value of the model range depends on spatial variation of SOC within the ecosystem. This spatial variation of organic carbon results from the factors influencing the organic carbon content, like slope, root distribution and vegetation type, soil type etc. However, there is a limitation in the model. The model range cannot be longer than the longest distance between two sampled points that were used in developing the estimation model.

This means that if the intensive sampling plot used to develop the variogram from which the model is developed was 100 m^2, the model range can't be more than 100 m. The angular tolerance defines the width with which the interpolation is applied in order to include or exclude points in the interpolation. For example, if the angular tolerance is set at 25º, the maximum number of points for interpolation is eight and only six points are covered by the angle, and the interpolation will include only six points covered by the angle despite the maximum number of points being eight.

The difference between the model ranges in the two directions in pine plantations was small compared to that of indigenous forests indicating a more uniform (less variation) SOC distribution in pine plantations.

Figure 4.12 shows SOC spatial variation within each ecosystem in an area of 50 m^2. This variation resulted from different site characteristics such as slope, species diversity and soil type.

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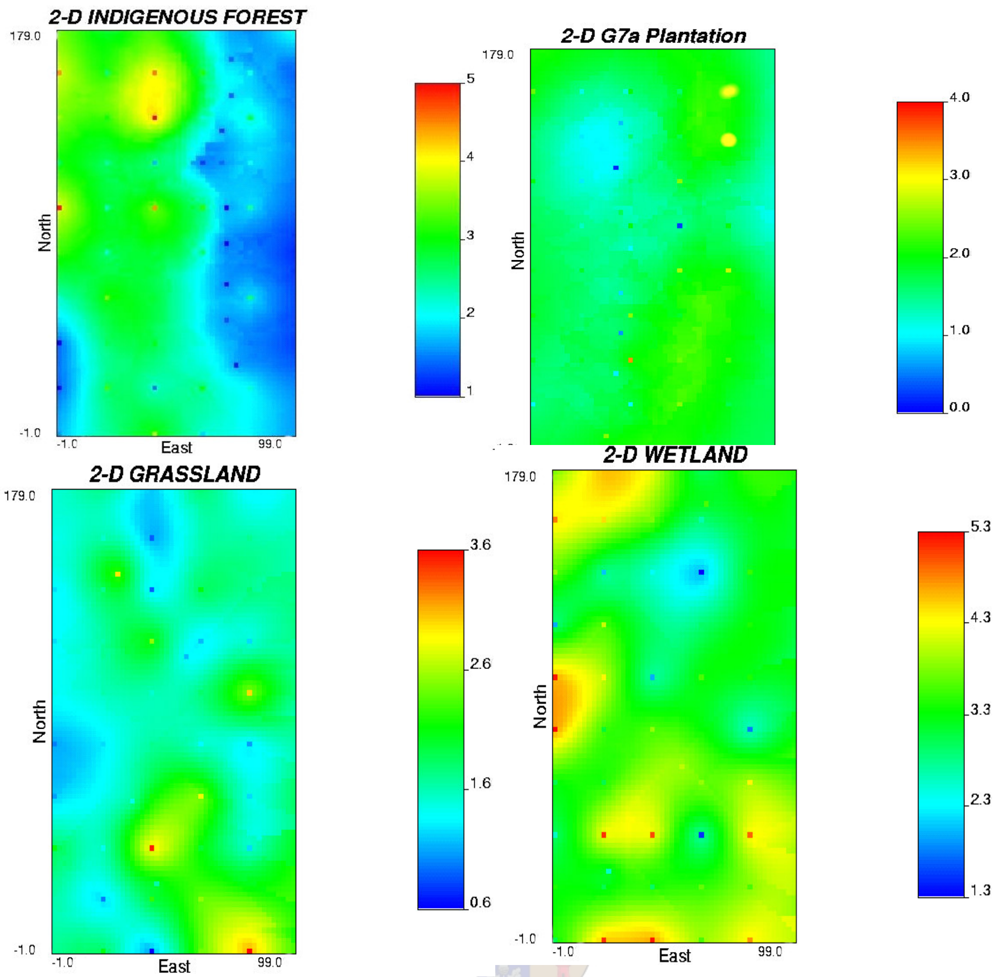

Figure 4.12. Spatial distribution of SOC content in the topsoil

Organic carbon distribution under indigenous forests, pine plantations and grasslands was strongly directionally orientated. Soil organic carbon distribution was correlated to soil moisture patterns and this was reflected by high organic carbon content found in areas with high moisture content. High spatial variance was found in grasslands, followed by wetlands, indigenous forests and plantations. Low spatial variability in plantations was attributed to human activities and their influence on species diversity and distribution. Soil carbon variability is greater in less disturbed than in more disturbed soils (Conant *et al.,* 2003). Several different factors contributed to the spatial variance found in all ecosystems.

The high spatial variation found in grasslands was attributed to stones (their effect on D_b), slope and soil moisture. Wang *et al* (2002) found that spatially structured variance (variance due to the location of sampling site) accounted for a large proportion of the value variance for elevation (99%), D_b (90%), SOC (68%), aspect (56%) and soil moisture (44%). The short model range of 31 m at 140º and 24 m at 40º found in grasslands is an indication of high spatial variability and discontinuity of SOC distribution. Yanai *et al* (2002) found that the ranges of spatial dependence were approximately 20 – 30 m for total C, total N and exchangeable Na.

Comparison between plots showed that the highest values were observed in wetlands, followed by indigenous forests, where high values occurred more in moister areas than in topographic depressions. Midslopes had less moisture content and SOC in topsoil than foot slopes. The moisture content and SOC increased towards river terraces. The distribution pattern was more pronounced under indigenous forests than in pine plantations. Plots in indigenous forests with low SOC fell in a moderate slope, while relatively high SOC was mainly in a gentle slope (Table 4.6).

Table 4.6. Slope classes from the FSD guidelines version 1.2

Class	Percent	Description
1	0 – 12	Level
2	13 – 20	Gentle
3	21 – 35	Moderate
4	35 – 50	Steep
5	> 50	Very steep

Although all indigenous forests profiles were relatively deep, shallow soils found in ridges and convex slopes had low SOC and low moisture content.

SOC under pine plantations was spatially uniform; and no major directional patterns were observed in the selected sites, probably because of the uniform slope, less species diversity and uniform moisture content. The sampled compartment G7a had a gentle slope and the soil type was relatively uniform, mainly Inanda 1200 soil families.

A high SOC content under grasslands was observed only in small patches of grass between drainage lines. In general, SOC within the grass tufts was high.

Wetlands showed a spatial variation in SOC distribution and a directional SOC distribution pattern. The slope found in wetlands was class 1 (0 - 12%), with a small slope gradient towards the Dap Nuade Dam, which resulted in a directional moisture and SOC distribution pattern. There was a generally high SOC content in wetter sites as indicated by reddish colours (Figure 4.12) and some indication of low SOC levels shown as bluish colours.

There was a noticeable variation in organic matter distribution in wetlands. Near the river, there was high organic matter content that had not completely decomposed and away from the river, organic matter had decomposed and homogenously mixed with mineral soil. There were more species with broad leaves and vigorous growth near the river, while less vigorous growth, and fewer broad-leafed species were found away from the river.

Several factors might have contributed to the difference in SOC spatial variation between ecosystems, factors such as topography, climatic conditions, soil properties and soil organisms. Homann *et al* (1995) found that

SOC increased with annual temperature, annual precipitation, actual evapo-transpiration, clay, and available water-holding capacity and decreased with slope angle. Lugo and Brown (1993) found that in a mature tropical forest in Costa Rica, variability and upper limit in SOC increased with increasing water availability.

Organic matter in upper slopes was likely to be eroded by water down to the river terrace. Depending on the steepness of the slope and the amount of vegetation cover on the soil, varying amounts of organic matter may be gradually deposited down the slope. The areas with gentle slopes had high organic carbon content because of higher soil moisture content. The slope gradient causes a shift in organic carbon content from steep slope areas to gentler slope areas, the same way moisture content is distributed.

Results from the study of Weaver *et al* (1987; in Lugo and Brown, 1993) concerning spatial distribution of SOM with landforms and percent slopes showed different accumulation of soil organic matter in different landforms and slopes. Middle slopes had higher organic matter content than ridges and convex slopes as well as concave slopes and bottoms. Slopes of 0 –25% had higher soil organic matter than 26 – 45% and > 45% slopes.

The diversity of species constituting each ecosystem also affected the distribution pattern as the decomposition rate of litter from different species and root distribution varied. SOC distribution variability also resulted from the ratio of above ground biomass production to below ground biomass production of species. The SOC accumulation in tree plantations is species-dependent as some species produced and accumulated more litter or roots than others and these differential rates of organic matter production eventually influenced SOC stocks (Lugo and Brown, 1993).

At least for two plantation species, pines and mahogany, the rate of root production was lower, and the rate of litter production was higher, than that of secondary forests of similar age growing in similar climatic and edaphic conditions at locations with similar land use history (Lugo and Brown, 1993). The soil types and moisture content further increased the variation of species within the same area, as some species are adapted to sandy soil, and the moisture requirement varied. With uniform slope, uniform soil type and very little variation in litter type deposited to the soil, there was no major variation in terms of distribution.

Soil organism's activities also influence the spatial variation of SOC. Soil fauna such as earthworms significantly increase average soil organic carbon content and also change the spatial distribution from uniform to patchy (Shuster *et al.*, 2001). Pennock and Corre (2001) found that significant transfers of SOC and surface soil from the convex shoulder units to lower slope positions has occurred over the past 90 years. With the slope class 4 (35% - 50%) in grasslands sites, water speed was high and small tracks were formed around and between grass tufts, eroding high amounts of organic matter to river terraces and lower lying areas. The slope also adversely affected soil depth and, as a result, three profiles in grasslands were very shallow, hence low organic carbon content (in terms of volume) was found. The slope gradient also affected species diversity through its effect on soil moisture distribution. As water availability increases, there is a greater diversity of possible plant and geo-morphological associations, each with a particular SOC content (Lugo and Brown, 1993).

SOC spatial variation in wetlands, which had model ranges of 45º at 0º and 38º at 90º, was attributed to soil moisture and organic matter. Soil moisture content and organic matter quality affect the rate of decomposition. Organic matter components such as bark and branches decompose at a slower rate compared to leaves and fine roots (Francis and Sheldon, 2002). Wang *et al* (2002) found that SOC varied closely with elevation and soil moisture depending on the distance between samples. In indigenous forests, relatively less (compared to wetlands and grasslands) variability was found in the northern direction (0º). A drainage depression in the sampled plot was found along the same direction and it suggested that SOC variation was determined mainly by soil moisture and slope.

The high (compared to plantations) variability in indigenous forests was attributed to species diversity and soil fauna activities (earthworms in particular). Li Xu Yong *et al* (2002) found that earthworm activity stimulated the activity of soil microorganisms, probably by enhancing organic C availability via processing and mixing of litter. Plantations had relatively less variability compared to indigenous forests. Its model ranges that were longer to both perpendicular directions were a good indication of this low variation. The less variation found in plantations was attributed to species diversity and relatively uniform slope that affected soil moisture gradient. Because of human influence on species diversity and vegetation distribution, organic matter and SOC were influenced in their spatial distribution.

4.6. GIS analysis of soil associations, elevation and slope

SOC content and stocks were analyzed using ARCVIEW GIS. The digital map of Woodbush with data on soil characteristics, vegetation, roads, loading tracks, rivers and streams, water bodies and fire points, and contour lines was provided by SAFCOL. The GIS analysis was aimed at assessing the effect of topography, elevation, soil type, and vegetation on the accumulation and distribution of SOC stocks.

Images of SOC distribution (at depth 0 – 7 cm) that were created with GSLIB were geo-referenced, projected and overlaid with indigenous forests theme, plantations theme, wetlands theme, grasslands theme and contours to establish a relationship between the elevation and distribution patterns shown on the images (Figure 4.13).

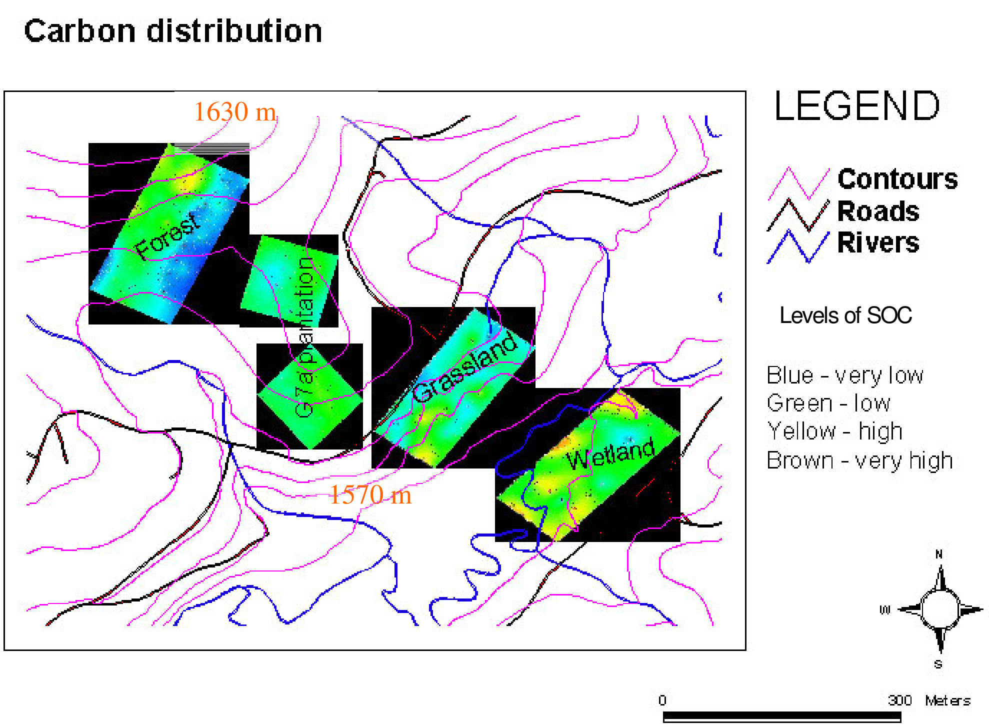

Figure 4.13. Kriged maps of SOC within the intensive sampling plots overlying topography and drainage lines

The combined kriged map (Figure 4.13) shows spatial variation of soil organic carbon content with terrain change in each ecosystem.

The images were overlaid with rivers and streams to establish a relationship between moisture content and SOC distribution. The highest values of SOC and highest degree of variation were observed in wetlands along watercourses, where micro drainage depressions and pools formed during floods in the year 2000, were important factors.

The magnitude of this variation covered the whole spectrum from low to very high SOC content. The least variation was observed in plantations, where all trees were of the same age and SOC contribution from other species was minimal. In indigenous forests increased SOC was associated with drainage lines in the form of depression in the sampling plot. Grasslands were strongly affected by slope and subsequently, ESD that resulted in a high spatial variation.

During sampling, the positions of the sampled points within plots, transects and profiles were recorded. These points were geo-referenced and projected to the same projection as SAFCOL data so that they can be overlaid on other GIS layers. Plantations, indigenous forests, grasslands, and wetlands data were separated from each other and themes of those vegetation types were created. A theme of soil types was created to determine the different types of soil in Woodbush and the sizes of areas they occupied. Within the soil type theme, themes for soils with different depths in different slopes were created and overlaid with each other to assess the effect of soil depth and slope degree on SOC distribution within each soil type in each ecosystem.

A grid of contours was created from the contour theme and themes of soil types were overlaid with the contour grid to establish a relationship between elevation and distribution of soil types together with soil depth. A contour grid was also overlaid with vegetation themes to establish a relationship between elevation and distribution of vegetation, although vegetation distribution was influenced by human activities.

GIS provided a different analytical approach in understanding and describing SOC distribution patterns both vertically and horizontally. The contours theme showed the topology and aspect that prevails in Woodbush. The soil theme showed different soil types that were found in the study area (Figure 4.14) and their distribution throughout Woodbush. The contour grid was overlaid with soil types and showed a soil distribution pattern in relation to altitude.

Most shallow (root limiting factor within 90 cm) Inanda soils were distributed at elevations between 1545 m and 1777 m, and on a gentle slope in the Northern aspect of the mountain. Deep (root limiting factor beyond 90 cm) Inanda soils were found mostly in lower elevation range of 967m and 1545 m (Figure 4.14.) on moderate slopes. Deep and shallow Inanda soils were found on the southern aspect.

The deep Kranskop soils are evenly distributed and mostly found at an elevation range of between 1080 and 1430 m on gentle slopes, while at an elevation range of between 1430 and 1780 m, they were found on moderate slopes.

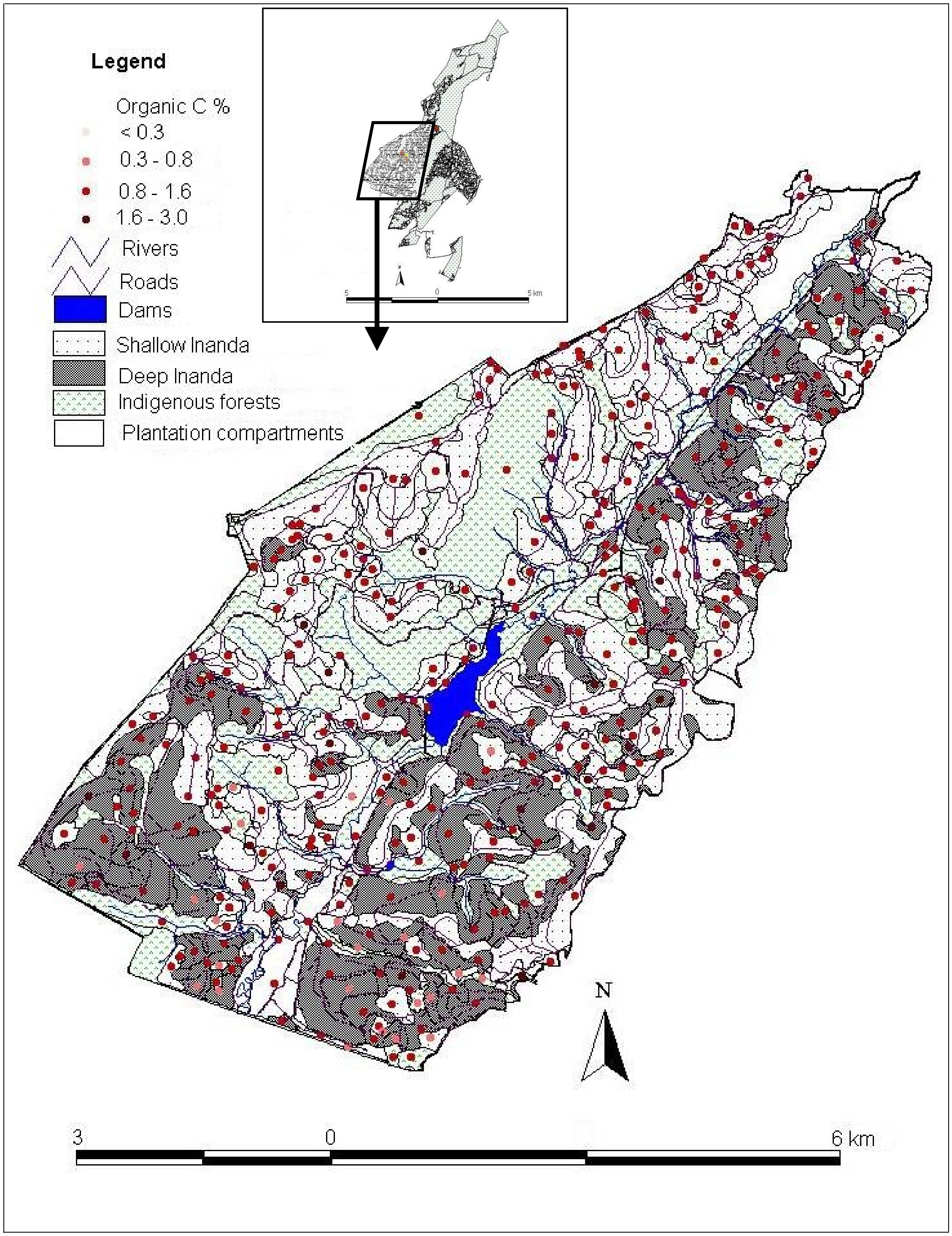

Figure 4.14. Distribution of soil organic carbon in relation to soil type and soil depth in the Broederstroom River catchment

4.7. Analysis of SOC content, D_b and soil pH in transects

The three transects made in plantations (compartment G7a, F1 and F23/21d) and two transects in indigenous forests were compared to assess the influence of aspect and sampling method on the surface (0 – 7 cm), and the results of transects in plantations are presented in Table 4.7.

Table 4.7. SOC content variation in transects through plantations

Compartment	Count	Average	Variance
F23/F21d	16	0.97	0.24
G7a	16	1.10	0.22
F1	16	0.86	0.09

Source of Variation	SS	Df	MS	F	P-value	F crit
Among Compartments	0.46	2.0	0.23	1.21	0.31	3.20
Within Compartments	8.45	45.0	0.19			
Total	8.91	47.0				

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The SOC content means in all three compartments were compared to assess the influence of aspect on spatial variation of SOC. There was no significant difference in surface SOC content means between transects through Compartment F1 and G7a. This could mean that the accumulation of SOC content was not significantly affected by aspect. Similar results were found between compartment F23/21d and compartment G7a. There was high SOC content variation within G7a, F23/F21d, and little variation in F1 (Table 4.7). Comparison of soil bulk density means was also done to assess the effect of aspect in the three transects made in the above-mentioned compartments. There was a significant difference in surface bulk density between transects through compartment F1 and G7a. The difference in bulk density could be attributed to soil texture rather than soil organic carbon as SOC content was not significantly different between the two transects. There was also a significant difference in surface D_b between transects through F23/F21d and G7a. Within each transect, there was little soil bulk density spatial variation (Table 4.8).

Table 4.8. Soil bulk density (g/cm^3) variation in transects through plantations

Compartment	Count	Average	Variance
F23/F21d	16	0.69	0.05
G7a	16	0.57	0.03
F1	16	0.78	0.02

Source of Variation	SS	Df	MS	F	P-value	F crit
Among Compartment	0.36	2	0.18	5.28	0.01	3.20
Within Compartment	1.51	45	0.03			
Total	1.87	47				

There was a significant difference in soil pH between transects through compartments F23/F21d and G7a. There was also significant difference in soil pH between transects through G7a and F1. High soil pH spatial variation was found in transects through G7a and F1 (Table 4.9). Soil temperature of these two compartments might be the main factor influencing decomposition rate and that can further influence the decomposition products and soil pH.

Table 4.9. Soil pH (KCl) variation in transects through plantations

Compartment	Count	Average	Variance
F23/F21d	16	4.22	0.07
G7a	16	3.68	0.11
F1	16	4.10	0.11

Source of Variation	SS	MS	F	P-value	F crit
Among Compartment	2.55	1.28	13.58	0.00	3.20
Within Compartment	4.23	0.09			
Total	6.78				

Transect samples from compartment G7a were compared to surface plot samples (0 - 7 cm) in the same compartment to assess the effect of sampling methods. There was a significant difference in SOC content between transects and surface plot samples in compartment G7a. There was a higher spatial variation in transects than within plots (Table 4.10).

Table 4.10. Comparisons of SOC content (%) between transect and plot sampling methods in pine plantations

Sampling Method	Count	Average	Variance
Transect	16	3.68	0.11
Plot	16	4.68	0.04

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Methods	7.99	1	7.99	108.30	0.00	4.17
Within Method	2.21	30	0.07			
Total	10.20	31				

There was a significant difference in soil bulk density between transects and plots. Soil bulk density in plots is significantly higher than in transects. However, D_b spatial variation in both sampling methods was low (Table 4.11).

Table 4.11. Comparisons of D_b (g/cm^3) between transect and plot sampling methods in pine plantations

Method	Count	Average	Variance
Transect	16	0.57	0.03
Plot	16	0.78	0.02

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Methods	0.34	1	0.34	14.19	0.00	4.17
Within Method	0.73	30	0.02			
Total	1.07	31				

Soil pH in plots was significantly higher than that of transect samples. There was a higher soil pH spatial variation in transects than in plots (Table 4.12). SOC content D_b and soil pH in transect samples were significantly lower than values found in surface plot samples.

Table 4.12. Comparisons of soil pH (KCl) between transect and plot sampling methods in pine plantations

Method	Count	Average	Variance
Transect	16	3.68	0.11
Plot	16	4.68	0.04

Source of Variation	SS	MS	F	P-value	F crit
Between Methods	7.99	7.99	108.30	0.00	4.17
Within Method	2.21	0.07			
Total	10.20				

A comparison was done on transects made in indigenous forests on opposite aspects to assess the effect of aspect on SOC content.

Table 4.13. SOC content (%) variation in transects through indigenous forests

Compartment	Count	Average	Variance
Forest G7a	16	1.67	0.05
Forest F1	16	1.61	0.13

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Compartments	0.03	1	0.03	0.31	0.58	4.17
Within Compartments	2.66	30	0.09			
Total	2.69	31				

There was no significant difference in SOC content between transect samples collected in indigenous forests adjacent to compartment F1 and transect samples collected in indigenous forests adjacent to compartment G7a. Therefore, southern and northern aspects in this case did not have a significant effect on the accumulation of SOC. There was a higher spatial variation in transects adjacent to compartment G7a than in transect adjacent to compartment F1.

Table 4.14. Soil bulk density (g/cm^3) variation in transects in indigenous forests

Compartment	Count	Average	Variance
Forests G7a	16	0.41	0.01
Forests F1	16	0.47	0.01

Source of Variation	SS	df	MS	F	P-value	F crit
Between Compartments	0.03	1	0.03	3.60	0.07	4.17
Within Compartments	0.21	30	0.01			
Total	0.24	31				

There was no significant difference in soil bulk density between transect adjacent to G7a and transect adjacent to F1. There was little spatial variation within each transect (Table 4.14). Similar analysis was done on soil pH for the same transects and the results are presented in Table 4.15.

Table 4.15. Soil pH (KCl) variation in transects in indigenous forests

Compartment	Count	Average	Variance
Forest G7a	16	4.19	0.11
Forest F1	16	4.09	0.18

Source of Variation	SS	MS	F	P-value	F crit
Between Compartments	0.08	0.08	0.52	0.48	4.17
Within Compartments	4.47	0.15			
Total	4.55				

There was also no significant difference between the two transects. However, spatial variation was slightly higher in transect adjacent to F1 than in transect adjacent to G7a. The effect of sampling strategy was assessed by analyzing statistically the mean difference in SOC content, D_b and soil pH between transect samples and plot samples. There was a significant difference in SOC between transects samples and plot samples. Plot samples had a higher SOC content than transect samples. There was higher spatial variation in plots than in transects (Table 4.16).

Table 4.16. Comparisons of SOC content (%) between transect and plot sampling methods in indigenous forests

Method	Count	Sum	Average	Variance
Plot	16	47.35	2.96	0.98
Transect	16	26.69	1.67	0.05

Source of Variation	SS	df	MS	F	P-value	F crit
Between Methods	13.34	1	13.34	25.95	0.00	4.17
Within Method	15.42	30	0.51			
Total	28.76	31				

There was no significant difference in soil bulk density between transect samples and plot samples. There was little variation within both transects and plots (Table 4.17).

Table 4.17. Comparisons of D_b (g/cm^3) between transect and plot sampling methods in indigenous forests

Method	Count	Average	Variance
Transect	16	0.41	0.01
Plot	16	0.41	0.01

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Methods	0.00	1	0.00	0.01	0.91	4.17
Within Method	0.16	30	0.01			
Total	0.16	31				

Soil pH, however, was higher in transect samples than in plot samples. Spatial variation within transects was also higher than in plot samples (Table 4.18).

Table 4.18. Comparisons of soil pH (KCl) between transect and plot sampling methods in indigenous forests

Method	Count	Average	Variance
Plot	16	4.13	0.02
Transect	16	4.19	0.11

Source of Variation	SS	MS	F	P-value	F crit
Between Methods	0.03	0.03	0.51	0.48	4.17
Within Method	2.00	0.07			
Total	2.03				

It is also interesting to note that average values of SOC content obtained from transects were substantially (and statistically) significantly lower compared to average values received from intensive sampling plots, both in pine plantations and indigenous forests. This phenomenon can only be explained by the natural tendency of a sampler to choose intuitively a “representative” spot during random sampling along transect, when a person subconsciously avoids spots that may be “abnormally” rich or poor in organic matter. It may also simply be a choice of the most accessible route with the least dense ground cover.

This tendency resulted in the positioning of both transects and plots in the landscape. In pine plantations (compartment G7a), transects were made along the areas with low SOC content and these areas are indicated with greenish colour in Figure 4.14, while the plot covered low and high SOC areas. Transects in pine plantations had high spatial variation because they covered a long distance that was not covered in plots along the crest of the drainage depression that had low SOC content (Figure 3.4).

In indigenous forests, transects were made in low SOC areas illustrated in Figure 4.13. However, SOC spatial variation was high in plots despite the small area they covered. The direction of transect was the same as the drainage depression illustrated in Figure 4.12 represented by green colours with yellow spots. However, transect was on the blue area in Figure 4.13. Plots covered both high (green & yellow) and low (blue) areas, which resulted in high variation.

4.8. SOC Stocks of Woodbush

SOC stocks were estimated using predicting functions developed using fitted curves that best described SOC and soil bulk density (D_b) distribution down the profile for each ecosystem. The SOC amount was estimated at different soil layers and then multiplied by D_b at the same depth. SOC stocks were calculated using the standard approach of calculating carbon stock as SOC%*D_b*d, where SOC content is the concentration of carbon in the layer of depth increment d, and D_b is soil bulk density within the (d) depth increment.

In this case SOC content was calculated as Cs*f (d) and D_b as F (d). Soil organic carbon stocks were estimated using equation 4.17. The equations that were used to estimate SOC content are listed in Table 4.2. Soil bulk density estimation was tested using observed SOC content values.

$$SOC = \int_0^{100} Cs * f(d) * F(d) * d \tag{4.17}$$

This approach of D_b estimation was recommended by Huntington (1989), where organic matter was used to estimate bulk density for use in the calculation of SOC stocks. The correlation between SOC and D_b was poorer than that of D_b and soil depth, therefore soil depth was used to predict soil bulk density.

The profile approach of estimating SOC stocks based on SOC content and D_b applied in this study, was previously applied by Batjes (1996) to estimate total carbon and nitrogen in the soils of the world. Schwartz and Namri (2002) used a similar approach in mapping the total organic carbon in soils of the Congo.

The SOC stock estimation equations of indigenous forests, plantations and wetlands did not include the coarse fragment component as described by the equation of Batjes (1996) because little fragments were found in soils under these ecosystems. Fragments were included in grasslands equation only to cater for the stones found in the soil. Schwartz and Namri (2002) did similar simplifications by making the coarse fraction of soils less important in mapping the total organic carbon in soils of the Congo. Subsequently, a finite integral was resolved numerically to yield a reliable assessment of SOC stock to the depth of one meter. A similar integration to 20 cm was conducted to assess topsoil stocks. Cherkinsky and Brovkin (1993) applied the same technique successfully to estimate the SOC turnover rates based on ^{14}C data. When total soil depth was less than 100 cm, the integral was calculated to soil depth instead. Total Soil Depth was adjusted to Effective Soil Depth (ESD) by subtracting the percentage of stones in each layer, if stones were present. This adjustment was made for depth (d) value.

Integration was conducted at d = 5 cm increments to the depth of 20 cm, and the value of d increased to 10 cm increments to a depth of 60 cm, and to 15 cm and 25 cm increments since increased integration intervals at greater depth had less effect on the error of stocks estimation because of less variation in deeper soil layers. The integral value was obtained as a sum of values for all depth increments.

This approach allowed accurate assessment for soils of variable depth, which was particularly important in the mountainous environments. Another advantage of the suggested technique was that only topsoil sampling was required at directionally unequal intervals for accurate evaluation of carbon stocks.

Carbon stocks were calculated for each ecosystem (Table 4.19) from intensive sampling and transect data for topsoil SOC content, using the equations in Tables 4.20 and 4.21.

Pectora roborant cultus recti

Table 4.19. The average carbon stocks (ton) per hectare

Vegetation	SOC %	St.Dev	SOC at 0.2 m	St.Dev	SOC at 1m	St.Dev
Plantations	1.36	0.71	13	3	46	20
Forests	1.83	0.70	24	8	64	23
Grasslands	1.70	0.67	13	5	28	11
Wetlands	3.85	0.69	33	9	71	19

Integral (equation 4.17) was calculated by step-integration illustrated in Figure 4.16. Values for grasslands were also adjusted by the average percentage of stones observed in soil profiles excavated within the intensive sampling plots.

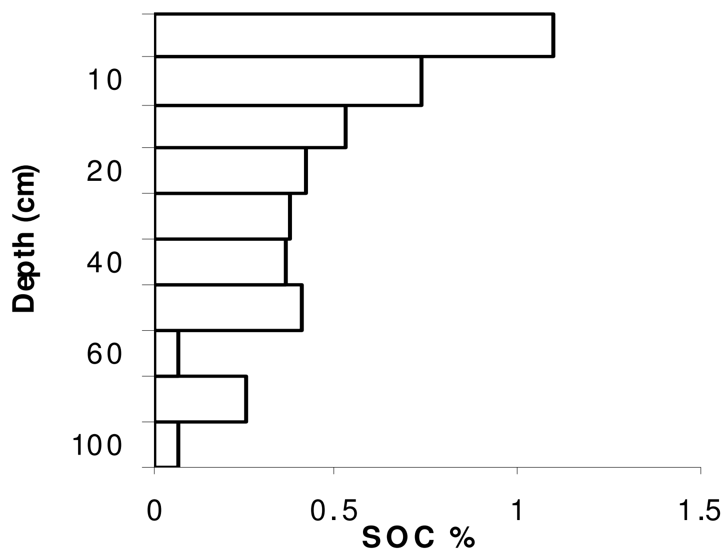

Figure 4.15. Example of integration for carbon stock estimation with SOC% and depth for pine plantations

Table 4.20. Prediction model equation used in the different ecosystems and their r^2 values

Ecosystem	Prediction model	R^2	Equation no.
Indigenous forests	$C = C_s*(0.24+\exp -4.3)*d$	0.92	(4.2)
Pine plantations	$C = C_s*(0.28+\exp -12.35)*d$	0.98	(4.4)
Grasslands	$C = C_s*(1.50+\exp 0.31)*d$	0.77	(4.6)
Wetlands	$C = C_s*(0.10+\exp -3.75)*d$	0.79	(4.8)

C = normalized SOC; C_s = surface SOC; d = soil depth (m)

Table 4.21. Prediction model equations for D_b at depth <= 1m used in the different ecosystems and their r^2 values

Ecosystem	Prediction model	R^2	Equation no.
Indigenous forests	D_b = 0.42Ln(d)+1.59	0.93	(4.9)
Pine plantations	D_b = 0.40Ln(d)+1.99	0.99	(4.11)
Grasslands	D_b = 0.48Ln(d)+1.79	0.86	(4.13)
Wetlands	D_b = 0.42Ln(d)+1.46	0.96	(4.15)

D_b = Soil bulk density; d = Soil depth (m).

Wetlands had the highest carbon stocks per hectare compared to other ecosystems. With an average of 33 t/ha within the top 20 cm depth (Table 4.19.), wetlands were significant high sinks of organic carbon per hectare. However, wetlands occupy a very small area in Woodbush forestry, lying only along rivers, dams and swamps. The average soil carbon stocks per hectare at one-meter depth in wetlands were also very high, but their contribution to carbon sequestration in Woodbush might be low compared to indigenous forests and pine plantations due to limited occurrence of wetlands.

Since soils under grasslands do not reach one-meter depth, an appropriate comparison was made between the four ecosystems using stocks values in the top 20 cm.

Total SOC stocks per hectare were low in grasslands, and it's difficult to predict the levels of carbon storage in deep soils, since the estimation function derived from the data may not be applicable to a soil depth greater than 60 cm. Furthermore, grasslands were annually burnt as a fire control measure, so the build up of organic matter was annually disturbed. The storage within 20 cm depth was lower than in pine plantations, with an average of 13 t/ha.

Pectora roborant cultus recti

Soils under indigenous forests stored higher carbon stocks in tons per hectare than plantations. They had second highest organic carbon stocks per hectare after wetlands and cover a large area in Woodbush because they occupy a large accessible area as well as most inaccessible steep slopes. Indigenous forests had larger average carbon stocks per hectare at 20 cm and one meter soil depth compared to pine plantations.

Low soil carbon stocks in pine plantations were possibly due to the age of plantations compared to the age of indigenous forests. Maps of SOC content on the surface (7 cm), carbon stocks in the top 20 cm and 100 cm depths were created for each ecosystem. The maps for the whole plantation were developed using modified SAFCOL data set.

Table 4.22. The influence of sampling method on evaluation of carbon stocks estimation for the main land use types in Woodbush

Land use	Type of Survey	Obs	SOC at 5cm Mean	St.Dev	C stocks at 20 cm Mean	StDev	C stocks, 1m Mean	StDev	Ratio C^{20}/C^{100}
Plantations	Profiles	3	1.23	0.33	18	4	48	13	36.3%
	Transects	59	0.98	0.44	11	2	35	13	32.1%
	Area	46	1.83	0.71	15	3	59	20	26.0%
	Combined	105	1.36	0.71	13	3	46	20	28.6%
Forests	Profiles	4	4.12	0.67	52	1	121	30	43.5%
	Transects	35	1.40	0.86	18	3	48	9	37.3%
	Area	52	1.96	0.86	28	9	75	24	37.1%
	Combined	87	1.83	0.70	24	8	64	23	37.2%
Wetlands	Profiles	4	3.85	0.69	32	4	73	14	43.4%
	Areas	51	3.60	1.09	33	9	71	19	46.6%
Grasslands	Profiles	4	1.95	0.51	23	2	36	13	64.0%
	Areas	47	1.70	0.67	13	5	28	11	45.7%

Where Obs = Number of observations

The prediction model was applied to the soil organic carbon content database complied by Strydom (1997) for SAFCOL to estimate SOC stocks in Woodbush under pine plantations. The symbols used in SAFCOL database to estimate organic carbon content in the topsoil were substituted by values in Table 4.23. The model required SOC and soil bulk density in the topsoil.

Table 4.23. Classes of topsoil carbon used in the SAFCOL database (source: Strydom et al., 1997)

Description Symbols	Organic carbon
Extremely high (eh)	> 1.8%
High (h)	>1.4 - <1.8%
Medium to high (m – h)	1 – 1.8%
Medium (m)	0.7 – 1%
Low to medium (l – m)	0.3 – 0.6%
Low (l)	<0.3%

The database was modified, and values in Table 4.23 were added instead of descriptive data and used to calculate carbon stocks at 20 cm and 100 cm soil depths using estimation equation 4.6. Since a considerable number of topsoil samples contained more than 1.8% organic carbon content, descriptive statistics were used to define a value for this data range to be used in calculations (Figure 4.16). The derived average value of 2.42% was used for stock estimations with the SAFCOL database.

This value did not contribute substantially to overall stock estimations, due to very limited number of observation points with “extremely high” carbon content values in SAFCOL database.

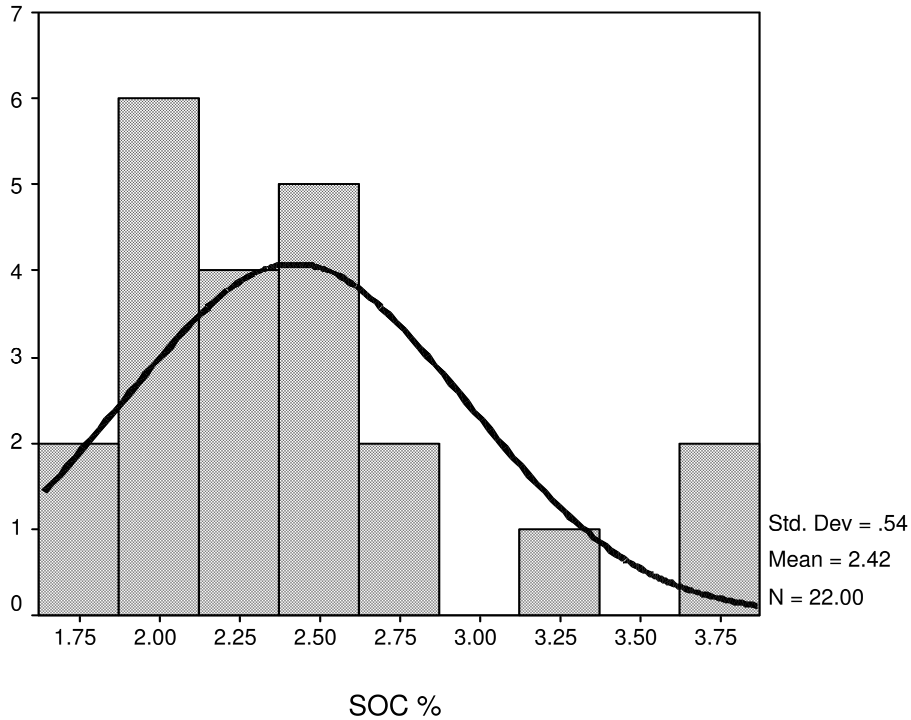

Figure 4.16. Frequency histogram for topsoil organic carbon content in excess of 1.8% in samples from pine plantations

Due to lack of soil bulk density data in SAFCOL database, an average soil bulk density of the topsoil was calculated from the study site data and applied to SAFCOL data. However, other methods of calculations were also assessed.

Estimation of D_b from soil texture recorded in the field according to look-up Table 4.24. (McKenzie *et al.*, 2000)

Estimation of D_b with logarithmic equation for pine plantations (Table 4.21.)

This was combined with two methods of carbon content estimation.

Extrapolation of carbon content estimated in the field to the whole A horizon and assigning a value of 0.5 to B-horizon – a look-up method.

Exponential estimation of carbon content at depth increments of 10 cm.

Table 4.24. Look-up table for bulk density estimation from soil texture Calculated from K.E. Saxton et al. (1986)

Clay%	20	25	30	35	40	45	50	55	60
BD	1.43	1.39	1.36	1.33	1.31	1.28	1.25	1.23	1.22

The results of these estimations are summarized in Table 4.25 together with estimations based on experimental observations in soil profiles, where stocks were calculated directly at every depth increment, as well as extrapolations to the combined set of transect and intensive sampling points of topsoil sampling using exponential equation in Table 4.20.

Table 4.25. Impact of estimation method on assessment of carbon stocks under pine plantations in Woodbush

Estimation Method	Bulk density estimation	Obs*	SOC at 5cm Mean	SOC at 5cm St.Dev	C stocks at 20 cm Mean	C stocks at 20 cm StDev	C stocks at 1m Mean	C stocks at 1m StDev	Ratio (%) C^{20}/C^{100}
Horizon	Lookup table 4.24	1643	1.56	0.18	44	3	92	16	47.4
	linear	1643	1.56	0.40	35	3	82	14	42.8
	Ln*	1643	1.56	0.40	32	3	72	12	44.6
Curve	Linear	1643	1.56	0.40	22	2	47	5	46.3
	Ln	1643	1.56	0.40	19	2	45	5	43.0
Experimental	Profiles	3	1.23	0.33	18	4	48	13	36.3
	Plantation	105	1.36	0.71	13	3	46	20	28.6

Obs* is the number of observations and Ln* is logarithm

As shown in Table 4.25, the results of predictions using exponential SOC curve and logarithmic D_b curve yielded on average, similar results for experimental profiles, and predicted stocks for the complete data set of topsoil sampling points, and for the plantation as a whole with values ranging from 45 to 48 t/ha within 1-m soil depth. These results also showed that linear D_b estimations combined with exponential curve of SOC distribution also produced results within the above range. All estimations based on values for individual soil horizons and their thickness were much higher, mainly due to the fact that organic carbon content within these horizons was not uniformly distributed, but followed the same exponential curve, as can be seen from the analysis of individual soil profiles. These observations fall in line with results obtained by use of Century model for prediction of carbon stocks (Motavalli *et al*., 1994).

Subsequently, maps of organic carbon content and calculated carbon stocks over the Broederstroom catchment were produced as Arcview shape files. Additional fields were inserted into the auguring point's database for values of SOC content and SOC stocks. The resulting map of SOC content (Figure 4.17) represented the distribution of soils with medium, high, and extremely high carbon content as reflected in results of the soil survey.

Pectora roborant cultus recti

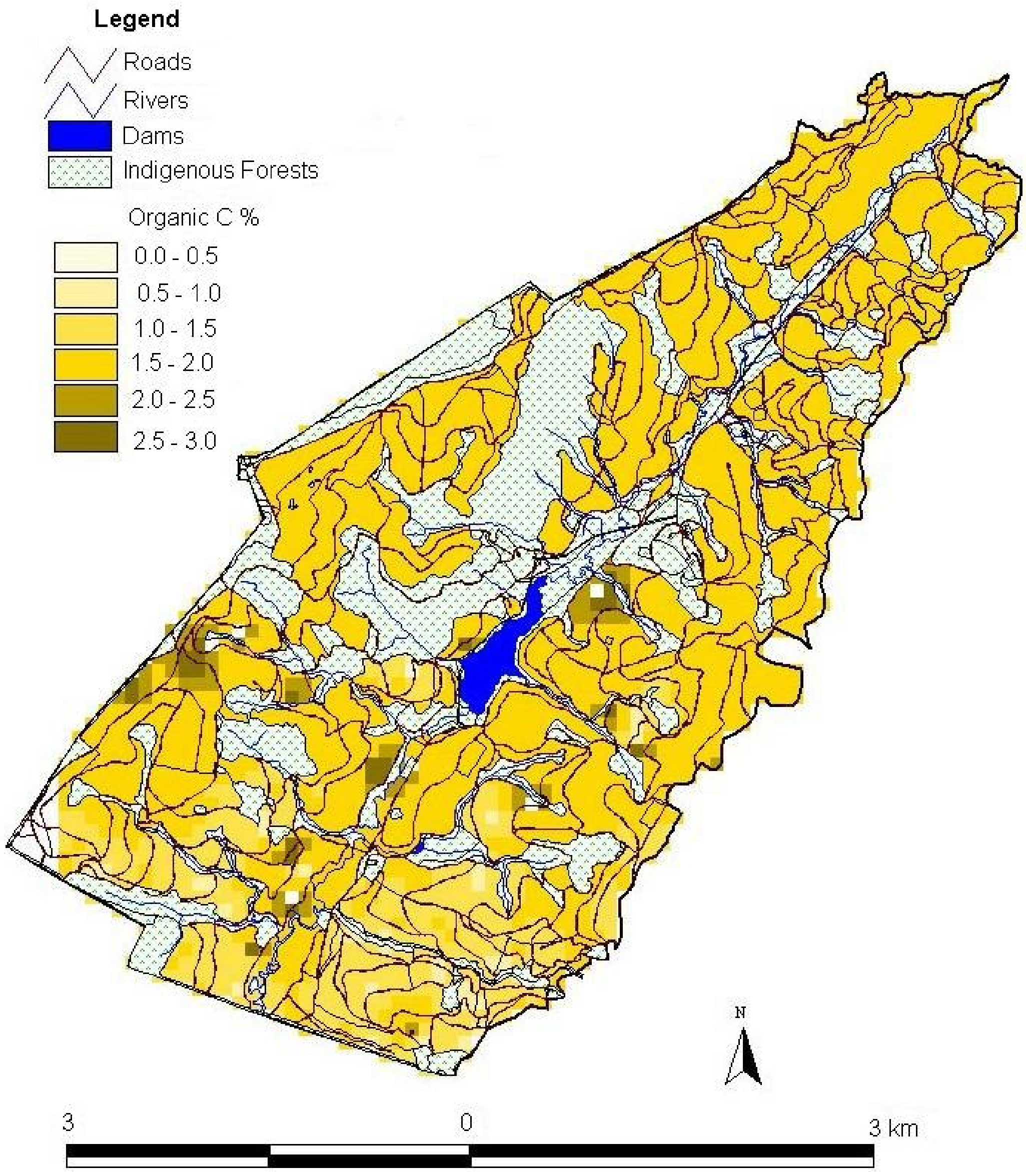

Figure 4.17. Map of SOC content derived from the Woodbush database

The auguring points with predicted values of SOC stocks were interpolated within the boundaries of the forest to produce a grid showing the distribution of SOC stocks in the area (Figure 4.18).

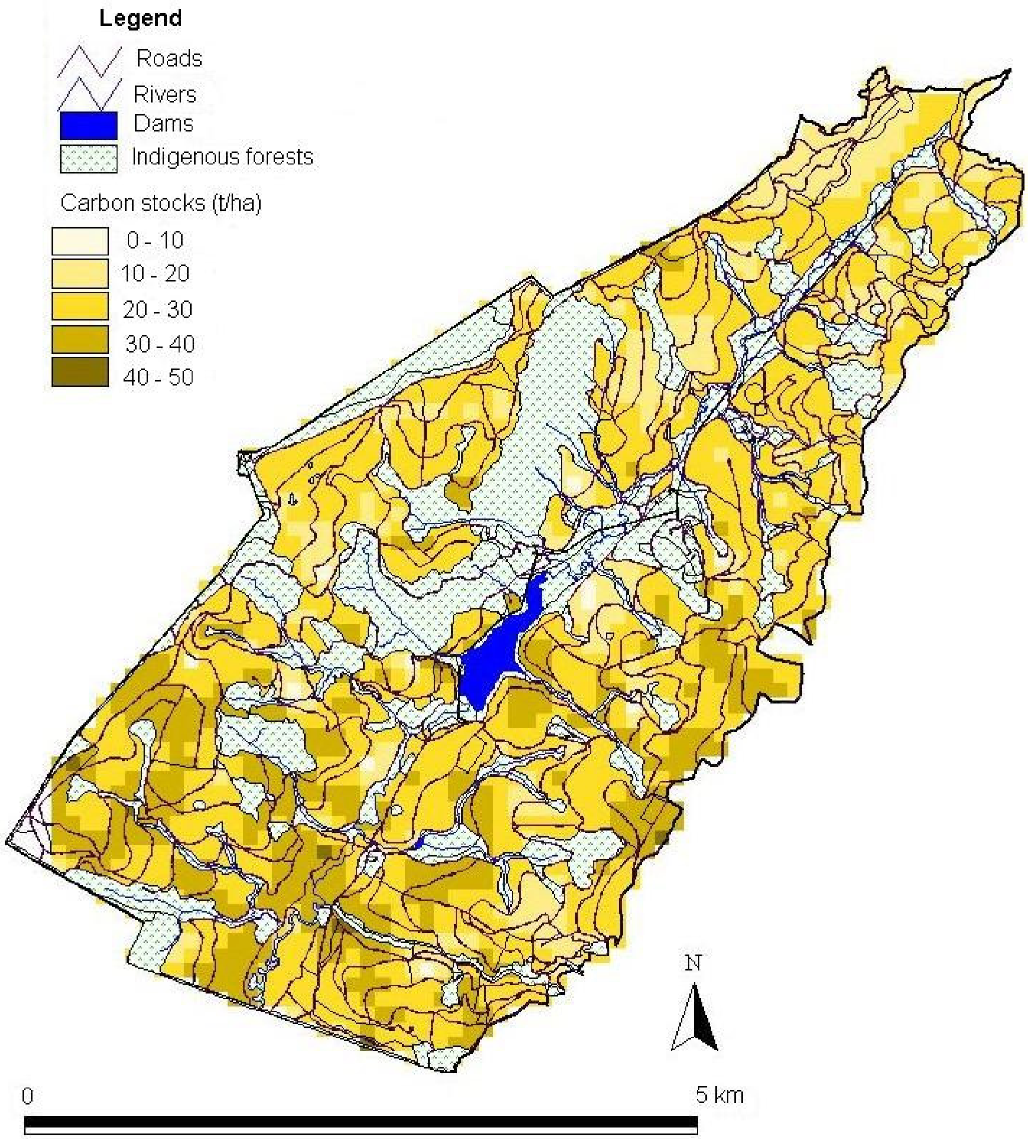

Figure 4.18. Map of SOC stocks (t/ha) derived from the Woodbush database.

The resulting map differed from the map of SOC content mainly due to variation in soil depth reflected by the survey within relatively uniform blocks of SOC content. The rock outcrops stand out distinctively, while spatial variation with topography is not seen. This may be attributed either to insufficient resolution of the survey or simply to lack of analytical data and inaccuracy of field estimations of SOC content recorded during the field survey.

The map of standard deviations from mean value of organic C % (1.6 %) (Figure 4.19) shows bands of high (3 %) to low (< -3 %) organic matter content reflecting in broad terms the impact of topography and elevation. It corresponded well to the soil map of the area in Figure 4.14.

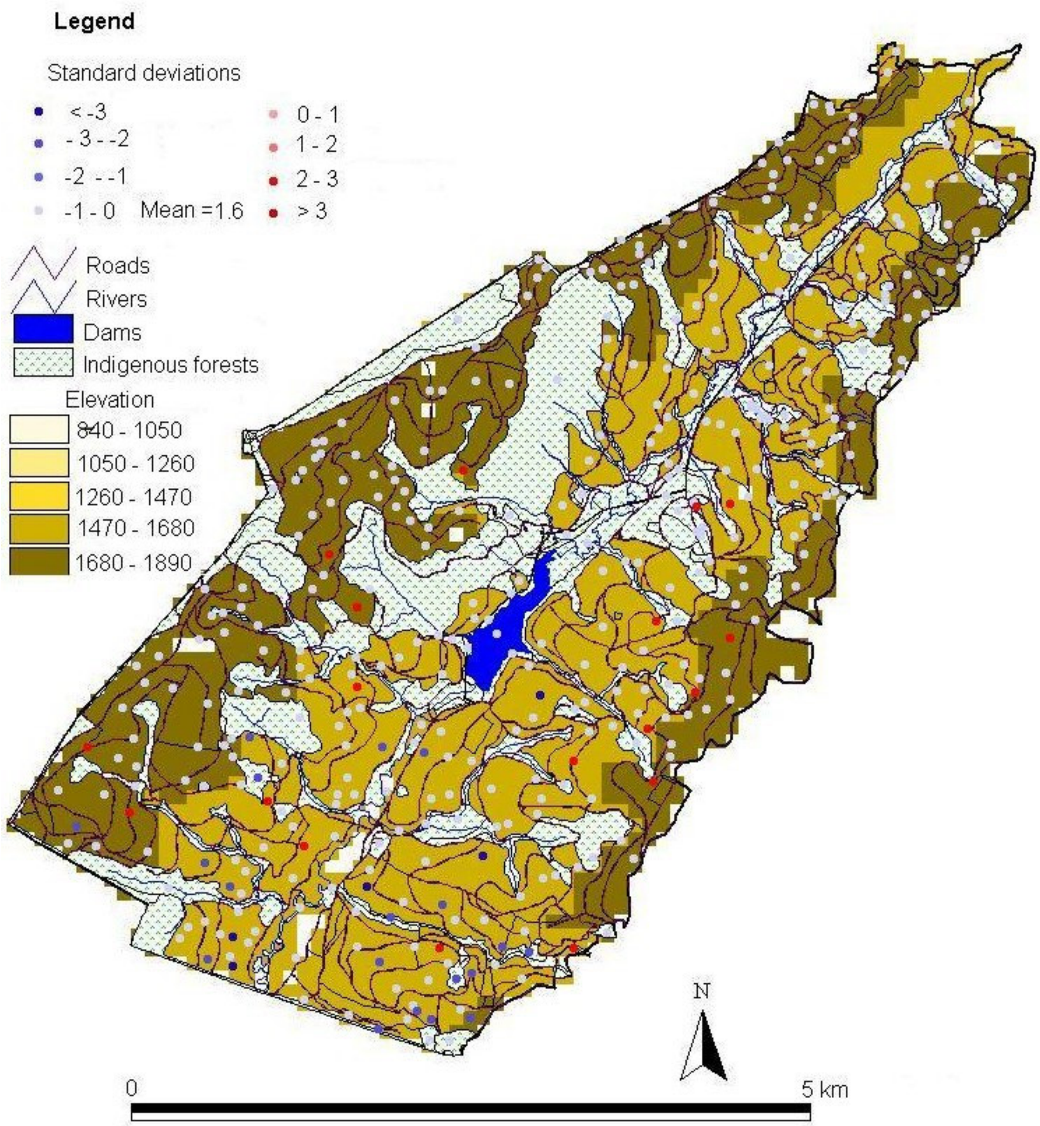

Figure 4.19. Point map of standard deviations from the mean (1.6 %) in estimations of SOC content.

Wetlands were found to have high SOC stocks, followed by indigenous forests, plantations and grasslands. The soil moisture seemed to be the most determining factor in accumulation of SOC stocks. Schwartz and Namri (2002) found similar trends of SOC stocks accumulation in soils of the Congo where the largest stocks where found in hydromorphic soils. They attributed high SOC stocks to excess water in the soils that led to slow mineralization of fresh organic matter. Van Noordwijk *et al* (1997) attributed high SOC reserves found in wetlands to conditions like high pH, low temperatures and high silt and clay.

Indigenous forests were second to wetlands in SOC stocks. They had higher SOC stocks than plantations and grasslands. Sparling and Schipper (2002) found an overall tendency for SOC to be greater in pasture and indigenous forests than in cropland and plantation forests, while Krishnaswamy and Richter (2002) found SOC under pasture to be less than that of the forests. The high SOC stocks in indigenous forests were attributed to soil aggregate stability. Six *et al* (2002) found aggregation and SOC content to be higher in forests than in agric ecosystem.

Plantations had the second lowest amount of SOC stocks after grasslands. Several factors were associated with SOC stocks level found in plantations. Plantations were found on gentler slopes than grasslands and that resulted in more soil moisture in plantations than in grasslands. Plantation age (24 yrs) might have improved the level of SOC stocks. Davis and Condron (2002) found that SOC stocks under plantations were similar to those of grasslands after 20 yrs. After initial losses of SOC during initial stages of afforestation (Davis and Condron, 2003), plantations are capable of recovering SOC lost and accumulate high SOC amounts if left to maturity. Davis *et al* (2003) found that SOC in all pools peaked in 125-year-old stands and declined as the stands matured after more than 150 years. However, as mentioned earlier, plantations had less SOC stocks than wetlands and indigenous forests. The soil moisture partly explained the variation. Soil moisture was higher in wetlands and in indigenous forests than in plantations. Less species diversity in plantations also explained the lower SOC stocks found in plantations as it affected the litter quality and the rate of organic matter decomposition. Wit and Kwindesland (1999) found SOC stocks in mineral soils to be the lowest in pure forests while mixed forests had the highest SOC stocks.

Pectora roborant cultus recti

5. Conclusions

There are several options of sequestering organic carbon that promise to have the potential to reduce atmospheric carbon dioxide and global warming. As much as ocean disposal and other proposed ways of sequestering anthropogenic carbon in the atmosphere are promising, there is still much to be understood before the rate of carbon absorption in aquatic systems is increased. The only option that seems practical currently is the terrestrial sink, with soil as part of the terrestrial system. However, more effective sampling and estimation methods for organic carbon in soils are necessary to gather information on the contribution of soil to global carbon sequestration.

Several factors (climate, topography, vegetation and land use) play a role in developing accurate models for estimating the amount of organic carbon in the soil. Understanding the contribution of these factors is the basic limitation to a broader application of several models already developed, and models specific to certain areas and environments are required to effectively and accurately estimate the amount of soil organic carbon.

The model developed in this study not only helps to estimate the organic carbon stocks in Woodbush, but also constitutes a basic approach in developing models that can be applied under different ecosystems and in estimating the concentration of other elements in the soil. The fact that the model uses surface (0 – 7 cm) samples collected at a certain distance apart to estimate SOC down to a metre deep reduces the cost and time needed for sampling and laboratory analysis. The approach needs to be tested in other

Pectora roborant cultus recti

places of similar environmental conditions and vegetation to confirm its accuracy and reliability.

The following outcomes of this study should be noted specifically:

1. Vertical distribution of soil organic carbon and bulk density for calculation of carbon stocks in pine plantations and adjacent ecosystems of Woodbush forestry was successfully modeled.

1.1. Soil carbon content throughout the profiles of texturally-differentiated soils in the Woodbush forestry area (Hutton, Inanda and Kranskop soil forms) is not uniformly distributed within the thickness of individual horizons. Instead, SOC may rather be accurately predicted (R^2= 0.90) from values of topsoil concentrations with a set of exponential functions relating normalized carbon content to depth. Introduction of other easily measured variables, such as bulk density and soil pH did not improve the quality of predictions. This approach will allow the reduction, by almost a half, of the number of samples and analytical costs required for predictions by models such as "Century" (Natural Resource Ecology Laboratory, 2001).

1.2. The successful derivation of vertical distribution functions for SOC vs. depth from experimental observations was achieved by normalizing carbon content at each soil depth with respect to the value of SOC in the surface sample. This procedure overcame the influence of variation in absolute values of SOC resulting from environmental conditions such as parent material, slope and aspect.

1.3. Since all the soils in the Woodbush forestry area are texturally similar with a high clay content, a simple logarithmic regression proved to be the most suitable equation (R^2=0.99) for predicting soil bulk density at any depth up to 1 m under the canopy of pine plantations. A more complicated, multiple regression, relating bulk density to carbon content at a specific depth, proved to be less accurate judging from the values of the regression coefficient (R^2=0.92). In other ecosystems it may be best to use the existing relationship between carbon content and bulk density of soil although the precision of the prediction still has to be improved substantially to make use of these equations in practice.

1.4. The use of equations derived for forestry areas compares favourably with other methods of carbon stock estimation. It was shown that rough assessments per soil horizon using bulk density values derived from textural class and carbon content values per soil horizon tend, in the context of the Woodbush forestry area, to overestimate the actual stocks. On the other hand, the error of using linear regression for D_b vs. depth results in a rather small error of under 10%, and subsequently, in other areas linear estimates may be made for bulk density distribution vs. depth within the depth limit of observations. This may be justified by cost saving (using only two experimental points to derive the function) with little loss of accuracy.

2. Soils of the Woodbush forestry area are characterized by a rather high degree of spatial variation in SOC content at the soil surface and, consequently, in calculated carbon stocks.

2.1. The variography of intensive sampling plots has shown strong directional dependence on SOC values. The derived variograms can successfully predict the values of SOC at distances of some 54 m along the slope and some 40 m across in all four of the studied ecosystems.

2.3. A high degree of spatial variation in SOC and carbon stocks in soils will require large data sets for carbon inventory purposes.

2.4. It is also interesting to note that average values of SOC obtained from transects were substantially (and statistically) significantly lower compared to average values received from intensive sampling plots, both in plantations and indigenous forest. This phenomenon can only be explained by the natural tendency of a sampler to intuitively choose a “representative” spot during random sampling along transect, when a person subconsciously avoids spots that may be “abnormally” rich or poor in organic matter. It may also simply be a choice of the most “passable” or accessible route with the least dense ground cover.

3. The analysis of soil profiles and intensive survey plots has shown that all the major ecosystems in the Woodbush forestry region form a gradient of carbon stocks: Grasslands < Pine Plantations < Indigenous Forest < Wetlands.

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Pectora roborant cultus recti

Appendix A. Field and analytical methods

A.1. Soil Bulk density

Soil samples were collected into a polyethylene bag using a core auger that has a volume of 289cm^3. All surface (7cm) and profile samples at depth levels 5, 10, 15, 20, 30, 40, 50, 60, 75, 100 cm were first air dried and then dried in a oven at a temperature of 105^{o}c for 48 hours. Roots, organic material and stones were removed in all soil samples before they were dried in the oven. The mass was then measured, and the bulk density was calculated as mass / volume. The removal of roots, organic material and stones from soil samples resulted in low mass and hence the low bulk density values.

A.2. pH

Soil pH was measured in both H_2O and KCl using the 744 Metrohm pH meter at 25:1 (H_2O /KCl) soil ratio. 1g of soil was mixed with 25 ml of water, shaken for 10 minutes and left to settle for 30 minutes and pH was measured. 1g of the same soil was mixed with 25 ml of 1MKCl, shaken for 10 min and allowed to settle for 30 min and pH was measured.

A.3. Organic carbon determination

Total organic carbon was determined using the colometric method by Baker (1976). The organic carbon was analyzed in the fine fraction (soil passing through 105um sieve before grinding) and in the whole sample (soil passing 105um sieve after grinding).

About 15g of sucrose was dried at 105^{o}c for two hours and allowed to cool in a desiccator. A mass of 11.886g of dried sucrose was then dissolved in water and made up to the mark in a volumetric flask. This made a 50g/ml C solution. From the stock solution, 0,5,10,15,20,25 ml were transferred into labeled 100ml volumetric flasks using pipette, made to the mark with water and mixed. These working standards contained 0, 2.5, 5.0, 7.5, 10.0, 12.5 mg/ml of carbon concentrations. A volume 2.0 ml of each working standard was transferred into a labeled 100ml digestion tubes and dried at 105^{o}c. These tubes finally contained 0, 5.0, 10.0, 15.0, 20.0 25.0 mg C. Standards were prepared for every batch of soil samples.

About 1.0g of grind soil (< 0.15mm) was weighed into a labeled 100 ml digestion tube. Depending on the darkness of the soil or the site, the soil mass ranged between 1.0g and 0.25g in this case. 2ml of water was added to the sample followed by 10.0ml of 5% potassium dichromate solution and allowed to completely wet the sample. 5ml of concentrated H_2SO_4 was slowly added to the tube and the mixture gently swirled. The tube was then heated at 150ºC in a digestion block for 30 minutes. The tube was then cooled down, and 50ml of 4% barium chloride was added, and swirled to mix thoroughly and left to stand overnight to leave a clear supernatant solution.

Finally, an aliquot of the supernatant solution was transferred into a colometer cuvette, and the sample absorbance was measured at 600nm. The same procedure applies to the standards.

A.4. Qualitative profile description.

Indigenous Forests

Profile no.: 1
Latitude : 23º48,999'
Longitude: 29º58,152'
Soil form : Kranskop
Soil family : 1200 (Dargle)
Altitude : 1612.72 m
Terrain unit : Middle slope
Slope: 3 %
Slope shape: Convex
Aspect : South east

Water table : None
Occurrence of flooding: Nil
Surface rockiness : None
Surface stoniness: None
Erosion: Gully, class 1
Land use: Conservation
Underlying material: Granite-Gneiss

Horizon depth	Description	Diagnostic Horizon
0 – 300	Dry, dark brown 10YR3/3, weak blocky, SaClLm, firm, few clay cutans No gravel, root abundant, abundant soil fauna, litter layer 50 mm, clear transition.	Humic A
300 – 600	moist, brown 7.5YR4/3, apedal, SaCl, friable, few stones, few soil fauna and a lot of roots.	Yellow brown apedal B
600 – 1100+	Moist, Strong brown 7.5YR4/6, apedal, SaCl, friable.	Red apedal B

Geology: Granite-Gneiss

Indigenous Forests

Profile no.:	2	Water table:	None
Latitude:	23º48,947'	Occurrence of flooding:	Nil
Longitude:	29º58,145'	Surface rockiness:	None
Soil form:	Kranskop	Surface stoniness:	None
Soil family:	1200 (Dargle)	Erosion:	Gully, class 2
Altitude:	1652.76 m	Land use:	Conservation
Terrain unit:	Middle slope	Underlying material:	Granite-Gneiss
Slope:	3%		
Slope shape:	Convex		
Aspect:	South east		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 300	Dry, dark yellowish brown 10YR3/4, SaClLm, weak blocky, firm, few clay cutans No gravel, root abundant, abundant soil fauna, litter layer 48 mm, clear transition.	Humic A
300 – 600	Moist, strong brown 7.5YR4/6, apedal, SaCl, friable, few stones, few soil fauna lot of roots.	Yellow brown apedal B
600 – 1100+	Moist, reddish brown 5YR4/4, apedal, friable, SaCl.	Red apedal B

Geology: Granite-Gneiss

Indigenous Forests

Profile no.:	3	Water table:	None
Latitude:	23º48,901'	Occurrence of flooding:	Nil
Longitude:	29º58,153'	Surface rockiness:	None
Soil form:	Kranskop	Surface stoniness:	None
Soil family:	1200 (Dargle)	Erosion:	Gully, class 2
Altitude:	1623.51 m	Land use:	Conservation
Terrain unit:	Middle slope	Underlying material:	Granite
Slope:	4%		
Slope shape:	Concave		
Aspect:	South east		

Horizon depth	Description	Diagnostic Horizon
0 – 300	Dry, dark yellowish brown 10YR4/3, SaClLm, weak blocky, firm, few clay cutans No gravel, root abundant, abundant soil fauna, litter layer 46 mm, clear transition.	Humic A
300 – 600	Moist, strong brown 7.5YR4/6, apedal, friable, SaCl few stones, few soil fauna, lot of roots.	Yellow brown apedal B
600 – 1100+	Moist, reddish brown 5YR4/3, apedal, friable, SaCl.	Red apedal B

Geology: Granite

Indigenous forests

Profile no.: 4
Latitude: 23º48,838'
Longitude: 29º58,179'
Soil form: Inanda
Soil family: 1200 (Highlands)
Altitude: 1618.82 m
Terrain unit: Middle slope
Slope: 3%
Slope shape: Convex
Aspect: South east

Water table: None
Occurrence of flooding: Nil
Surface rockiness: None
Surface stoniness: None
Erosion: Gully, class 1
Land use: Conservation
Underlying material: Granite

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 300	Dry, dark yellowish brown 10YR3/3, SaClLm, weak blocky, firm, few clay cutans No gravel, root abundant, abundant soil fauna, litter layer 56 mm, clear transition.	Humic A
300 – 700	Moist, red 5YR4/6, apedal, friable, SaCl, few stones, few soil fauna, lot of roots.	Red apedal B
700 – 1200+	Moist, red 5YR4/3, apedal, friable, SaCl.	Red apedal B

Geology: Granite

Pectora roborant cultus recti

Pine Plantations

Profile no.: 1
Latitude: 23º48,991'
Longitude: 29º58,230'
Soil form: Griffin
Soil family: 1200 (Deelspruit)
Altitude: 1586,85 m
Terrain unit: Middle slope
Slope: 2 %
Slope shape: Convex
Aspect: West

Water table: None
Occurrence of flooding: Nil
Surface rockiness: None
Surface stoniness: None
Erosion: Gully, class 1
Land use: Agro-ecosystem
Underlying material: Granite

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 360	Dry, dark brown 10YR3/3, apedal, SaClLm, firm, No gravel root abundant, few soil fauna, litter layer 10.6 mm, clear transition.	Orthic A
360 – 700	Dry, strong brown 7.5YR4/6, apedal, SaCl, friable, few stones, few of roots.	Yellow brown apedal B
700 – 1200+	Moist, red 5YR4/4, apedal, friable, SaCl.	Red apedal B

Geology: Granite

Pine plantations

Profile no.: 2
Latitude: 23º48,973'
Longitude: 29º58,206'
Soil form: Hutton
Soil family: 1200 (Kelvin)
Altitude: 1581,90 m
Terrain unit: Middle slope
Slope: 2%
Slope shape: Convex
Aspect: South east

Water table: None
Occurrence of flooding: Nil
Surface rockiness: None
Surface stoniness: None
Erosion: Gully, class 1
Land use: Agro-ecosystem
Underlying material: Granite

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 380	Dry, dark brown 10YR3/3, weak blocky, SaClLm, firm, fine roots abundant, few soil fauna, litter layer 123 mm, clear transition.	Orthic A
380 – 700	Moist, red 5YR4/6, apedal, friable, few stones, few soil fauna few of roots.	Red apedal B
700 – 1100+	Moist, red 5YR4/3, apedal, friable, SaCl.	Red apedal B

Geology: Granite

Pine plantations

Profile no.:	3	Water table:	None
Latitude:	23º48,904'	Occurrence of flooding:	Nil
Longitude:	29º58,209'	Surface rockiness:	None
Soil form:	Kranskop	Surface stoniness:	None
Soil family:	1200 (Dargle)	Erosion:	Gully, class 1
Altitude:	1590,79 m	Land use:	Agro-ecosystem
Terrain unit:	Middle slope	Underlying material:	Granite/Gneiss
Slope:	2 %		
Slope shape:	Convex		
Aspect:	South east		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 300	Dry, dark yellowish brown 10YR3/3, SaClLm, weak blocky, firm, No gravel, root abundant, few soil fauna, litter layer 106 mm, clear transition.	Humic A
300 – 700	Moist, strong brown 7.5YR4/6, apedal, SaCl, friable, few stones few roots.	Yellow brown apedal B
600 – 1200+	Moist, red 5YR4/4, apedal, friable, SaCl.	Red apedal B

Geology: Granite/ Gneiss

Pine plantations

Profile no.:	4	Water table:	None
Latitude:	23º48,819'	Occurrence of flooding:	Nil
Longitude:	29º58,222'	Surface rockiness:	None
Soil form:	Hutton	Surface stoniness:	None
Soil family:	1200 (Kelvin)	Erosion:	Gully, class 1
Altitude:	1592,94 m	Land use:	Agro-ecosystem
Terrain unit:	Middle slope	Underlying material:	Granite
Slope:	3 %		
Slope shape:	Convex		
Aspect:	South		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 380	Dry, dark brown 10YR3/4, weak blocky, firm, SaClLm fine roots abundant, few soil fauna, litter layer 105 mm, clear transition.	Orthic A
380 – 700	Moist, red 5YR4/4, apedal, SaCl, friable, few stones, few soil fauna, few of roots.	Red apedal B
700 – 1100+	Moist, red 5YR4/3, apedal, SaCl, friable.	Red apedal B

Geology: Granite

Grassland

Profile no.:	1	Water table :	None
Latitude:	23º49,047'	Occurrence of flooding:	Nil
Longitude :	29º58,259'	Surface rockiness :	Boulders, 1 m diameter, 75 m apart.
Soil form :	Clovelly	Surface stoniness:	Round, 0.20 m diameter, 3 m apart.
Soil family :	1200 (Brereton)	Erosion:	Gully, class 2
Altitude :	1563.64 m	Land use:	Conservation
Terrain unit :	Middle slope	Underlying material:	Granite-Gneiss
Slope:	4 %		
Slope shape:	Convex		
Aspect :	South east		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 300	Dry, dark brown 10YR3/3, weak blocky, SaLm, firm, few clay cutans root abundant, abundant soil fauna, litter layer 50 mm, clear transition.	Orthic A
300 – 600	moist, brown 7.5YR4/3, apedal, friable, SaCl, abundant stones, few soil fauna lot of roots.	Yellow brown apedal B
600 – 700+	Moist, Strong brown 7.5YR4/6, apedal, SaCl, friable, abundant stones, big boulders.	Yellow brown apedal B

Geology: Granite-Gneiss

Pectora roborant cultus recti

Grassland

Profile no.:	2	Water table :	None
Latitude:	23º48,989'	Occurrence of flooding:	Nil
Longitude :	29º58,259'	Surface rockiness :	Boulders, 1 m diameter, 75 m apart.
Soil form :	Inanda	Surface stoniness:	Round, 0.20 m diameter, 3 m apart.
Soil family :	1200 (Highlands)	Erosion:	Gully, class 2
Altitude :	1563.37	Land use:	Conservation
Terrain unit :	Middle slope	Underlying material:	Granite
Slope:	4 %		
Slope shape:	Convex		
Aspect :	South		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 200	Dry, dark brown 10YR4/3, weak blocky, SaLm, firm, few clay cutans root abundant, abundant soil fauna, litter layer 50 mm, clear transition.	Humic A
200 – 400+	Moist, reddish brown 5YR4/3, apedal, friable, SaClLm, abundant stones few soil fauna, few roots, big boulders.	Red apedal B

Geology: Granite

Grassland

Profile no.:	3	Water table :	None
Latitude:	23º48,989'	Occurrence of flooding:	Nil
Longitude:	29º58,259'	Surface rockiness:	Boulders, 1000 mm diameter, 75 m apart.
Soil form:	Hutton	Surface stoniness:	Round, 200 mm diameter, 3 m apart.
Soil family:	1200 (Kelvin)	Erosion:	Gully, class 2
Altitude:	1563.37 m	Land use:	Conservation
Terrain unit:	Middle slope	Underlying material:	Granite
Slope:	4%		
Slope shape:	Convex		
Aspect :	South		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 200	Dry, dark brown 10YR4/3, weak blocky, SaLm, firm, few clay cutans root abundant, abundant soil fauna, litter layer 50 mm, clear transition.	Orthic A
200 – 400+	Moist, reddish brown 5YR4/3, apedal, SaCl, friable, abundant stones few soil fauna, few roots, big boulders.	Red apedal B

Geology: Granite

Pectora roborant cultus recti

Grassland

Profile no.:	4	Water table:	None
Latitude:	23º48,846'	Occurrence of flooding:	Nil
Longitude:	29º58,298'	Surface rockiness:	Boulders, 1 m diameter, 75 m apart.
Soil form:	Inanda	Surface stoniness:	Round, 0.20 m diameter, 3 m apart.
Soil family:	1200 (Highlands)	Erosion:	Gully, class 2
Altitude:	1578.11m	Land use:	Conservation
Terrain unit :	Middle slope	Underlying material:	Granite
Slope:	4%		
Slope shape:	Convex		
Aspect :	East		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 300	Dry, dark brown 10YR3/3, weak blocky, SaClLm, firm, few clay cutans root abundant, abundant soil fauna, litter layer 55 mm, clear transition.	Humic A
300 – 700+	Moist, reddish brown 5YR4/3, apedal, SaCl, friable, abundant stones few soil fauna, few roots, big boulders.	Red apedal B

Geology: Granite

Wetlands

Profile no.:	1
Latitude:	23º49,049'
Longitude:	29º58,306'
Soil form:	Tukulu
Soil family:	2120 (Scheepersrus)
Altitude:	1565.41 m
Terrain unit:	Valley bottom
Slope:	1%
Slope shape:	Concave
Aspect:	North west

Water table:	1 m
Occurrence of flooding:	Many times
Surface rockiness:	None
Surface stoniness:	None
Erosion:	Gully, class 1
Land use:	Conservation
Underlying material:	Unspecified with signs of wetness

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 400	Moist, black 10YR2/1, weak blocky, firm, SaCl, stratified, root abundant, abundant soil fauna, litter layer 56 mm, clear transition.	Orthic A
400 – 700	Very moist, yellow 7.5YR5/6, apedal, friable, SaClLm, no stones, few soil fauna few roots.	Neocutanic B
700 – 1000+	Wet, yellow 7.5YR5/8, ClLm, apedal, friable,	Unspecified material with signs of wetness

Geology: Unspecified Material

Wetlands

Profile no.:	2	Water table:	1000 mm deep
Latitude:	23º48'975″	Occurrence of flooding:	Many times
Longitude:	29º58'322″	Surface rockiness:	None
Soil form:	Tukulu	Surface stoniness:	None
Soil family:	2120 (Scheepersrus)	Erosion:	Gully, class 1
Altitude:	1561.61 m	Land use:	Conservation
Terrain unit:	Valley bottom	Underlying material:	Unspecified material with signs of wetness
Slope:	1%		
Slope shape:	Concave		

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 420	Moist, black 10YR2/1, weak blocky, firm, SaLm, stratified, root abundant, abundant soil fauna, litter layer 58 mm, clear transition.	Orthic A
420 – 700	Very moist, yellow 7.5YR5/6, apedal, friable, no stones, few soil fauna SaClLm, few roots.	Neocutanic B
700 – 1000+	Wet, yellow 7.5YR5/8, apedal, SaClLm, friable.	Unspecified material with signs of wetness

Geology: Unspecified

Wetlands

Profile no.:	3	Water table:	1000 mm deep
Latitude:	23º48'937″	Occurrence of flooding:	Many times
Longitude:	29º58'344″	Surface rockiness:	None
Soil form:	Tukulu	Surface stoniness:	None
Soil family:	2120 (Scheepersrus)	Erosion:	Gully, class 1
Altitude:	1570.60m	Land use:	Conservation
Terrain unit:	Valley bottom	Underlying material:	Unspecified with signs of wettness
Slope:	1%		
Slope shape:	Concave		
Aspect:	West		

<u>Horizon depth (mm)</u>	<u>Description</u>	<u>Diagnostic Horizon</u>
0 – 360	Moist, black 10YR2/1, weak blocky, firm, SaCl, stratified, root abundant, abundant soil fauna, litter layer 58 mm, clear transition.	Orthic A
360 – 780	Very moist, yellow 7.5YR5/6, apedal, friable, SaClLm, few soil fauna, few roots.	Neocutanic B
780 – 1000+	Wet, yellow 7.5YR5/8, apedal, friable, SaClLm	Unspecified

Geology: Alluvium

Wetlands

Profile no.:	4
Latitude:	23º48'869″
Longitude:	29º58'357″
Soil form:	Tukulu
Soil family:	2120 (Scheepersrus)
Altitude:	1572.63m
Terrain unit:	Valley bottom
Slope:	1%
Slope shape:	Concave
Aspect:	South

Water table:	1000 mm deep
Occurrence of flooding:	Many times
Surface rockiness:	None
Surface stoniness:	None
Erosion:	Gully, class 1
Land use:	Conservation
Underlying material:	Unspecified with signs of wetness

Horizon depth (mm)	Description	Diagnostic Horizon
0 – 420	moist, black 10YR2/1, weak blocky, firm, stratified root abundant, abundant soil fauna, litter layer 48 mm, clear transition SaLm.	Orthic A
420 – 750	Very moist, yellow 7.5YR5/6, apedal, friable, no stones, SaClLm few roots.	Neocutanic B
750 – 1200+	Wet, yellow 7.5YR5/8, apedal, SaClLm, friable.	Unspecified

Geology: Unspecified

Appendix B.

B.1. Soil data for indigenous forests surface samples

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97115	-23.79964806	3.7	0.44	5.6	4.4
29.9709375	-23.79958611	4.5	0.38	5.2	4.2
29.97068972	-23.79948417	3.8	0.32	4.7	3.9
29.97044611	-23.79939583	3.0	0.43	4.6	3.9
29.97024694	-23.79933389	4.9	0.42	4.8	4.0
29.97035333	-23.79914333	3.5	0.34	4.9	4.0
29.9705525	-23.79924083	2.6	0.3	4.8	4.0
29.97080917	-23.79935611	1.3	0.36	5.1	4.3
29.97101278	-23.79944444	1.5	0.3	5.2	4.3
29.9712475	-23.79950639	2.0	0.46	5.1	4.1
29.97133583	-23.79935583	2.5	0.43	4.9	4.1
29.97114111	-23.79927611	2.8	0.55	5.1	4.1
29.97089333	-23.79918333	3.2	0.44	5.2	4.3
29.97064111	-23.79909472	2.7	0.46	5.1	4.2
29.9704375	-23.79898417	2.6	0.52	5.1	4.3
29.97056139	-23.79878056	2.5	0.41	4.9	4.1
29.97079139	-23.79882472	3.7	0.48	4.7	3.9
29.97104833	-23.79891778	3.0	0.41	4.8	3.7
29.97128278	-23.79900167	3.5	0.39	4.8	4.0
29.97148639	-23.79908139	2.7	0.4	4.8	3.9
29.97156611	-23.79890444	4.0	0.33	4.8	3.8
29.97137361	-23.79880694	4.7	0.35	4.8	3.7
29.97108806	-23.79869639	5.7	0.52	4.7	3.7
29.97088444	-23.79863889	2.2	0.37	5.1	4.2
Longitude (dd)	**Latitude (dd)**	**Carbon content (%)**	**D_b (g/cm^3)**	**pH (H_2O)**	**pH (KCl)**
29.9707075	-23.79855917	4.5	0.47	4.0	4.0

29.97074278	-23.79850167	3.0	0.57	4.4	4.0
29.97092861	-23.79858139	3.2	0.52	4.5	3.9
29.97121639	-23.79869194	3.2	0.53	4.8	4.3
29.97139778	-23.79876722	1.9	0.59	4.2	3.9
29.97157056	-23.79883806	3.9	0.65	4.4	3.9
29.9716325	-23.79867417	2.1	0.37	4.7	4.1
29.97144667	-23.79862111	3.4	0.38	4.5	3.9
29.9712075	-23.79854583	2.5	0.48	5.1	4.1
29.9709775	-23.79846611	1.7	0.45	5.2	4.3
29.97080028	-23.79833778	3.4	0.44	5.2	4.3
29.97087111	-23.79813861	3.1	0.46	5.1	4.2
29.97093583	-23.79821389	2.3	0.32	4.7	4.1
29.97130056	-23.7983025	2.5	0.42	5.1	4.2
29.97152639	-23.79836889	3.3	0.35	6.0	4.6
29.97173	-23.79842194	2.3	0.4	5.0	4.2
29.97181389	-23.79819611	1.6	0.54	4.8	4.1
29.97161472	-23.7981075	2.5	0.43	5.6	4.4
29.97139778	-23.79800139	3.1	0.49	4.7	4.3
29.97119	-23.79791722	2.4	0.5	4.9	4.3
29.97098194	-23.79784194	2.7	0.48	5.4	4.5
29.97103944	-23.79770472	2.0	0.39	4.9	4.1
29.97121194	-23.79777556	2.9	0.45	4.7	4.0
29.97144222	-23.79785083	2.0	0.5	4.9	4.2
29.97165028	-23.797935	2.6	0.37	4.9	4.0
29.97187167	-23.79801028	2.4	0.48	4.3	3.9

Pectora roborant cultus recti

B.2. Soil data for pine plantations surface samples

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97203972	-23.80044028	2.1	0.89	4.7	3.8
29.97214611	-23.80055556	2.1	0.81	4.6	3.8
29.97226556	-23.80065278	1.4	0.87	4.4	3.8
29.97237167	-23.80075028	1.7	0.85	4.7	4.0
29.97251778	-23.80088306	1.5	0.66	4.6	3.8
29.97265944	-23.80101139	1.6	0.80	4.9	4.1
29.97219472	-23.80028111	1.8	0.52	4.9	3.9
29.97237167	-23.80045361	1.6	0.97	4.7	3.8
29.97255333	-23.8006175	0.9	0.98	5.0	4.3
29.97273028	-23.80078556	1.7	0.83	4.8	4.0
29.97298694	-23.80072361	1.8	0.91	4.3	3.7
29.97280111	-23.80054667	1.0	0.72	4.6	3.9
29.97266833	-23.80040056	0.8	0.74	5.0	3.9
29.97251778	-23.80025889	0.8	0.78	4.8	4.0
29.97240722	-23.800135	1.2	0.75	4.6	4.0
29.97255778	-23.8000375	1.6	0.42	4.4	3.9
29.972695	-23.80017028	1.3	0.73	4.6	3.8
29.97285861	-23.80032972	1.6	0.55	4.3	3.8
29.97303583	-23.80047583	1.3	0.33	4.9	3.9
29.97320833	-23.80062194	1.6	0.88	4.6	3.9
29.97337222	-23.80044028	2.0	0.71	4.3	3.7
29.973235	-23.80033861	1.7	0.88	4.6	3.9
29.97306222	-23.8001925	1.4	0.71	4.5	3.9
29.97287639	-23.80001972	1.4	0.56	4.7	4.1
29.97273917	-23.79989139	1.7	0.61	4.9	4.1
29.97268167	-23.79975417	1.4	0.63	4.9	4.3
29.97240278	-23.79968333	2.2	0.85	4.9	4.1
29.97215028	-23.79962583	3.0	0.36	5.1	4.0
29.97196444	-23.79956833	0.9	0.79	5.0	4.1

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97183611	-23.79951083	1.8	0.47	5.0	4.1
29.9719025	-23.7993425	1.9	0.50	4.8	3.9
29.97207083	-23.79938694	1.4	0.59	4.9	4.2
29.97230972	-23.79947528	1.5	0.45	4.5	3.8
29.97256194	-23.79954167	2.2	0.82	5.2	4.0
29.97277	-23.79960389	0.2	1.10	4.9	4.1
29.97284972	-23.79938694	2.3	0.37	5.0	4.0
29.97261972	-23.79929833	1.6	0.69	5.2	4.0
29.97243806	-23.7992275	2.1	0.94	4.9	4.1
29.97218139	-23.7991125	2.2	0.70	5.0	4.2
29.97196444	-23.7990725	2.3	0.87	4.8	4.0
29.97204417	-23.7989	1.6	0.47	4.8	4.1
29.97224333	-23.79895306	2.6	0.91	4.6	4.1
29.97249111	-23.79902389	2.8	0.88	4.6	4.0
29.97277444	-23.79908583	1.3	0.71	4.8	4.2
29.97295167	-23.79914333	1.9	0.69	4.6	4.2
29.97295611	-23.79901056	2.4	0.42	4.2	3.8
29.9727125	-23.79892639	1.8	0.83	4.8	3.9
29.97246917	-23.79885583	2.0	0.77	4.7	4.0
29.97225667	-23.79877611	1.5	0.50	4.6	3.7

Pectora roborant cultus recti

B.3. Soil data Grasslands surface samples

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97415389	-23.80125917	1.5	0.7	5.8	4.41
29.97385889	-23.80116194	1.5	0.5	5.8	4.35
29.97372167	-23.80106889	1.3	0.7	5.6	4.19
29.97358444	-23.80099361	1.3	0.6	3.8	4.29
29.973465	-23.80090944	1.5	0.6	5.9	4.34
29.97358889	-23.80075472	1.1	0.8	5.5	4.11
29.97371306	-23.80085194	1.1	0.6	6	4.23
29.97385028	-23.80095389	2.2	0.8	5.6	4.54
29.97402722	-23.80106	1.7	0.7	5.8	4.4
29.97420861	-23.80116639	1.8	0.5	5.6	4.23
29.97436806	-23.80099361	2	0.6	4.4	4.37
29.97419556	-23.80083861	1.6	0.5	5.6	4.22
29.97403611	-23.80074139	1.8	0.5	5.3	4.26
29.97388111	-23.80059528	1.7	0.6	5.6	4.25
29.97376167	-23.80052	1.7	0.4	4.6	4.2
29.97389889	-23.80035194	1.3	0.7	4.8	4.27
29.9740625	-23.8004625	1.5	0.6	5.3	4
29.97426639	-23.80056417	1.5	0.6	4.9	4.28
29.97444778	-23.80068389	1	0.5	5.2	4.28
29.97458056	-23.80079444	2.2	0.7	5.1	4.34
29.97469111	-23.80064833	1	0.6	5.3	4.57
29.97454056	-23.80054222	0.9	0.7	5.4	4.25
29.97434583	-23.80041389	0.9	0.7	5.2	4.13
29.97415556	-23.8003075	2.7	0.6	5.9	4.41
29.97401389	-23.80021028	1.6	0.6	5.5	4.18
29.97406694	-23.80014389	1.8	0.5	5.5	4.59
29.97422639	-23.80025	2.3	0.6	5.5	4.41
29.97437694	-23.80035194	3.8	0.7	5	4.56
29.97456722	-23.80047139	2.5	0.8	5.1	4.54

Pectora roborant cultus recti

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97477528	-23.80060417	0.6	0.6	6	5.12
29.97485944	-23.80047139	2.1	0.6	5.9	4.52
29.97466917	-23.80036944	1.7	0.7	5.8	4.46
29.97448306	-23.80025444	2.2	0.7	5	4.42
29.97427944	-23.80013944	3	0.5	5.9	4.53
29.97412917	-23.80005083	2.1	0.7	5.8	4.3
29.97429722	-23.79984278	2.7	0.5	5.3	4.17
29.97446556	-23.79997556	2.6	0.6	5.8	4.4
29.97463806	-23.80008194	1.2	0.5	5	4.53
29.97483722	-23.8001925	1.8	0.5	5.7	4.41
29.97500111	-23.80032972	1.9	0.4	5.1	4.55
29.97515583	-23.80016139	1.3	0.7	5.4	4.51
29.97501	-23.80002861	3.2	0.4	5.5	4.44
29.9747975	-23.79987833	1.1	0.5	5.8	4.32
29.97462472	-23.79969667	1.3	0.6	5.7	4.43
29.97449194	-23.79959056	1.3	0.7	5.8	4.39
29.97461583	-23.79945333	2.5	0.6	5.6	4.37

Pectora roborant cultus recti

B.4. Soil data for wetlands surface samples

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97477528	-23.80157806	3.4	0.4	5.3	4.5
29.97496111	-23.80171083	5.0	0.3	4.9	4.4
29.97516917	-23.8018525	4.0	0.3	4.7	4.3
29.97536389	-23.80199417	2.0	0.4	5.2	4.2
29.97551889	-23.80211806	5.4	0.5	5.3	4.4
29.97569167	-23.80196306	5.5	0.3	4.3	4.2
29.97551	-23.80184361	3.1	0.5	5.5	4.5
29.97532861	-23.80168861	2.6	0.3	5.3	4.5
29.97514722	-23.80154694	3.5	0.3	5.6	4.5
29.97498333	-23.80141861	3.1	0.4	5.1	4.5
29.97516472	-23.80132111	5.1	0.4	5.6	4.4
29.97531083	-23.80141861	4.6	0.4	5.3	4.5
29.97552333	-23.80157361	2.1	0.4	5.1	4.2
29.97571361	-23.80167528	4.2	0.5	4.5	4.5
29.97589083	-23.80179056	4.5	0.3	5.4	4.2
29.97605	-23.80165333	3.3	0.3	5.1	4.6
29.97585083	-23.801485	3.1	0.4	5.3	4.3
29.97562528	-23.80133	5.3	0.3	5.4	4.5
29.9754525	-23.80119722	4.8	0.5	5.4	4.4
29.97531972	-23.8011175	3.9	0.3	5.1	4.4
29.97544806	-23.80100694	2.4	0.4	5.7	4.5
29.97563833	-23.80113083	3.0	0.4	5.3	4.6
29.97584639	-23.80128139	2.1	0.5	5.9	4.3
29.9759925	-23.80140972	4.0	0.4	5.8	4.6
29.97617861	-23.8015425	4.1	0.3	5.3	4.4
29.97620944	-23.80148056	5.2	0.3	6.1	4.6
29.97602361	-23.80135222	2.9	0.4	5.9	4.4
29.97582	-23.80119278	5.4	0.4	5.6	4.5
29.97565167	-23.80105556	2.3	0.3	4.9	4.6

Pectora roborant cultus recti

Longitude (dd)	Latitude (dd)	Carbon content (%)	D_b (g/cm^3)	pH (H_2O)	pH (KCl)
29.97552333	-23.80095389	2.7	0.4	5.3	4.3
29.97566056	-23.80083	1.3	0.4	5.2	4.5
29.97581556	-23.80094944	3.0	0.5	5.2	4.2
29.97602806	-23.80110444	3.7	0.3	4.8	4.6
29.97622278	-23.80124167	3.4	0.3	5.2	4.4
29.97638639	-23.8013875	4.0	0.3	5.2	4.5
29.97656361	-23.80122389	1.5	0.3	4.8	4.6
29.97635111	-23.80108222	3.8	0.4	5.1	4.5
29.97614306	-23.80108222	3.7	0.4	5.3	4.4
29.97593944	-23.80095389	4.0	0.4	4.8	4.4
29.97583333	-23.80078111	3.2	0.4	5.4	4.4
29.97600583	-23.80067056	3.6	0.3	5.4	4.6
29.976205	-23.80051556	3.5	0.3	4.3	4.6
29.9764175	-23.80061306	3.5	0.3	5.0	4.2
29.97660333	-23.80074583	1.8	0.4	5.1	4.3
29.97680694	-23.80090083	4.6	0.4	5.5	4.5
29.97690889	-23.80102028	5.1	0.4	5.6	4.6
29.97674944	-23.80078111	3.7	0.4	4.8	4.4
29.97654139	-23.80063944	4.9	0.4	5.4	4.3
29.97636	-23.80051111	2.4	0.4	4.8	4.5
29.97616972	-23.80038722	2.2	0.3	5.2	4.5

B. 5. Soil data for profiles all four ecosystems

	Depth(cm)	Carbon content (%)	D_b (g/cm^3)	pH(H_2O)	pH(KCl)
Forest. profile 1	0.0 - 5.0	5.1	0.5	5.0	4.5
23º48' 999˝	5.0 - 10.0	3.4	0.7	4.6	4.1
29º58' 152˝	10.0 - 15.0	3.9	0.8	4.8	4.3
	15.0 - 20.0	3.4	0.8		4.5
	20.0 - 30.0	2.1	1.1	4.3	4.0
	30.0 - 40.0	1.9	1.0	5.1	4.7
	40.0 - 50.0	1.7	1.0	5.1	4.7
	50.0 - 60.0	1.6	1.1	5.0	4.6

	60.0 - 75.0	1.3	1.1	5.1	4.6
	75.0 - 100	1.6	1.1	4.9	4.5
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Forest. profile 2	0.0 - 5.0	1.6	0.5	5.7	4.2
23º48' 947˝	5.0 - 10.0	2.8	0.6	5.0	4.3
29º58' 145˝	10.0 - 15.0	3.6	0.6	5.3	4.4
	15.0 - 20.0	3.0	0.7	5.3	4.5
	20.0 - 30.0	1.6	1.0	5.2	4.7
	30.0 - 40.0	1.9	1.0	5.2	4.5
	40.0 - 50.0	1.1	1.1	5.2	4.5
	50.0 - 60.0	0.9	1.0	5.4	4.6
	60.0 - 75.0	2.1	1.1	5.0	4.6
	75.0 - 100	1.5	1.1	5.4	4.5
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Forest. profile 3	0.0 - 5.0	3.6	0.5	4.4	4.0
23º48' 901˝	5.0 - 10.0	3.9	0.7	4.9	4.2
29º58' 153˝	10.0 - 15.0	2.6	0.8	5.0	4.3
	15.0 - 20.0	1.4	0.9	5.2	4.4
	20.0 - 30.0	1.1	0.8	5.2	4.4
	30.0 - 40.0	1.1	1.0	5.4	4.5
	40.0 - 50.0	0.9	1.0	5.2	4.5
	50.0 - 60.0	0.8	1.1	5.4	4.5
	60.0 - 75.0	0.6	1.0	5.4	4.6
	75.0 - 100	0.6	1.1	5.4	4.5
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Forest. profile 4	0.0 - 5.0	3.9	0.5	4.6	4.0
23º48' 838˝	5.0 - 10.0	3.9	0.6	4.9	4.2
29º58' 179˝	10.0 - 15.0	2.9	0.7	5.0	4.3
	15.0 - 20.0	3.0	0.9	5.1	4.4
	20.0 - 30.0	1.3	1.0	5.2	4.5
	30.0 - 40.0	0.9	1.0	5.1	4.5
	40.0 - 50.0	1.0	1.1	5.1	4.5
	50.0 - 60.0	1.0	1.1	5.1	4.4
	60.0 - 75.0	0.8	1.1	5.2	4.5
	75.0 - 100	1.1	1.1	5.0	4.3
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Grassland profile1	0.0 - 5.0	1.2	0.6	5.6	4.5
23º48' 226˝	5.0 - 10.0	1.9	0.6	5.9	4.4
29º58' 385˝	10.0 - 15.0	4.0	0.7	5.8	4.3
	15.0 - 20.0	1.0	0.7	5.3	4.5
	20.0 - 30.0	0.7	0.8	6.0	4.7
	30.0 - 40.0	1.4	0.8	5.9	4.6
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Grassland. Profile 2	0.0 - 5.0	2.0	0.5	5.1	4.4

23º48' 227˝	5.0 - 10.0	0.9	0.6	5.2	4.4
29º58' 403˝	10.0 - 15.0	1.8	0.7	5.3	4.5
	15.0 - 20.0	2.1	0.7	6.0	4.6
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Grassland. profile 3	0.0 - 5.0	2.4	0.5	5.8	4.5
23º48' 501˝	5.0 - 10.0	1.7	0.7	5.8	4.5
29º58' 168˝	10.0 - 15.0	1.6	0.7	5.6	4.6
	15.0 - 20.0	1.3	0.8	5.2	4.6
	20.0 - 30.0	1.3	1.2	5.2	4.5
	30.0 - 40.0	1.0	1.4	5.9	4.8
	40.0 - 50.0	0.7	1.7	5.6	4.7
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Grassland profile 4	0.0 - 5.0	2.2	0.5	5.7	4.3
23º48' 153˝	5.0 - 10.0	2.5	0.6	5.5	4.4
29º58' 458˝	10.0 - 15.0	1.2	0.7	5.5	4.4
	15.0 - 20.0	1.4	0.8	5.5	4.6
	20.0 - 30.0	0.9	1.0	5.3	4.6
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Plantation profile 1.	0.0 - 5.0	1.1	0.9	5.3	4.2
	5.0 - 10.0	0.7	1.1	4.7	4.3
	10.0 - 15.0	0.5	1.3	4.4	3.9
	15.0 - 20.0	0.4	1.4	4.9	4.4
	20.0 - 30.0	0.4	1.6	5.2	4.5
	30.0 - 40.0	0.4	1.7	5.6	4.5
	40.0 - 50.0	0.4	1.7	5.1	4.4
	50.0 - 60.0	0.1	1.8	5.7	4.7
	60.0 - 75.0	0.3	1.9	5.4	4.6
	75.0 - 100	0.1	2.2	5.5	4.7
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Plantation profile 2.	0.0 - 5.0	1.6	0.9	5.0	4.2
	5.0 - 10.0	1.1	1.0	5.4	4.3
	10.0 - 15.0	0.9	1.0	5.3	4.3
	15.0 - 20.0	0.6	1.1	5.0	4.4
	20.0 - 30.0	0.4	1.1	5.0	4.4
	30.0 - 40.0	0.4	1.1	5.1	4.4
	40.0 - 50.0	0.4	1.1	5.2	4.5
	50.0 - 60.0	0.4	1.2	5.3	4.5
	60.0 - 75.0	0.3	1.2	5.2	4.5
	75.0 - 100	0.2	1.2	5.3	4.8
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Plantation profile 3.	0.0 - 5.0	3.6	0.8	4.5	3.8
	5.0 - 10.0	1.5	1.0	4.7	4.2
	10.0 - 15.0	1.2	1.0	4.9	4.2
	15.0 - 20.0	1.1	1.1	4.9	4.3
	20.0 - 30.0	0.9	1.1	5.0	4.4

	30.0 - 40.0	0.9	1.1	5.0	4.3
	40.0 - 50.0	0.9	1.2	4.8	4.3
	50.0 - 60.0	0.9	1.2	5.0	4.5
	60.0 - 75.0	0.9	1.2	5.0	4.4
	75.0 - 100	1.4	1.2	4.8	4.2
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Plantation profile 4.	0.0 - 5.0	1.0	0.8	5.6	4.1
	5.0 - 10.0	1.3	0.9	5.2	4.2
	10.0 - 15.0	0.9	1.0	5.2	4.2
	15.0 - 20.0	0.8	1.0	5.1	4.3
	20.0 - 30.0	0.8	1.0	5.2	4.3
	30.0 - 40.0	0.7	1.1	5.2	4.4
	40.0 - 50.0	0.5	1.1	5.3	4.4
	50.0 - 60.0	0.5	1.2	5.1	4.4
	60.0 - 75.0	0.8	1.2	5.3	4.6
	75.0 - 100	0.1	1.2	5.5	4.7
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Wetland profile 1	0.0 - 5.0	4.8	0.3	5.6	4.6
23º48' 251˝	5.0 - 10.0	2.3	0.5	5.6	4.5
29º58' 543˝	10.0 - 15.0	3.2	0.7	5.3	4.5
	15.0 - 20.0	2.9	0.8	5.5	4.4
	20.0 - 30.0	0.7	1.0	5.3	4.5
	30.0 - 40.0	0.3	1.1	6.0	4.7
	40.0 - 50.0	0.1	1.1	5.9	4.6
	50.0 - 60.0	0.2	1.2	5.9	4.7
	60.0 - 75.0	1.2	1.3	5.9	4.7
	75.0 - 100	0.8	1.6	4.8	4.0
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Wetland profile 2	0.0 - 5.0	3.2	0.3	5.6	4.7
23º48' 232˝	5.0 - 10.0	4.6	0.4	5.6	4.4
29º58 '541˝	10.0 - 15.0	2.7	0.5	5.2	4.4
	15.0 - 20.0	3.0	0.5	5.3	4.6
	20.0 - 30.0	1.6	0.6	5.8	4.5
	30.0 - 40.0	0.2	0.6	5.9	4.8
	40.0 - 50.0	0.2	0.8	5.3	4.6
	50.0 - 60.0	0.3	0.8	5.8	4.7
	60.0 - 75.0	5.3	0.9	5.7	4.3
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Wetland profile 3	0.0 - 5.0	3.8	0.3	5.4	4.4
23º48' 275˝	5.0 - 10.0	4.0	0.5	5.7	4.6
29º58' 422˝	10.0 - 15.0	3.6	0.5	5.8	4.6
	15.0 - 20.0	4.2	0.6	5.2	4.6
	20.0 - 30.0	2.9	0.6	5.4	4.7
	30.0 - 40.0	0.7	0.7	5.7	4.7
	40.0 - 50.0	0.4	0.7	5.7	4.8
	50.0 - 60.0	2.1	0.8	5.6	4.9

	60.0 - 75.0	0.3	0.8	5.9	5.0
	75.0 - 100	0.1	0.9	5.6	5.1
	Depth(cm)	**Carbon content (%)**	**D_b (g/cm^3)**	**pH(H_2O)**	**pH(KCl)**
Wetland profile 4	0.0 - 5.0	3.7	0.3	5.8	4.5
23º48' 272˝	5.0 - 10.0	4.6	0.4	6.1	4.5
29º58' 447˝	10.0 - 15.0	2.9	0.5	5.3	4.7
	15.0 - 20.0	4.3	0.6	5.9	4.6
	20.0 - 30.0	2.8	0.6	5.2	4.6
	30.0 - 40.0	0.3	0.7	6.1	4.8
	40.0 - 50.0	0.3	0.8	5.5	4.8
	50.0 - 60.0	0.3	0.8	5.9	4.8
	60.0 - 75.0	0.2	0.9	5.9	4.9
	75.0 - 100	0.2	0.9	5.8	4.9