Assessment of the soil carbon storage potential of the Kikonda reforestation project, Uganda.

MSc Thesis Thomas Martin Grome (tmgrome@gmail.com)
Universität Für Bondenkultur Wien (BOKU): Dpt. of Forest and Soil Sciences
University of Copenhagen: Faculty of Life Sciences (LIFE)

Research conducted at the Kikonda Forest Reserve, Uganda: International Woodland Company A/G
Under the supervision of: Prof. Winfried Blum, BOKU; Dr. Thilde Bech Bruun, LIFE;
Dr. Andreas de Neergaard, LIFE; and with local supervision by Dr. Twaha Ateenyi (Makerere University)

UNIVERSITY OF COPENHAGEN

Abstract

The purpose of this project was to assess the carbon storage potential of soils under different land use classes at the Kikonda Forest Reserve, Uganda. The primary source of data was generated at the Kikonda Forest Reserve, a commercial forestry project in the Kiboga district, Western Uganda. The land use classes investigated were: 8 year pine rotation; 5 year pine rotation; 3 year pine rotation; recently cleared areas within the reserve; secondary forest; and primary forest acting as a baseline for comparison. The closest primary forest was the Budongo Forest Reserve in the Masindi district, approximately 150km away from Kikonda. No significant differences in SOC stocks or %SOC were found between the planted areas; the cleared area; or the primary forest were detected in the top 20 cm of soil. Some significant differences arose at deeper depths; however, SOC was unlikely affected by land use change past 20-30 cm depth due to a change in land management within the investigated time period. An increase of SOC storage, following the conversion of degraded land on the Kikonda FR to forest, may potentially manifest itself in the long term once a new equilibrium in carbon content occurs. The data also suggests that %C in the litter layer increases linearly with stand age. Continued production at the Kikonda FR is encouraged for both potential carbon mitigation; financial gain for the IWC; and as a continued source of employment for local communities.

Abstrakt

Die Aufgabe dieses Projekts war es, das Carbon-Speicher-Potential von verschieden genutzten Böden im Kikonda Wald Reservat, Uganda. Die primäre Datenquelle wurde im Kikonda Wald Reservat generiert, ein kommerzielles Bewaldungsprojekt im Kiboga District, West Uganda. Die folgenden Klassen wurden untersucht: 8-jahres Kiefer Zyklus; 5-jahres Kiefer Zyklus; 3.jahres Kiefer Zyklus; kürzlich abgeholztes Gebiet innerhalb des Reservats; Sekundärwald; und Primärwald, der als Ausgangspunkt zum späteren Vergleich diente. Beim nächst gelegenen Primärwald handelt es sich um das Budongo Wald Reservat im District Masindi, ungefähr 150km von Kikonda entfernt. Keine signifikanten Unterxchiede in SOC stocks oder %SOC wurden zwischen den zwei Gebieten gefunden; das abgeholzte Areal; oder der Primärwald wurden an den obersten 20cm der Erdschicht ermittelt. Einige signifikante Unterschiede kann man jedoch in tieferen Erdschichten ermitteln; wie auch immer, SOC wurde durch Bodennutzung unter 20-30cm kaum beeinflusst, dies lässt sich durch das veränderte Bodenmanagment während dem Untersuchungszeitraum erklären. Eine Erhöhung der SOC Lagerung, die durch Umwandlung von verrottendem Material in Wald im Kikonda Wald Reservat, könnte sich manifestieren, sobald ein neues Gleichgewicht im Carbongehalt einstellt. Ebenfalls suggerieren die Daten, dass %C in der Abfallschicht linear mit dem Standalter ansteigt. Die anhaltende Produktion im Kikonda Wald Reservat ist empfehlenswert für “potential carbon mitigation”; finanzieller Profit für den IWC, und als ständige Quelle für Beschäftigung der lokalen Gemeinschaften.

Table of Contents

List of Figures and Tables

Abbreviations and Acronyms

Budongo Forest Reserve	Budongo FR
Carbon	C
Figure	Fig
Forest Department	FD
Forest Stewardship Council	FSC
Global-Woods A/G	GW
Grams per Cubic Centimeter	g cm^3
Greenhouse Gas	GHG
Humic substances	HS
International Woodland Company	IWC
Kikonda Forest Reserve	Kikonda FR
Meters Above Sea Level	masl
P	P-Value
Particulate Organic Matter	POM
Petagrams	Pg
Reduced Emissions from Deforestation and Degradation	REDD
Soil Organic Carbon	SOC
Soil Organic Matter	SOM
Tons per hectare	t/ha^{-1}
United Nations Framework Convention on Climate Change	UNFCCC

1. Introduction

The research objective of this project is to assess the soil carbon storage potential and the vegetation diversity of the Kikonda Forest Reserve (Kikonda FR), with an area of 121.86 km^2 (12,186 ha), in the northwest of Uganda. The Kikonda FR is the first in Uganda to 'be granted CarbonFix certification for its one-of-a-kind positive social and ecological impact' (CarbonFix Standard 2010). The Kikonda FR has been leased by the International Woodland Company (IWC) and Global Woods AG (GW) from the Ugandan government for the purpose of generating carbon credits via the planting of conifer and broad leaved fast growing tree species to qualify for financial benefits under the REDD (now known as REDD+) due to conservation and sustainable management being recognized as important activities in reducing emissions from forests) and CarbonFix certification incentives; the production of saw timber; and the production of energy (charcoal) and 'gasification of wood chips for cogeneration of electric power' (Baur 2007). Tree plantations have the potential to occupy approximately 70% of Kikonda FR where as the remaining 30% is either swampy, a community forest or areas set aside for conservation (Baur 2007). The area set aside for conservation under the Forest Stewardship Council (FSC) requirements will be approximately 10-20% of the total area planted with what is deemed natural forest cover.

1.1 Rationale

IWC is able to generate profit from its incentives in Kikonda FR, however economic incentive is not the only interest shown in the forestation project. An emphasis has also been placed upon natural and social objectives. The work undertaken within this project will focus on the natural objectives. At Kikonda FR, more than 1 million trees had been planted by 2008, over 1000 ha, which has the potential to store at a minimum 200,000 tons of CO_2 in above ground biomass.

The difference in forestry and land-use issues remain as some of the more controversial components of the responses related to global climate change (Niles *et al* 2002) such as the intensity of impacts land use management schemes can affect e.g. utilizing a rotational forest harvesting scheme where impact is minimized to a specific area of the forest where as a single harvest would cause a greater impact on the land as a whole. Furthermore, it could potentially be beneficial for the future mitigation of climate change if a relationship can be determined. Changes in land-use management, for the mitigation of climate change, can include reforestating degraded lands, avoiding deforestation and the adoption of sustainable agriculture practices (Niles *et al* 2002). However, under the Kyoto protocol, only reforestation is eligible for financing (Niles *et al* 2002).

IWC has data in carbon storage by the above ground biomass, however no data has been collected on the soil carbon storage capacity of Kikonda FR. Soil carbon is excluded from the Carbon Certification schemes currently utilized in Kikonda FR, however IWC and GW have expressed interest in determining how soil carbon content differs between the different landuse categories (i.e. primary (natural) forest vs. secondary (degraded) forest, three year forest rotation vs. five year forest rotation).

1.2 Carbon *storage and Climate Change*

Carbon storage is the long-term storage of carbon in soils, oceans, geologic formations and vegetation (especially forests). The relevance of this is that forests sequester and store more carbon than any other terrestrial ecosystem and could potentially act as an important natural "break" on climate change (Gibbs *et al* 2007). Emissions of greenhouse gasses (GHG) into the atmosphere have been rising rapidly since the dawn of the industrial revolution (Le Treut *et al* 2007) and there is a possibility that these trends may be irreversible and damaging to the environment (Solomon *et al* 2007). Of these GHG, CO^2 is considered the most important anthropogenic emission (Solomon *et al* 2007). Global atmospheric concentration of CO^2 has increased from a pre-industrial value of 280 ppm to 379 ppm by 2005 (Solomon *et al* 2007). The natural range over the last 650,000 years (180 to 300 ppm), as determined from ice cores, shows that the atmospheric concentrations of CO^2 exceed those – and with an annual CO^2 concentration growth rate of 1.9 ppm (annual average from 1995-2005) (Solomon *et al* 2007) it becomes apparent that measures are needed to reduce the amount of carbon exhibited in the atmosphere due to anthropogenic emissions.

As previously mentioned, the largest source of GHG emissions in the majority of tropical countries is the result from deforestation and forest degradation (Detwiler 1986, Gibbs *et al* 2007). For example, deforestation accounts for approximately 70% of total emissions in Africa (FAO 2005). Forests act as a significant carbon sink and stored carbon, in the form of CO^2, is released into the atmosphere when forests are cleared or degraded (Gibbs *et al* 2007). This represents a significant contribution to global emissions as tropical deforestation causes an estimate of 20% of worldwide anthropogenic carbon emissions (Niles 2002).

The primary source of increased atmospheric concentrations of CO_2 results from anthropogenic emissions, primarily from fossil fuel use, with land use changes providing a significant, but otherwise small, contribution. Globally, forest vegetation and soil organic carbon (SOC) storage in the top 3 m of soil has been estimated to be 2344 petagrams (Pg) of C where as 1500-1600 Pg C is the estimated value for the first meter (Jobbagy & Jackson 2000). This represents a significant contribution to global emissions as tropical deforestation causes an estimate of 20% of worldwide anthropogenic carbon emissions (Niles 2002). **Fig. 1** shows the annual net flux of carbon to the atmosphere from land use changes from 1850-2000. In **Fig. 1**, it is apparent that land use changes in tropical Africa has significantly contributed to global carbon emissions albeit in much lesser amounts than land use changes present in Latin America and tropical Asia. In total, tropical deforestation is estimated to have released approximately 1-2 billion tons of carbon per year during the 1990s (Niles 2002, Gibbs et al 2007, Houghton 2005).

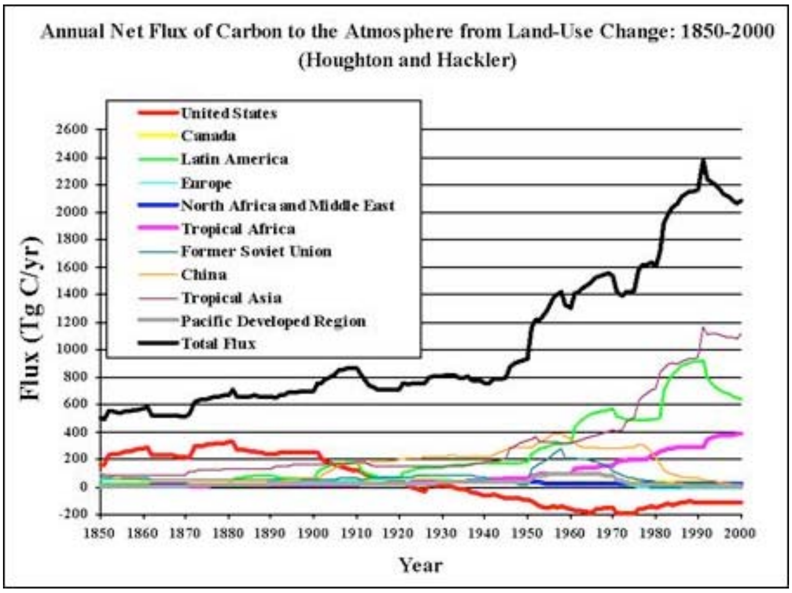


Figure 1: Annual net flux of carbon to the atmosphere from land use change: 1850-2000 (source: http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html)

Carbon in soils is a major component of the terrestrial carbon cycle. Globally, the amount of carbon stored in soils is greater than the combined total amounts found in vegetation or the atmosphere (Swift 2001). Land-use change, especially the conversion to agricultural practices, degrades soil C stock and thus depleted agricultural soils have 'lower SOC stock than their potential capacity' (Lal 2005, Detwiler 1986). The Third Assessment Report of the

Intergovernmental Panel on Climate Change confirms that emissions avoidance and changes in land use management in the form of carbon storage can make a potentially significant contribution in the short term, if not limited in the long term, to the mitigation of climate change (Kauppi & Sedjo 2001). The afforestation of agricultural soils and proper management of forest plantations can potentially promote SOC stock via carbon sequestration (Lal 2005).

Carbon storage potential in soil is dependent on its capacity to ‘store resistant plant components in the medium term and to protect and accumulate the humic substances (HS) formed from the transformations of organic materials in the soil environment and climate (Swift 2001). Factors that determine the sequestration of carbon in soil include the vegetation; the mineralogical composition of the soil; the depth of the solum; soil drainage; water available; oxygen available; temperature of the soil environment; chemical characteristics of soil organic matter (SOM) and its ability to resist microbial decomposition (Swift 2001).

1.3 Factors influencing SOC stocks

Increased SOC, from afforestation, should result from (1) increased litter inputs, (2) lower top soil temperatures due to enhanced canopy cover, thus lower decomposition rates and (3) Decreased decomposition due to decreased aeration and an enhancement of physiochemical protection mechanisms (Bruun *et al.* 2009). Changes in SOC stock largely depends on a variety of factors e.g. climate (and climate change), species, soil type and management practices (Bruun *et al.* 2009, Lal 2005)

The general consensus is that, to a certain limit, SOC is diminished when land use changes occur from natural forest to managed ecosystems (Jobbagy & Jackson 2000). Furthermore, the older the forest, the more SOC should be present (Jobbagy & Jackson 2000).

Soil texture provides insight into the properties of forest soils, as its influence on hydrologic and biogeochemical processes is strong enough to affect the ability of soils to retain carbon, water and nutrient ions (Gee & Bauder 1986). Numerous authors have described the relationship between clay (or clay + silt) content and SOM in LAC soils (Parton *et al.* 1993, Feller & Beare 1997) from different sites in the tropics. These studies have shown that clay (or clay + silt) content is a relatively important determinant of SOC levels in low activity clay soils. The relationship between clay and SOC levels appears to apply to both cultivated soils and soils under natural vegetation

(Feller & Beare 1997). However, the linear increase between clay content and C is only valid up to a certain amount of clay depending on the type of soil and region (e.g. climatic conditions i.e. mean annual temperature) (Feller & Beare 1997). The formation of passive C pools with low turnover rates can be facilitated by clay rich soils as clay particles can physically (pores) and chemically protect SOC in organo-mineral complexes (Christensen 1992, Lützow *et al* 2006). Increasing concentration of carbon levels in soils may occur in clay rich soils as carbon can be captured within the small pores of clay particles (Gee & Bauder 1986).

Soil structure may influence the way SOC is stored via two mechanisms proposed by Feller & Beare (1997): '(1) the physical protection of SOM against mineralization due to its inaccessibility to microbial attack and (2) a reduction in the detachment of fine particles that contribute to losses of SOM by erosion, particularly in semi-arid and subhumid tropical soils.'

Bulk density is an important feature for carbon storage. Although %SOC in an area may be high, unless the volume of soil is high enough, potentially only moderate amounts of SOC will be stored. Bulk densities generally increase with depth in the soil profile, probably as a result of lower organic matter contents, fewer roots and compaction (Brady & Weil, 2004). Furthermore, soil texture is an important indicator of both bulk densities as fine textured soils such as silt loams, clays, and clay loams generally have lower bulk densities than sandy soils (Borggaard & Elberling 2003) and that coarser, sandy soils generally have lower SOC concentrations when compared to silt loam and sandy loam soils (Borchers & Perry 1992).

1.4 FSC requirements

A scheme aimed at promoting sustainable forestry is the Forest Stewardship Council (FSC). The FSC is an attempt to regulate the global forestry industry 'which was only loosely regulated prior to 1990' (Klooster 2010). The FSC certification scheme is similar to REDD in that it is a voluntary, third party regulatory mechanism. It strives to incorporate a wide range of stakeholders that includes environmentalists and private sector actors with a connection to forestry – whether it is management or product retailing.

Globally, as of September, 2007, 90,780,769 ha and 886 forest management operations in 76 countries have been FSC certified (Klooster 2010). 'Most of the area certified was in Europe (53%), 31% in North America, 10% in Latin America, 3% in Africa, 2% in Asia, and 1% in

Oceania. Publicly managed forests made up 62% of the area certified, private forests 34%, and community managed forests only 4%' (Klooster 2010). Plantations contribute to 8% of the FSC certified area and portfolio where as mixed operations (a combination of plantations, semi-natural and natural forests), such as the Kikonda FR comprise 39% of the certified area (Klooster 2010). Certifying plantations is controversial and critics have suggested that plantations are 'sometimes associated with the spread of exotic species, the use of dangerous agrochemicals, the dessication of watersheds, and the loss of millions of hectares of biodiverse landcovers' and negative social aspects i.e. loss of employment and conflicts of land tenure (Klooster 2010). As a response to this, in 1996 the FSC adopted principle 10 and its criteria which 'require plantation managers to establish wildlife corridors, streamside zones, a mosaic of stands of different ages and rotation periods, and give preference to native species, among other factors' (Klooster 2010).

1.5 REDD+ policy

Although it is generally recognized that the reduction of deforestation and associated emissions into the atmosphere, developing countries have had few incentives to participate in policy making aimed at reducing emissions from land-use change (Santilli *et al* 2005). Therefore, the United Nations Framework Convention on Climate Change (UNFCCC) launched discussions with forest-rich developing nations on what economic and social incentives can be offered to mitigate this.

The UNFCC CoP13 in Bali in December 2007 produced a major decision that resulted in the parties associated with the UNFCCC discussing the REDD (Reduced Emissions from Deforestation and Degradation in developing Countries UNFCCC, 2007) policy due to the recognition that tropical deforestation is responsible for emitting 20-25% CO^2 (Gibbs *et al* 2007, UNFCCC 2007, Skutsha & Ba 2010). At its core, the REDD policy aims to provide financial incentives in order to afford developing countries the option of voluntarily reducing natural deforestation rates and to ensure the associated carbon emissions are emitted below a baseline – derived from either historical references or based on future projections (Gibbs *et al* 2007). Countries that are able to demonstrate a reduction in emissions will be eligible to sell carbon credits on the international market, in proportion to the amount of carbon that is saved (Skutsch & Ba 2010), or from a specially managed run by a large multi-lateral organization. The exact details of how such a mechanism would work is still unclear, but would most likely be conducted on a national level (Skutsch & Ba 2010).

Countries that choose to participate will have to commit to retaining forests and not allow an increase of their rates of deforestation in the following period. The potential of this scheme allows for the addition of a powerful tool to combat climate change. Furthermore, the REDD policy is aimed at conserving biodiversity and the protection of ecosystem goods and services (Gibbs *et al* 2007). As every area is different, it is not possible to develop a single, overall global policy or strategy and thus it is left to the participating country to develop its own set of policies and strategies insuring greater flexibility of the scheme – thus allowing for countries to develop its own plans for sustainability.

1.6 Research Objectives and Questions

The objectives of this study at the Kikonda Forest Reserve, Uganda are defined as follows:

- *Estimate soil organic carbon storage in three land-use categories: primary forest, secondary forest, recently afforested ages and in three forest age classes: 3 year age, 5 year and 8 year rotations*. This will enable us to deduce areas where carbon sequestration potential is the highest and in what quantities carbon is expected to be found.

- *Identify which land use and/or age class sequesters the most carbon.*

- *Investigate the relationship (if any) between changes in soil organic carbon and land use and age class changes.*

The research questions are:

- *How much below ground carbon is sequestered/stored?*

- *Which areas store the most soil carbon?*

- *Why do certain areas store more carbon than other areas?*

- *What environmental factors might influence carbon storage?*

These objectives are approached using the data collected from the Kikonda FR and Budongo FR.

2. Materials and methods

2.1 Site descriptions

2.1.1 Uganda

Uganda (Coordinates: 1°17′N 32°23′E / 1.28°N 32.39°E / 1.28; 32.39) is a landlocked country in East Africa on the Western coast of Lake Victoria. Uganda encompasses a total area of 236,040 km^2. The capital of Uganda is Kampala.

As of 2009, the population is estimated to be at 32,369,558 (C.I.A. world fact book, 2009). The official languages are English and Swahili, however many other languages are spoken especially in rural areas. Uganda has access to vast natural resources – including fertile land, ample rainfall during the rainy season and mineral deposits – and thus has great economic potential. However, due to political instability and economic management, Uganda has been placed amongst the poorest countries in the world.

Figure 2: Uganda in Africa. Red depicts Uganda. Blue depicts Lake Victoria (source: http://www.mrmyers.org/Time_Zones/Africa/Maps/uganda.html)

2.1.2 Kikonda Forest Reserve

The Kikonda FR is located approximately 180 km North-West of Kampala and 38 km East of Hoima. Kikonda FR is found in the sub counties of Butemba and Nsambya of Kiboga County, in Kiboga district of Buganda Kingdom. It is found at latitudes between $1^{\circ}00'$ and $1^{\circ}15'$ north and longitudes of $31^{\circ}30'$ and $31^{\circ}45'$ east. The FR covers an area of 12,186 ha. The FR station is located along the Kampala-Hoima road. The FR is located on either side of the Kampala-Hoima road, with the largest area of the FR being found towards the west of the road.

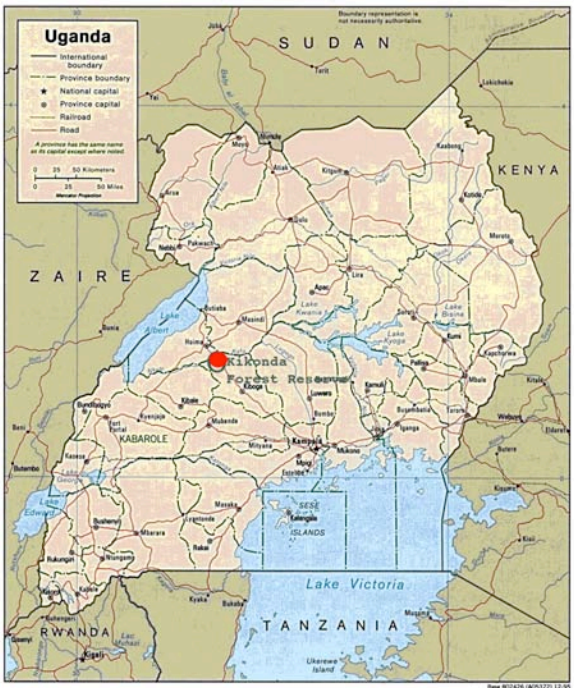


Figure 3: Map of Uganda marking location of Kikonda FR (in red). Depiction of Kikonda FR not to scale. (source: http://www.computers4africa.org/impact/ugandamap.htm)

2.1.2.1 History and Land use

The Kikonda FR belongs to the North Singo FRs, which are set aside areas for the protection of vital water catchments (Karani 1999). The area was set aside in order to fulfill requirements from the forest policy objective of 1951 that required 8 – 9% of the total Buganda Kingdom land area to be reserved for forestry products and services by 1956 (Karani 1999). In 1963, the area was uninhabited and not under private ownership. Therefore, the area (12,041 ha) had no boundaries or limits set. The FR area was demarcated in 1968 due to political and administrative changes that led to the recognition of the FR having high potential for conifer timber production (Karani 1999). Prior to its status as a forest reserve, Kikonda was part of the Singo county and ample game animals (i.e. elephants, buffalo, antelope) were present attracting hunters from Mengo (Karani 1999).

The Forest Department (FD) began experimenting with conifer cultivation by the early 1970s due to previous success in cultivation elsewhere in the Kiboga and Mubende districts. This lead to the large scale planting of mainly *P. caribea* and *P. oocarpa* (with some occurrence of *P. kesiya*) over an area of 145 ha (Karani 1999). The project was subsequently abandoned due to political instability in Uganda at the time and the loss of needed funding. The region became increasingly unstable during and after the war of 1979 and the FR was left largely unprotected with only a few forest guards in place (Karani 1999). Despite the lack of management (i.e. weeding, thinning, pruning) harvesting the remaining crop for saw logs was viable – thus the species used were deemed acceptable for cultivation in the region. In 2002, GW received the tree farming license for Kikonda in 2002. Since then the Kikonda FR gradually built up the forest management structures in Kikonda and planted 1500 ha until, in 2010, Capricorn Forest Fund managed by IWC bought the majority of shares of GW. The tree farming license still remains with GW and GW still manages the FR.

2.1.2.2 Land Management Practices

The Kikonda FR is divided into different age classes ranging from recently planted areas to the 8 year rotation plots. The oldest rotation (8 years) comprises of *P. oocarpa* where as all other age classes consist of *P. caribea*. There is a small plot of a broadleaf spp. *Maesopsis eminii* planted on 8 ha. planted simultaneously as the 8 year rotation of *P. oocarpa*.

No fertilizers are used on the FR. A combination of various techniques is applied in order to keep plants free of competition. After an area has been cleared from trees and shrubs, it is sprayed with Weed All, which uses the active ingredient glyphosate to kill off young growth of grasses and tree coppice. In more established areas, flocks of grazing sheep are used to target weeds and undergrowth detrimental to tree production. All rotations older than 4 years have been thinned at least once. Occasional brush back cutting is used to encourage tree establishment and early growth, however this was not apparent during the study period due to the large undergrowth present. This was most likely due to management shifting priority to seedling planting during the rainy season. Cuttings are left on the forest floor.

2.1.2.3 Climate

The climate in Kikonda is typical of that in Western Uganda – with dry and wet seasons. The first dry season occurs during January to March, characterized by a high mean annual temperature of 27 - 30℃ that coincide with summer in the southern hemisphere, while mean minimum temperature of 15 - 17℃ occur during June to July. Daily variation is nominal and exists between 11 to 14℃.

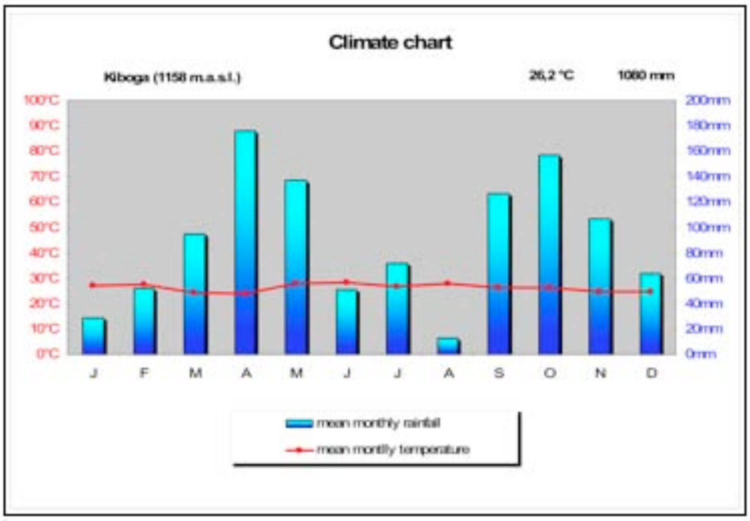


Figure 4: Climate Chart of Kiboga (Baur, 2007)

2.2.2.4 Topography and Drainage

The Kikonda FR is located on a flat plain formed by the erosion of Singo granite (Karani 1999). The remnants of which can still be seen towards the east in the form of hills i.e. Kawuka (peaking at 1295m asl) and Kikonda (1265m asl) to the north-west. The Kikonda FR lies between 1067m and 1227m asl (Karani 1999). Seasonal streams and rivers have caused the flat plain to become divided, characterized by expansive valleys that become waterlogged during rainy seasons (Karani 1999).

The whole project lies in the catchment of the Kafu river. The Kinawoga and Nankende rivers drain the area and subsequently drain into Kafu to the west and northwest. The land is flat on the upper reaches of Kinawoga which causes stream stagnation that is only alleviated following periods of heavy rainfall.

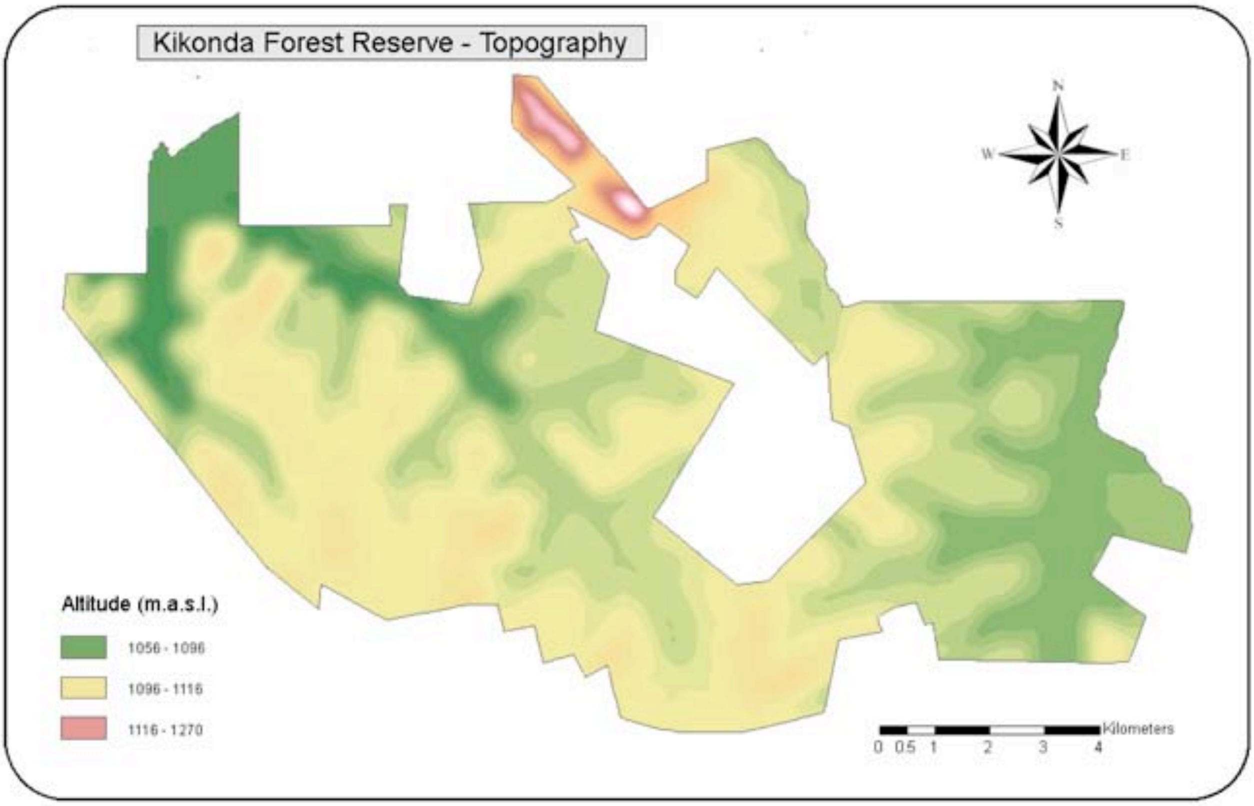


Figure 5: Topography of the Kikonda Forest Reserve (Baur 2007)

2.2.2.5 Geology and Soil

The rock formation of the FR belong to the Singo series that are made up of 'grit and sandstone with basal conglomerate shale facies' (Karani 1999). The characteristic red-brown soils, present in many parts of Uganda, are formed by the weathering of parent rock materials. These soils are ferrallic, predominantly loam in the south and sandy clay loams on broad flat valleys. Peat is present in cases of waterlogged swamps (Karani 1999). In most cases the soils exhibit a fine, granular structure that are porous – thus have a low water holding capacity. Soils present in seasonal swamps in the broad valleys are influenced by waterlogging and as of such consist of hydromorphic soil types.

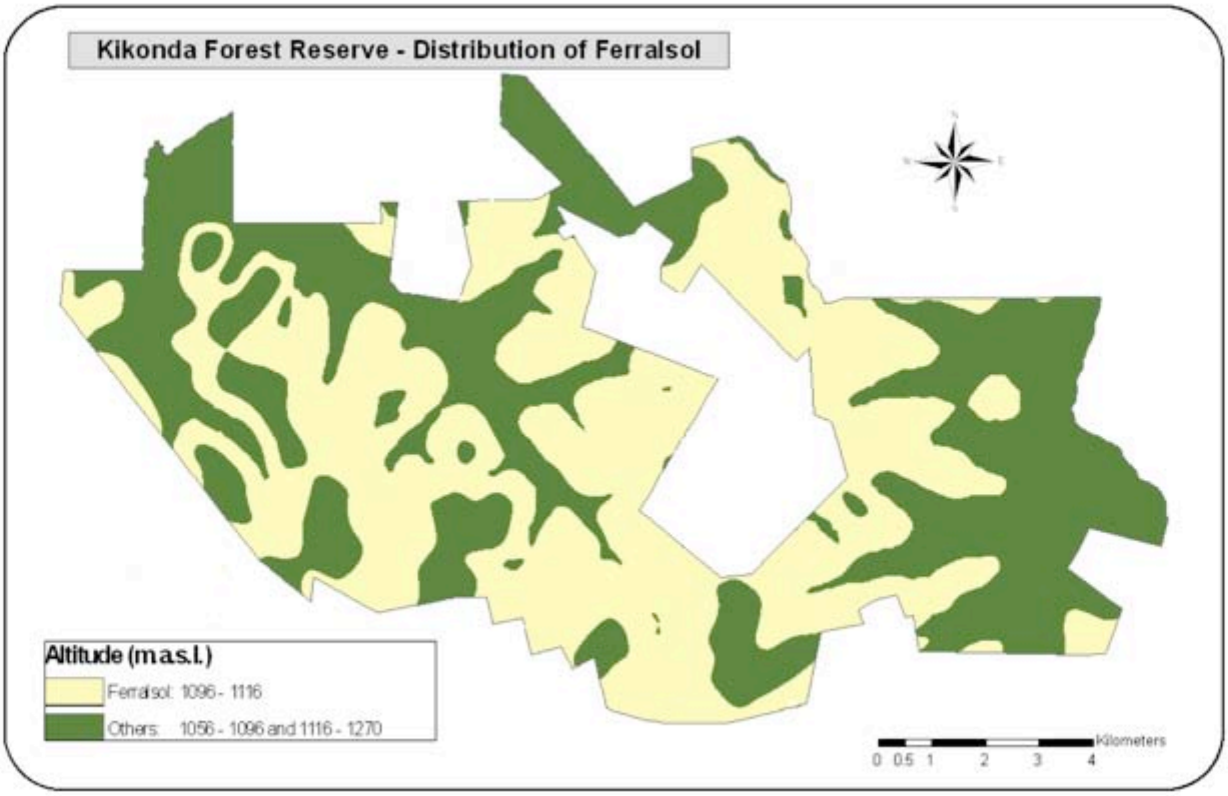


Figure 6: Distribution of Ferralsol at Kikonda FR (Baur 2007)

Kaolinite type clay minerals are strongly exhibited and are ‘associated with high quantities of iron and aluminium hydroxides. The base saturation is usually below 40% and the heavier textured types are more fertile than the lighter textured and possess features common to ferrisols’ (Karani 1999). Soils in the region have low content of inorganic components in the solids fraction of the soil (Karani 1999).

2.2.2.6 Vegetation

In 2006, Olivia Wannyana, of Makerere University, Kamapala, and her team, conducted a vegetation assessment of the Kikonda FR. The assessment concluded that vegetation types present are mainly woodlands and wooded grasslands. Natural tree vegetation found to be most prominent was the Combretaceous species, Acacia woodlands, forest remnants or savanna / forest mosaic, colonising forests, thickets mainly of Grewia and Rhus spp. and *wooded grasslands* mainly of Hyparrhenia and Loudetia spp. For a more inclusive list of vegetation present, please refer to **Appendix 1**. This vegetation is the result of grazing and burning of formerly supported forests and woodlands.’ (Project Design Document 2008). **Table 1** shows the changes in land use between the years 1990 – 2001 and the types and conditions of vegetation inside the project area up until 2006.

The construction of housing and administrative offices for management staff of the project, as well as two stone quarries for the construction of the Kampala-Hoima road, leads to the increase in “Settlement” in 2006. The above tables highlight the continuous affects of deforestation and subsequent increase of Bush and Grasslands.

Table 1: (Project Design Document 2008).

Land use type (area in ha)	1990	1995	2001	2006	Land use change 1990-2001 (ha)
	Land use changes in and around project area (1990-2001)				
Natural forest	11,946	9,471	6,815		-5,130
Bush/grassland	27,290	28,383	25,084		-2,206
Wetland	10,539	10,685	10,594		55
Cropland	4,365	5,590	11,698		7,333
Settlement		3	17		17
Other land	1,959	1,967	1,891		-68
Total area (ha)	**56,099**	**56,099**	**56,099**		
	Land use changes within project area (1990-2006) (Project Design Document 2008)				
Natural forest	3,376	3,273	2,945	2,569	-431
Bush/grassland	7,321	7,390	7,745	8,229	424
Wetland	1,402	1,434	1,409	1,006	7
Cropland	0.02	0.01	0.01	0.1	
Settlement				12	
Other land	82	85	82	83	
Planted area				282	
Total area (ha)	**12,182**	**12,182**	**12,182**	**12,182**	

Land use history in the project area (1990 to 2006) (source: Landsat and Spot images groundtruthed by GEOfis GmbH and global-woods AG for details see documents “GAF_KFR_Eligibility.pdf” and “GeoFIS_KFR_Groundtruthing.pdf” under www.carbonfix.info/kfr)

2.1.3 Budongo Forest Reserve

There were no primary forests located close to the vicinity of the fieldwork, however due to the importance of having a baseline in order to draw comparisons to the other land use classes, the Budongo nature reserve in the Masindi district (approximately 150 km away) was chosen. Due to the uniformity of soil characteristics in Uganda (Twaha pers. comm. 2010), a comparison should be able to be drawn up front.

The Bundongo FR is located on the edge of the Western Rift Valleya steep slope east of Lake Albert. It is found at latitudes between 1°34’ and 1°43’ north and longitudes of 31°28’ and 31°31’ east. The FR covers an area of 79,300 ha. The area of focus is found between 1°40′N 31°28′E / 1°43′N 31°31′E. (See **Appendix 2**, samples taken from quadrant N185000-190000 E335000-340000)

2.1.3.1 History and Land use

The Budongo Forest Reserve was designated as a FR in 1932 (Mwavu & Witkowski 2008). The composition of Budongo's mixed forests and colonizing forests has been very much affected by forestry and logging activities (Patterson 1991). Historically, the silvicultural practices included selective logging, enrichment planting and ‘controlled shooting to reduce animal populations in the forest’ (Mwavu 2007). In 1944 the main Budongo block was 60% mixed forest, 32% ironwood (*Cynometra* spp.) climax, 6% colonizing forest and 2% swamp forest (Patterson 1991). In the 1940s and early 1950s, African mahoganies were replanted in the logged areas in order to encourage regeneration (Mwavu 2007). In 1991, ‘it was estimated that about 77% of the forest had been cut at least once, and most of the forest has been altered through timber exploitation’ (Mwavu 2007).

2.1.3.2 Climate

The climate in Budongo is a tropical climate characterized by dry and rainy seasons with two rainfall peaks from March to May and September to November with a mean annual rainfall of 1500 mm (mean monthly rainfall of 138.5 – 66.7 mm). Dry seasons are from June to August and December to February. The area has high temperatures with little variation (Mwavu & Witkowski 2008).

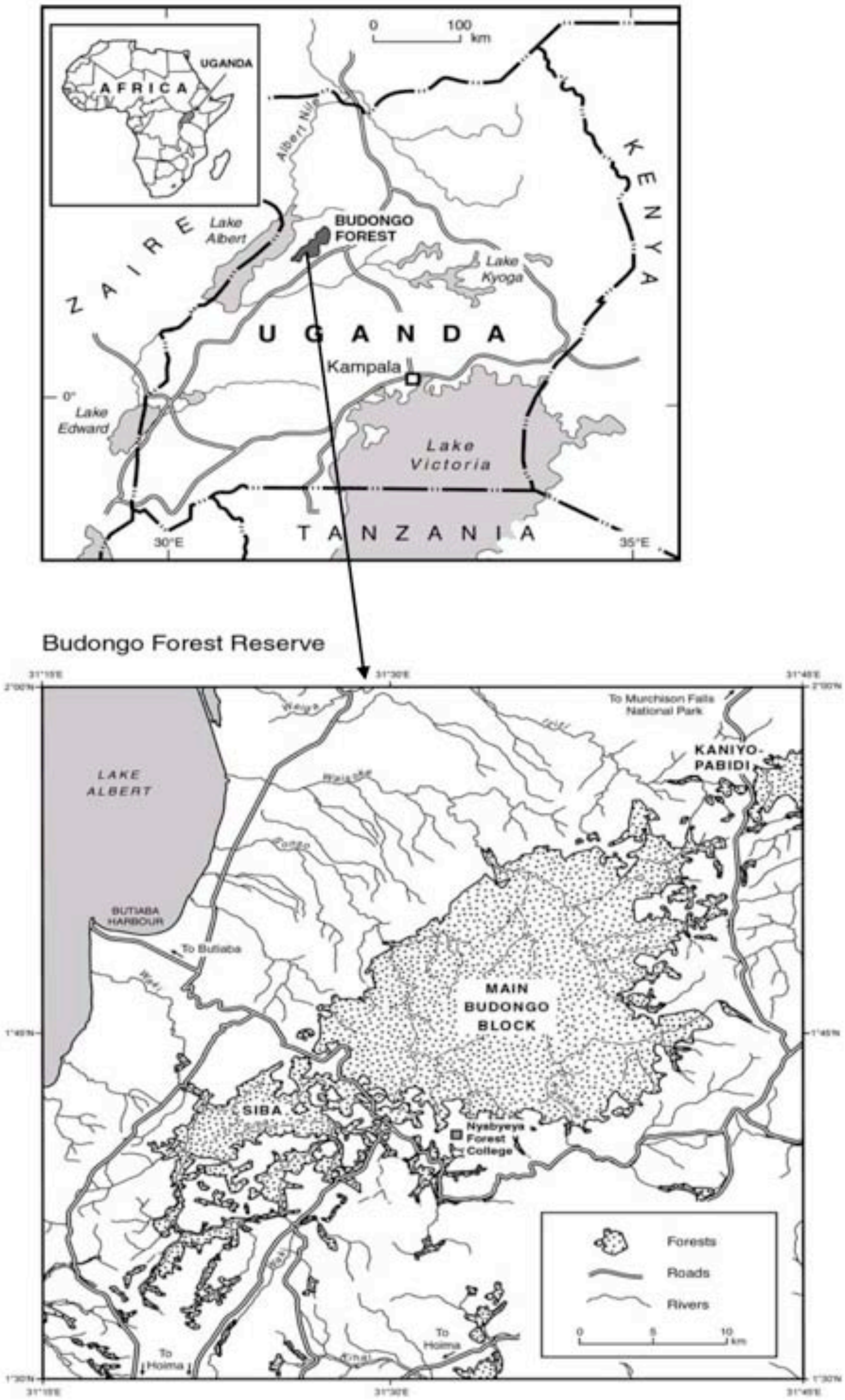


Figure 7: Map of Budongo FR (Mwavu 2007)

2.1.3.3 Topography and Drainage

The altitudinal range of the area is 700-1270 m asl, with 0.2 km of the area lying below 750 m, 385 km2 at 750 - 1000, 408 km2 at 1000 - 1250 m and 0.1 km2 above 1250 m (Mwavu 2007). The altitudunal mean is about 1050 m with a moderate undulating terrain including hills rising to approximately 1200 masl (Eggeling 1947). Valley bottoms are generally soft 'and many of the so called streams are mere trickles through rattan swamps, with no apparent flow in dry weather' (Mwavu 2007).

2.1.3.4 Geology and Soil

The underlying rocks are 'ancient gneisses, schist's and granulites of the Basement Complex' (Mwavu 2007). The soils are ferralitic, mainly sandy or sandy clay laoms of low to moderate fertility (Mwavu 2007). The soils are, generally, deep with clearly defined horizons and have a fine granular structure molded into larger, weakly coherent clods that are friable and porous. The basement complex consists of highly metamorphoses sandstone, shale and limestone (Eggeling 1947).

2.1.3.5 Vegetation

The Budongo FR has approximately 53% forest cover as of 1991 (Patterson 1991). The vegetation zone is distributed between 700 and 1270 masl (Patterson 1991). This forest type is classified as medium altitude semi deciduous moist forest due to the presence of several, at least briefly, deciduous dominant species (e.g. *Celtis* spp., *Ficus* spp. Etc) (Eggeling 1947, Mwavu 2007). A thick canopy is present and thus virtually no light reaches the forest floor. Leaf shedding is present in the majority of trees found in Budongo FR, typically during the dry seasons (June to August and December to February) (Patterson 1991). This is, however, not an automatic response but relies instead on 'the water economy of individual trees, and it is noticeable on well drained soils' (Mwavu 2007). The vegetation of Budongo FR was classified into four forest types by Eggeling (1947): *Cynometra* forest, mixed forest, colonizing woodland and swamp forest.

2.2 Site selection

The Kikonda FR is based in an area with homogenously flat land with +/- 50m elevations. In order to reduce effects of spatial variability, samples were not collected on slopes or in land depressions (i.e. flood plains). Samples were collected from three landuse classes and three age classes associated with the planted areas within the FR (**Table 2**).

Table 2: Land use classes and age classes investigated

Landuse class	
	Recently afforested area
	Secondary forest
	Primary Forest
	Planted areas (3 age classes)
Age classes	
	8 year rotation
	5 year rotation
	3 year rotation

The sites were selected at random using arcGIS 9.0 in order to avoid biased data. The exception was the Budongo FR where access to the Ugandan National Forest Agency GIS files was limited. Sites selected within the Budongo FR were selected by walking to random locations at least 1 km apart.

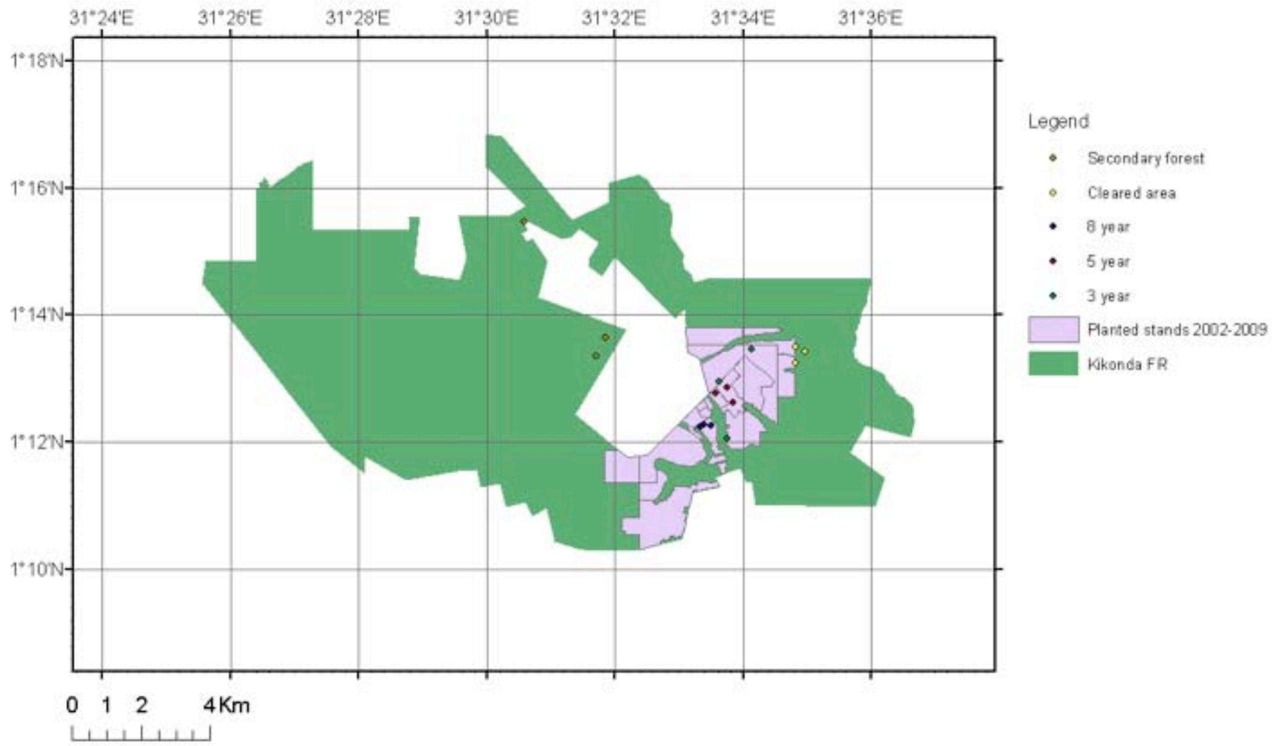


Figure 8: Map of Kikonda FR with site locations.

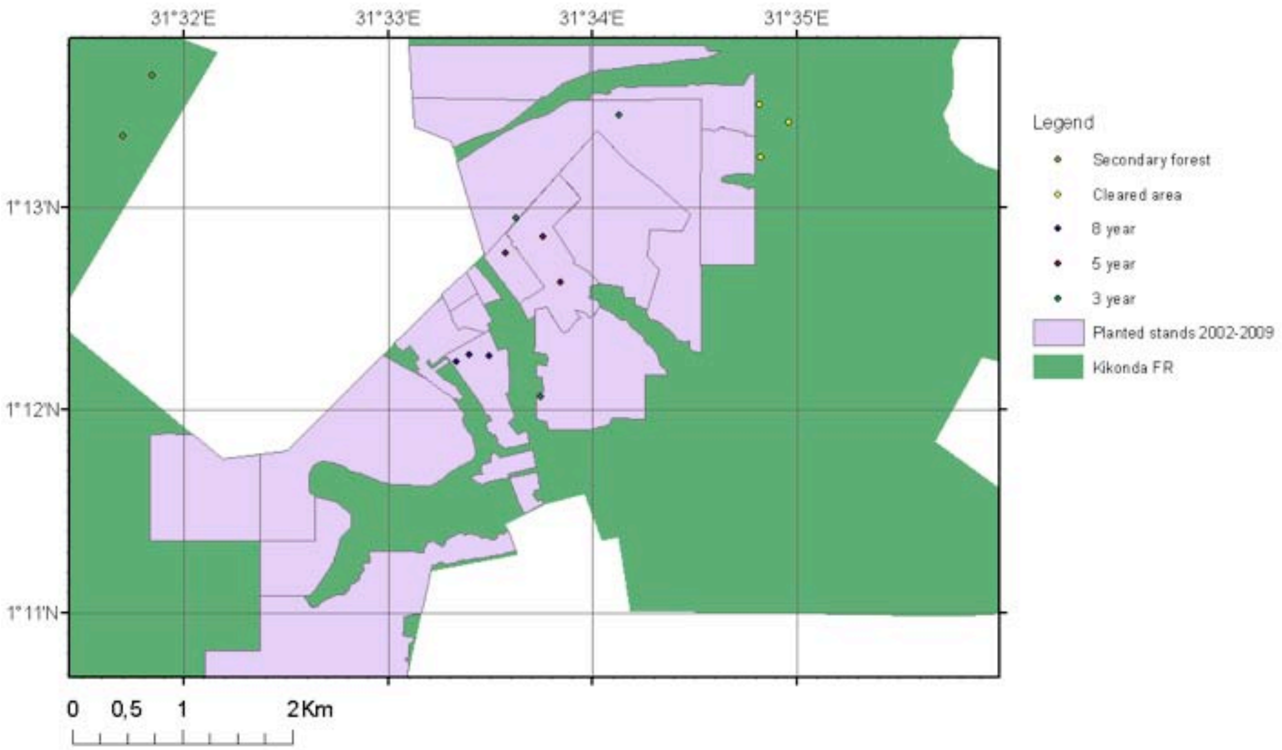


Figure 9: Map of Kikonda FR with site locations within the planted area.

Each land use and age class had three location replicates (e.g. three sampling areas for 3-year rotations) with three pits for soil profiling at each site at a distance of 15-20m.

Any tree dominated community was considered a forest. Secondary forests are characterized by a period of re-growth after a major disturbance (e.g. fire, timber harvest, insect infestation) to a point that the effects of the disturbance are no longer evident. In the case of the Kikonda FR, secondary forests were degraded due to a combination of timber harvesting and charcoal production. Conversely, primary forests have not undergone such disruptions.

Figure 10: 8 year rotation with access road within Kikonda FR.

Figure 11: Example of secondary forest within Kikonda FR.

Figure 12: Example of primary forest in Budongo FR.

The recently cleared areas were former bush land that had been slashed and burned for commercial conifer seedling planting. Recently cleared areas were selected as they could double as an “age zero” rotation as well as an indication of bush land C levels in the B-horizon.

The original intention had been to include an arable landuse class but it was not possible to locate local farmers who would permit data collection from their lands due to the risk of disturbing crop production during the period of heavy rainfall.

Figure 13: Recently Afforested area (Baur 2007)

2.3 Soil sampling and in situ measurements

Soil samples were collected from pits (40cm x 40cm x 60cm) in April and May 2010. Profiles were described and horizon boundaries identified (refer to **Appendix 3**).

Each area had three pits dug for sampling (*n* = 3). The replicate pits were located within 20-30m of one another, forming a triangle. Repetition samples (*n* = 2) were taken at the same layer of the four levels from each pit:

- At 5 cm representing 0-10 cm depth
- At 15 cm representing 10-20 cm depth
- At 30 cm representing 20-40 cm depth
- At 50 cm representing 40-60 cm depth

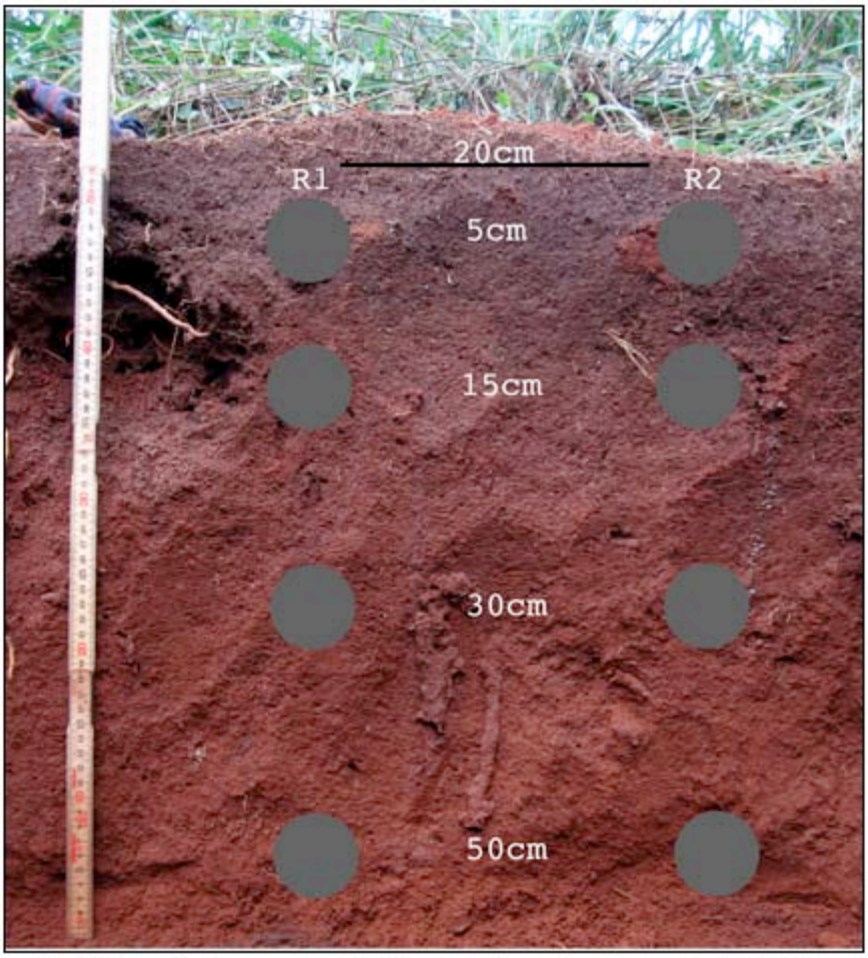


Figure 14: 3 year rotation land use/age class, area 2, pit A. Grey circles depict where samples were extracted; R1, replicate 1; R2, replicate 2.

The rings method was applied to collecting soil samples under natural conditions by obtaining a core of cylinder of soil, of $100cm^3$, and by pushing the core sampler intro the soil. Samples were not taken cross horizon, for example if a new horizon started at 25 cm and ceased at 35 cm, then the sample would have been taken at 35 cm. However, during the course of the fieldwork, this did not occur so all samples are consistent with the figures mentioned. Once collected, the samples were left to air dry before further sample preparation.

Additionally, the presence of termites poses some problem for accurate carbon sampling and chosen sample sites were a minimum of 20m from any mounds in order for the data to be as unbiased as possible.

In addition to the soil samples, litter layer samples (n = 54) were also collected at the 54 sites prior to the pit being dug. The litter layer sample was collected within a 50x50cm frame in order to produce consistent results.

Samples were transported to Makerere University, Kampala, for further initial preparation. Soil samples were placed in an oven over night at a temperature of 100℃ and the forest floor litter layer samples were dried at a temperature of 60℃, in order to avoid the destruction of the vegetation samples. Once oven dried, samples were weighed to deduce the bulk density. The material soil subsamples was ground and passed through a sieve (2 mm). The organic material in the litter layer samples was ground into fine POM (53um-0.5mm) at the University of Copenhagen. Spectroscopic analyses of the soil and forest floor sub-samples were conducted at the University of Copenhagen to determine the C percentage present.

Figure 15: Example of 50x50 cm frame used for collection of litter layer.

2.4 Soil properties

2.4.1 pH measurements

In total, the pH of 72 sub-samples was measured. Selected samples represent a full profile of one of the three sites in each of the six land use classes (0-10cm, 10-20 cm, 20-40 cm and 40-60 cm). 6 g subsamples were measured and dissolved in 15ml in a 0,01 M $CaCL_2$ solution in a 1:3 ratio. The solutions were shaken for 30 seconds each and left to rest for an hour. The solutions were then shaken a second time for 5 seconds and left to rest for an additional 5 minutes in order for the solution to settle.

2.4.2 Texture Analysis

Due to lack of samples, 40 g composite subsamples representing the soil depth 0-60cm were used to determine soil texture of the 54 investigated pits within the six land use classes.

Sand fractions were determined by sieving in order to determine particle size distribution and sand texture class (i.e. coarse sands (500-2000 µm), medium sand (250-500 µm), fine sand (100-250 µm) and very fine sand (50-100 µm)). Each subsample was placed inside high-speed reciprocating shakers for 20 minutes to sieve through 850 µm, 355 µm, 212 µm, 106 µm and 75 µm sieves (Elberling 2011, *in comm.)*.

Used particle-sized distribution curves and plotted sand fractions against logarithmic scale to produce frequency distribution curves for various particle sizes via physical dispersion. Through this, it was possible to use the sand fraction to estimate the percent value of the silt (coarse silt (20-50 µm), fine silt (2-20 µm)) and clay (i.e. coarse clay (0.2-2 µm), fine clay (< 0.2 µm)) fractions (Elberling 2011, *in comm.)*. 'The percentage of particles less than a given particle size is plotted against the logarithm of the effective particle diameter.' (Gee & Bauder, 1986)

Details for interpretation of the textural triangle for soil classification purposes are given by the Soil Survey Staff (1975) using the USDA classification system (**Fig. 16**).

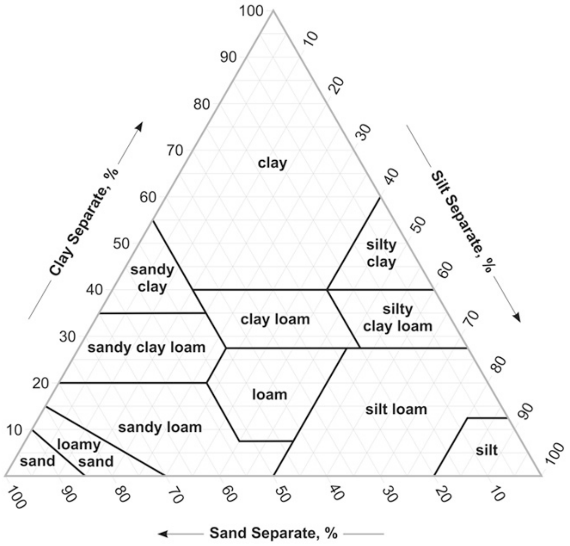


Figure 16 USDA soil textural triangle (http://soils.usda.gov/education/resources/lessons/texture/)

2.4.3 Soil organic carbon analysis

The three main questions addressed in this study were (a) to estimate soil C storage (below ground) in the different land use and age classes, (b) the difference in soil C in sites of a given land use from the other investigated sites, and (c) whether there is a relationship between changes in soil C and their respective land use and age class.

In order to compare the vertical distribution of SOC independently of total SOC content, the relative SOC contents for each soil layer, the stocks of carbon were calculated by multiplying the concentration of C by soil bulk density and the depth. The two repetition sample sets taken at each pit (4 x R_1 & R_2) were averaged in order to derive an interval that took into account spatial variability. The interval unit was then converted to SOC (t ha^{-1}). For equations used, and raw data, please refer to Appendix **7**.

Analysis of variance (ANOVA) was used to assess whether there exists a significant statistical difference in bulk density, C concentrations and stocks using a confidence interval of 0.05. The results of a one-way ANOVA can be considered reliable as long as the following assumptions are met:

- Samples are independent.
- Response variable must be normally (or approximately normally) distributed
- Variances of populations are equal.

In cases of a failed normality test or equal variance test, a Kruskal-Wallis One Way Analysis of Variance on Ranks was applied due to its non-parametric nature that does not assume a normal population. A normal population is not necessarily a requirement as the number of intervals tested (n = 9) within each group is >12, the recommended number of intervals for accurate population distribution. The Turkey test was used to separate treatments in the case of significant differences between the groups (confidence interval of 0.05).

Total C stock in the upper one meter (60 cm) was obtained using the sum of 4 depth intervals and forest floor litter layer sample at each site.

3. Results

3.1 Soil organic carbon % (%SOC) distribution

Summarizing the methodology, there are three pits per site, and three sites per land use or age class category. The objective of the following statistical analyses is to determine if there is a significant difference in SOC between the three sites within each land use and age class category. The null hypothesis is that there is no significant difference in SOC between the sites in each category. The results are summarized in **Table 7**, **Fig. 17** and **Fig. 18**.

3.1.1 8-year rotation

Mean % SOC content found at **5 cm** was 2.32% ± 0.8 and no significant difference between the sites (P = 0.348). At the **15 cm** depth, mean % SOC was 1.32% ± 0.7 and no significant difference was found (P = 0.54). The data at the 15 cm depth failed a normality test (P = 0.008), thus this negative result should be interpreted carefully. However, the low number of test samples (n = 9) could be the cause of a failed normality test. No significant difference was found when an ANOVA on ranks was applied (P = 0.132). At **30 cm** depth, mean % SOC was 0.85% ± 0.4, however a statistically significant difference was found between the sites (P = 0.001), thus a Turkey Test was utilized. The results generated show that there is a significant difference between Site 2 and Site 3 (P = 0.001) and Site 1 and Site 3 (P = 0.013). No significant difference was found between Site 1 and Site 2 (P = 0.062). Likewise, at **50 cm**, which has a mean % SOC of 0.68% ± 0.4, a significant difference between the sites was detected (P = 0.002). The results reflect the results found at 30 cm in that a significant difference between Site 2 and Site 3 (P = 0.002) and Site 1 and Site 3 (P = 0.016) where as there was no significant difference between Site 1 and Site 2 (P = 0.062). Additionally, the 50 cm depth failed an equal variance test (P = 0.038). This indicates that Site 3, past a certain depth, has a different rate of storing carbon. Of the three sites, Site 3 also contains a lower % of SOC at all depths than the other two investigated sites.

3.1.2 5-year rotation

Mean % SOC content found at **5 cm** was 1.59% ± 0.6 and no significant difference between the sites (P = 0.807) was found. At the **15 cm** depth, mean % SOC was 1.13% ± 0.5 no significant difference between the sites (P = 0.12) was found. No significant difference was found at the **30 cm** depth (P = 126) with a mean % SOC of 0.85% ± 0.3. However, at the 30 cm depth, the data failed to pass an Equal variance test (P = 0.002) that could affect the negative result despite the low number of tested samples (n = 9). An ANOVA on ranks resulted in no significant difference (P = 0.196) at this depth. A significant difference was found at the **50 cm** depth (P = 0.002) thus a

Turkey test was run. No significant difference between Site 1 and Site 2 (*P* = 0.821) was found, however significant differences were found between Site 3 and Site 1 (*P* = 0.003) and Site 2 (*P* = 0.005).

3.1.3 3- year rotation

Mean % SOC found at **5 cm** depth was 2.20% ± 1.0, however a significant difference (*P* = 0.02) was found between the sites. Turkey test results concluded that there is a significant difference between Site 1 and Site 2 (*P* = 0.017), however no other significant differences were detected (Site 1 vs. Site 3 *P* = 0.137; Site 2 vs. Site 3 *P* = 0.269). No other significant differences were detected at any of the other depths. Mean % SOC at **15 cm** was 1.48% ± 0.5 (*P* = 0.113). At **30 cm** depth, mean % of SOC was 1.26% ± 0.5 (*P* = 0.886). At **50 cm** depth, mean % SOC was 0.84% ± 0.2 (*P* = 0.882). Overall, Site 2 has the lowest percentage of SOC between 0-15 cm. Conversely, Site 3 has lower % SOC at depths past this however the difference is not significant.

3.1.4 Cleared area

Mean % SOC found at **5 cm** depth was 2.52% ± 0.7, however a significant difference (*P* = 0.016) was found between the sites. Turkey test results concluded that there is a significant difference between Site 1 and Site 3 (*P* = 0.017) and Site 2 and Site 3 (*P* = 0.048). There was no significant difference between Site 1 and Site 2 (*P* = 0.655). No other significant differences were detected at any of the other depths. Mean % SOC at **15 cm** was 1.56% ± 0.4 (*P* = 0.159). At **30 cm** depth, mean % of SOC was 1.0% ± 0.2 (*P* = 0.847). At **50 cm** depth, mean % SOC was 1.16% ± 1.1 (*P* = 0.727). Overall, Site 1 has the lowest percentage of SOC between 0-30 cm. Conversely, Site 3 has lower % SOC at 50 cm however the difference is not significant. It is noteworthy to point out that there is a higher % SOC at 50 cm than at 30 cm and that the difference is significant (*P* = 0.003) – out of all the investigated land use classes, this is the only instance where % SOC is higher at a lower depth.

3.1.5 Secondary forest

Mean % SOC found at **5 cm** depth was 2.63% ± 1.5, however a significant difference (*P* = 0.005) was found between the sites. Turkey test results concluded that there is a significant difference between Site 1 and Site 3 (*P* = 0.016) and Site 1 and Site 2 (*P* = 0.006). No significant difference was found between Site 2 and Site 3 (*P* = 0.655). Mean % SOC found at **15 cm** was 1.77% ± 0.6 (*P* = 0.095). Mean % SOC found at **30 cm** was 1.29% ± 0.5, however a significant difference (*P* = 0.017) was found. Running a Turkey test, the results show that there is a significant difference between Site 1 and Site 3 (*P* = 0.015), but not between Site 1 and Site 2 (*P* = 0.422) nor Site 2 and Site 3 (*P* = 0.074).

3.1.6 Primary forest

There were no significant differences at any of the depths in the Primary forest land use class. Mean SOC % at **5 cm** was 3.03% ± 1.5 (*P* = 0.765). Mean SOC % at **15 cm** was 1.16% ± 0.3 (*P* = 0.629). Mean SOC % at **30 cm** was 0.75% ± 0.12 (*P* = 0.548). Mean SOC % at **50 cm** was 0.68% ± 0.1 (*P* = 0.241).

3.1.7 Comparison of %SOC in planted areas: 8 year; 5 year; and 3 year rotations

In the top soil (**5 cm**), the 8 year rotation has the highest % of SOC within the planted area land use class where as the 5 year rotation has the lowest. However, at 5 cm, there is no significant difference in % SOC (*P* = 0.142). At the **15 cm** depth, the 3 year rotation has the highest % of SOC and again the 5 year rotation has the lowest. Again, there is no significant difference (*P* = 0.407) of % SOC at this depth. Conversely, there is a significant difference at the **30 cm** depth (*P* = 0.043) – yet, when a Turkey test is run between the individual land use classes there does not appear to be a significant difference: 3 year vs. 5 year (*P* = 0.065); 3 year vs. 8 year (*P* = 0.081); 8 year vs. 5 year (*P* = 0.153). This may be an error in the ANOVA calculation – and when the P values of the individual sites are compared, the 3 year rotation is the only land use class wherein the data shows no anomalies (Normality passed, Equal variance passed and no significant difference). When we arrive at the **50 cm** depth, there is again no significant difference in % SOC (*P* = 0.460).

3.1.8 Comparison of %SOC in all land use classes

In order to determine whether or not there is a difference in % SOC between the investigated land use classes, a comparison between the six classes will be made. The results are summarized in **Fig. 17.**

At **5 cm** depth, an ANOVA analysis shows that *P* = 0.055, which would indicate that there is no significant difference. However, the data set failed a Normality test (*P* = 0.012), which is assumed by an ANOVA. In the previous section, negative results were interpreted carefully yet the small data set (n = 9) could have been the reason for a failed normality test. However, when comparing all six land use classes, the data set is substantially higher (n = 54). Combining the low P value of the normality test and the borderline negative result of the ANOVA test – although there is no significant value – the results may not be conclusive enough to assure there is no significant difference at this depth. When just the means of all the land use classes are examined, the value equals 2.38% ± 0.483 with a standard error of 0.197 – and using a simple T test results in a passed normality test (P = 0.908).

At **15 cm**, no significant difference (P = 0.082), which suggests there is no difference between % SOC at this depth. At the **30 cm** depth there also is no significant difference (P = 0.079), however the data set again failed a standard normality test (P = 0.044) – yet it is closer to the 5% CI used than the results generated at the 5 cm depth. The combined means equal 1.00% ± 0.23 with a standard error of 0.09 – therefore, the results are more confident than those at the 5 cm depth. The same level of caution is still applied to this negative result and will be discussed further in the discussion.

At **50 cm** depth, no significant difference (P = 0.322) was detected. However, the data set failed a test for equal variance (P = 0.044). The likely cause of the discrepancy in how the data is spread out is most likely due to Sites in the 8 year and 5 year rotation. In both land use classes, the data had a significant difference in that 8 year: Site 3 and 5 year: Site 3 did not match the other sites within the individual land use classes. When these two sites are removed from the overall analysis, the equal variance test passes (P = 0.502) and the ANOVA test still responds with no significant difference between the land use classes (P = 0.108).

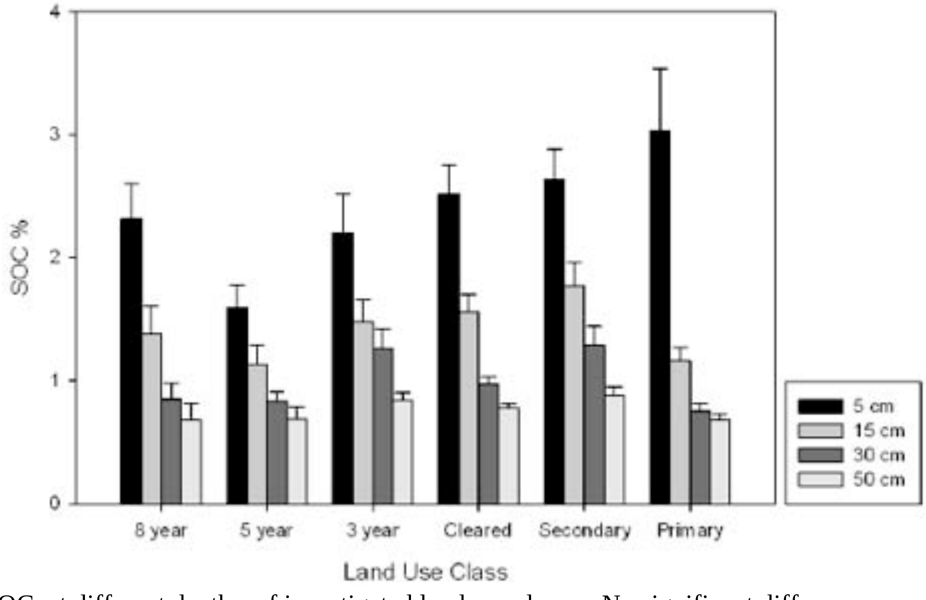


Figure 17: %SOC, at different depths, of investigated land use classes. No significant differences were detected when an ANOVA was applied. ANOVA on ranks resulted in a significant difference between the primary forest and the 5 year rotation at the 5 cm depth; and again at the 30 cm depth between the primary forest and the 5 year rotation and cleared area, respectively.

Table 3: Soil organic carbon % (0-60 cm) of investigated sites.

		Soil organic carbon % by depth (cm)			
	No. of samples	5	15	30	50
8 year rotation	81				
Site 1	27	2.38	1.37	0.91	0.75
Site 2	27	2.83	1.99	1.26	1.04
Site 3	27	1.77	0.79	0.75	0.24
Mean		2.32 ± 0.8	1.38 ± 0.7	0.85 ± 0.4	0.68 ± 0.4
P		0.348	0.54N	0.001	0.002
5 year rotation	79				
Site 1	26	1.69	1.36	0.98	0.86
Site 2	26	1.70	1.35	0.96	0.8
Site 3	27	1.40	0.69	0.61	0.32
Mean		1.59 ± 0.6	1.13 ± 0.5	0.85 ± 0.3	0.66 ± 0.3
P		0.807	0.12	0.126E	0.002
3 year rotation	81				
Site 1	27	3.19	1.95	1.37	0.88
Site 2	27	1.31	1.05	1.26	0.83
Site 3	27	2.12	1.46	1.15	0.8
Mean		2.2 ± 1.0	1.48 ± 0.5	1.26 ± 0.5	0.84 ± 0.2
P		0.02	0.113	0.886	0.882
Cleared area	81				
Site 1	27	1.98	1.28	0.95	0.77
Site 2	26	2.28	1.48	1.00	0.75
Site 3	25	3.3	1.91	1.05	0.82
Mean		2.52 ± 0.7	1.56 ± 0.4	1.0 ± 0.2	1.16 ± 1.1
P		0.016	0.159	0.847	0.727
Secondary forest	78				
Site 1	27	1.72	1.25	0.9	0.67
Site 2	27	3.22	1.87	1.19	0.93
Site 3	27	2.95	2.2	1.79	1.03
Mean		2.63 ± 0.8	1.77 ± 0.6	1.29 ± 0.5	0.88 ± 0.2
P		0.005	0.095	0.017	0.076
Primary Forest	81				
Site 1	27	2.82	1.26	0.82	0.78
Site 2	27	3.61	1.21	0.65	0.68
Site 3	27	2.65	1.00	0.79	0.58
Mean		3.03 ± 1.5	1.16 ± 0.3	0.75 ± 0.12	0.68 ± 0.1
P		0.765	0.629	0.548	0.241

All intervals derive from the means of R_1 and R_2. Means, in the table, are generated from subsample results (n = 9) found in **Appendix 6** and are **not** simply means derived from intervals within the table (e.g. mean of Cleared 5cm = 14.7 because n=9 and not n=3 like in the table). Standard deviation (n = 9) given as ±; *P*: The P value is derived from one-way ANOVA used to test for treatment effects, unless otherwise stated by use of one of the following superscripted symbols; ^{f}: When normality test fails (P > 0.05), When Equal Variance Test fails (P > 0.05), Samples missing: Cleared site 3, pit A – 50cm R_1; Cleared site 3, pit C – 50cm R_2; Cleared site 2, pit B 50cm R_2; 5 year, site 2, pit A Litter; 5 year, site 3, pit B Litter.

Figure 18: Percentage of soil organic carbon (SOC) with depth.

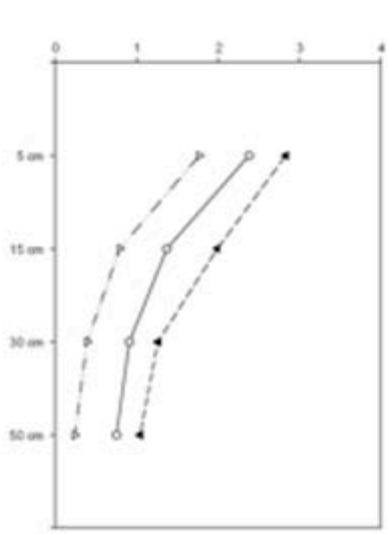


Fig. 18a: 8 year rotation

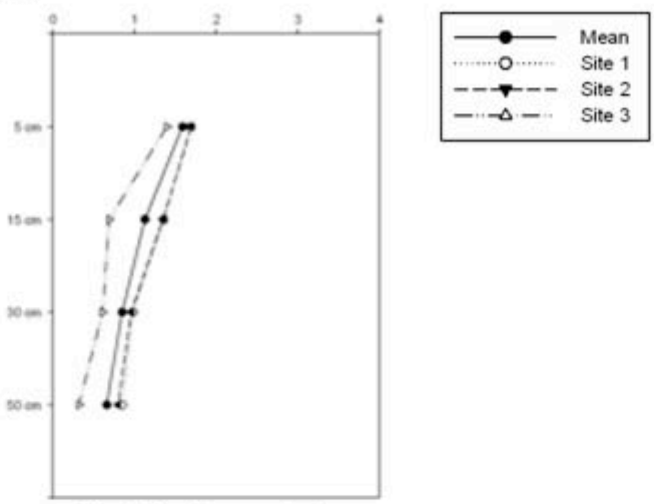


Fig. 18b: 5 year rotation

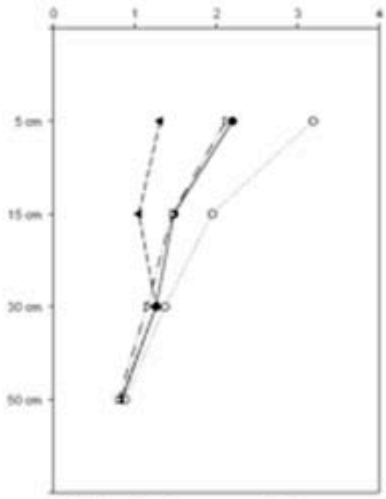


Fig. 18c: 3 year rotation

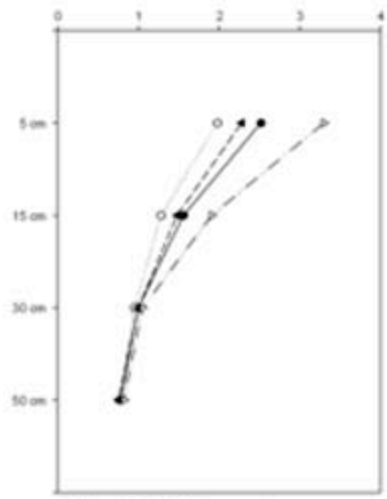


Fig. 18d: Cleared area

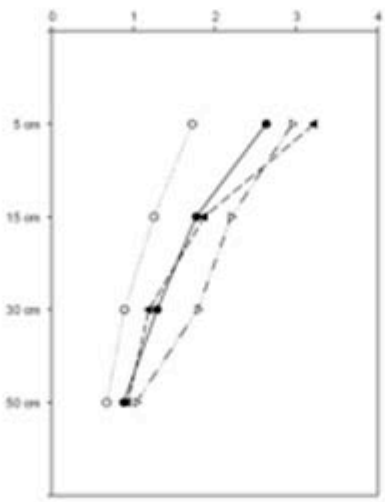


Fig. 18e: Secondary forest

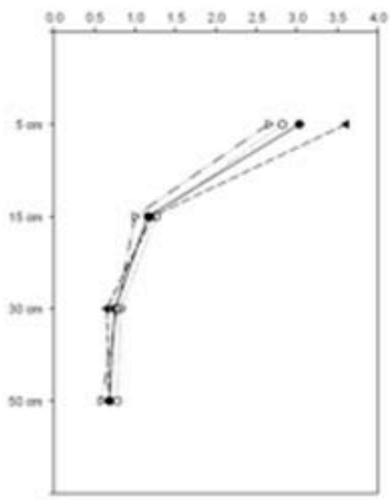


Fig. 18f: Primary forest

3.2 Litter on forest floor

The hypothesis, within this study, for litter content is that the older the plot, the more litter will be found on the forest floor. A significant difference exists at the 8 year rotation and secondary forest sites.

Table 4: Litter content (t ha^{-1}) on forest floor

Land use	Pit A	Pit B	Pit C	Mean	Land use	Pit A	Pit B	Pit C	Mean
8 year					Cleared				
Site 1	1.06	1.57	1.57	1.4	Site 1	0.72	0.13	0.08	0.31
Site 2	0.74	0.61	0.84	0.73	Site 2	0.11	0.29	0.21	0.20
Site 3	1.22	1.08	0.78	1.03	Site 3	0.08	0.11	0.19	0.13
				1.05 ± 0.35					**0.21** ± 0.2
P				0.029	*P*				0.610
5 year					Secondary				
Site 1	0.33	0.46	0.47	0.42	Site 1	0.39	0.67	0.36	0.47
Site 2	0.81	0.49	N/A	0.65	Site 2	1.33	2.04	1.56	1.64
Site 3	0.87	N/A	0.52	0.7	Site 3	1.31	0.6	0.64	0.85
				0.57 ± 0.2					**0.99** ± 0.59
P				0.277	*P*				0.013
3 year					Primary				
Site 1	0.4	0.46	0.74	0.53	Site 1	0.85	0.56	0.79	0.73
Site 2	0.19	0.6	0.17	0.32	Site 2	0.55	0.86	0.72	0.71
Site 3	0.25	0.47	0.47	0.4	Site 3	0.8	2.42	0.94	1.39
				0.42 ± 0.19					**0.94** ± 0.57
P				0.441	*P*				0.238

In the planted areas, the 8-year rotation has the highest mean litter layer content with a mean value of 1.05 t ha^{-1}. There is a significant difference between site 1 and site 2 (P = 0.025), however no other significant differences were found. The 5 year rotation contained 0.57 t ha^{-1} and the 3 year rotation with 0.42 t ha^{-1} (35.7% less than the 5 year rotation). The 8 year rotation has 84.2% more litter content on the forest floor than the 5 year rotation. There is no significant difference between the 5 year and 3 year rotations (P = 0.503), however a significant difference was found between the 8 year rotation and the 5 year (P = 0.004) and 3 year rotations (P = <0.001).

The cleared areas have the lowest mean litter content of 0.21 t ha^{-1}. The secondary forest area has the second highest mean litter content of 0.99 t ha^{-1} where as the Primary forest, in Budongo, has the third highest litter layer content of 0.94 t ha^{-1}. A comparison between all the land use classes can be seen in **Fig. 19**. There were a number of significant differences between the cleared area and: the

8 year rotation (*P* = <0.001); the Secondary forest (*P* = 0.002); and the Primary forest (*P* = 0.004). Significant differences between the 3 year rotation and: the 8 year rotation (*P* = 0.016); Primary forest (0.018) and Secondary forest (*P* = 0.04) were detected.

%C in the litter layer can be seen in **Fig. 20**. ANOVA was applied to the land use classes. There were significant differences detected between the 8 year rotation and the: Primary forest (*P* = <0.001); 3 year rotation (*P* = <0.001); cleared area (*P* = <0.001); and Secondary forest (*P* = 0.026). Significant differences were detected between the 5 year rotation and the: Primary forest (*P* = 0.003); and 3 year rotation (*P* = 0.009); There was a significant difference between the Primary forest and the Secondary forest (*P* = 0.018).

The %SOC and dry weight used to calculate litter stocks can be found in **Appendix 8** and **Appendix 9** respectively.

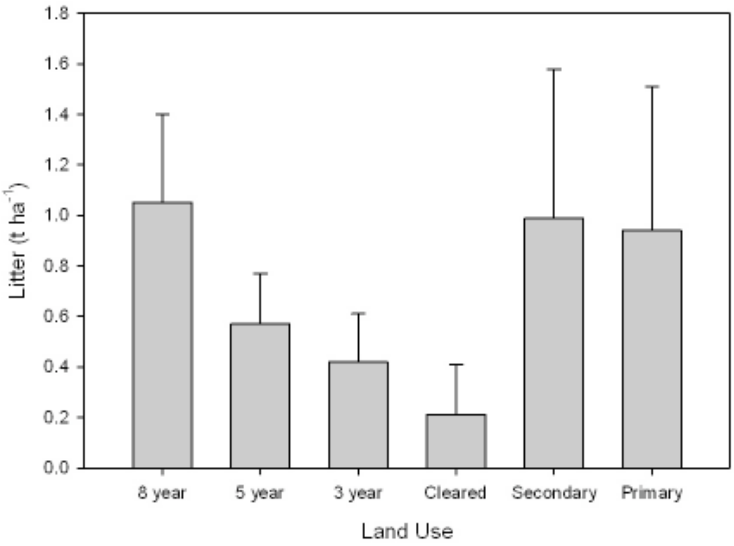


Figure 19: Mean litter layer stock of the investigated land use classes. Significant differences were detected between the cleared area and: the 8 year rotation; the Primary forest; and the Secondary forest. Significant differences were detected between the 3 year rotation and: the 8 year rotation; Primary forest; and the Secondary forest.

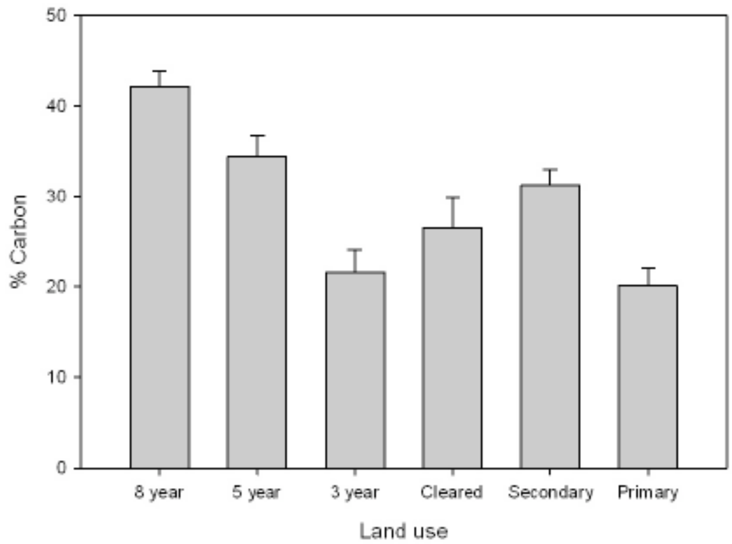


Figure 20: Mean litter layer %SOC content of the investigated land use classes. Significant differences were detected between the 8 year rotation and the: Primary forest; 3 year rotation; cleared area; and Secondary forest. Significant differences were detected between the 5 year rotation and the: Primary forest; 8 year rotation and 3 year rotation; There was a significant difference between the Primary forest and the Secondary forest.

3.3 Soil organic carbon (SOC) stocks

3.3.1 8-year rotation

Total mean SOC (t ha^{-1}) found at the 8-year rotation areas was 46.7 t ha^{-1} ± 21.0. A significant difference (*P* = 0.016) in total mean SOC was found between the three sites and a Turkey test was run in response. It was found that there exist significant differences between Site 1 and Site 3. There was no significant difference, however, between Site 1 & Site 2 and it was found, using a T-test, that the *P* value = 0.120.

The mean value of SOC found in the **litter layer** of the forest floor was found to be 1.1 ± 0.4**,** however, although the difference was small, there was a significant difference between the three sites (*P* = 0.029. The small number of litter layer samples tested (*n*=9) could have reduced the power of the test. There was no significant difference in depths **0-10 cm** (20% of SOC) (*P* = 0.288) or **10-20 cm** (26% of SOC) (*P* = 0.072), however there appears to be a large significant difference in the depths **20-40 cm** (25% of SOC) (*P* = 0.002) and 40-60 cm (27% of SOC) (*P* = 0.001) in that the differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference. In response, an all pairwise multiple comparison procedure (Turkey test) was run to determine whether or not there was variation between the sites at these depths. At the depth of 20-40 cm, there was a significant difference found Site 1 and Site 3 (*P* = 0.0.24) and between Site 2 and Site 3 (*P* = 0.002). No statistical significant difference was found between Site 1 and Site 2 (*P* = 0.100). The results generated from the **40-60** cm depths mirrored the former depth in that there was a significant difference between Site 1 and Site 3 (*P* = 0.011) and Site 2 and Site 3 (*P* = 0.001) but not between Site 1 and Site 2 (*P* = 0.109). Overall, Site 3 had the lowest SOC stock content of all the sites – where as Site 2 had the highest SOC stock content. SOC stock content found between soil depths 5-50cm appears to be somewhat evenly distributed (**Fig. 21a**).

3.3.2 5-year rotation

Total mean SOC (0-60cm) (t ha^{-1}) found at the 5-year rotation areas was 41.1 ± 12.8 t ha^{-1}. A significant difference (*P* = 0.022) was found between the three sites. The mean C content of the **litter layer** found on the forest floor was 0.6 ± 0.2 t ha^{-1} (1% of total mean C) and there was no significant difference between the three sites tested (*P* = 0.277). However, the 5-year/site-2/pit A Litter and 5-year/site-3/pit B Litter samples were missing reducing the number of samples tests (*n* = 7) that could have reduced the power of the test. Taken in regard with the other land use classes where the litter layer samples (n = 9), the reduced number of samples tested should not have a profound effect. Mean SOC content found at the depths **0-10 cm** was 7.1 ± 2.6 (17% of SOC) and no significant difference was found between the sites (P = 0.849). **10-20 cm** accounted for 10.0 ± 4.2 t ha^{-1} (24% of SOC) and no significant difference was found between the sites (P = 0.096). Mean SOC content at **20-40 cm** was 11.2 ± 3.3 (27% of SOC), however it failed the normality test (p = 0.029) and equal variance test (p = *0.003)*. This should not pose a problem, as the sample size (n = 9) is below the recommended number of samples needed for an accurate normality test (minimum n = 12). The mean SOC content found at depths **40-60 cm** was 12.3 ± 5.4t ha^{-1} (31% of total mean SOC). There appears to be little variation in mean SOC content between the depths of 5-30 with a SD of 0.1 and overall SOC content is not as evenly distributed as in the 8-year rotation (**Fig. 21b**).

3.3.3 3-year rotation

Total mean SOC (0-60 cm) (t ha^{-1}) found at the 3-year rotation areas was 54.3 ± 12.1 t ha^{-1} and no significant difference (P = 0.233) was found between the sites. The mean value of C found in the **litter layer** of the forest floor was found to be 0.4 (1% of C) and no significant difference (P = 0.441) was found between the three sites. Mean SOC content found **at 0-10 cm** was 9.5 ± 4.0 t ha^{-1} (17% of total mean SOC) and no significant difference between the sites (P = 0.054). Mean value of C found at **10-20 cm** was 12.9 ± 4.9 t ha^{-1} (24% of total mean SOC) with no significant differences (P = 0.14) between sites. Mean value of SOC found at **20-40 cm** was 16.8 ± 6.8 t ha^{-1} (31% of total mean SOC) no significant difference (P = 0.899) found between sites. The mean value of SOC found at **40-60 cm** was 14.7 ± 2.7 (27% of total mean SOC (**Fig. 21c**) with no significant difference (P = 0.901) between the sites.

3.3.4 Cleared areas

Total mean SOC (0-60 cm) (t ha^{-1}) found at the afforested areas was 54.2 ± 10.8 t ha^{-1}. No significant difference was found between the three sites (P = 0.211).

The **litter layer** of the forest floor represents cleared areas only as it is directly influenced from the burning and slashing practices of afforestation. The mean value of C found in the litter layer was 0.2 (<1% of total mean C) with no significant difference between the investigated sites (P = 0.61). A significant difference was found between the investigated sites at depths **0-10 cm** (11.6 ± 3.2 t ha^{1}) (P = 0.026). A Turkey test was run to compare the three sites and found that Site 1 and Site 3 had a significant difference (P = 0.025), whereas there was no significant difference between Site 2 and Site 3 (P = 0.085) nor Site 1 and Site 2 (P = 0.599). Mean C at 10-20 cm depth was 13.8 ± 4.8 (21% of SOC) with no significant difference (P = 0.276) between the investigated sites. Mean C content of **20-40 cm** accounted for 13.8 ± 2.6 t ha^{1} (26% of SOC) with no significant difference between the sites (P = 0.782). SOC stock calculations at depths **40-60 cm** were 14.6 ± 1.8 (27% of SOC) with no significant differences between the sites (P = 0.556). However, it should be noted that several samples were missing at the **40-60 cm** depths (Cleared site-3, pit A – 50cm R_1; Cleared site-3, pit C – 50cm R_2; Cleared site-2, pit B 50cm R_2) thus the limited number of samples tested could have reduced the power of the test.

3.3.5 Secondary forest

Total mean SOC (0-60 cm) (t ha^{-1}) found at the secondary forest sites was 60.1 ± 15.1. However, there was a significant difference between the investigated sites (P = 0.013) – thus a Turkey test was applied and the results were that there is a significant difference between Site 1 and Site 3 (P = 0.012). No significant difference was found between Site 1 and Site 2 (P = 0.053) or between Site 2 and Site 3 (P = 0.466).

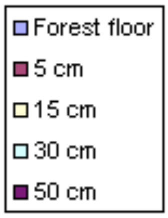
The mean value of C in the **litter layer** of the forest floor was 1.0 ± 0.6 t ha^{-1} (2% of total mean C) with a significant difference between the investigated sites (P = 0.013). There is a significant difference (P = 0.006) at the depth **0-10 cm** of mean SOC (11.9 ± 3.6 t ha^{-1} which accounts for 20% of total mean SOC). When applying a Turkey test it was found that there is a significant difference between Site 1 and Site 3 (P = 0.045) and between Site 1 and Site 2 (P = 0.005) but not between Site 2 and Site 3 (P = 0.207). No significant difference (P = 0.325) between the investigated sites was found at depth **10-20 cm** with a mean SOC of 14.7 ± 5.9 t ha^{-1} (24% of total SOC). Mean SOC at depth **20-40 cm** was 17.0 ± 5.1 t ha^{-1} (28% of total mean SOC) – with a significant difference (P = 0.016) between the investigated sites. An applied Turkey test concludes that there is a significant difference between Site 1 and Site 3 (P = 0.013) but no significant differences elsewhere (Site 1 vs. Site 2 P = 0.265; Site 2 vs. Site 3 P = 0.105). Mean SOC of depth **40-60 cm** was 15.6 ± 4.1 t ha^{-1} (26% of total mean SOC) and with no significant difference (P = 0.054) between the investigated sites.

3.3.6 Primary forest

Total mean SOC (0-60 cm) (t ha^{-1}) found in the Primary forest (Budongo FR, Masindi) was 33.2 ± 8.8. No significant difference (P = 0.269) was found between the investigated sites. The mean value of C found in the **litter layer** of the forest floor was found to be 0.9 ± 0.6 t ha^{-1} (3% of total mean

C) – with no significant difference found between the three sites ($P = 0.238$). Mean SOC at depth **0-10 cm** was found to be 8.3 ± 4.7 t ha^{-1} (25% of total mean SOC) with no significant difference ($P = 0.464$) between the investigated sites, however the three sites at this depth failed to pass an equal variance test ($p = 0.018$) indicating unequal variance meaning the values lie far from the mean. In response, the Kruskal-Wallis One Way ANOVA on Ranks was applied and found that the *P* value of the medians was 0.339 (however, power of performed test with alpha = 0.050, which is below the desired power of 0.800 which may indicate that a difference is present). The small sample size ($n = 9$) may have been the cause of the failed equal variance test. Mean SOC content at **10-20 cm** depth was estimated to be 6.7 ± 3.4 t ha^{-1} (20% of total mean SOC) with no significant differences ($P = 0.323$). The mean SOC value at **20-40 cm** depth is 7.8 ± 2.2 t ha^{-1} (24% of total mean SOC) with no significant difference between the investigated sites ($P = 0.882$). Mean SOC found at **40-60 cm** depth is 9.4 ± 2.5 t ha^{-1} (28% of total mean SOC) with no significant difference ($P = 0.247$) between the three sites.

Figure 21: Overview of total mean SOC stocks of investigated sites with percentages of individual depths



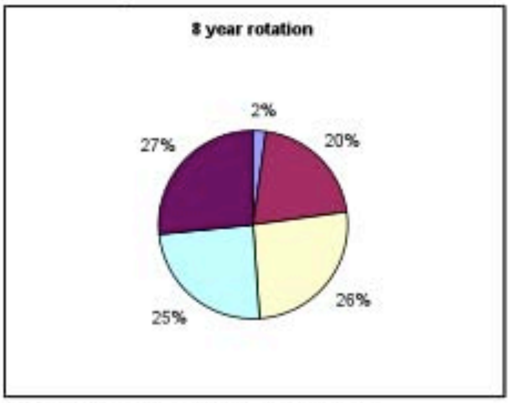


Fig. 21a: 8 year rotation carbon stocks

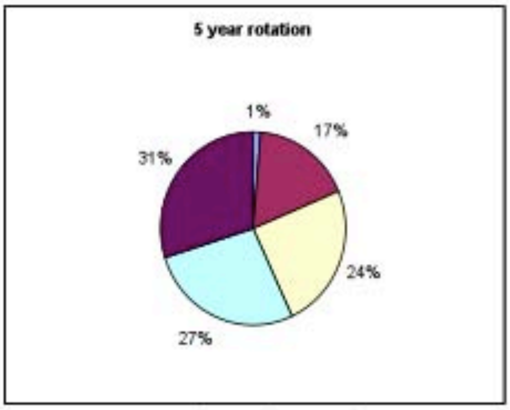


Fig. 21b: 5 year rotation carbon stocks

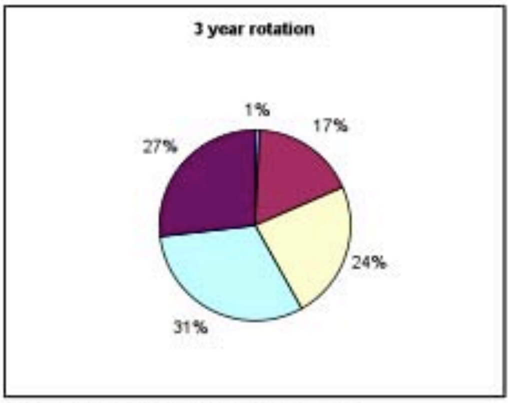


Fig. 21c: 3 year rotation carbon stocks

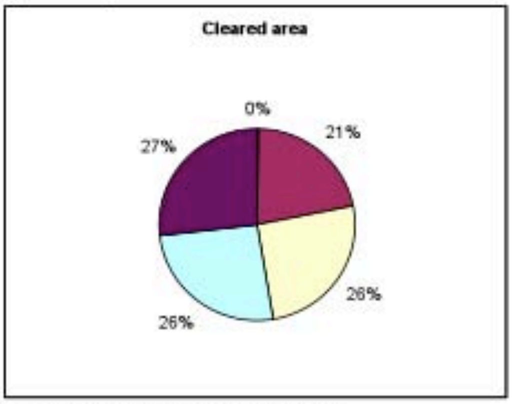


Fig. 21d: Cleared area carbon stocks

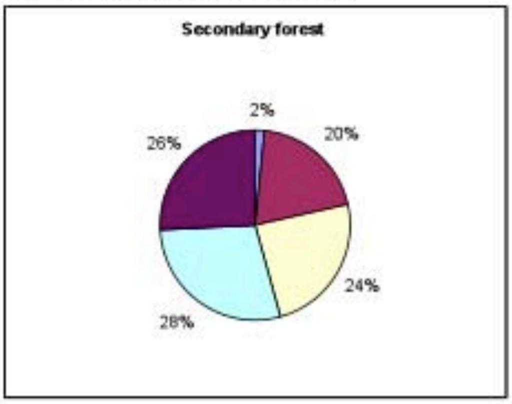


Fig. 21e: Secondary forest carbon stocks

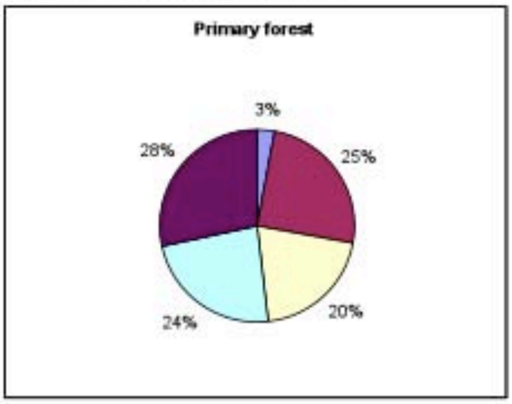


Fig. 21f: Primary forest carbon stocks

Total mean SOC (t ha^{-1}) including litter 0-60 cm of: 8-year rotation plot: 46.6; 5-year rotation plot: 41.2; 3-year rotation plot: 54.3; Cleared areas: 54.1; Secondary forest: 60.1: Primary forest: 33.2.

Table 5: SOC stocks (0-60 cm) of investigated sites. N.b. C (t ha^{-1}) converted from C (g cm^{-3}).

		Soil organic carbon (C t ha^{-1}) by depth (cm)					
	No. of samples	Forest floor	0-10	10-20	20-40	40-60	0-60
8 year rotation	81						
Site 1	27	1.4	7.5	11.3	12.3	13.7	46.2
Site 2	27	0.7	13	18.3	16.9	19	67.9
Site 3	27	1	7.9	7.1	5.5	4.4	26
Mean		1.1 ± 0.4	9.5 ± 4.5	12.2 ± 6.4	11.5 ± 5.3	12.4 ± 6.8	**46.7** ± 21.0
P		0.029	0.288	0.072^{E}	0.002	0.001	0.016^{N}
5 year rotation	79						
Site 1	26	0.4	7.3	12.1	12.3	16.9	49.1
Site 2	26	0.6	7.6	12.1	13.1	14.3	47.5
Site 3	27	0.7	6.3	5.9	8.3	5.7	26.6
Mean		0.6 ± 0.2	7.1 ± 2.6	10 ± 4.2	11.2 ± 3.3	12.3 ± 5.4	**41.1** ± 12.8
P		0.277	0.849	0.096	$0.154^{E, N}$	0.001	0.022
3 year rotation	81						
Site 1	27	0.5	13.2	16.9	17.9	15.4	64
Site 2	27	0.3	5.9	9.1	17.3	14.6	47.3
Site 3	27	0.4	9.3	12.6	15.2	14.2	51.7
Mean		0.4 ± 0.1	9.5 ± 4.0	12.9 ± 4.9	16.8 ± 6.8	14.7 ± 2.7	**54.3** ± 12.1
P		0.441	0.054	0.14	0.899	0.901	0.233
Cleared area	81						
Site 1	27	0.3	9.1	11.7	12.9	13.9	47.9
Site 2	26	0.2	10.7	12.1	14	14.4	51.5
Site 3	25	0.1	15.1	17.7	14.6	15.6	63.1
Mean		0.2 ± 0.2	11.6 ± 3.2	13.8 4.8	13.8 ± 2.6	14.6 ± 1.8	**54.2** ± 10.8
P		0.61	0.026	0.276	0.782	0.556	0.211
Secondary forest	78						
Site 1	27	0.5	7.9	11.4	12.2	11.3	43.3
Site 2	27	1.6	15.3	13.1	16.4	17.8	64.2
Site 3	27	0.8	12.4	18.5	22.4	17.8	72.9
Mean		1.0 ± 0.6	11.9 ± 3.6	14.7 ± 5.9	17 ± 5.1	15.6 ± 4.1	**60.1** ± 15.1
P		0.013	0.006	0.325	0.016	0.054	0.013
Primary Forest	81						
Site 1	27	0.7	5.8	4.9	7.2	9.5	28.2
Site 2	27	0.7	11	9.2	7.9	11.1	39.9
Site 3	27	1.4	8	6.2	8.2	7.7	31.4
Mean		0.9 ± 0.6	8.3 ± 4.7	6.7 ± 3.4	7.8 ± 2.2	9.4 ± 2.5	**33.2** ± 8.8
P		0.238	0.464^{E}	0.323	0.882	0.247	0.269

All intervals derive from the means of R_1 and R_2. Means, in the table, are generated from subsample results (n = 9) found in **Appendix 7** and are **not** simply means derived from intervals within the table (e.g. mean of Cleared 5cm = 14.7 because n=9 and not n=3 like in the table). Standard deviation (n = 9) given as ±; *P*: The P value is derived from one-way ANOVA used to test for treatment effects, unless otherwise stated by use of one of the following superscripted symbols; ^{f}: When normality test fails (P > 0.05), Kruskal-Wallis One Way Analysis of Variance on Ranks is used; ◦: When Equal Variance Test fails (P > 0.05), Kruskal-Wallis One Way Analysis of Variance on Ranks is used; *: When normality test and Equal Variance Test passes but is a statistically significant difference is still present, additional Turkey test is run. Samples missing: Cleared site 3, pit A – 50cm R_1; Cleared site 3, pit C – 50cm R_2; Cleared site 2, pit B 50cm R_2; 5 year, site 2, pit A Litter; 5 year, site 3, pit B Litter.

Figure 22: SOC stocks with depth

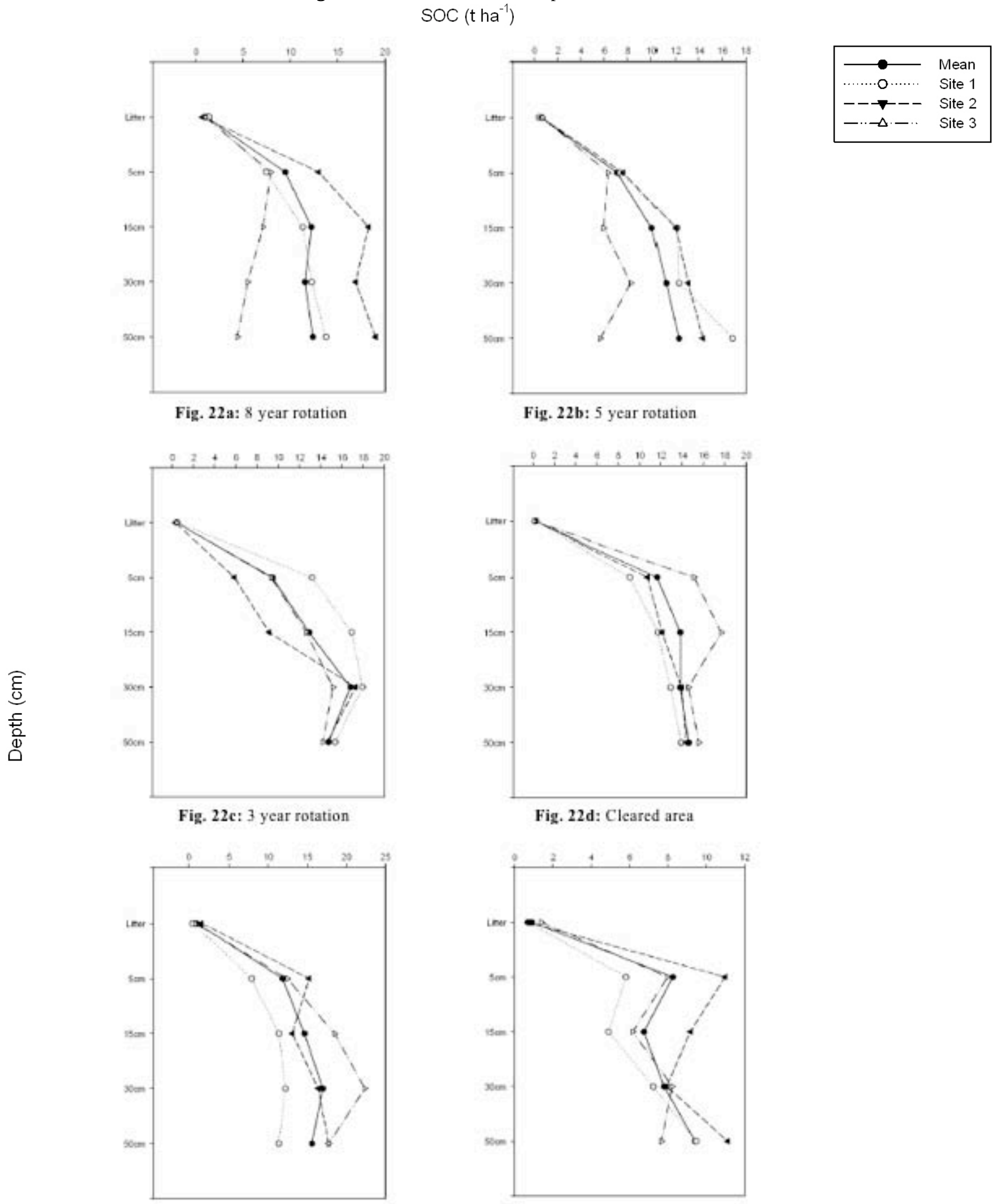


Fig. 22a: 8 year rotation

Fig. 22b: 5 year rotation

Fig. 22c: 3 year rotation

Fig. 22d: Cleared area

Fig. 22e: Secondary forest

Fig. 22f: Primary forest

3.4 Extrapolated vertical SOC stock distribution

The results in **Table 6** show the average vertical SOC distribution within the independent land use and age classes. The results show that the secondary forest has the highest average SOC (60.1 ± 15.1 C t ha^{-1}) followed by the 3 year rotation area (54.3 ± 12.1 C t ha^{-1}). The 8-year and 5-year rotation contains the lowest total mean C, within the planted area, with a value of 46.7 ± 21.0 C t ha^{-1} and 41.1 ± 12.8 C t ha^{-1}, respectively. The primary forest contains the overall lowest amount of SOC with 33.2 ± 8.8 C t ha^{-1}. All the land use classes express the greatest gain in SOC stocks between 0-20 cm (**Table 7**).

Table 6: Extrapolated vertical soil organic carbon (SOC) (t ha^{-1}) distribution

	Land-use					
Depth	8 year	5 year	3 year	Cleared	Secondary	Primary
SOC (t ha^{-1})						
Forest floor	1.05	0.57	0.42	0.21	0.99	0.94
0-10 cm	10.5	7.7	9.9	11.9	12.8	9.2
0-20 cm	21.5	17.1	22.4	25.5	26.5	15.0
0-40 cm	33.1	28.3	39.2	39.3	43.5	22.8
0-60 cm	46.7	41.1	54.3	54.2	60.1	33.2

Table 7: Percentage increase of vertical soil organic carbon (SOC) distribution

	Land-use					
Depth	8 year	5 year	3 year	Cleared	Secondary	Primary
SOC (t ha^{-1})						
0-10 cm	10.5 ± 1.5	7.7 ± 0.9	9.9 ± 1.3	11.9 ± 1.1	12.8 ± 1.3	9.2 ± 1.6
0-20 cm	+104.8%	+122.1%	+126.3%	+114.3%	+107.0%	+63.0%
0-40 cm	+54.0%	+65.5%	+75.0%	+54.1%	+64.2%	+52.0%
0-60 cm	+41.1%	+45.2%	+38.5%	+37.9%	+38.2%	+45.6%

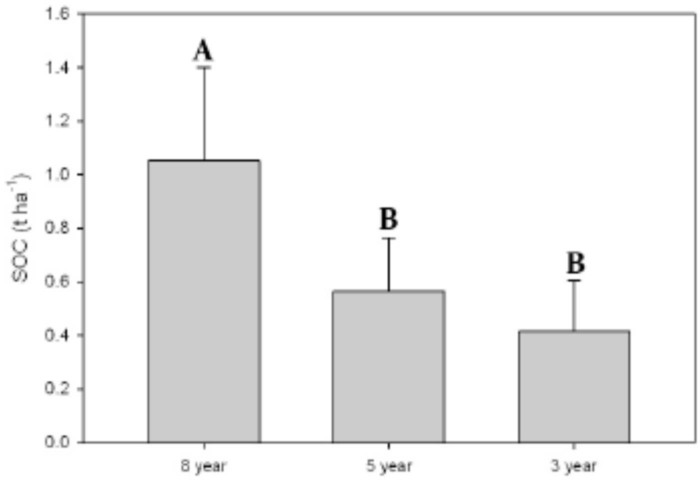


Figure 23: Statistical comparison of litter between planted areas within the reserve. The 8 year rotation had the largest dry weight of and highest SOC content of litter. There is a significant difference between the 8 year rotation and the other age classes.

3.4.1 Comparison of land use classes between 0-10 cm

The top soils (0-10 cm + litter) appear to follow a similar distribution, with SOC storage ranging between 7.5 to 12.8 t ha^{-1}. The content of SOC in the layer between 0-10 cm is highest in the secondary forest (12.8 SOC t ha^{-1}) (**Table 6**) followed by the 8 year rotation (10.5 SOC t ha^{-1}). The 5-year rotation has the lowest SOC (7.7 SOC t ha^{-1}). The were no significant differences present was between any of the land use classes (**Fig. 24a**)

3.4.2 Comparison of land use classes at between 0-20 cm

The average stored SOC stocks between 0 and 20 cm ranges from 15.0 to 26.5 C t ha^{-1}. The secondary forest has the highest amount of SOC (26.5 SOC t ha^{-1}) and increased by 107.0% (**Table 7**). Similar to previous depths, the cleared area has the second highest amount of SOC (25.5) and increased by 114.3%. The 3 year rotation (22.4 SOC t ha^{-1}) expressed the largest percent gain of 126.3% - whereas the 8 year rotation (21.5 SOC t ha^{-1}) increased by 104.8%. The 5 year rotation has the second lowest SOC content (17.7 SOC t ha^{-1}), however this land use class expressed the second largest increase by percent (122.1%). The primary forest has the lowest SOC content at this depth (15.0 SOC t ha^{-1}) and also expressed the lowest increase by percent (63.0%).

Figure 24: SOC according to land use class at different depths.

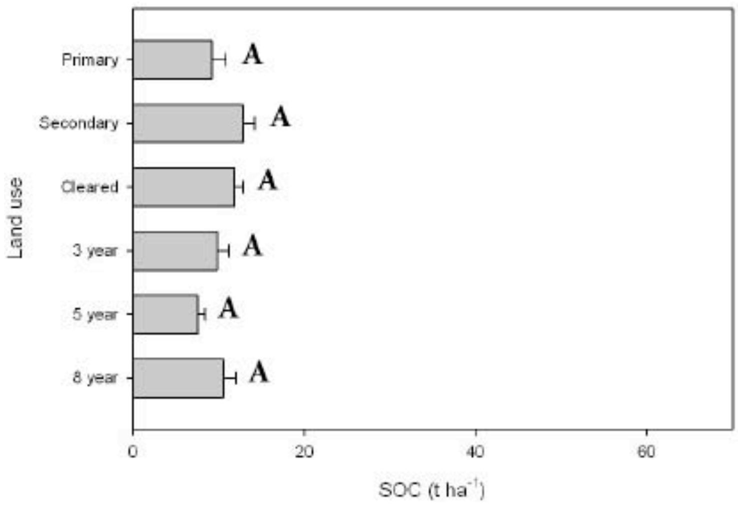


Figure 24a SOC according to land use class at 0-10 cm depth

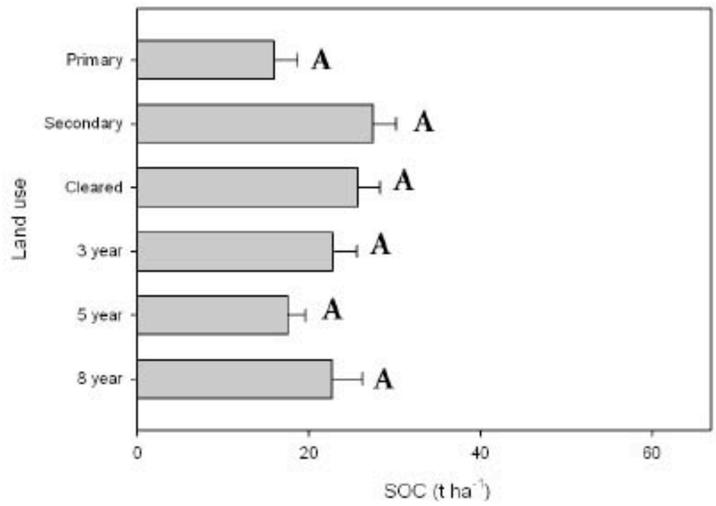


Figure 24b: SOC according to land use class at 0-20 cm depth

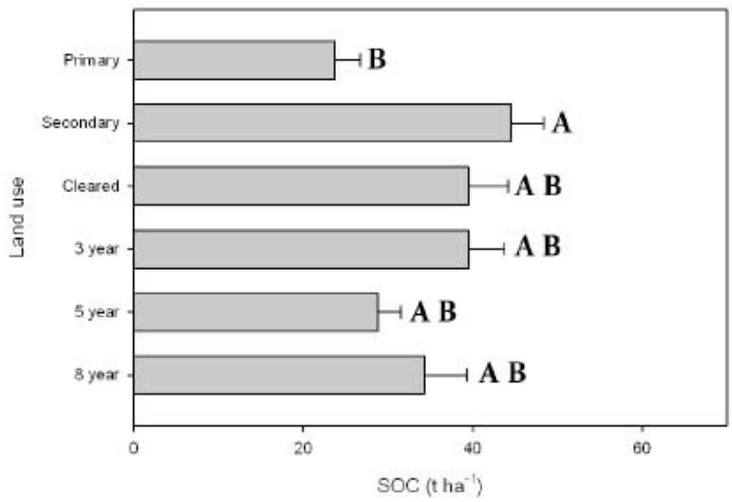


Figure 24c: SOC according to land use class at 0-40 cm depth

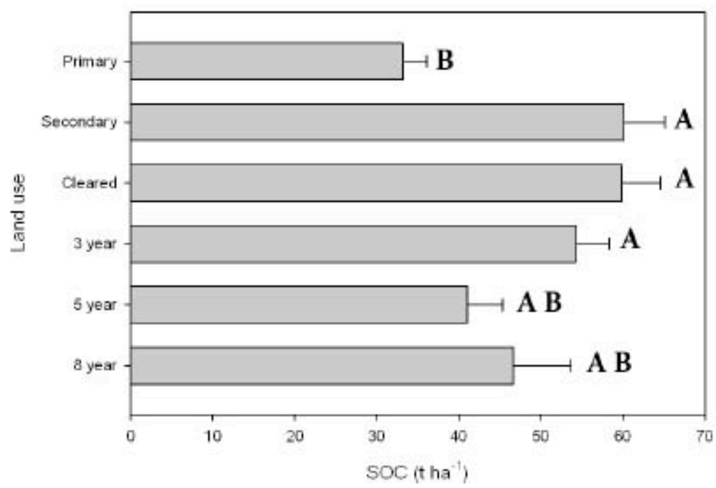


Figure 24d: SOC according to land use class at 0-60 cm depth

3.4.3 Comparison of land use classes between 0-40 cm

Average SOC content stored between 0-40 cm ranges from 23.8 to 43.5 SOC t ha^{-1}. The data displays a wider standard distribution range of values than seen in the previous depths and the differences in vertical SOC distribution are more apparent and diverse at the 0-40 cm depth. The secondary forest (43.5 SOC t ha^{-1}) has the largest SOC content, expressing an average increase of 64.2% from the 0-20 cm depth. The 3 year rotation (39.2 SOC t ha^{-1}) contained the third largest SOC content, with an increase of 54.1%. However, the average result for the cleared areas (39.3 SOC t ha^{-1}) differs from the 3 year rotation by 0.1 t ha^{-1} showing no significant difference. The cleared area increased from the 0-20 extrapolated result by 54.1%. The 8 year rotation has an average extrapolated SOC content of 33.1 SOC t ha^{-1} with an increase of 54.0%. The 5 year rotation has an average extrapolated SOC content of 28.3 SOC t ha^{-1} with an increase from the previous depth of 65.5%. The land use class with the lowest SOC content was the primary forest with an average SOC of 22.8%, marked by an increase of 52%. There was a significant difference between the secondary forest and primary forest (P = 0.004) (**Fig. 24c**) but no other significant differences were detected.

3.4.2 Comparison of land use classes between 0-60 cm

Average SOC content stored between 0-60 cm ranges from 33.2 to 60.1 SOC t ha^{-1}. The data displays the widest standard distribution range of values compared the previous depths. The secondary forest (60.1 SOC t ha^{-1}) has the highest SOC content, expressing an increase of 45.6%. The 3-year rotation (54.2 SOC t ha^{-1}) expressed an increase in SOC (37.9%), from the previous depth, of all the investigated land use classes and contains the second largest amount of SOC. SOC content in the cleared area (54.2 SOC t ha^{-1}) had an increase of 37.9%. SOC within the 8 year rotation increased by 41.1% to a total of 46.7 SOC t ha^{-1}, followed by the 5 year rotation which increased by 41.1% to a total of 45.2 SOC t ha^{-1}. Lastly, SOC in the primary forest increased by 45.6% to a total of 33.2 SOC t ha^{-1}, with the lowest overall SOC content of the investigated land use classes. The largest differences between the land use classes occur at this depth and it may be assumed that discrepancies will continue to arise the further in depth the samples are tested. There were several significant differences between the land use classes (**Fig. 24d**). There was a significant difference between the secondary forest and primary forest (P = 0.002), similar to the results generated at the 0-40 cm depth. However, there was also a significant difference between the primary forest and the 3 year rotation (P = 0.027) and the primary forest and the cleared areas (P = 0.029). No other significant differences were detected using a standard ANOVA.

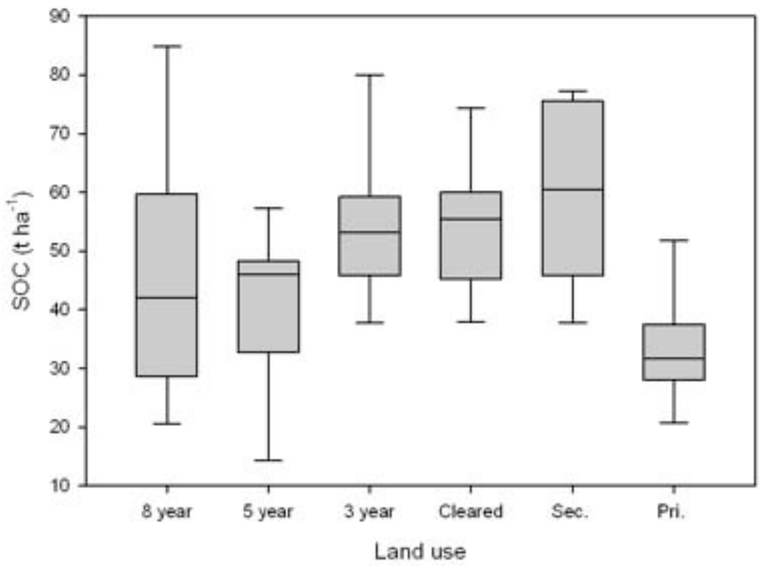


Figure 25: Box plot of land use classes SOC content at 0-60 cm depth. Sec. = Secondary forest. Pri. = Primary forest. Significant differences between the Primary forest and the cleared area and the 3 year rotation were detected.

The results from the varying depths are summarized in **Fig. 26**. SOC content of the land use classes appears to, for the most part follow a linear progression – however, the differences in SOC content become more prominent the deeper the soil profile becomes.

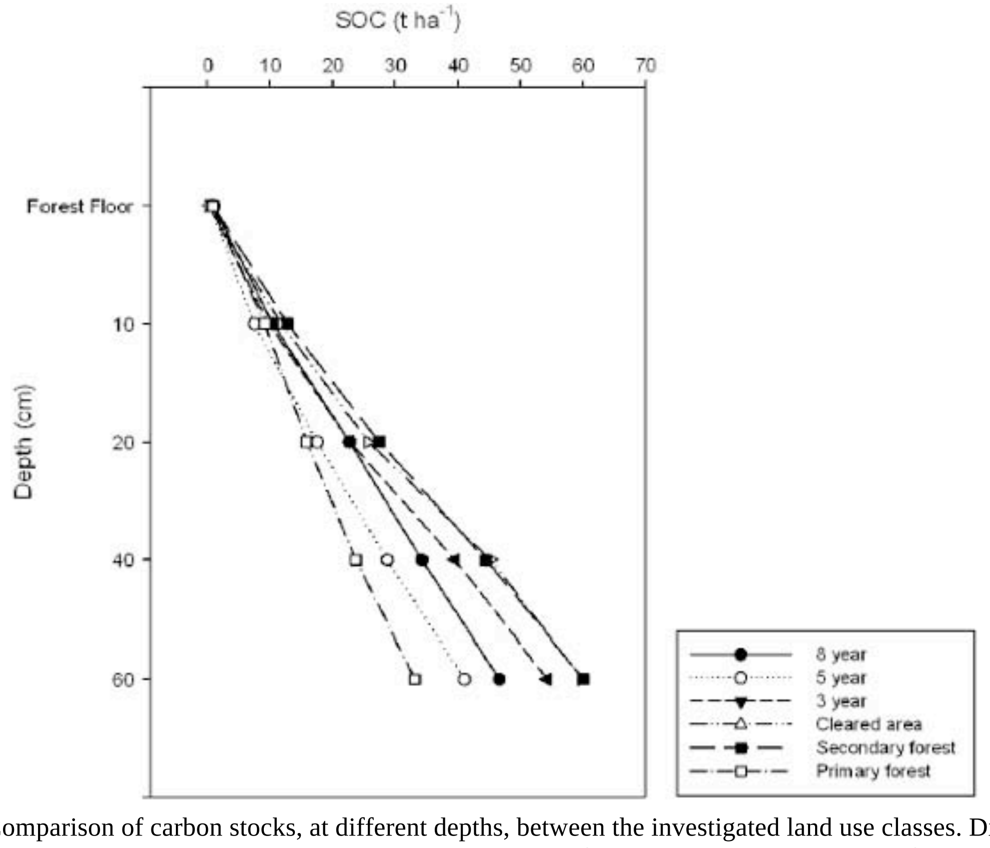


Figure 26: Comparison of carbon stocks, at different depths, between the investigated land use classes. Differences in SOC distribution become more prominent the deeper the soil profile becomes. As a result, significant differences become to manifest. It is possible that further significant differences will arise as the depth increases.

3.5 pH analysis

The results from the pH analysis are shown in **Table 8**. Correlation between pH and % SOC, based on Pearson correlation and R_2 values are shown in **Fig. 27**. Due to a lack of availability of samples, one pit in each of the three sites per land use class was tested and had the pH measured. pH ranged from ~3 to ~6 in between the sites where as the gross average of each land use class averaged from 4.38 (cleared forest) to 5.48 (primary forest). pH levels generally decreased with depth.

A Pearson product movement analysis was performed in order to deduce what correlation, if any, soil pH had with % SOC found at individual pits (**Fig. 27**). The value R^2 quantifies goodness of fit. It is a fraction between 0.0 and 1.0, and has no units. Higher values indicate that the model fits the data better. No correlation is detected, positive or negative, if R^2 = 0.0 to 0.09. There is a small correlation if R^2 = -0.1 to -0.3 or 0.1 to 0.3. A medium correlation is considered if R^2 = -0.3 to -0.5 or 0.3 to 0.5. Lastly, a large correlation is considered if R^2 = -0.5 to -1.0 or 0.5 to 1.0 (Cohen 1988).

The 8 year rotation (**Fig. 27a**) has an r^2 = 0.44 suggesting a medium positive correlation and passed the Pearson correlation test (P = 0.018). The 5 year rotation (**Fig. 27b**) has an r^2 = -0.04 and failed the Pearson correlation test (P = 0.544). The 3 year rotation (**Fig. 27c**) has an r^2 = 0.46 indicating a medium correlation and a passed Pearson test (P = 0.015). The cleared area (**Fig. 27d**) resulted in an r^2 = 0.93, thus a large correlation was detected in conjunction with a passed Pearson test (P = <0.005). The secondary forest (**Fig. 27e**) yielded an r^2 = 0.03 and failed the Pearson test (P = 0.631), thus no correlation exists. The primary forest (**Fig. 27f**) yielded a result of r^2 = 0.56 indicating a large correlation as well as a passed Pearson test (P = 0.005).

Interpretation of the indirect effects of pH on SOC will be discussed further in the discussion and will include topics such as limited nutrient availability, limited root growth and the effect on microbial activity.

Table 8: pH results

	5 cm	15 cm	30 cm	50 cm
8 year 1A	4.84	4.24	3.87	3.84
8 year 2A	6.39	6.35	6.08	6.12
8 year 3A	5.34	5.81	4.38	4.17
Avg	**5.52** ± 0.79	**5.47** ± 1.1	**4.78** ± 1.16	**4.71** ± 1.23
5 year 1A	4.61	5.48	4.31	3.91
5 year 2A	4.08	3.76	3.74	3.81
5 year 3A	5.04	6.51	5.15	4.58
Avg	**4.58** ± 0.48	**5.25** ± 1.39	**4.40** ± 0.71	**4.10** ± 0.42
3 year 1A	6.46	6.32	6.18	5.25
3 year 2A	4.22	3.80	3.91	3.91
3 year 3A	4.09	3.85	3.86	3.93
Avg	**4.92** ± 1.33	**4.66** ± 1.44	**4.65** ± 1.33	**4.36** ± 0.77
Clr 1A	4.93	4.67	4.06	3.98
Clr 2A	4.89	4.45	3.98	4.09
Clr 3A	5.11	4.55	4.01	3.84
Avg	**4.98** ± 0.12	**4.56** ± 0.11	**4.02** ± 0.04	**3.97** ± 0.13
Sec 1A	6.66	5.15	5.21	5.39
Sec 2A	4.73	4.55	3.96	4.01
Sec 3A	5.75	5.61	5.09	5.12
Avg	**5.71** ± 0.97	**5.10** ± 0.53	**4.75** ± 0.69	**4.84** ± 0.73
Pri 1A	5.89	5.26	5.13	5.50
Pri 2A	6.11	5.90	5.65	5.45
Pri 3A	5.99	5.31	5.11	4.50
Avg	**6.00** ± 0.11	**5.49** ± 0.36	**5.30** ± 0.31	**5.15** ± 0.56

Figure 27: Correlation between %SOC and pH

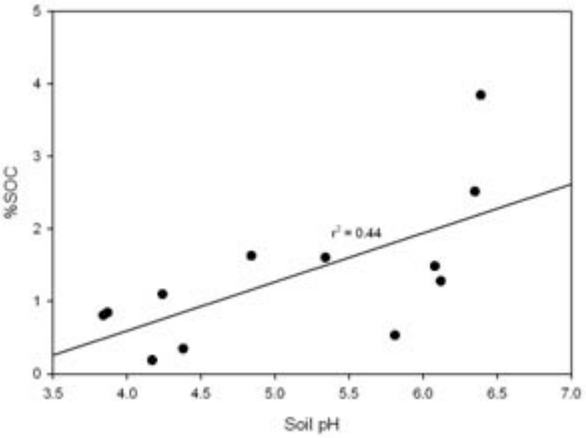


Fig. 27a: 8 year rotation

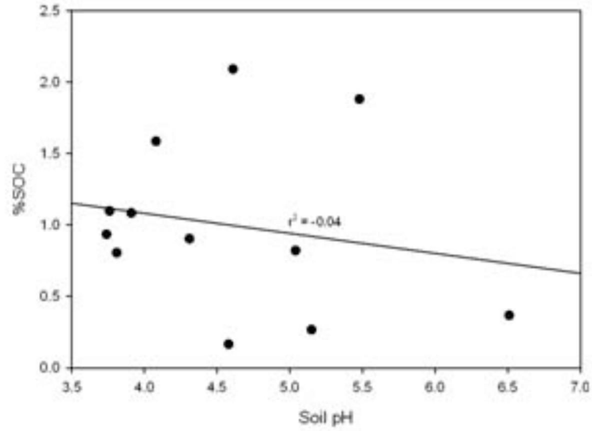


Fig. 27b: 5 year rotation

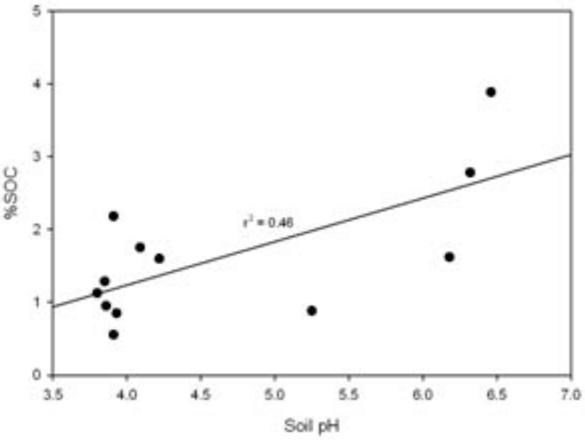


Fig. 27c: 3 year rotation

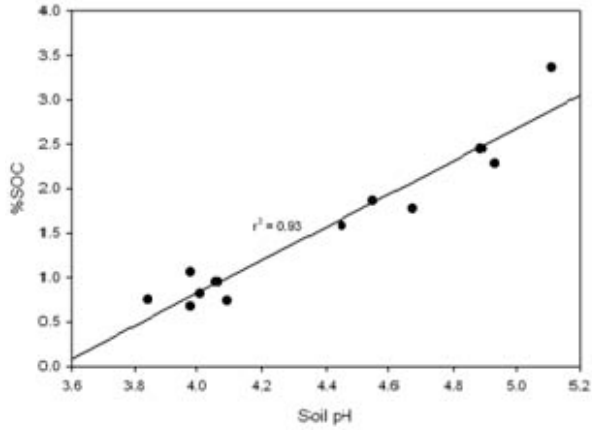


Fig. 27d: Cleared area

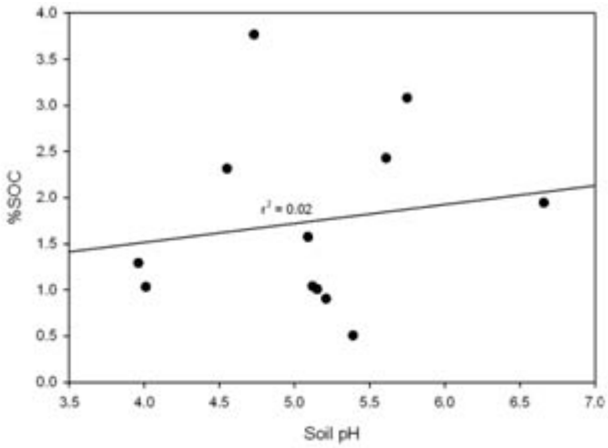


Fig. 27e: Secondary forest

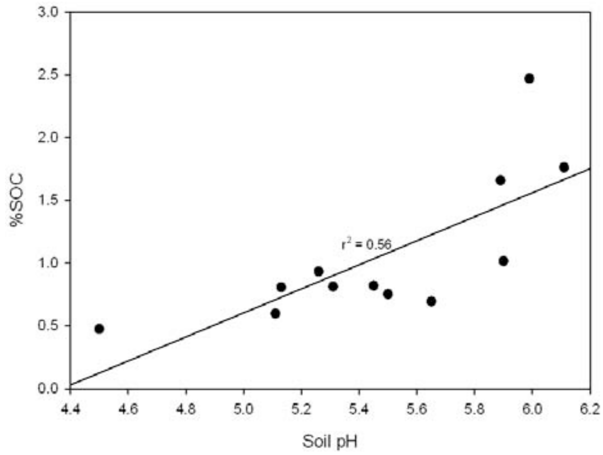


Fig. 27f: Primary forest

3.6 Soil textural properties of investigated land use classes

The results from the textural analysis are displayed in **Table 9**. It was not possible to precisely classify the soil as only the sand fraction has been weighed. However, the percentage of sand should give more insight into the properties of the investigated land use classes.

The majority of samples contained particles smaller than 0.212 mm (fine sand), however there were some instances of samples containing larger particles that will be described within the text below. Unless it is stated otherwise, sand particles are below 0.212 mm.

The primary forest contained the lowest percentage of the sand fraction of all the land use classes. On average, sites located within the primary forest contained 54% of sand and 47% of silt+clay. Three samples in the primary forest contained particles larger than 0.106 mm (Pri1A – 0.7%, Pri1B – 0.2%; Pri1C – 1.1%; Pri 2A 0.1%; Pri2B – 0.7%) and larger than 0.212 mm (Pri1A – 0.5%, Pri1B – 0.1%; Pri1C – 0.1%; Pri 2A 0.1%; Pri2B – 0.1%). The secondary forest averaged 61% sand and 39% silt+clay in the soil samples and has the second highest silt+clay fraction. The cleared area, on average, contained 67% sand and 33% silt+clay. Two of the samples contained particles larger than 0.106 mm (Clear 3B – 0.1%: Clear 2C – 0.1%), however this sand fraction is of a very low percentage. The 3 year rotations, on average, contained 68% sand and 33% silt+clay. The 8 year rotation contained the second highest percentage of sand, with 69% sand and 31% silt+clay. Two of the samples contained particles larger then 0.106 mm (8 year 3A – 0.9%: 8 year 3 C – 1.2%). The land use class that contained the highest amount of sand was the 5 year rotation with 72% sand and 28% silt+clay.

A line of regression analysis (**Fig. 28**) and Pearson correlation analysis were conducted between SOC stocks of the land use classes and the %silt+clay fraction to determine whether there exists a correlation or not. SOC stocks (0-60 cm) used in the calculations did not include C stocks from the litter layer results as soil texture presumably has no influence on litter.

A correlation was only present in the 8 year rotation and the cleared area. All other land use classes resulted in no correlation between soil texture and SOC stocks according to the Pearson correlation test. The 8 year rotation (**Fig. 28a**) has an $r^2 = 0.51$ and a direct correlation was detected using the Pearson test ($P = 0.03$). The 5 year rotation (**Fig. 28b**) has an $r^2 = -0.1$ indicating a small negative correlation, however no correlation was detected via the Pearson test ($P = 0.414$). No correlation was detected within the 3 year rotation (**Fig. 28c**) with either a linear regression ($r^2 = 2.71$) nor a

Pearson test (*P* = 0.966). The cleared area (**Fig. 28d**) resulted in an r^2 = 0.66 and passed the Pearson test (*P* = 0.008) indicating a large correlation. The secondary forest (**Fig. 28e**) yielded an r^2 = 0.15 indicating a small correlation, however the secondary forest failed the Pearson test (*P* = 0.305). The primary forest (**Fig. 28f**) yielded a result of r^2 = -0.36 indicating a negative medium correlation, however it also failed the Pearson test (*P* = 0.09) indicating no correlation between SOC stocks and soil texture.

Table 9: Soil texture analysis results

	% Silt+Clay	% Sand		% Silt+Clay	% Sand		% Silt+Clay	% Sand
8 year 1A	20	80	5 year 1A	34	66	3 year 1A	31	69
8 year 1B	39	61	5 year 1B	24	76	3 year 1B	30	70
8 year 1C	38	62	5 year 1C	22	78	3 year 1C	30	70
Avg	**32**	**68**	**Avg**	**27**	**73**	**Avg**	**30**	**70**
8 year 2A	37	63	5 year 2A	21	79	3 year 2A	35	65
8 year 2B	34	66	5 year 2B	34	66	3 year 2B	29	71
8 year 2C	34	66	5 year 2C	21	79	3 year 2C	36	64
Avg	**35**	**65**	**Avg**	**25**	**75**	**Avg**	**33**	**67**
8 year 3A	24	76	5 year 3A	38	62	3 year 3A	33	67
8 year 3B	34	66	5 year 3B	24	76	3 year 3B	29	71
8 year 3C	20	80	5 year 3C	34	66	3 year 3C	32	68
Avg	**26**	**74**	**Avg**	**32**	**68**	**Avg**	**31**	**69**
Total Avg	**31**	**69**	**Total Avg**	**28**	**72**	**Total Avg**	**32**	**68**
Clr 1A	30	70	Sec 1A	46	54	Pri 1A	48	52
Clr 1B	31	69	Sec 1B	36	64	Pri 1B	48	52
Clr 1C	32	68	Sec 1C	49	51	Pri 1C	46	54
Avg	**31**	**69**	**Avg**	**44**	**56**	**Avg**	**47**	**53**
Clr 2A	30	70	Sec 2A	35	65	Pri 2A	47	53
Clr 2B	33	67	Sec 2B	34	66	Pri 2B	45	55
Clr 2C	26	74	Sec 2C	35	65	Pri 2C	46	54
Avg	**30**	**70**	**Avg**	**35**	**65**	**Avg**	**46**	**54**
Clr 3A	38	62	Sec 3A	38	62	Pri 3A	48	52
Clr 3B	39	61	Sec 3B	37	63	Pri 3B	46	54
Clr 3C	42	58	Sec 3C	37	63	Pri 3C	49	51
Avg	**40**	**60**	**Avg**	**37**	**63**	**Avg**	**48**	**52**
Total Avg	**33**	**67**	**Total Avg**	**39**	**61**	**Total Avg**	**47**	**53**

Figure 28: Correlation between SOC stocks and %silt+clay fraction

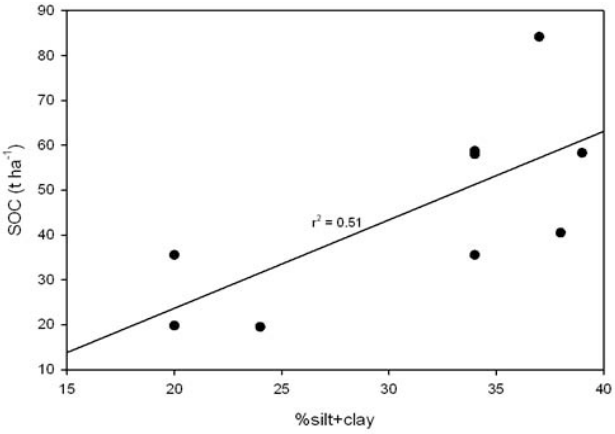


Fig. 28a: 8 year rotation

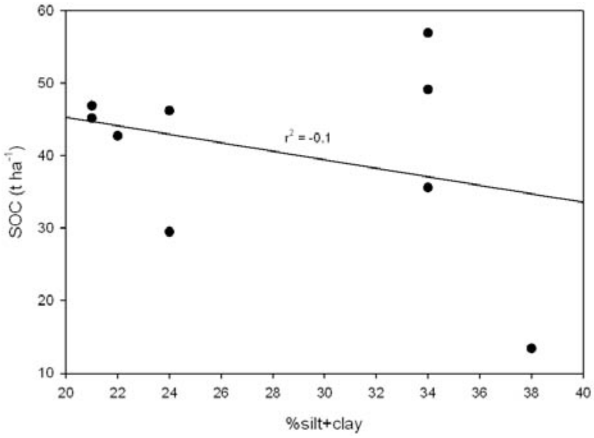


Fig. 28b: 5 year rotation

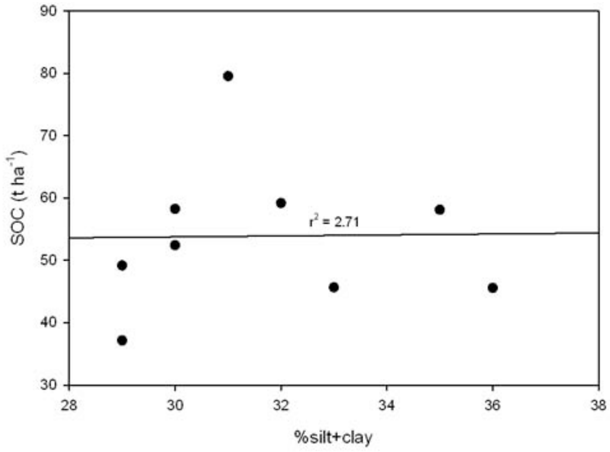


Fig. 28c: 3 year rotation

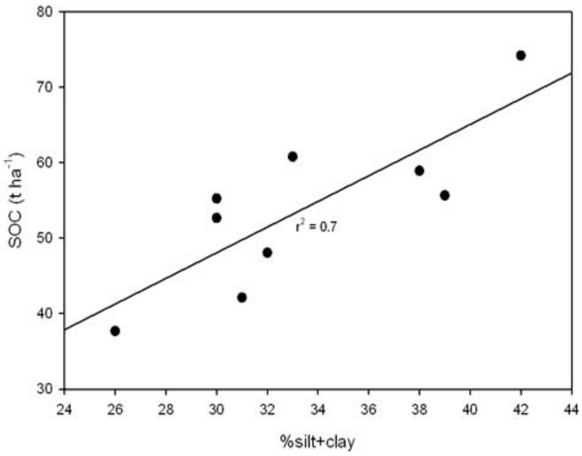


Fig. 28d: Cleared area

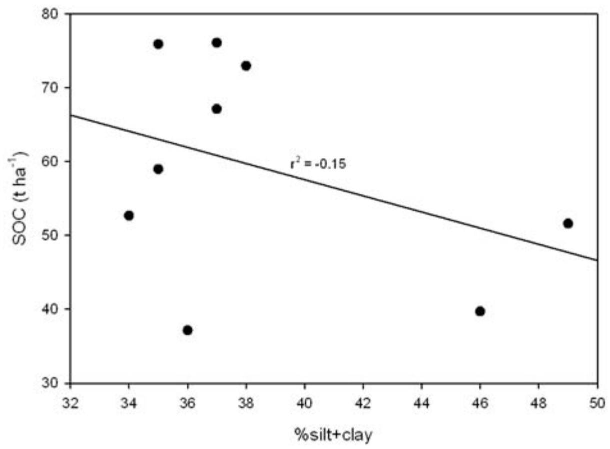


Fig. 28e: Secondary forest

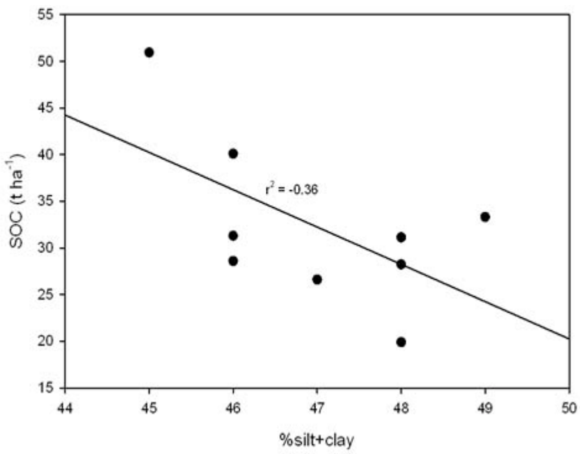


Fig. 28f: Primary forest

4. Discussion

4.1 General discussion of SOC results

The original hypothesis stated that the primary forest would have the highest %SOC and, dependent on bulk density, the highest stocks of SOC (n.b. stocks include C t/ha^{-1} derived from litter layer). Furthermore, within the planted areas of the forest reserve, older rotations would contain higher SOC stocks and %SOC in the top soil. Primary forests are often assumed to have higher quantities of SOC as other surrounding land use classes (Jobbagy & Jackson 2000). Similarly, older forests should have accumulated more SOC than younger forests (Jobbagy & Jackson 2000). However, the results generated within this study appear to suggest that the Budongo primary forest contains less total SOC (0-60cm) than the land use classes found at the Kikonda FR (**Table 5, Fig. 24**). This contradicts the findings in previous studies that indicate primary forests should have higher SOC stocks at all depths than degraded lands such as those found at the Kikonda FR (Jobbagy & Jackson 2000, Guo & Gifford 2002, Situala *et al* 2004, Post & Kwon 2008).

It was found that although the primary forest has the highest mean %SOC in the top soil (3.03% at 0-10 cm) (**Table 3, Fig. 17**), this land use class contained the lowest extrapolated stocks (33.2 SOC t/ha^{-1} at 0-60 cm) (**Table 5, Fig. 24d**). In general, the secondary forest contained the highest extrapolated mean SOC stocks (60.1 SOC t/ha^{-1} 0-60 cm) (**Table 5, Fig. 24d**) as well as high %SOC levels (e.g. 2.63% 0-10cm, 1.77% 10-20 cm) compared to the other land use classes (**Table 3, Fig. 17**). Within the FR, the 3 year rotation contained the highest extrapolated mean SOC stocks (54.3 C t/ha^{-1} 0-60 cm) (**Table 5, Fig. 24d**) despite the second lowest mean %SOC in the top soil (2.2%) (**Table 3**). The carbon stock results from the cleared area indicate that this land use class contained the second highest, within the FR, mean amounts (54.2 SOC t/ha^{-1} 0-60 cm) (**Table 5, Fig. 24d**) as well as the highest mean %SOC at all depths) (**Table 3, Fig. 17**) (with the exception of 20-40 cm where the 3 year rotation contained 0.26% more mean %SOC). The 8 year rotation, the oldest rotation at the FR, contained the second lowest mean SOC stocks (46.7 SOC t/ha^{-1} at 0-60 cm) (**Table 5, Fig. 24d**) with slightly lower %SOC levels than the 3 year rotation (**Table 3, Fig. 17**). The 5 year rotation, overall, contained the second lowest SOC stocks (41.1 SOC t/ha^{-1} 0-60 cm) (**Table 5, Fig. 24d**) (lowest in the FR) and also the lowest mean %SOC at all depths (**Table 3, Fig. 17**).

A comparison of the extrapolated SOC stocks at different depths (**Fig. 24**) was made in order to see the variability present under differing land use classes. Differences in SOC at different depths would suggest factors that influence SOC stock quantities.

There were no significant differences in SOC stocks or %SOC (**Fig. 17**), between any of the land use classes, at the extrapolated depths of 0-10 cm or 0-20 cm when testing consisted of a standard ANOVA. However, when ANOVA on ranks was applied, due to non-normality, a significant difference in %SOC was present between the primary forest and the 5 year rotation at 0-10 cm. There was a greater variability of SOC stock quantity present within the individual pits of the 5 year rotation, which accounts for the failed test of normality. This variability could be due to a slight upwards slope from East to West in the 5 year rotation which could cause a decrease of surface runoff and soil erosion which has been suggested reduces SOC loss (Jia *et al*. 2007). However, there were no significant difference in either %SOC or SOC stocks within the 5 year rotation (with the exception of a significant difference in SOC stocks at 40-60 cm) and therefore the difference in slope does not have a significant impact on SOC levels and is only an explanation for the failed test of normality.

There was a significant difference between the primary and secondary forest at the extrapolated depths of 0-40 cm and 0-60 cm (**Fig. 24**), however no significant differences were found between %SOC (**Fig. 17**). Furthermore, significant differences between the primary forest and the cleared area; 5 year rotations were also detected in %SOC.

Although no significant difference was found between most of the sites within the investigated land use classes, significant differences were detected that influenced the mean e.g. significant differences in %SOC were found at 0-10 cm for the 3 year rotation (P = 0.02, **Table 3**); 8 year rotation (significant differences at 10-20 cm, 20-40 cm, 40-60 cm); 5 year rotation (significant differences at 10-20 cm, 40-60 cm); and secondary forest at 0-10 cm (P = 0.005, **Table 3**). Therefore, the means may not necessarily be taken as absolute values as this indicates variability within the investigated land use classes.

Fig. 18 shows the variability of %SOC within land use classes at the various sites and it is apparent how some sites are more uniform within the land use class – particularly in the primary forest – and suggests the variability present in the degraded soils of the Kikonda FR. Due to this variability (and the differences between the age classes) it is not possible to simply conclude that older rotations will contain higher SOC content. Other factors, such as available nutrients on the forest floor and the soil texture of the sites are suspected to overrule the age of the rotations.

The SOC stocks of the investigated land use classes remain relatively evenly distributed whereas previous studies have stated that SOC stocks decrease linearly with depth (Jandl et al 2007, Muñuz et al 2007). The results in **Fig. 21**, regarding the relative distribution of SOC stocks at different depths, contradict previous studies (Jandl et al 2007, Muñuz et al 2007). However, the results are similar to findings by Zinn *et al.* (2002), with the exception of considerably higher SOC stocks in the top soil (0-10 cm). Additionally, the %SOC results in **Fig. 18** correlate with previous studies (Jobbagy & Jackson, 2000) in that %SOC generally decreases with depth.

The SOC stock (**Table 5**) and bulk density (**Appendix 5**) results, in the planted area of the Kikonda FR, are comparable to Zinn *et al.* (2002) on a *Pinus caribea* plantation with ferralsol soils (similar to the soils found at the Kikonda FR) in Cerrado region of the state of Minas Gerais, Southeastern Brazil However, the climate differs somewhat with Minas Gerais having mean annual temperatures between 22.5° and 21.0 °C and mean annual precipitation between1445 and 1540 mm (with a dry season in winter) (Zinn *et al.* 2002). The mean annual temperature is slightly lower than the Kikonda FR in Koboga (**Fig. 4**) however there is a significantly higher mean annual precipitation (**Fig. 4**). This is another example of the difficulty in obtaining comparable studies.

Total SOC stocks (0-60 cm) in the Kikonda FR were lower than the averaged total SOC reported in Zinn *et al.* (2002) (65.8 t/ha^{-1}). However, it was reported that the soils had a high clay content where as the Kikonda FR have a high amount of sand. This could account for the higher amount of SOC in the top soil (0-10 cm) which was the primary cause of higher overall SOC stocks. SOC stocks at lower depths reflect the findings at the Kikonda FR. %SOC was not reported in Zinn *et al.* (2002), therefore it is not possible at this time to compare %SOC results.

%SOC (**Table 3**), in the Kikonda FR, was significantly higher than results reported at *Pinus caribea* stands (aged 14 years) found in the tropical savannah zone of Nigeria (Kadeba & Aduayi, 1985, results shown in **Appendix 10**). This is despite relatively high clay content (soil texture in this region was classified as clay loam to a depth of 260 cm) found in the Nigerian soil (**Appendix 10**). Bulk density, as reported in Kadeba & Aduayi (1985) was also considerably higher, averaging 1.50 g/cm^3 (0-60 cm). However, although both the Kikonda FR and the investigated stands in Nigeria utilize the same species of pine, some environmental conditions in the savannah zone differ from those found at the Kikonda FR (e.g. the elevation of the Kikonda FR is twice as high as the 610 m.a.s.l. elevation reported in Kadeba & Aduayi (1985) and the parent material differs). Therefore, a direct comparison is not advisable but rather serves as an example of %SOC content in another *Pinus caribea* plantation in somewhat comparable conditions. Data comparing different age classes were not reported therefore it is not possible to make direct comparisons in regard to the scope of the Kikonda FR study.

4.2 Bulk density and soil texture

The differences between %SOC and overall SOC stocks suggests that the bulk density is an important feature for carbon storage and although %SOC in an area may be high, unless the bulk density is high enough, potentially only moderate amounts of SOC will be stored. The variability of bulk densities within some of the land use classes (**Appendix 5**) suggest that an error may have occurred whilst collecting the data. Bulk densities fluctuate more than would be assumed and in some cases the recorded bulk density ranges from 0.36 in the top soil to 0.91 at 50 cm depth (8 year 1A, **Appendix 5**). Therefore, the calculated carbon stocks may not be indicative of the true values of the carbon stocks on the plantation and in the Budongo forest reserve. However, this error may only be relevant to the primary forest and the results from Site 1 in the 8 year rotation as such a wide range in bulk densities is not present in any of the other results. Conversely, the %SOC results are conclusive enough that that data may be taken as accurate.

Different land use classes can have a significant impact on soil texture which can affect soil fertility. Cultivated lands often result in particle desegregation which can increase the bulk density of a soil (Yao *et al.* 2010). Studies have shown that conversion of tropical natural forest to cultivated lands increased bulk density (King and Campbell 1994, Fisher 1995). The authors found that average bulk densities in the Téné protected forest (0.60 g cm^{-3}) were lower than cultivated areas (0.90 g cm^{-3}). This may account for the lower soil volume in the Primary forest, although the cleared area has comparable, to the planted area and secondary forest, bulk densities at all depths. However, the secondary forest and cleared areas are on degraded land and particle desegregation may have increased the bulk densities. Unfortunately, this is another example of how it would have been beneficial to have sampled from a Primary forest in the Kikonda area in order to make a proper comparison.

A study investigating changes in the physical and chemical properties of soils under a *Pinus caribea* plantation (aged 14 years) compared to adjacent natural savannah forest cover in Nigeria (Kadeba & Aduayi 1985) found that 'no significant differences in soil physical characteristics were noted except modest increases in top soil bulk density values under the pine' plantation. Based on this finding, it may be the case that physical changes in the soil structure will not occur through afforestation of the surrounding areas in the Kikonda FR.

Borchers & Perry (1992) note that coarser, sandy soils have lower total SOC concentration when compared to silt loam and sandy loam soils. It was not possible to classify the soils in the Kikonda FR due to a lack of data, therefore coarseness was estimated based on %sand. The primary forest contained the highest %SOC in the top soil (**Table 3**) which corresponds with the lowest %sand (**Table 9**). There appears to be a small negative correlation (using the r^2 value) between %silt+clay and SOC stocks, which was unexpected (**Fig. 28f**). Similarly, the Secondary forest (**Fig. 28e**) and 5 year rotations (**Fig. 28b**) also had a small negative correlation between SOC stocks and clay+silt.

Jones (1973), via Feller & Beare (1997) found a negative correlation between SOC and clay content from the West African savannah (mostly in Nigeria) in vertisols that contained >35% clay which Feller & Beare (1997) believe may have been due to a strong influence of sheet erosion and/or contamination of top soils with soils from deeper horizons due to the soils vertical properties. It is unknown what the %clay of the soils at the Budongo FR as a combined %silt+clay fraction was measured, however soils are typically ferralitic and sandy loams with a lower boundary of %50 sand fraction (Mwavu 2007) which corresponds to the results in **Table 9**. It may be possible that contamination of the upper horizon by deeper horizons occurred, however it is not known how that may have occurred within the 5 year rotation. No correlation was detected within the 3 year rotation (**Fig. 28c**). Conversely, a large positive correlation was detected in both the 8 year rotation (**Fig. 28a**) and the cleared area (**Fig. 28c**).

It was noted in the introduction that soil clay (or silt+clay) content is a relatively important determinant of SOC in low activity clay soils, however, it is surprising that the in the three planted areas, the correlation results were varied. Of course, correlative studies can only suggest a relationship between two variable and it may be that texture alone is not as an important determining factor for SOC in the Kikonda FR as originally hypothesized.

Discrepancies among studies regarding changes in SOC in relation to soil texture have been noted by Paul *et al.* (2002). In the meta-study, Change in soil carbon following afforestation, Paul *et al.*

noted that some studies found that ‘the change in soil C was least in clay soils while others have found that the rate of soil C accumulation was directly related to clay content, the relationship between C accumulation and soil texture being strongest at higher soil C contents’. Paul *et al.* continues by stating that the time period considered could be a cause for the discrepancies and that such temporal effects in afforestation decreased SOC in some cases e.g. top soils <30 cm with a high clay content experienced a decrease in %SOC by 0.62% per year (relative to initial concentrations) in the first 10 years following forest establishment – however, in the long term (>10 years), SOC had an average increase of 1.01% per year (relative to initial soil C content). The underlying mechanism behind this was due to within the short term SOC was protected in organo-mineral complexes where as in the longer term, soils with higher clay concentrations have the potential to accumulate large SOC stocks. Although soils within the planted area do not appear to have high clay contents, it may be possible that higher rates of SOC storage will present itself over time through establishment. For example, SOC levels after afforestation of an agricultural area will initially drop but will then gradually begin to rise to higher than initial C content after a period of approximately 30 years (Paul *et al.*, 2002). Forest soils generally contain higher quantities of SOC than bushland (Jobbagy & Jackson, 2000) and so it may be assumed that a similar trend will present itself following afforestation within the Kikonda FR.

4.3 Soil pH

Soil pH values do not show very marked differences between the 5 and 3 year age classes in the planted area and the cleared area (**Table 8**). However, the 8 year rotation had a higher pH level despite the acidifying effect of of *Pinus carbibea* (and conifers in general) on soil (Kadeba & Aduayi 1985, Berthrong *et al.* 2009). The lower pH levels of the planted area, when compared with the secondary and primary forest, may have be caused by a smaller production of humic acids under pine plantations due to inhibited litter decomposition in conjunction with the acidifying effects of conifers on soil (Kadeba & Aduayi 1985, Berthrong *et al.* 2009). The increased acidity of forest soils may be caused by ‘increased uptake of cations by trees and consequent changes in the proportions of cations adsorbed to the soil exchange complex’ (Berthrong *et al.* 2009). However, it would follow to reason that the 8 year rotation (being the oldest stand in the Kikonda FR) would have a lower pH as a result. Instead, pH is higher at all depths. There is no evidence that would point towards the planting of conifer based stands would increase pH but rather it may be that the soils in the 8 year rotation already had a high pH which may have been reduced. Although pH varied considerably among the age classes within the planted area, pH also varied in the secondary forest and, to a lesser degree, in the primary forest which suggests that the mechanism of acidification across the plantation is similar but the actual impact is ultimately dependent on site conditions.

Correlation between pH and %SOC was observed in some of the land use classes, namely the 8 year and 3 year rotations which had a medium correlation; and the cleared area and primary forest which both had a large correlation. It is not known, at this time, why there would be a correlation in all of the planted and cleared areas with the exception of the 5 year rotation. The limitation of correlation studies is that they can only suggest there is a relationship but cannot prove a relationship exists i.e. correlation does not equal causation. The lower levels of %SOC in the 3 year rotation might account for the lack of a correlation as pH levels are similar within all of the planted and cleared areas suggesting that there is a limiting factor within the 5 year rotation in regards to the %SOC and that neither variable has a direct effect. Had pH had a direct effect on %SOC, then there would have been suggestion of at least a small correlation within the 5 year rotation. The lack of a correlation within the secondary forest reflects the variability in pH, %SOC and SOC stocks and suggests that the secondary forest is not as uniform a land use class as the other investigated classes.

pH has an indirect effect on soil carbon retention rates as it affects a wide range of chemical and biological functions in soil which could account for the correlations found. Strongly acidic soils, such as forest soils (Lorenz & Lal 2009), reduce the availability of macronutrients (e.g. Ca, Mg, K, P, N and S) while, in contrast, higher pH levels increases the availability of micronutrient cations (Fe, Mn, Zn, Cu and CO) (Borggaard & Elberling 2003, Lorenz & Lal 2009). Nitrification (conversion via microbial activity of NH_4^+ to nitrate) in acidic soils ($pH < 6$), such as those found within the Kikonda FR, is slow and plants that are able to utilize NH_4^+ may have an advantage (Brady & Weil 2004) such as conifers which tend to prefer uptake of NH_4^+ as opposed to other inorganic sources of N e.g. NO_3^- (McFee & Stone 1968). Juo and Manu (1996) found that soil pH generally decreased when actively growing vegetation with low nutrient stocks. This may be related to cation uptake by vegetation with “subsequent release of H^+ ions, organic matter decomposition into organic acids, increased CO_2 levels through root respiration and nitrification” (Yoa *et al* 2010).

4.4 Litter layer

The C content of litter was expected to increase with increasing stand age as a higher production of biomass would be expected (i.e. larger trees produce more dry weight litter) and a denser litter layer on the forest floor as the trees grow new leaves. Significant difference in litter between the 8 year rotation and the other age classes were expected due to the stands age (**Fig. 19**). However, it was also expected that all the age classes would be significantly different due to the same reason. It was found that the cleared area differed significantly from all the land use classes with the exception of the 3 year rotation. It would otherwise have been assumed that 3 years would be time enough to produce ample biomass greater than a recently cleared area. %C in the litter layer shows a linear increase (**Fig. 20**), within the planted area, with age. %C is higher in the cleared area than the 3 year rotation so it may be that %C decreases initially before increasing again with the additional vegetative input produced by the trees.

When the litter layer of the land use classes were compared in an ANOVA test, the data set failed the Normality test (P = 0.025). Regardless, the only significant difference detected was between the cleared area and the primary forest (P = 0.015). All other land use classes were P = >0.05, thus no significant differences were found. When sites within the independent land use classes were compared, significant differences were detected in all classes with the exception of the cleared area (P = 0.986) and the primary forest (P = 0.252).

Although the climate and soil textural properties of an area are speculated to be the primary regional controls of the total amount of SOC, Jobbagy & Jackson (2000) suggest that C stored in the litter layer and vegetation may influence the vertical distribution of SOC more so. SOC in the top soil is heavily influenced by SOC contained on the forest floor in the litter layer (Jobbagy & Jackson 2000). Jobbagy & Jackson (2000) hypothesized that ‘vegetation is a major determinant of the vertical distribution of SOC. Although climate and soil texture are the primary regional controls of the total amount of SOC, their influence on the vertical distribution of SOC may be eclipsed by the effects of plant allocation’. Soil texture can still influence vegetation e.g. the dominance of woody plants is associated with coarse textured soils however it is only one of many factors that influence vegetation on a local scale (Dodd *et al.* 2000).

The amount of SOC in soil is largely dependent on the ecological zone in which it occurs (Sitaula *et al* 2004). Higher content of litter layer (both dry weight and SOC content) should lead to higher SOC levels in the topsoil layer as more SOC are available. The primary forest has the third highest dry weight of litter found on the forest floor (0.94 ± 0.57 C t/ha^{-1}, **Table 4**) as shown in **Fig. 19**. However, the primary forest topsoil (0-10 cm) contains the second largest SOC stock (28%, **Fig. 21f**), relative to total SOC content 0-60cm, which accounts for 8.3 SOC t/ha^{-1} out of the total SOC content 0-60cm (33.2 SOC t ha) – this is most likely due to the high dry weight of organic matter in the litter layer (3% of total SOC, **Fig. 21f**) which transports C into the soils. However, this is not always an indication of high SOC in the topsoil. For example, the secondary forest has the second highest dry weight of litter on the forest floor (**Fig. 19**) with a dry weight of 0.99 ± 0.59 (**Table 4**). However, the litter layer only contributes 2% (**Fig. 21e**) to the total SOC compared to the 20% of total SOC at 0-10cm depths.

Following this trend, the expected low dry weight of litter in the cleared area (0.21 ± 0.2C t ha, **Table 4**; >1% of total SOC, **Fig. 21d**) does not correspond to the resultant 21% total SOC found at 0-10 cm depth. However, the results from the cleared area, at this depth, are misleading in that they are not directly comparable to the other land use classes without first documenting the unique characteristics associated with this particular land use class. Firstly, the area was recently cleared in order to plant seedlings for the new age class/rotation. As SOC sequestration in afforestation has temporal variation associated, generally there is an initial decrease in SOC before a gradual increase (Paul *et al.* 2002). In the case afforestation of agricultural soils, changes within the top 30 cm occur after approximately 30 years to levels greater than baseline levels prior to a shift in land use (Paul *et al.* 2002). Thus, at this time, the litter layer weight cannot be directly attributable to SOC sequestration. Conversely, the management method for clearing bush and grassland at the Kikonda FR utilized the slash and burn method. Biomass burning significantly reduces SOC in the upper few centimeters of the soil but has a nominal impact on SOC content below 10 to 20 cm depth (Vågen *et al* 2005). Therefore, the results from 20cm onwards can be considered representative of bushland, as this was the former land use class of the investigated areas and there might be an effect in the top soils but not at deeper depths.

Compared to the primary forest, the 8-year rotation also has a high percentage of SOC in the topsoil (20%, **Fig. 21a**) due to the dry weight of the litter layer (1.05 ± 0.35 C t ha, **Table 4**) resulting in a SOC content of 2% of total SOC. The reason for higher SOC content in the litter layer is simply the result of more litter generated by older rotations thus larger dry weights of litter.

A point of interest is that although the dry weight of the primary forest litter layer was larger than e.g. the 8 year rotation, a higher %C was recorded for the 8 year rotation which would indicate a higher C retention in coniferous leaves of the pine in the planted area than the broad leaved trees within the primary forest (**Appendix 8**). Furthermore, the litter layer in the primary forest contained the lowest %C of all the investigated land use classes. This would suggest that a combination of coniferous leaves with a temporal accumulation of bushes, shrubs and weeds significantly increase %C found: the 8 year rotation has the highest and the 5 year rotation second highest. The secondary forest has higher %C levels than the 3 year rotation and cleared area, however, given time, it may increase to levels higher than the secondary forest. A follow up study investigating changes in %C at the investigated sties is suggested in order to confirm or deny this.

Within the planted areas, the 8 year rotation had the highest dry weight of litter on the forest floor (**Table 4**). As this is the oldest rotation, it is not surprising that the 8 year rotation would contain a significantly higher amount of litter than either the 5 or 3 year rotations. However, there was no significant difference of litter between the 5 and 3 year rotations where as it was assumed there would be due to an additional two years growth. The mechanism behind this could be due to a lower nutrient content present in the 5 year soil which may have limited plant growth (Brady & Weil, 2004)), as also evidenced by the dry weight of litter (**Table 4**) and visual observations of pronounced vegetation in the 3 year rotation (e.g. an abundance of shrubs and long grass). The pH levels between the two areas are comparable and this alone is not enough to justify the lack of vegetation.

Vågen *et al.* (2005) stated that 'biomass burning significantly reduces SOC in the upper few centimeters of soil, but has little impact below 10 to 20 cm depth' (Vågen *et al.* 2005) whereas other studies show no effect (Van de Vijver *et al.* 1999 via Vågen *et al.* 2005) or an increase of SOC (Bruun *in comm.* 2011). The burning and slashing method employed by Kikonda FR to the cleared area, prior to planting, did not appear to have a detrimental effect on SOC in the top soil (**Table 3**). However, without a bushland land use class for comparison, it is not able at this time to say determinately whether or not SOC levels changed as a result. Bruijnzeel (1998), via Vågen *et al.,* concluded the intensity of the fire affected the amount of SOC lost. Increases of SOC in sub-surface horizons occur due to the transport of hydrophobic organic matter from the surface soil and subsequent stabilization with cations (Paul *et al* 2002). Lower temperature fires may cause no change or an increase of SOC within the top 10 cm due to the 'incorporation of charcoal and partially burned organic matter into mineral soil' (Paul *et al* 2002).

‘The timing of burning is also important, and periods with large amounts of biomass available generally have the largest losses of SOC’ (Vågen *et al.* 2005) and the cleared areas had been slashed and burned within a month of the data collection. Afforestation has been known to increase SOC stocks, nevertheless this obviously cannot be the case for an area that had only just recently been planted with seedlings. SOC stocks may have diminished as a result of biomass burning and the area may have already yielded high SOC stocks comparable with those of the secondary forest in the surrounding areas (**Table 5**). In hindsight, it would have been beneficial to have sampled from an untouched bushland, as this was the previous land use class of the cleared area, for a comparison to be made. Future studies may also benefit from repeated SOC sampling from the cleared areas over a number of years in order to assess changes in SOC levels.

4.5 Other factors influencing SOC quantities

The Kikonda FR consists of afforestation on sites of former degraded forests and bushlands. As stated in section *2.1.2.1* (*History and Land use*), the area used to consist of untouched forests but through poor management practices the area became degraded. When shifting land use from forest to a plantation, baseline forest SOC stocks revert to original levels after approximately 40 years (Guo & Gifford 2002). Furthermore, forest soils generally contain higher quantities of SOC than bushland (Jobbagy & Jackson 2000) and thus it can be assumed that a similar trend will present itself following afforestation within the remainder of the unplanted areas in the Kikonda FR. However, these are long term changes whereas SOC levels may initially decrease as a result of planting *Pinus* (Kadeba & Aduayi 1985). Regardless of tree species, afforested areas contain higher SOC stocks than arable areas (Jobbagy & Jackson 2000, Nsadimana *et al*. 2008)

A study investigating changes in the physical and chemical properties of soils under a *Pinus caribea* plantation (aged 14 years) in Nigeria (Kadeba & Aduayi 1985) found a statistically significant decline of SOC in the upper 10 cm of the mineral soil as a result of afforestation with *Pinus caribaea*. However, the results also compared the pine stands to adjacent savannah natural forest cover and found that no significant differences in soil chemical properties were present. Therefore, it may be the case that afforestation of the surrounding bushland in the Kikonda FR may not alter the soil chemical properties, at least not within the time period reported.

Deeper soil horizons may have a high capacity to sequester significant amounts of SOC as the turnover time and chemical recalcitrance of soil organic matter (SOM) increases with depth (Lorenz & Lal 2005). Although no significant differences in SOC stocks (with the exception of the primary forest and secondary forest at 0-40 and 0-60 cm; the primary forest and the 3 year rotation/cleared area at 0-60 cm (**Fig. 24**) were present, differences may arise at further depths such as 2 and 3 meters based on the meta-study conducted by Jobbagy & Jackson (2000), however no data was collected at Kikonda FR or Budongo FR do support this speculation. The Primary forest may potentially have higher SOC stocks at greater depths due to greater root activity and, in the long run, may have comparable (or higher) SOC stocks (Sommer *et al.* 2000)

The study conducted by Kaonga & Bayliss-Smith (2008) into carbon pools in tree biomass and the soil in improved fallows in eastern Zambia can be used as an example into how the vertical distribution of SOC differs with depth. In the study, SOC stocks rose significantly from 50 to 100 cm most likely due to the volume of the subsoil rather than %SOC density; the deep tree root systems (with extra root C); leaching of SOC; and 'reduced susceptibility of SOC stocks to microbial oxidation at depth due to gradients of biophysical and chemical conditions that impose limitations on mineralization'. Furthermore, their results concluded that SOC stocks increased with longer tree rotations and biomass yields and that, in general, fine-textured soils stored more C than sandy soils. This corresponds to findings in other studies (Jobbagy & Jackson 2000, Silver *et al.* 2000, Paul *et al.* 2002).

The volume of the subsoil is expected to be higher at greater depths under all the investigated land use classes (based on the bulk density data shown in **Appendix 5**), however *P. caribaea* root activity and nutrient absorption is the most pronounced in the upper 30 cm (Kadeba & Aduayi 1985) and based on visual observation while collecting data at the Kikonda FR (**Appendix 3**). Root activity was more pronounced at greater depths within the Primary forest at Budongo FR (**Appendix 3**). A reduction in SOC may occur, within the planted area, due to the lack of root activity at greater depths depending on the former land use class. The shallower root system and, presumably, lower root biomass of *P. caribaea* (compared to that of a Primary forest) may not provide the necessary input of C to maintain comparable SOC stocks at great depths (Sommer *et al.* 2000)

It appears that the clearing and use of tropical soils affects their carbon content to a depth of about 40 cm. (Detwiler 1986). The paper did not specify how long it would take for such changes to occur; however, as seedlings are planted in cleared areas nearly immediately, the growth of trees in the cleared area should mitigate any potential negative effects on soil quality as seen in the conversion of land to an agricultural land use class (Detwiler 1986, Jobaggy & Jackson 2000, Post & Kwon 2008).

Generally, afforestation by *Pinus* plantations has been reported to reduce SOC by 15 – 20% and decreases of N, Ca and Mg indicate that the trees utilize considerable amounts of available soil nutrients (Berthrong *et al.* 2009). Although commercial logging in tropical primary forests appear to have little effect on SOC (Detwiler 1986), repeatedly harvesting biomass of may impair soil productivity and soil fertility in the long term (Berthrong *et al.* 2009). One suggested management method mitigating potential impacts on forest soils is to avoid the removal of harvest residues. Sustainable harvest practices would 'slow soil compaction, erosion, and organic matter loss, maintaining soil fertility to the greatest extent possible' (Berthrong *et al.* 2009). It is, therefore, recommended that the Kikonda FR adopt these practices when the stands reach an age adequate for harvest.

4.5.1 Monocutlure vs. multiculture stands

The Kikonda FR is a monoculture plantation consisting of the hard pine *Pinus caribea*, with some management geared towards the slashing and sheep grazing of weeds. It has been noted that different forest types and tree species will influence SOC levels differently (Paul 2002). Short-rotation deciduous hardwoods established in tropical or subtropical regions will accumulate more C than long-rotation softwoords e.g. *Pinus radiata* (Paul 2002). Broadleaf tree plantations do not appear to affect SOC stocks on former primary forests or pasture land use classes while monoculture Pinus plantations reduce SOC stocks by 12-15% (Guo & Gifford 2002). Nsabimana *et al*. (2008) observed that increases of SOC occurred mainly in mixed stands consisting of mixed native species. This would stand to reason that fast growing *Pinus* species in combination with agroforestry and native species could maintain or improve soil physical and chemical properties. It may be beneficial for the Kikonda FR to experiment with a mixed culture plantation consisting of both broadleaf and conifers in order to assess if SOC stocks improve as a result. The Kikonda FR already has a small planted area consisting of broadleaf trees and future studies into the differences of SOC stocks between the broadleaf and *Pinus* plantations would be beneficial in order to gain a better insight into the dynamics of the SOC pool of the plantation.

4.5.2 Competition between nontree vegetation and trees

Species of shrubs are known to quickly invade disturbed lands; however it is not yet clear how shrubs affect the growth of trees, whether tree growth is inhibited or encouraged (Duncan & Chapman 2003). Duncan & Chapman (2003) conducted a series of experiments involving the affect shrub density had on tree species at the Kibale National Park in Uganda and observed that tree seedlings did not appear to be affected by shrubs, nor was there a correlation between shrub density and height and seedling presence and density. Conversely, a positive correlation between tree sapling presence and density was found between shrub density and height. Experimental shrub removal yielded little response from tree species and despite a temporary increase in tree growth following the removal of all 'nontree' vegetation, the effect appeared to only last for two years before levels returned to what they were prior to removal. Duncan & Chapman (2003) recommend increasing 'facilitation for seedlings' while reducing 'competition for saplings'. This contradicts previous studies that suggest that shrubs did inhibit tree growth, although in subtropical successional forests did increase nutrients in the soil (Li *et al.* 1999) and nontree vegetation in general inhibited tree seedling growth (Berkowitz *et al*. 1995).

4.5.3 Harvesting

Dewar and Cannell (1992) suggested that plantation ecosystems may act as major carbon sinks because of the build-up of SOC, mainly during the first rotation period. However, as previously noted, other studies have suggested that quantities of SOC will decrease following afforestation (Paul 2002). The time of harvest and management methods will also influence SOC quantities (Paul 2002). Johnson and Curtis (2001), via Paul, 2002, investigated the effects of harvesting on changes in SOC in primary forests and concluded that the post harvest period resulted in an approximate 5% increase of SOC in the top soil, most likely 'caused by increased input from slash and roots'. The time of the harvest was not specified in the study, however, and as the study focused on harvesting from a primary forest, it is not directly applicable to the Kikonda FR. However, it does give an indication that SOC levels may increase due to an increase in carbon input as a result from slashing and roots, if left on the forest floor. This further strengthens the argument by Jobbagy & Jackson (2000) that vegetation may be a primary influence in SOC quantities. It would, therefore, be beneficial to conduct a similar study after the first rotation harvest in order to assess changes in SOC content.

4.5.4 Termites

It is not clear in the project documentation what species of termites inhabit the Kikonda FR, however visual observations confirmed that presence of large mounds such as those seen in **Fig. 13**. There appeared to be a higher abundance of termite activity within the planted area towards the east of the Kikonda FR, particularly in the 5 year rotation age class of the reserve. Most large mounds in Uganda are built by termites of the genus *Macrotermes* (Pomeroy 1976) thus it may be assumed that this is the case in the Kikonda FR. Such termite mounds were not apparent in either the secondary forest or the primary forest, at least not to the same level of activity expressed within the investigated planted areas of the Kikonda FR. There is evidence that termite mounds only slightly affect the chemical and physical properties of soils (Pomeroy 1976), however disturbance associated with the constant erosion and reconstruction of above ground nests appear to significantly affect soil physical properties rather than chemical (Wood 1988). Termite mounds 'essentially act as islands of fertility' and as a result induce an indirect or direct heterogeneity through nest building and foraging activities (Sileshi *et al.* 2010). The 5 year rotation contained a large variety of vegetation which may have been influenced by termites and, thus, in turn increased competition for nutrients resulting in overall lower SOC levels found. However, this is speculation as this study did not focus on the effect of termite mounds on the soils of the Kikonda FR and thus further research may be warranted.

4.5.5 Biochar

The use of biochar ('charcoal or biomass-derived black carbon') in soils as a method of establishing a long term sink for atmospheric carbon dioxide was proposed by Lehmann *et al.* 2006 and there is growing interest in the use of biochar as a method of mitigating the effects of climate change with a number of African nations submitting proposals to the UN for the inclusion of biochar during the next round of climate negotiations (Whitman & Lehman 2009). The conversion of biomass to biochar has been proposed before, however not towards soils in terrestrial ecosystems (Lehmann *et al.* 2006). Lehmann *et al.* (2006) concluded that the conversion of biomass C to biochar C significant increased C sequestration (50% of initial C) compared to tradition burning (3%) and biological decomposition (<10–20% after 5–10 years) thus yielding more stable and higher quantities of SOC vs. burning or direct application of biomass. If the application of biochar can be applied to a large enough scale within the Kikonda FR, it may be possible to increase C sequestration to a high enough level that consideration of the inclusion of SOC into the REDD+ scheme may be possible.

Apart from the positive effect increasing the sequestration of C, biochar has also been shown to enhance plant grown by increasing soil fertility as well as improving on the physical, chemical and biological properties of soils (Lehmann *et al.* 2006, Whitman & Lehman 2009). With an increase of soil fertility and nutrients, it may be assumed that the *Pinus caribea* stands may increase productivity thus increasing potential economic benefits. Additionally, Whitman & Lehman (2009) proposed that small scale biochar systems 'with net emission reductions may hold a key for Africa to engage with the international offset mechanisms and open the door to soil carbon sequestration projects'.

4.6 Comments on the inclusion of SOC in the REDD+ scheme on a local scale at the Kikonda FR

Tropical deforestation accounts for a larger release of carbon and the release of carbon from soils is small when compared with vegetation loss and fossil fuel emissions (Detwiler 1986, Jobaggy & Jackson 2000). In this context, the potential for attaining carbon credits under the REDD+ scheme makes sense when applied to above ground biomass. The REDD+ scheme is still considered controversial with both critics and supporters highlighting the impacts the scheme may have such as an overestimation of carbon stocks in forests and the impact on both the biophysical and socioeconomic spheres (Caplow *et al.* 2011).

Changes in SOC with afforestation can be significant on a regional or national scale (Paul *et al.* 2002) however, at the time, there does not seem to be enough ample evidence to encourage the Kikonda FR approaching the use of SOC in this way. The results, albeit short term, data does not strengthen the argument that incorporating SOC within the REDD+ framework on a local scale is viable at this time as no significant differences in %SOC at 0-60 cm were detected between the different land use classes (**Fig. 17**), with the exception of the Primary forest as a result of the ANOVA on ranks and lower SOC stocks (**Fig. 24**). A difference between the Primary forest and the other land use classes was expected, however higher quantities of SOC should have been present.

As the oldest stand is only 8 years old, it may be the case that over time higher SOC stocks may manifest. Additionally, studies have shown that, with proper management, SOC stocks may increase after the first initial harvest (Paul *et al.* 2002). As SOC sequestration in afforestation has temporal variation associated, generally there is an initial decrease in SOC before a gradual increase (Paul *et al.* 2002). In the case of agriculture soils, changes within the top 30 cm occur after approximately 30 years to levels greater than previously. Previous land use, and to a lesser extent climate and forest type influence the extent of change in soil C.

The results suggest that SOC levels will not, within the short term, increase when converted from bushland to a plantation. The collected data provides no evidence that SOC levels will increase after planting seedlings when the results from the cleared area are compared to the other rotations. Had Kikonda FR included former agricultural lands, then perhaps an increase in SOC would have occurred as there is evidence that this happens (Post & Kwon, 2000).

Conversely, commercial logging and harvesting does not appear to have a large impact on long term decreases in SOM (Houghton 2001) and as a result the eventual incorporation of SOC under the REDD+ scheme may be possible in the long term. However, the data collected within this report is too short term to make any viable conclusions on this matter.

4.7 Limitations

It was not possible to produce a larger sample set, due to time constraints, and as the results show there is a considerable amount of variability within some of the age and land use classes. Furthermore, it was difficult to locate comparable studies that deal with factors that influence forest SOC stocks in Eastern Africa as the bulk of the studies in the region deal with a shift from forest to arable lands.

It was difficult to assess the change in SOC quantities at the Kikonda FR in relation to other similar studies due to a lack of available material. Studies tended to focus on the land use changes occurring as a result of deforestation in Eastern Africa as opposed to afforestation. Comparable studies were used when possible, such as Zinn *et al.* (2005) and Kadeba & Aduayi (1985), however the environmental conditions did not completely reflect those found at the Kikonda FR.

The inclusion of an arable land use class close to the Kikonda FR would have been beneficial as it would have made a comparison of the effects of deforestation vs. afforestation more easily attainable. In addition, as many studies focus on arable land use classes in relation to SOC, it would have made easier a more comprehensive study of the effects of changing land use classes in the Kikonda area. Traditionally, arable lands are chosen as they exhibit the best conditions for crop growth where as nearby secondary forests are not cultivated due to poorer conditions (Bruun *in comm.* 2010). In addition to the lack of an arable land use class, it would have been advantageous to have had access to a primary forest closer to the Kikonda FR as opposed to the Budongo FR approximately 70 km to the Northeast in order to draw a better comparison of different land use classes within the Kikonda area.

The %SOC results are considered by the author to be more reliable than the SOC stock results due to the discrepancies in the bulk density data. Overall, the bulk density appears lower than expected, based on previous results collected by Baur (2007) and there appears to be a great deal of variability. Therefore, the results should be approached extremely cautiously and SOC stocks are most likely higher than reported. Conversely, the %SOC results appear to mostly mirror the results of the SOC stocks in terms of significant differences.

Baur (2007) conducted a soil survey at the Kikonda FR and in order to produce results that could be compared to Baur (2007) within the scope of this study, replicate samples were taken in the cleared area; site 1; pit 1 (labeled as Kikonda Soil Profile 2 in Baur 2007). The findings in Baur (2007) show that the bulk density, at 0-10 cm, was 1.28 g/m^3 compared to mean 0.9 g/m^3 (**Appendix 5**), a 29.7% decrease from the results in Baur (2007). Furthermore, differences in soil texture analysis resulted between this study and Baur (2007). Due to a lack of large enough samples, the soil texture analysis conducted in this study was based on composite (0-60 cm) samples where as Baur (2007) conducted a texture analysis based on horizons. Despite this, a higher %sand (70%, **Table 9**) was detected compared to Baur (0-10 cm, 64% sand; 10-60 cm, 56% sand) was found at cleared area; site 1; pit A.

The methodology used for texture analysis was based on the grind and sieve method (*section 2.4.2*). Results from the estimation of silt and clay fractions may not be as accurate as had the soil particles been dispersed in a sodium pyrophosphate solution. Several limitations, with the utilized method, have been noted in the past by Day (1965). The probability of a particle passing through a sieve is dependent on ‘the nature of the particle, the number of particles of that size, and the properties of the sieve’. Furthermore, Particle shape and sieve opening shape affect the probability of passage. As mesh sizes are generally unequal in size an extended length of time for shaking is necessary in order to ensure all particles are able to pass through. Particles shapes may only allow passage in one orientation, except after extensive shaking. (Gee & Bauder 1986). There is still a possibility that sand fractions may have been over estimated due to the possibility of highly aggregated, stable clay soils behaving like coarse sands (Borggaard & Elberling 2003). Lastly, this methodology only allowed for an analysis of the sand fraction and the silt+clay fraction and therefore it was not possible, at this time, to accurately classify the soil texture using **Fig. 16**. It is assumed that the lower the sand fraction, the higher the clay fraction will be, however it is possible to have a high silt content but a low clay content (e.g. loam). The texture analysis was based on composite samples due to a lack of samples. It would have been beneficial to have had texture results from all depths as to determine whether or not there is a correlation between texture and %SOC at the different depths.

5. Conclusion

The study showed that, compared to the Primary forest, tree plantation activities may have a negative impact on %SOC, however the difference is not significant in the top 20 cm of soil. Deeper depths would not have been affected by the plantation activities at Kikonda FR. Higher soil volume of the land use classes within the Kikonda area equates with higher overall SOC stock quantities despite a higher concentration of %SOC in the Primary forest of the Budongo FR. Tree plantations may act as an important C sink and, although anthropogenic activities most likely outweigh any mitigating effects offered by forests, may contribute significantly to reducing C in the atmosphere. As SOC is a key soil resource, sustainable activities are naturally encouraged. SOC is important for both plant growth and soil structural stability. This is especially true for Ugandan soils which are highly weathered, old soils and particularly vulnerable to degradation.

Although no apparent short term significant differences in %SOC or SOC stocks were found between the planted areas and the cleared area, the potential of increased SOC storage following the conversion of bushland on the Kikonda FR to forest could manifest itself in the long term. Larger differences arose at deeper depths, however, SOC was unlikely affected by land use change past 20-30 cm depth. The data also suggests that %C in the litter layer increases linearly with stand age.

There appears to be discrepancies between studies dealing with the result of increased or decreased SOC storage and, as of such, it have been shown that monoculture afforesation does not always lead to increases of SOC (Lal 2004) nor does increased production of forest biomass necessarily increase SOC stocks (Lal 2005). Regardless, the scope of this project was too short term to offer a concrete conclusion on whether or not the activities of the Kikonda FR will increase SOC based on the collected data. In theory, increases of SOC should begin to manifest itself in the long term and, as there is no evidence suggesting the plantation stands decreases SOC, it is encouraged to continue production. Increases of SOC may be possible if Kikonda FR alters its management practices to include mixed native species within the Pine plantations. Additionally, the use of biochar may also increase SOC quantities.

It would be beneficial to conduct a follow up survey, at the same coordinates as the investigated sites, in order to see how %SOC and SOC stocks may have changed over time as there are few studies that convincingly demonstrate the time required for a new equilibrium carbon content to occur after a change in land use and to what depth the change in land use would take effect (Bruun *in comm.* 2011, de Neergaard *in comm.* 2011).

Suggestions for future studies:

- Changes in %C in the litter layer overtime. E.g. 8 and 5 year rotations has higher %C than the secondary forest but the 3 year rotation does not. Will %C increase in the 3 year rotation over time?
- Comparison of SOC dynamics in broadleaf and pine within the planted areas.
- Experiment with mixed species plantation (pine plus native species).
- Effect of termite mounds on SOC.
- Sampling from bushland and arable land use classes.
- Effect on SOC quantities within the top soil after the first harvest.

6. Acknowledgements

I would like to sincerely thank the following people for their guidance and assistance, without which this thesis would not have been possible. The fieldwork was supported by the International Woodland Company and Global Woods A/G. Thank you to Dr. Mogens Pedersen (IWC) and Esben Brandi (IWC) and Mathias Baldus (GW) for arranging the opportunity to conduct my research. Further thanks to Johannes Mokwena (GW) and the entire staff at the Kikonda FR for onsite assistance & guidance during the fieldwork and in making me feel so welcome. Dr. Ateenyi Twaha Ali Basamba (Dpt. of Soil Sciences at Makerere University) provided excellent guidance and assistance throughout the entire project. Bo Elberling (Dpt. of Geology and Geography at the Uni. of CPH) for help in data analysis and providing the facilities to conduct analysis of the physical soil properties. Prof. Winfried Blum provided advice and comments on the final draft of this thesis. Thank you to Dr. Andreas de Neergaard for introducing me to IWC and arranging the opportunity to conduct research in Uganda and for the supervision of the entire project. My most sincere gratitude is extended towards Dr. Thilde Bech Bruun for advice in data collection, help in data analysis, reviewing various drafts of this thesis and, in general, being an excellent supervisor.

7. References

Baur, M. 2007. Soil description as the basis for soil classification, soil and site assessment and suitability evaluation for planting Pinus Caribaea and/or other species at the Kikonda Forest Reserve in the north-west of Uganda. BSc Thesis, Larenstein University of Professional Education. 69 p.

Berkowitz, A. R., Canham, C. D., and Kelly, V. R. 1995. Competition vs. facilitation of tree seedling growth and survival in early successional communities. Ecology 76, pp.1156–1168.

Berthrong, S. T., Jobbagy, E. G, and Jackson, R. B. 2009. A global meta-analysis of soil exchangeable cations, pH, carbon, and nitrogen with afforestation. Ecological Applications19, pp. 2228-2241.

Borggaard, O. K. & Elberling, B. 2003. Biogeochemistry in a pedological context. Holte: Holte bogtrykkeri A/S.

Brady, N. C. & Weil, R. R. 2004. Elements of the nature and properties of soils (2nd Ed.). Upper Sadle River, New Jersey, Pearson Prentice Hall.

Bruun, T. B., de Neergaard, A., Lawrence, D., and Ziegler, A. D. 2009. Environmental consequences of the demise in Swidden Cultivation in Southeast Asia: Carbon Storage and Soil Quality. Human Ecology Vol. 37, pp. 375-388.

Borchers, J. G. & Perry, D. A. 1992. The influence of soil texture and aggregation on carbon and nitrogen dynamics in southwest Oregon forests and clearcuts. Candian Journal of Forest Research vol. 22 (3), pp. 298-305.

Caplow, S., Jagger, P., Lawlor, K. and Sills, E. 2011. Evaluating land use and livelihood impacts of early forest carbon projects: Lessons for learning about REDD+. Environmental Science and Policy Vol. 14 (2), pp. 152-167.

CarbonFix Standard (2010). Kikonda Forest Reserve, Available at http://www.carbonfix.info/Project/Projectslist.html?itemid=69&ipage=0. (Accessed: 05/03/2010).

Central Intelligence Agency (2009). "Uganda". The World Factbook. Available at https://www.cia.gov/library/publications/the-world-factbook/geos/ug.html. (Accessed: 23/01/2010).

Christensen, B. T. 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. Advanced Soil Science Vol. 20, pp. 1–89.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Hillsdale, NJ: Erlbaum.

Muñoz, C., Ovalle, C. and Zagal, E.. 2007. Distribution of Soil Organic Carbon Stock in an Alfisol Profile in Mediterranean Chilean Ecosystems. R.C.Suelo Nutr. Veg. Vol. 7 (1), pp. 15-27.

Day, P. R. 1965. Soil texture. In C. L. Black, editor. Methods of soil analysis. Part 2. Agronomy Vol. 9, pp. 545-567.

Detwiler, R. P. 1986. Land use change and the global carbon cycle: the role of tropical soils. Biogeochemistry 2, pp. 67-93.

Dewar, R.C. & Cannell, M. G. R.. 1992. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry Vol. 20, pp. 161-171.

Diaz, S., Hector, A. and Wardle, D. A. 2009. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Current Opinion in Environmental Sustainability 2009, 1: pp 55–60.

Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexler, M. C. and Wisniewski, J. 1994. Carbon Pools and Flux of Global Forest Ecosystems. Science 263, pp. 185-190.

Dodd, M. B., Lauenroth, W. K., Burke, I. C. and Chapman, P. L. 2000. Associations between vegetation patterns and soil texture in the shortgrass steppe. Plant Ecology 158 (2), pp. 127-137.

Duncan, R. B. and Chapman, C. A. 2003. Tree–Shrub Interactions During Early Secondary Forest Succession in Uganda. Restoration Ecology Vol. 11 (2), pp. 198–207.

FAO (Food and Agricultural Organization of the United nations) 2005. FAO statistical database available at http://faostat.fao.org/ (Accessed 02/03/2010)

Fisher, R.F., 1995. Amelioration of degraded rain forest soils by plantations of native trees. Soil Science Society American Journal Vol. 59, 544-549.

Gee, GW and JW Bauder. 1986. Particle-size analysis. p. 383-411. *In* A Klute (ed.) Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Agronomy Monograph No. 9 (2ed). American Society of Agronomy/Soil Science Society of America, Madison, WI.

Gibbs, H. K., Brown, S., Niles, O. J. and Foley, J. A. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2, 13 pp.

Houghton, R. A. 2005. Tropical deforestation as a source of greenhouse gas emissions. Tropical Deforestation and Climate Change (ed. Mutinho and Schwartzman) (Belem: IPAM).

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinen, K. and Byrne, K. A. 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, pp. 253 – 268.

Jia, S., Xiubin, H., and Fangqiang, W. 2007. Soil organic carbon loss under different slope gradients in loess hilly region. Wuhan University Journal of Natural Sciences Vol. 12 (4), pp. 695-698.

Jobbagy, E. G. & Jackson, R. B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10(2), pp. 423 – 436.

Juo A.S.R., Manu, A., 1996. Nutrient effects on modification of shifting cultivation in West Africa. Agric. Ecosys. Env. 58, 49-60.

Kadeba, O. & Aduayi, E. A. 1985. Impact on soils of plantations of *Pinus caribaea* stands in natural tropical savannas. Forest Ecology and Management Vol. 13 (1-2), pp. 27-39.

Kaonga, M. L. & Bayliss-Smith, T. P. 2008. Carbon pools in tree biomass and the soil in improved fallows in eastern Zambia. Agrifirestry Systems 76 (1), pp. 37-51.

Karani, P.K. 1999. reviewed 2007. Management Plan for the Kikonda Forest Reserve, Kiboga District, Uganda. Available at http://www.piqqoprojects.com/projects/view/project/51. (Accessed 05/03/2010).

Kauppi, P. & Sedjo, R. 2001. Technical and economic potential of options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. Climate Change 2001: mitigation (ed. B. Metz, O. Davidson, R. Swart & J. Pan). Contribution of Working Group III to the Third Assessment Report of the IPCC. (Cambridge University Press).

King, J.A., Campbell, B.M., 1994. Soil organic matter relations in five lands cover types in the iombo region (Zimbabwe). Forest Ecology Management 67, 225-239.

Klooster, D. 2010. Standardizing sustainable development? The Forest Stewardship Council's plantation policy review process as neoliberal environmental governance. Geoforum 41(1), pp. 117 - 129.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. Geoderma Vol. 123 (1-2), pp. 1-22.

Lal, R. 2005. Forest soils and carbon sequestration. Forest Ecology and Managements 220, pp. 242 - 258.

Lal, R. & Lorenz, K. 2009. Carbon sequestration in forest ecosystems. New York: Springer.

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lehmann, J., Gaunt, J., and Rondon, M. 2006. Bio-char sequestration in terrestrial ecosystems - A review. Mitigation and Adaptation Strategies for Global Change Vol. 11, pp. 403-427.

Li, X. D., andWilson, S. D. 1998. Facilitation among woody plants establishing in an old field. Ecology 79, pp. 2694–2705.

Lorenz, K. & Lal, R. 2009. Carbon sequestration in forest ecosystems. London, Springer.

McFeeE, W.W. & Stone, Jr. E.L. 1968. Ammonium and nitrate as nitrogen sources for *Pinus radiata* and *Picea glauca*. Soil Science Society Amer. Proc. 32, pp. 879-884.

Medina, E. & Cuevas, E. 1989. *Mineral Nutrients in Tropical Forest and Savanna Ecosystems* (ed. Proctor, J.) 217−240. Blackwell Scientific, Oxford, England.

Mwavu, E. N. 2007. Human impact, plant communities, diversity and regeneration in Budongo Forest Reserve, Northwestern Uganda. PhD Thesis. University of Witwatersrand.

Mwavu, E. N. & Witkowski, E. T. F. 2008. Land-use and cover changes (1988-2002) around budongo forest reserve, NW Uganda: implications for forest and woodland sustainability. Land Degradation & Development 19 (6), pp. 606-672.

Niles, J. O. 2002. Tropical forests and climate change. Climate Change Policy: a survey (ed. S. Schneider, A. Rosencranz & J. Niles). (Washington, DC: Island press).

Niles, J. O., Brown, S., Pretty, J., Ball, A. S. and Fay, J. 2002. Potential Carbon Mitigation and Income in developing Countries from Changes in Use and Management of Agricultural and Forest Lands. Philosophical Transactions: Mathematical, Physical and Engineering Sciences 360 (1797), pp 1621-1639.

Parton, W. J., J. M. O. Scurlock, D. S. Ojima, T. G. Gilmanov, R. J. Scholes, D. S. Schimel, T. Kirchner, J-C. Menaur, T. Seastedt, E. Garcia Moya, A. Kamnalrut, and J. I. Kinyamario. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochemical Cycles Vol. 7, pp. 785–809.

Paterson, J. D. 1991. The Ecology and History of Uganda's Budongo Forest. Forest & Conservation History 35 (4), pp. 179-187.

Paul, K. I., Polglase, P. J., Nyakuengama, J G. and Khanna, P. K. 2002. Change in soil carbon following afforestation. Forest Ecology and Management. Vol 168 (1-3), pp. 241-257.

Pomeroy, D. E. 1976. Some effects of mound-building termites on soils in Uganda. Journal of soil science Vol. 27 (3), pp. 377-394.

Post, W. M. & Kwon, K. C. 2008. Soil carbon sequestration and land-use change. Global Change Biology 6, pp. 317-327.

Project Design Document. 2008. Available at: http://www.piqqoprojects.com/uploads/documents/0/31.pdf/CCBS_KFR.pdf

Sammis, T. (1999). Irrigation Teaching Material. Chapter 5: Bulk density and particle density. Available at: http://weather.nmsu.edu/teaching_Material/soil252/Chapt5.htm

Santilli, M., Mouthino, P., Schwartsman, S., Nepstad, D., Curran, L. and Nobre, C. 2005. Tropical deforestation and the Kyoto protocol. Climate Change 71, pp. 267 – 276.

Sileshi, G. W., Arshad, M. A., Konaté, S. and Nkunika, P. O. Y. 2010. Termite-induced heterogeneity in African savanna vegetation: mechanisms and patterns. Journal of Vegetation Science Vol 21 (5), pp. 923-937.

Silver, W. H., Neff, J., McGrobby, M., Veldkamp, E., Keller, M. and Cosme, R. 2000. Effects of Soil Texture on Belowground Carbon and Nutrient Storage in a Lowland Amazonian Forest Ecosystem. Ecosystems Vol. 3 (2), pp. 193-209.

Skutsch, M.M. & Ba, L. 2010. Crediting carbon in dry forests: The potential for community forest management in West Africa. Forest Policy and Economics. Forest Policy and Economics Vol. 14 (4), pp. 264-270.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sommer, R., Denish, M. and Vlek, P. L. G. 2000. Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. Plant and Soil Vol. 219, pp. 231-241.

Swift, R. S. 2001. Sequestration of Carbon by soil. Science 166 (11), pp. 858 – 871.

Tiessen, H., Salcedo, I. H. & Sampaio, E. V. S. B. *Agric. Ecosyst. Envir.* **38**, 139−151 (1992

Vågen, T. G., Lal, R. and Singh, B. R. 2005. Soil carbon sequestration in sub-saharan Africa: A review. Land Degrad. Develop. 16, pp. 53-71.

Wood, T. G. 1988. Termites and the soil environment. Biology and Fertility of Soils Vol. 6, pp. 228-236.

Whitman, T. & Lehmann, J. 2009- Biochar - One way forward for soil carbon offset mechanisms in Africa? Environmental Science & Policy Vol. 12, pp. 1024-1027.

Yao, M. K., Angui, P. K. T., Konate, S., Tondoh, J. E., Tano, Y., Abbadie, L., Benest, D. 2010. Effects of Land Use Types on Soil Organic Carbon and Nitrogen Dynamics in Mid-West Côte d'Ivoire. European Journal of Scientific Research Vol. 40 (2), pp. 211-222.

Zinn Y. L, Resck, D. V. S, and da Dilva, J. E. 2002. Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil. Forest Ecology and Management Vol. 166 (1-3), pp. 285-294.

Appendix 1: List of abundant trees and shrubs

<u>Trees 9-15 m tall</u>

Acacia hockii	Evergreen
A. polycantha	Evergreen
Albizia coriaria	Deciduous
A. zygia	Deciduous
Allophylus africana	Evergreen
Annona senegalensis	Deciduous
Antiaris toxicaria	Deciduous
Bridelia micrantha	Evergreen
Combretum collinum	Deciduous
C. ghasalense	Deciduous
Erythrina abyssinica	Deciduous
Ficus capensis	Deciduous
F. gnaphalocarpa	Deciduous
Funtumia africana	Evergreen
Gardenia ternifolia	Evergreen
Hymenocardia acida	Evergreen
Lannea kerstingii	Deciduous
Markhamia lutea	Evergreen
Phoenix reclinata	Evergreen
Piliostigma thonningii	Evergreen
Prunus africana	Evergreen
Sapium ellipticum	Evergreen
Stereospermum kunthianum	Deciduous
Vepris nobilis	Evergreen
Terminalia glaucescens	Deciduous
Vernonia amuyydalina	Evergreen
Vitex doniana	Deciduous

<u>Herbs</u>

Acalypha villicaulis	Evergreen
Afromomum sanguineum	Evergreen
Asparagus pauli- guilelmi	Evergreen
Hoslandia opposita	Evergreen
Crotalaria spp	Evergreen

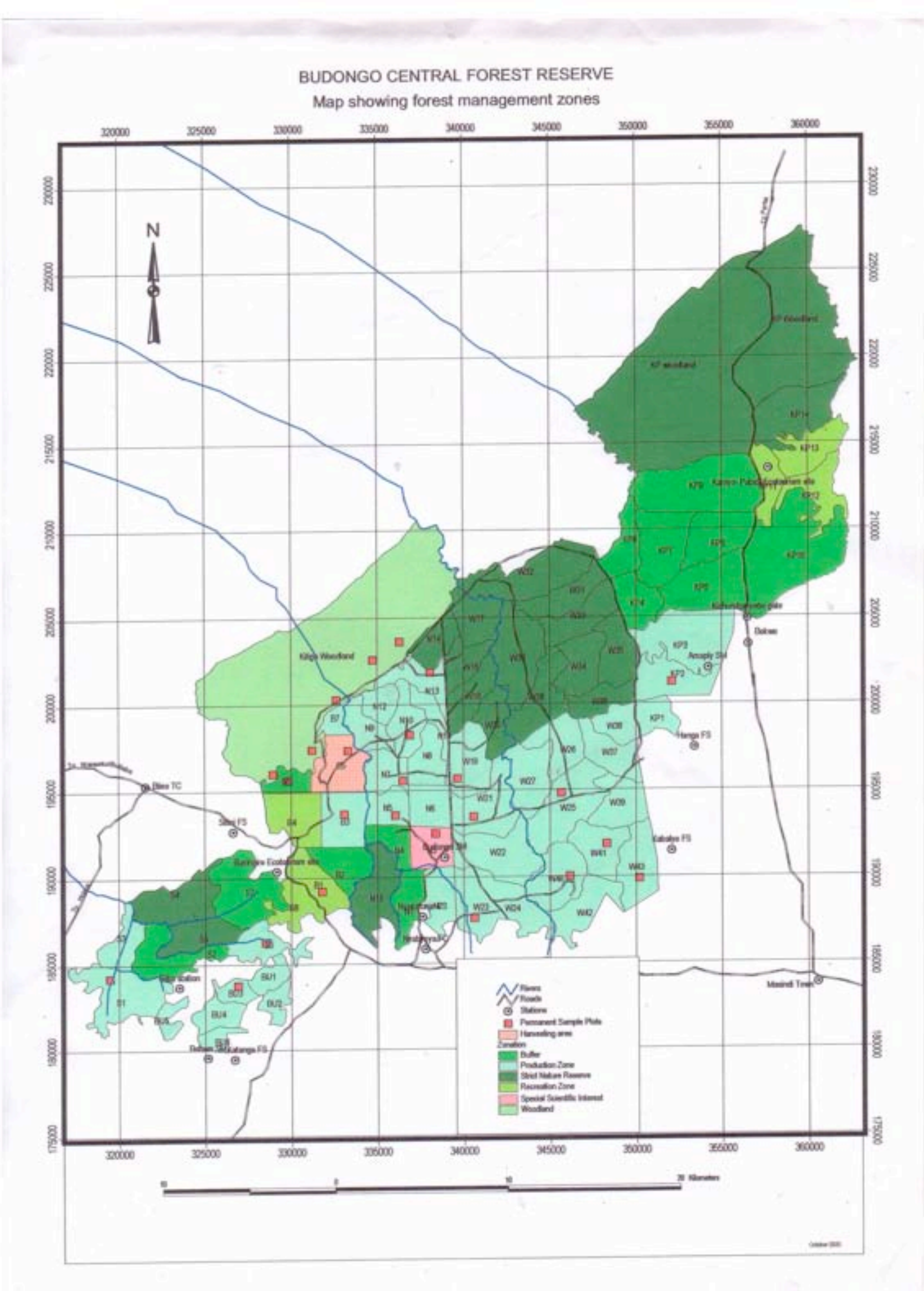
<u>Shrubs up to 5m tall</u>

Capparis edulis	Evergreen
Grewia mollis	Evergreen
Harrisonia abyssinica	Evergreen
Protea modiensis	Evergreen
Rhus natalensis	Evergreen
Securidaca longipendulata	Evergreen
Ziziphus abyssinica	Evergreen

Grasses
Brachiaria decumbens
Cymbopogon afronardus
Cynodon dactylon
Hyparrhemia dissoluta
H. filipendula
Imperata cylindrica
Leersia hexandra
Loudetia arundinacea
L. superba
Microchloa kunthii
Panicum maximum
Pennisetum parpureum
Setaria chevalieri
S. sphacelata

N.b. All grasses are during the dry season

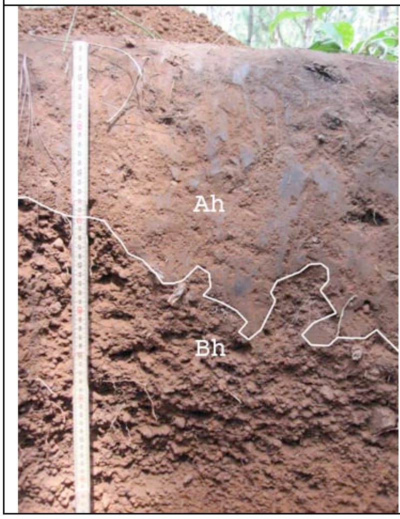
Appendix 2: Map of Budongo Nature Reserve

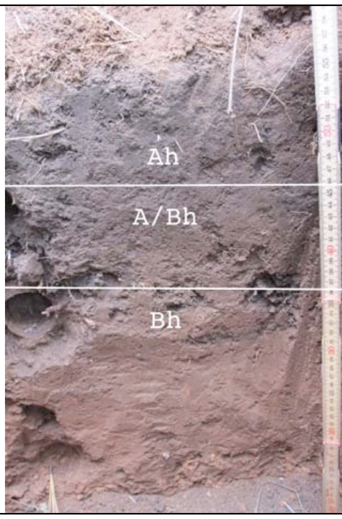


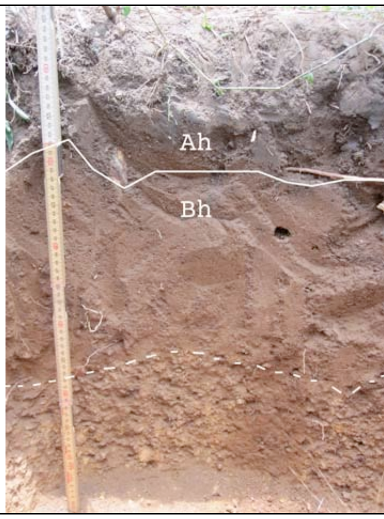
(source: http://www.jgiuganda.org/projects_budongo.html?src=mappery)

Appendix 3: Soil profile descriptions

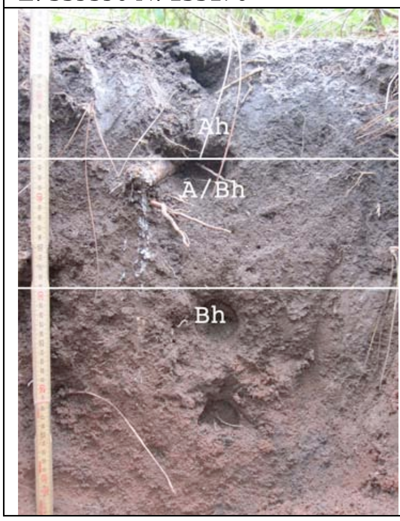
8 year – Site 1 - A	**8 year – Site 1 - B**	**8 year – Site 1 - C**
SOC t/ha: 35.6 Silt+Clay: 20% - Sand: 80% E: 339403 N: 133183	SOC t/ha: 58.3 Silt+Clay: 39% - Sand: 61% E: 339402 N: 122173	SOC t/ha: 40.5 Silt+Clay: 38% - Sand: 62% E: 339391 N: 133160

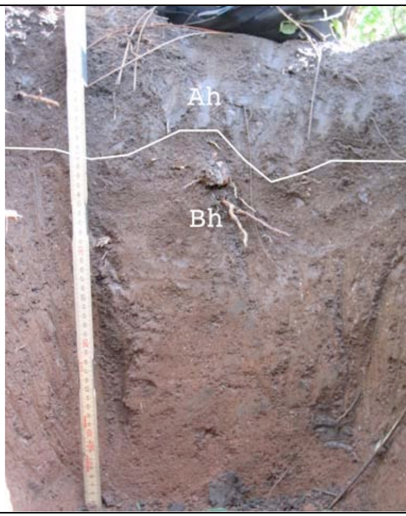


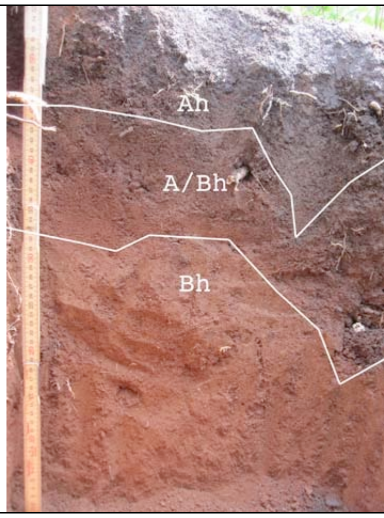




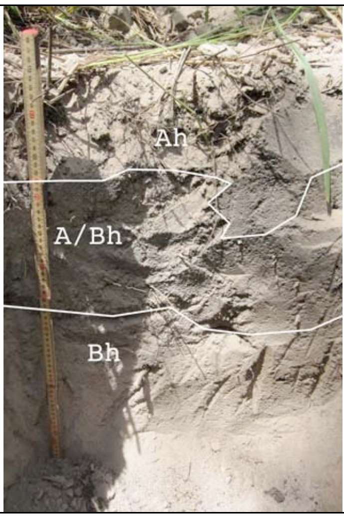
8 year – Site 2 - A	**8 year – Site 2 - B**	**8 year – Site 2 - C**
SOC t/ha: 84.2 Silt+Clay: 37% - Sand: 63% E: 339590 N: 133170	SOC t/ha: 58.7 Silt+Clay: 34% - Sand: 66% E: 339601 N: 122161	SOC t/ha: 58.0 Silt+Clay: 34% - Sand: 66% E: 339578 N: 133211

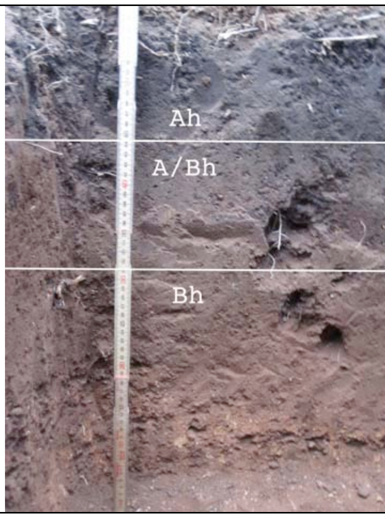




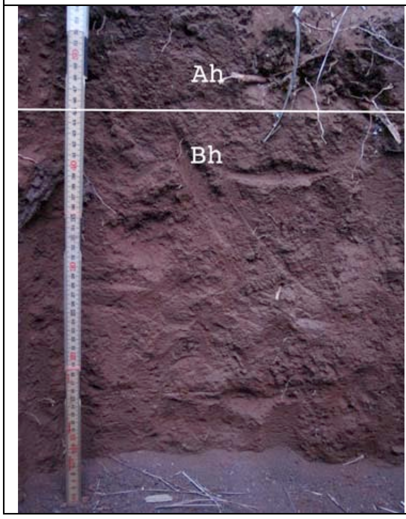


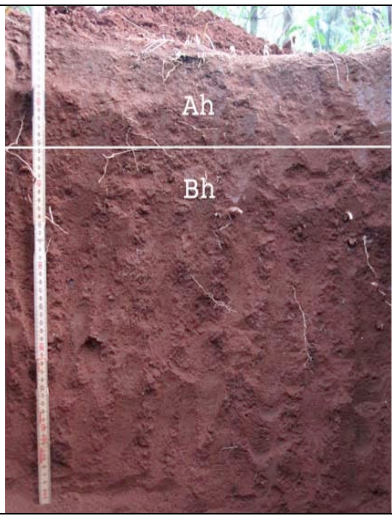
8 year – Site 3 - A	**8 year – Site 3 - B**	**8 year – Site 3 - C**
SOC t/ha: 19.5 Silt+Clay: 24% - Sand: 76% E: 339283 N: 133116	SOC t/ha: 35.5 Silt+Clay: 34% - Sand: 66% E: 339293 N: 133096	SOC t/ha: 19.8 Silt+Clay: 20% - Sand: 80% E: 339306 N: 133113

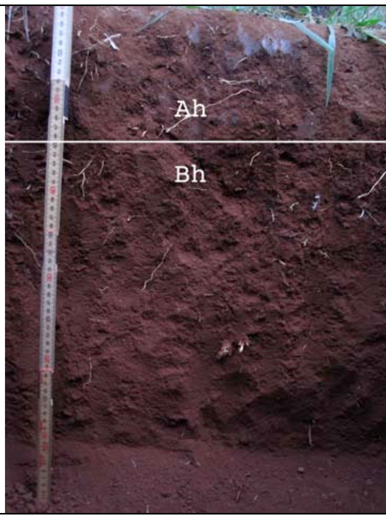




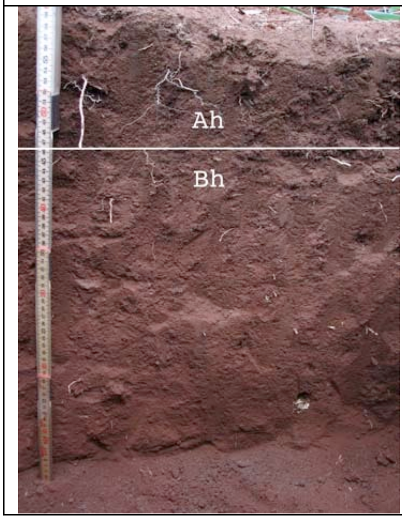
5 year – Site 1 - A	**5 year – Site 1 - B**	**5 year – Site 1 - C**
SOC t/ha: 57.0 Silt+Clay: 34% - Sand: 66% E: 339739 N: 134104	SOC t/ha: 46.2 Silt+Clay: 24% - Sand: 76% E: 339734 N: 134101	SOC t/ha: 42.7 Silt+Clay: 22% - Sand: 78% E: 339729 N: 134097

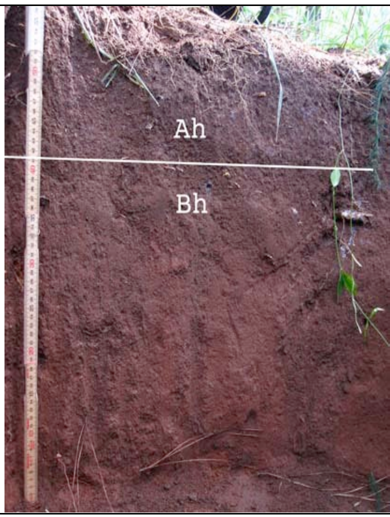


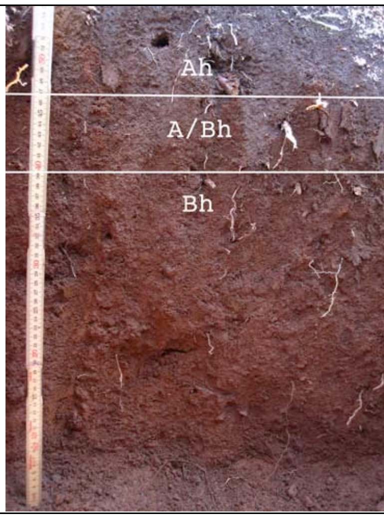




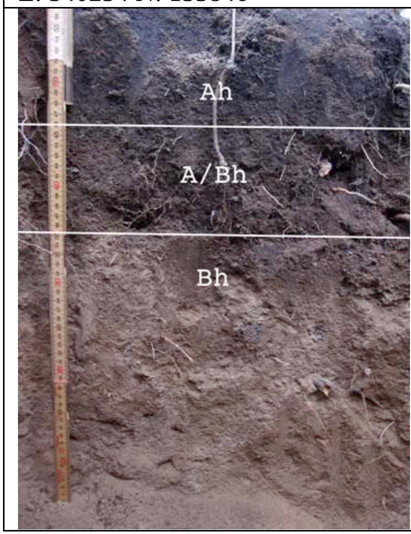
5 year – Site 2 - A	**5 year – Site 2 - B**	**5 year – Site 2 - C**
SOC t/ha: 45.2 Silt+Clay: 21% - Sand: 79% E: 340069 N: 134257	SOC t/ha: 49.2 Silt+Clay: 34% - Sand: 66% E: 340040 N: 134265	SOC t/ha: 46.9 Silt+Clay: 21% - Sand: 79% E: 340071 N: 134228

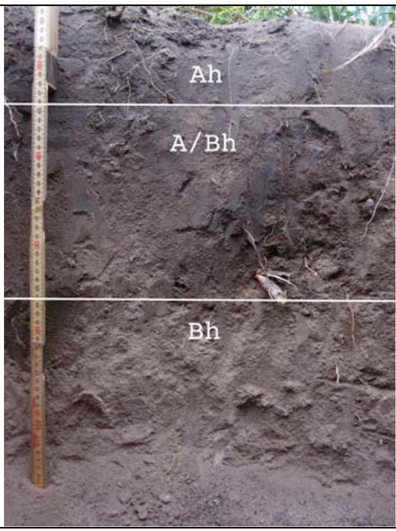


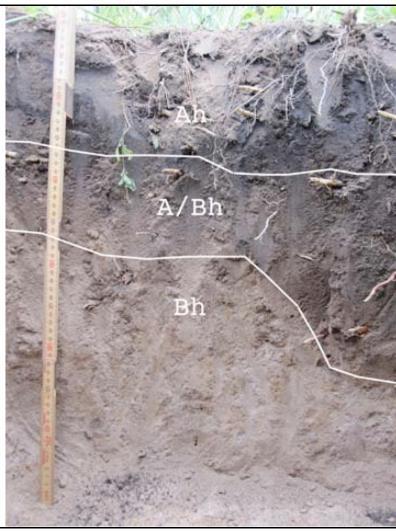


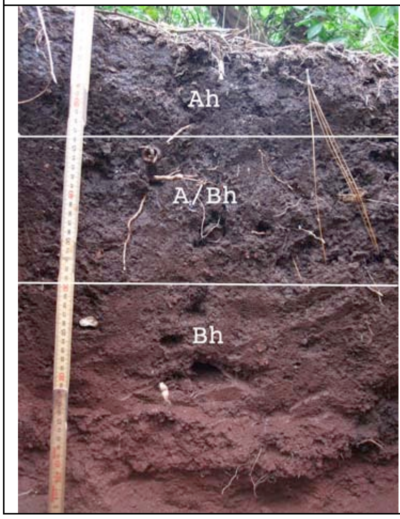
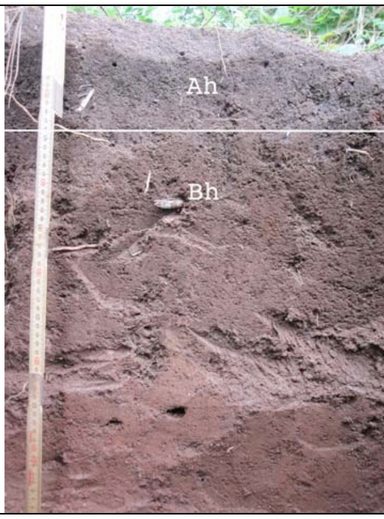


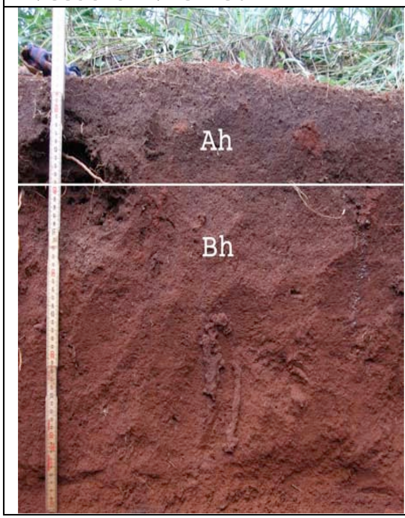
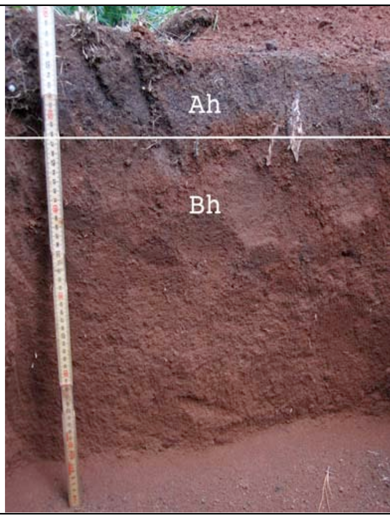
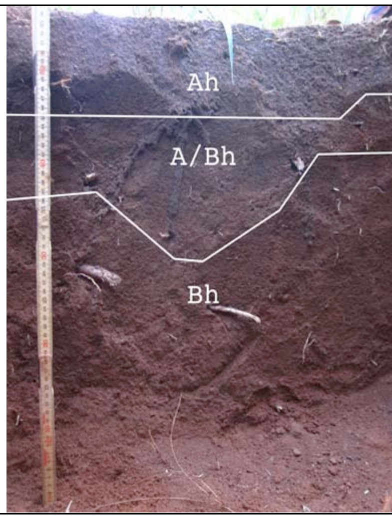
5 year – Site 3 - A	**5 year – Site 3 - B**	**5 year – Site 3 - C**
SOC t/ha: 13.4 Silt+Clay: 38% - Sand: 62% E: 340234 N: 133846	SOC t/ha: 29.5 Silt+Clay: 24% - Sand: 76% E: 340212 N: 133874	SOC t/ha: 35.6 Silt+Clay: 34% - Sand: 66% E: 339578 N: 133211

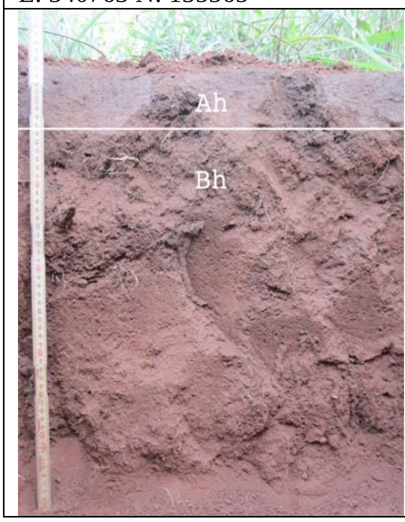
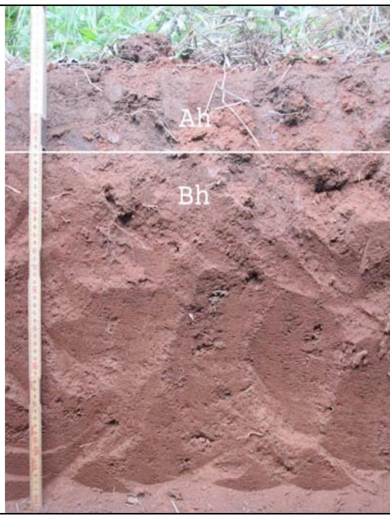
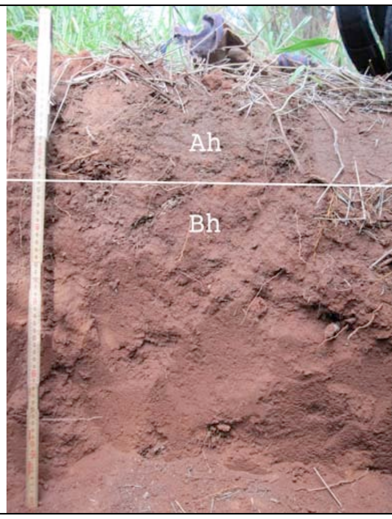




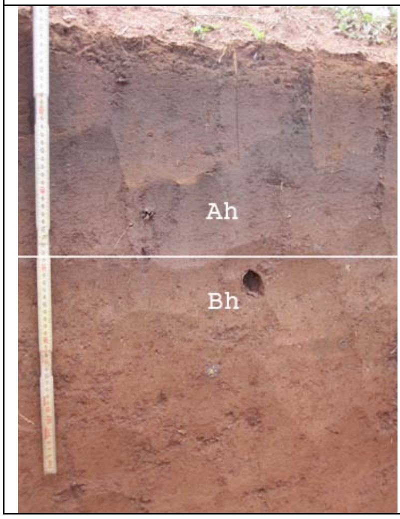


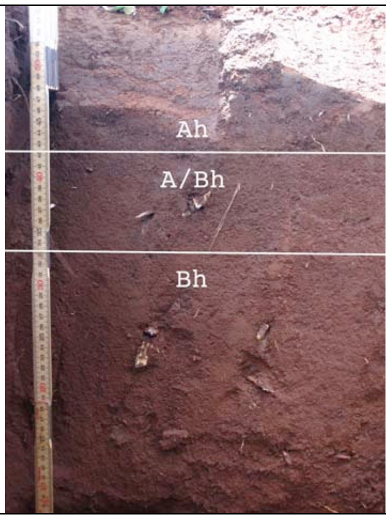
3 year – Site 1 - A	**3 year – Site 1 - B**	**3 year – Site 1 - C**
SOC t/ha: 79.6 Silt+Clay: 31% - Sand: 69% E: 340053 N: 132802	SOC t/ha: 58.3 Silt+Clay: 30% - Sand: 70% E: 340079 N: 132796	SOC t/ha: 52.4 Silt+Clay: 30% - Sand: 70% E: 340077 N: 132767
		

3 year – Site 2 - A	**3 year – Site 2 - B**	**3 year – Site 2 - C**
SOC t/ha: 58.1 Silt+Clay: 35% - Sand: 65% E: 339829 N: 134430	SOC t/ha: 37.4 Silt+Clay: 29% - Sand: 71% E: 339814 N: 134459	SOC t/ha: 45.6 Silt+Clay: 36% - Sand: 64% E: 339843 N: 134459
		

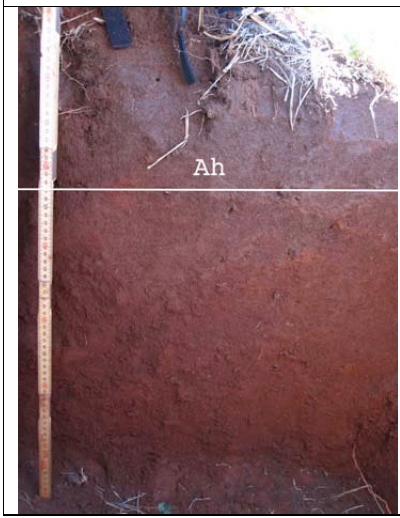
3 year – Site 3 - A	**3 year – Site 3 - B**	**3 year – Site 3 - C**
SOC t/ha: 45.6 Silt+Clay: 33% - Sand: 67% E: 340763 N: 135365	SOC t/ha: 49.2 Silt+Clay: 29% - Sand: 71% E: 340763 N: 135347	SOC t/ha: 59.2 Silt+Clay: 36% - Sand: 64% E: 340738 N: 135353
		

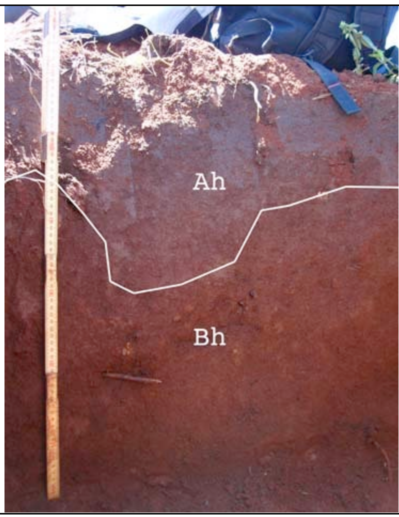
Cleared – Site 1 - A	Cleared – Site 1 - B	Cleared – Site 1 - C
SOC t/ha: 52.7 Silt+Clay: 30% - Sand: 70% E: 342300 N: 135300	SOC t/ha: 42.1 Silt+Clay: 31% - Sand: 69% E: 342301 N: 135271	SOC t/ha: 48.1 Silt+Clay: 32% - Sand: 68% E: 342274 N: 135280

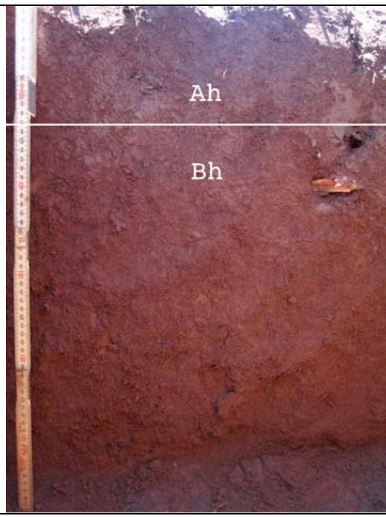




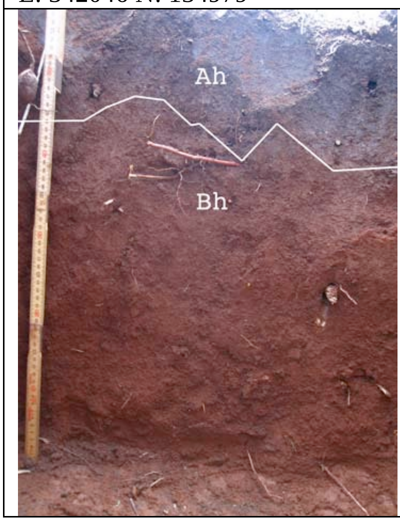
Cleared – Site 2 - A	Cleared – Site 2 - B	Cleared – Site 2 - C
SOC t/ha: 55.3 Silt+Clay: 30% - Sand: 70% E: 342037 N: 135452	SOC t/ha: 60.8 Silt+Clay: 33% - Sand: 67% E: 342033 N: 135424	SOC t/ha: 37.7 Silt+Clay: 26% - Sand: 74% E: 342061 N: 135419

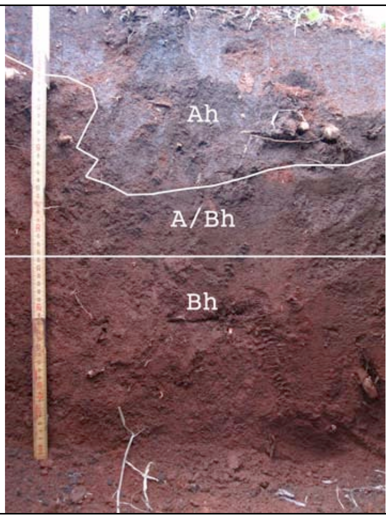


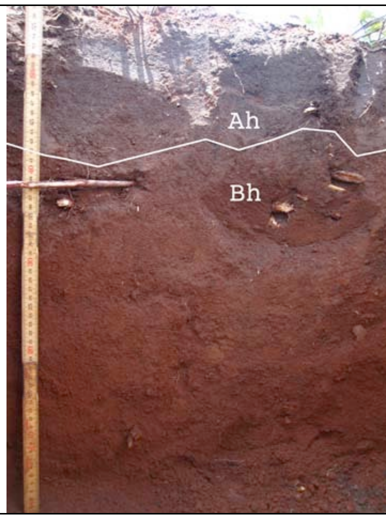




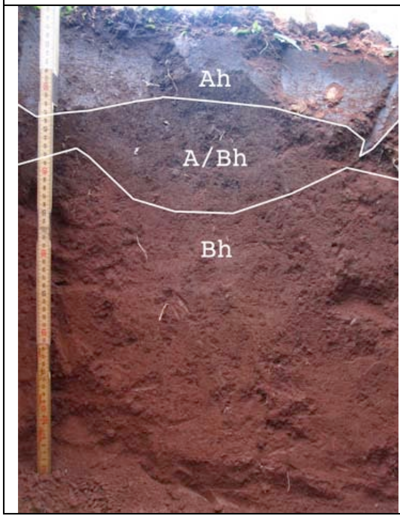
Cleared – Site 3 - A	Cleared – Site 3 - B	Cleared – Site 3 - C
SOC t/ha: 58.9 Silt+Clay: 38% - Sand: 62% E: 342046 N: 134979	SOC t/ha: 55.7 Silt+Clay: 39% - Sand: 61% E: 342046 N: 134979	SOC t/ha: 74.2 Silt+Clay: 42% - Sand: 58% E: 342076 N: 132953





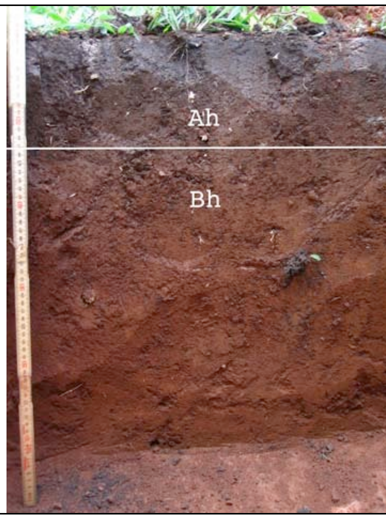


<table>
<tr><th>Secondary forest – Site 1 - A</th><th>Secondary forest – Site 1 - B</th><th>Secondary forest – Site 1 - C</th></tr>
<tr><td>SOC t/ha: 39.7
Silt+Clay: 46% - Sand: 54%
E: 336528 N: 135721</td><td>SOC t/ha: 37.1
Silt+Clay: 36% - Sand: 64%
E: 336525 N: 135754</td><td>SOC t/ha: 51.6
Silt+Clay: 49% - Sand: 51%
E: 336514 N: 135742</td></tr>
<tr><td>



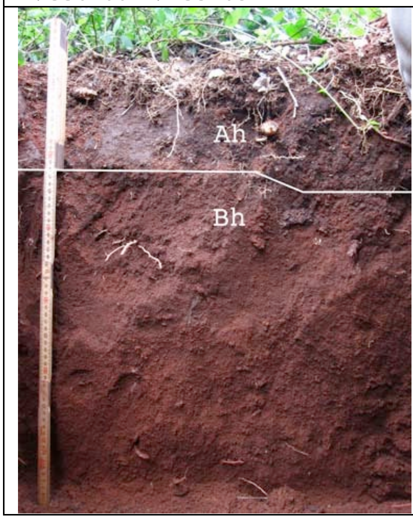
</td><td>

</td><td>

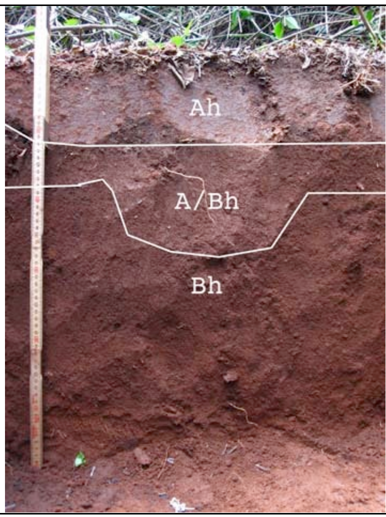


</td></tr>
</table>

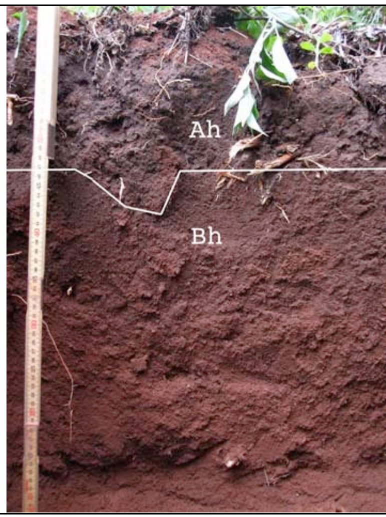
<table>
<tr><th>Secondary forest – Site 2 - A</th><th>Secondary forest – Site 2 - B</th><th>Secondary forest – Site 2 - C</th></tr>
<tr><td>SOC t/ha: 75.9
Silt+Clay: 35% - Sand: 65%
E: 336266 N: 135168</td><td>SOC t/ha: 52.7
Silt+Clay: 34% - Sand: 66%
E: 336287 N: 135174</td><td>SOC t/ha: 59.0
Silt+Clay: 35% - Sand: 65%
E: 336256 N: 135195</td></tr>
<tr><td>



</td><td>

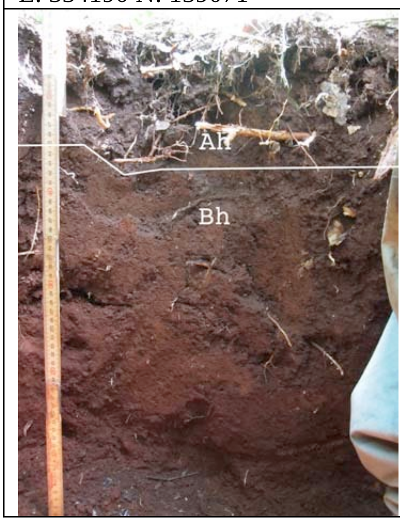


</td><td>

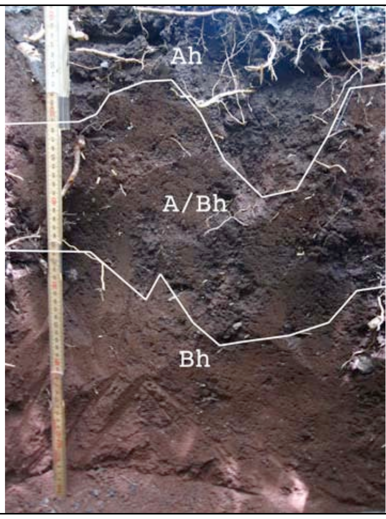


</td></tr>
</table>

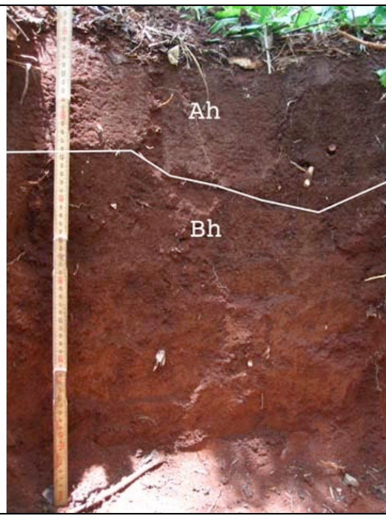
<table>
<tr><th>Secondary forest – Site 3 - A</th><th>Secondary forest – Site 3 - B</th><th>Secondary forest – Site 3 - C</th></tr>
<tr><td>SOC t/ha: 73.0
Silt+Clay: 38% - Sand: 62%
E: 334190 N: 139071</td><td>SOC t/ha: 76.1
Silt+Clay: 37% - Sand: 63%
E: 334176 N: 139088</td><td>SOC t/ha: 67.1
Silt+Clay: 37% - Sand: 63%
E: 334171 N: 139092</td></tr>
<tr><td>



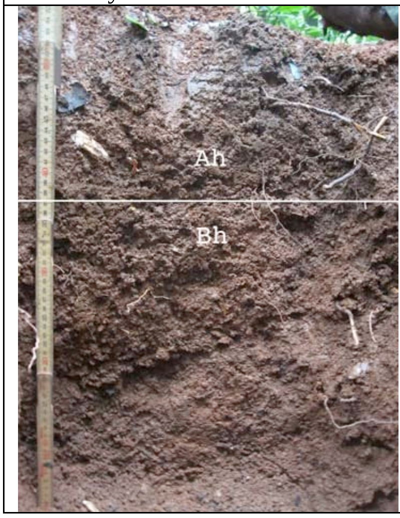
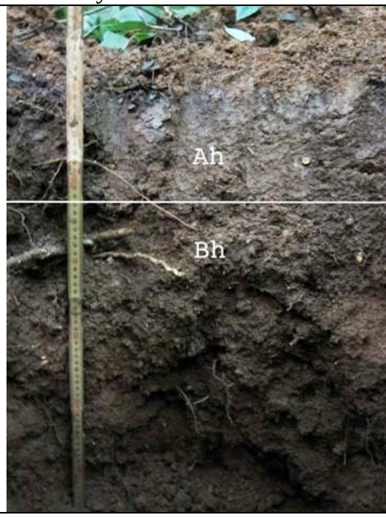
</td><td>

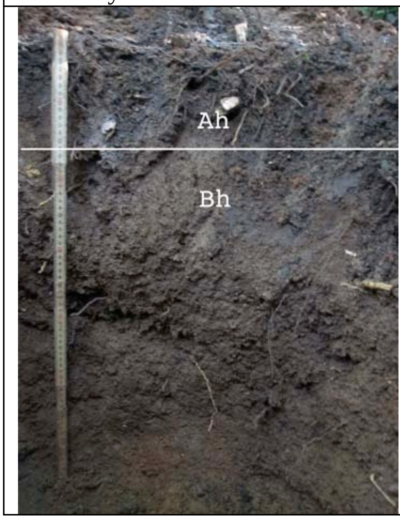
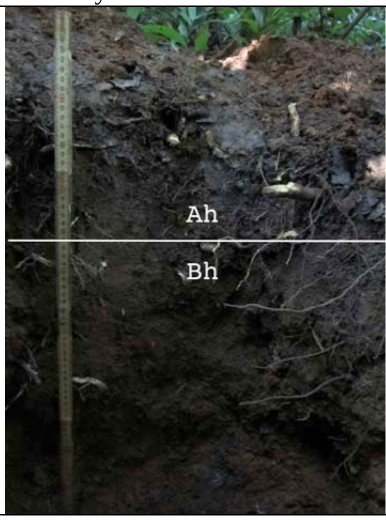
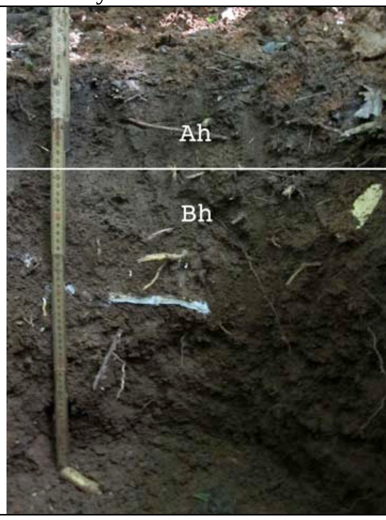


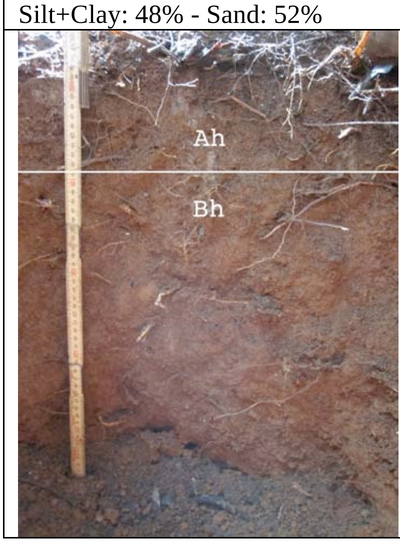
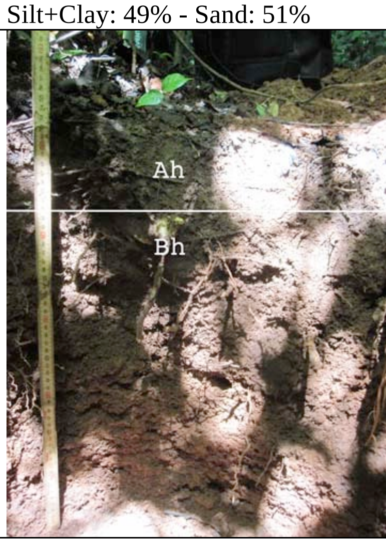
</td><td>



</td></tr>
</table>

Primary forest – Site 1 - A	Primary forest – Site 1 - B	Primary forest – Site 1 - C
SOC t/ha: 19.9 Silt+Clay: 48% - Sand: 52%	SOC t/ha: 31.1 Silt+Clay: 48% - Sand: 52%	SOC t/ha: 31.3 Silt+Clay: 46% - Sand: 54%
	NA	

Primary forest – Site 2 - A	Primary forest – Site 2 - B	Primary forest – Site 2 - C
SOC t/ha: 26.6 Silt+Clay: 47% - Sand: 53%	SOC t/ha: 50.9 Silt+Clay: 45% - Sand: 55%	SOC t/ha: 40.1 Silt+Clay: 46% - Sand: 54%
		

Primary forest – Site 3 - A	Primary forest – Site 3 - B	Primary forest – Site 3 - A
SOC t/ha: 28.2 Silt+Clay: 48% - Sand: 52%	SOC t/ha: 28.6 Silt+Clay: 46% - Sand: 54%	SOC t/ha: 33.3 Silt+Clay: 49% - Sand: 51%
		

Appendix 4: Oven dry weight of samples (g)

	5 cm R_1	5 cm R_2	15 cm R_1	15 cm R_2	30 cm R_1	30 cm R_2	50 cm R_1	50 cm R_2
8 year 1A	105.8	97.2	81.4	100.6	50.3	49.1	37.9	35.7
8 year 1B	83.2	101.7	85.6	91.7	105.8	76.6	68.3	68.3
8 year 1C	105	114.3	102.5	96.2	76	75.3	61	48.6
8 year 2A	85.7	83.5	76.2	78.5	64.1	93.8	74.6	65.9
8 year 2B	90.2	94.8	80	110	91.3	108.7	85.9	78.6
8 year 2C	112	79.7	75	109.2	84.8	103.3	79.8	86.8
8 year 3A	85.3	82.6	104.8	94.4	114	78.2	80	95.2
8 year 3B	103.8	110.4	91.6	96.2	79.9	73.5	87.4	83.1
8 year 3C	114.2	95.8	109.3	78.2	97.8	99.8	82.5	89.9
5 year 1A	78.9	85.5	102.9	100.9	80.2	91	80.1	74.6
5 year 1B	107.8	103	100.5	106.3	91.6	102.1	88.9	88
5 year 1C	88	100.5	86.8	91.9	79.6	85.7	62.1	58.5
5 year 2A	94	88.4	92.9	93.9	91.1	87.2	84.8	80
5 year 2B	91.5	88.8	84.8	101	85.7	83.5	83.3	88.6
5 year 2C	96.2	89.6	84	88.8	78.6	88.7	73.6	84.1
5 year 3A	101.9	121.8	101.8	99.5	114.1	110	108.1	107
5 year 3B	108.2	109.4	115.2	126.3	88.9	97	95	107
5 year 3C	106.7	110.4	106	122.6	95.8	102.6	92.4	112.1
3 year 1A	94.9	87.8	90.3	84.5	84.8	80.9	85.9	91.3
3 year 1B	113	110	101.4	109.4	105.7	103.7	95.8	95.8
3 year 1C	99.8	90	79.4	86.3	81.7	71.8	69	85.7
3 year 2A	116	111.2	115.8	120.7	102.7	100.6	97.6	95.1
3 year 2B	97.9	106	110.3	90.1	96.9	91.4	96.2	100.8
3 year 2C	100.9	91.5	97.7	103.8	67.8	93.6	97	84.7
3 year 3A	110.4	88.3	91.3	82.7	81.5	88.9	77.9	75.7
3 year 3B	84.1	97.3	108.7	109.3	79.2	91.4	88.3	94.8
3 year 3C	84.5	88.1	87.6	108.7	96.6	109	101.6	108

Clr 1A	103.7	109.1	106.1	127.5	122.5	118.3	94.1	80.4
Clr 1B	114.3	112.5	115.9	114.4	108.4	111.9	117.8	111.5
Clr 1C	99.4	99.3	96.7	111.7	98	111.4	101.4	105.8
Clr 2A	92.2	120.5	122.8	115.6	108.7	115.3	106.5	106.5
Clr 2B	114.9	118.6	124.6	111.1	109.2	117.8	99.5	99.5
Clr 2C	128.4	124.9	92.3	94.6	117.8	10	98.8	98.8
Clr 3A	122.3	115.5	108.5	128.4	113.2	108.7	105	110.6
Clr 3B	122.8	106.3	106.3	107.6	100.5	109.5	101.9	92.2
Clr 3C	121.3	121.3	111.5	120.3	109.8	114.6	98.2	102.2
Sec 1A	104.7	134.8	134	118.4	113.9	126.2	111.5	105.1
Sec 1B	115.2	115.2	134.4	127.2	119	121.1	119.7	124.2
Sec 1C	91.8	98.6	122.4	122.3	87.4	120.8	93.2	102.6
Sec 2A	104.9	104.9	90	110.4	112.9	90.3	112	96
Sec 2B	107.9	97.2	95.8	90.1	94.5	10	107.1	104.6
Sec 2C	98.9	116.5	115.9	103.5	100	10.095	94.9	105.9
Sec 3A	81.5	100.7	95.8	74.7	89.7	97.1	64.8	93.4
Sec 3B	101.4	101.4	84.5	83.5	98.7	87.7	75.9	88.9
Sec 3C	79.9	88.2	83.1	82.9	87.6	82.2	88.7	93.6
Pri 1A	60.3	39.7	47.6	39.1	35.3	37.9	33.3	41.7
Pri 1B	61.6	55.2	58.8	53.8	26.3	30	25	49.2
Pri 1C	50	64.4	60.2	60.2	52.5	41.5	57.3	40.4
Pri 2A	80.9	83.7	66.5	82.2	49.1	54	38.4	45.6
Pri 2B	75.3	67.7	103	94.8	100.9	119.8	56.5	77.4
Pri 2C	92.8	92.1	111.9	115.5	95.3	105.4	85.4	88.6
Pri 3A	52.3	79.2	87.6	77.9	86.4	71.1	81.6	59.7
Pri 3B	84.3	84.3	61.8	58.5	66.5	73.9	79.1	78.4
Pri 3C	10.075	77	80.7	80.1	57.8	51.1	51.1	51.1

Appendix 5: Bulk density (g/cm^3)

	5 cm R_1	5 cm R_2	15 cm R_1	15 cm R_2	30 cm R_1	30 cm R_2	50 cm R_1	50 cm R_2
8 year 1A	0.362173718	0.421776796	0.643982162	0.604979956	0.854421982	0.880137114	0.907809905	0.889107173
8 year 1B	0.772091124	0.804507366	0.913624979	0.901221235	0.892230858	0.91629055	0.920937464	0.911715917
8 year 1C	0.603942887	0.512888027	0.875272035	0.921961582	0.950409804	0.911822245	0.988201742	0.922781227
8 year 2A	0.898225446	0.889233345	0.892090457	0.926437986	0.929748128	0.921319377	0.931866259	0.904086059
8 year 2B	0.946939861	0.900073321	0.923420879	0.946784806	0.924691142	0.886248734	0.919982194	0.889291501
8 year 2C	0.919522858	0.91412764	0.75077231	0.935036831	0.911354593	0.923037602	0.92749951	0.930032944
8 year 3A	0.742268328	0.91459266	0.839891728	0.886751328	0.900653489	0.989722352	0.853544169	0.918264627
8 year 3B	0.95813994	0.928241599	0.917330535	0.89794037	0.937700341	0.941297629	0.954416802	0.9698467
8 year 3C	0.899997351	0.898496523	0.916036042	0.900459918	0.933146155	0.913612799	0.913039183	0.921101894
5 year 1A	0.92314023	0.909281197	0.858246709	0.92077051	0.86600686	0.920600827	0.837993609	0.864550967
5 year 1B	0.9198511	0.885293057	0.906644583	0.901028482	0.901059107	0.914370739	0.90137038	0.890068889
5 year 1C	0.773248332	0.786057978	0.886076898	0.875627606	0.865479523	0.88203298	0.905122113	0.858845917
5 year 2A	0.920726658	0.893046167	0.917795517	0.931450932	0.93268207	0.937926712	0.905433134	0.91911673
5 year 2B	0.895409758	0.903913054	0.901925818	0.894945213	0.878345643	0.908879446	0.905334422	0.909140613
5 year 2C	0.885885702	0.879099309	0.862032475	0.859714574	0.896071603	0.902793577	0.897961676	0.856880445
5 year 3A	0.921792091	0.907983866	0.857547491	0.89792078	0.814386547	0.869628806	0.875124471	0.947839573
5 year 3B	0.895462958	0.895712119	0.798040222	0.913732768	0.890463576	0.932236763	0.858701246	0.870103343
5 year 3C	0.905902613	0.898105191	0.902788394	0.81235627	0.83702761	0.96336205	0.852704601	0.921225046
3 year 1A	0.894388846	0.846334827	0.860803096	0.906981733	0.901163078	0.933395532	0.886573173	0.890180082
3 year 1B	0.843033845	0.887065556	0.914775534	0.92933797	0.91821974	0.896122431	0.917204655	0.894520962
3 year 1C	0.674573776	0.826950013	0.786136415	0.796931999	0.771013632	0.808509436	0.823844252	0.811666397
3 year 2A	0.908730104	0.917760888	0.913509344	0.907896261	0.925520344	0.921987879	0.921656556	0.93556792
3 year 2B	0.878757674	0.890671715	0.862481196	0.846908972	0.91923376	0.900304606	0.900158128	0.912471253
3 year 2C	0.886197977	0.891710085	0.809142546	0.877658122	0.893263192	0.89207455	0.920998167	0.814302954
3 year 3A	0.875706561	0.804355667	0.871188694	0.843296196	0.881896975	0.840255054	0.910072383	0.840245737
3 year 3B	0.899501823	0.892690036	0.807147821	0.89683279	0.887429525	0.815669251	0.876484255	0.860398402
3 year 3C	0.884827999	0.893569332	0.883946993	0.897279184	0.893081956	0.917816669	0.905143105	0.930798063

Clr 1A	0.931898231	0.873508575	0.903486849	0.949276716	0.908764036	0.947451691	0.888234264	0.964312427
Clr 1B	0.929832543	0.925311109	0.869155192	0.938648344	0.896452694	0.930431736	0.891855268	0.929990189
Clr 1C	0.931951788	0.91360509	0.903458873	0.899137382	0.865797924	0.890555962	0.869173452	0.887532569
Clr 2A	0.92476295	0.943857819	0.917187162	0.952783168	0.944626293	0.93270812	0.949685629	0.935988934
Clr 2B	0.932740593	0.976249808	0.956720992	0.949061359	0.950809845	0.956525961	0.968614329	0.969749851
Clr 2C	0.951335063	0.925458927	0.928162388	0.112401587	0.879575097	0.943461867	0.948688899	0.959745252
Clr 3A	0.903840733	0.959813777	0.905867237	0.93705553	0.937787974	0.943716684	0.948969346	0.964818157
Clr 3B	0.920925454	0.841399657	0.932251208	0.922045946	0.906342515	0.906644626	0.930467932	0.933375261
Clr 3C	0.913310131	0.949663632	0.918597862	0.931565103	0.934826847	0.943328282	0.951312414	0.948380856
Sec 1A	0.932320324	0.935853219	0.896762349	0.886245401	0.903763187	0.894264053	0.911663128	0.966019694
Sec 1B	0.894271418	0.9124343	0.858917014	0.877985946	0.907407093	0.883418093	0.873963108	0.807928965
Sec 1C	0.895338342	0.919375741	0.937839222	0.937479015	0.921362937	0.94168248	0.797989292	0.800826496
Sec 2A	0.951348153	0.948223549	0.852875468	0.956005504	0.83401383	0.954785881	0.947268169	0.968358857
Sec 2B	0.976752566	0.947605142	0.857928079	0.133401515	0.942770679	0.957135307	0.947687599	0.966476569
Sec 2C	0.952292729	0.90286501	0.988248284	0.123186788	0.961226493	0.887628123	0.951157245	0.935551719
Sec 3A	0.76427812	0.861466301	0.872645865	0.904181726	0.894884278	0.893060818	0.862073208	0.869641226
Sec 3B	0.880859857	0.833140597	0.90571516	0.906431407	0.793373829	0.800611515	0.875867566	0.895345969
Sec 3C	0.862389316	0.89051134	0.874642368	0.853099767	0.817492124	0.829391234	0.809200247	0.843871847
Pri 1A	0.307778742	0.429655638	0.351314235	0.443937044	0.471453885	0.425653422	0.563796903	0.463140028
Pri 1B	0.305797372	0.445013255	0.279249653	0.358373974	0.624147395	0.666421623	0.667887798	0.692222227
Pri 1C	0.565742755	0.434532986	0.526346876	0.380742393	0.774460302	0.577687532	0.541317669	0.713256258
Pri 2A	0.384020682	0.37033167	0.448827314	0.445359846	0.625449515	0.691767176	0.71242856	0.757614861
Pri 2B	0.511259033	0.665851604	0.862191663	0.910473254	0.904750622	0.911797588	0.900813592	0.909802229
Pri 2C	0.791372033	0.805493544	0.835944691	0.8702268	0.893887135	0.885856657	0.868151121	0.87742969
Pri 3A	0.730702363	0.666514402	0.869861586	0.694530937	0.829637827	0.753826174	0.521893886	0.765037416
Pri 3B	0.819510995	0.693631099	0.57893041	0.630803767	0.594372261	0.5285164	0.873056876	0.834562777
Pri 3C	0.460808685	0.431337534	0.531207748	0.508471689	0.741697713	0.706394005	0.182019073	0.722308755

Appendix 6: %SOC of samples

	5 cm R_1	5 cm R_2	15 cm R_1	15 cm R_2	30 cm R_1	30 cm R_2	50 cm R_1	50 cm R_2
8 year 1A	0.0158	0.01676	0.009335	0.01266	0.008162	0.008744	0.008348	0.007803
8 year 1B	0.02934	0.03545	0.02004	0.01759	0.00962	0.0113	0.00743	0.008079
8 year 1C	0.0239	0.02153	0.01275	0.009618	0.009234	0.007294	0.007406	0.005641
8 year 2A	0.0377	0.03925	0.02457	0.02574	0.01439	0.0153	0.01237	0.01324
8 year 2B	0.0214	0.01615	0.01588	0.01573	0.01084	0.01274	0.01255	0.008683
8 year 2C	0.02807	0.02704	0.02134	0.01625	0.01167	0.01041	0.008034	0.007644
8 year 3A	0.01626	0.01584	0.004579	0.006064	0.003535	0.003404	0.001844	0.001913
8 year 3B	0.02389	0.02514	0.01382	0.01303	0.005534	0.0046	0.002404	0.002433
8 year 3C	0.01301	0.01185	0.004825	0.005153	0.00307	0.003314	0.002927	0.002782
5 year 1A	0.01986	0.02199	0.01841	0.01924	0.01054	0.007544	0.00763	0.01407
5 year 1B	0.01407	0.01421	0.01177	0.0114	0.008763	0.008532	0.01088	0.008733
5 year 1C	0.01407	0.01705	0.01064	0.01001	0.009609	0.0103	0.007572	0.008916
5 year 2A	0.01445	0.01729	0.01055	0.01142	0.009962	0.00874	0.00799	0.008137
5 year 2B	0.01928	0.01942	0.0169	0.01309	0.01053	0.009181	0.007937	0.007263
5 year 2C	0.01411	0.0174	0.01252	0.01662	0.01052	0.008613	0.008684	0.007854
5 year 3A	0.008886	0.007554	0.003259	0.004084	0.002215	0.003123	0.001516	0.001778
5 year 3B	0.005587	0.01058	0.004912	0.005951	0.01102	0.007922	0.005115	0.004499
5 year 3C	0.02566	0.02557	0.01139	0.01174	0.005912	0.006617	0.003334	0.003035
3 year 1A	0.0362	0.04159	0.0251	0.03057	0.01568	0.01673	0.009001	0.008671
3 year 1B	0.03173	0.02408	0.01373	0.01454	0.01213	0.01235	0.009996	0.008246
3 year 1C	0.03396	0.02366	0.01779	0.01529	0.01347	0.0117	0.009043	0.007885
3 year 2A	0.01674	0.01526	0.009653	0.0129	0.02008	0.02358	0.004571	0.006526
3 year 2B	0.006088	0.006707	0.009312	0.01043	0.009022	0.009342	0.00698	0.007745
3 year 2C	0.01592	0.01768	0.009864	0.0108	0.007539	0.006088	0.00615	0.0179
3 year 3A	0.0179	0.01718	0.0131	0.01266	0.01002	0.008988	0.009244	0.007752
3 year 3B	0.02989	0.02475	0.01356	0.01508	0.008804	0.008902	0.007272	0.00816
3 year 3C	0.02137	0.01613	0.0144	0.0185	0.0192	0.0131	0.007776	0.007843

Clr 1A	0.02523	0.02047	0.01605	0.01953	0.009956	0.009112	0.007097	0.006481
Clr 1B	0.01526	0.02148	0.01085	0.009667	0.008436	0.008938	0.00684	0.00682
Clr 1C	0.01613	0.02025	0.01037	0.01047	0.01048	0.01007	0.0105	0.008596
Clr 2A	0.02592	0.02313	0.01717	0.01453	0.01098	0.01032	0.00775	0.007112
Clr 2B	0.02716	0.02829	0.01803	0.01636	0.01061	0.01108	0.008079	0.008079
Clr 2C	0.01458	0.01767	0.009584	0.01329	0.00864	0.008102	0.007488	0.006653
Clr 3A	0.03044	0.03688	0.02018	0.01716	0.007491	0.008937	0.007539	0.007539
Clr 3B	0.02564	0.03506	0.01352	0.01916	0.008589	0.009724	0.007454	0.008436
Clr 3C	0.03307	0.03703	0.0221	0.0226	0.01588	0.01214	0.009203	0.009203
Sec 1A	0.0236	0.01528	0.01077	0.009379	0.009337	0.008731	0.00574	0.004373
Sec 1B	0.02105	0.01368	0.009587	0.007194	0.006854	0.007513	0.007816	0.006874
Sec 1C	0.01931	0.01053	0.0228	0.01527	0.01188	0.009368	0.006717	0.008548
Sec 2A	0.02784	0.04752	0.02238	0.02389	0.013	0.01281	0.0104	0.01026
Sec 2B	0.02747	0.0327	0.01734	0.01652	0.0112	0.00996	0.006869	0.008403
Sec 2C	0.03161	0.02609	0.01822	0.01358	0.01201	0.01238	0.01023	0.009742
Sec 3A	0.03897	0.02264	0.02335	0.0252	0.01387	0.0176	0.01054	0.01024
Sec 3B	0.0267	0.02418	0.01719	0.01941	0.02295	0.02243	0.01217	0.01211
Sec 3C	0.03288	0.03147	0.02562	0.02123	0.01569	0.01499	0.008259	0.008475
Pri 1A	0.01851	0.01469	0.009371	0.009295	0.007287	0.008875	0.007815	0.007247
Pri 1B	0.0414	0.0416	0.01426	0.01627	0.008879	0.008172	0.006901	0.008072
Pri 1C	0.02716	0.02597	0.01406	0.01258	0.008246	0.007588	0.009066	0.007781
Pri 2A	0.01757	0.01769	0.008631	0.01169	0.00931	0.004585	0.009533	0.006875
Pri 2B	0.0585	0.07002	0.01557	0.01856	0.005722	0.006471	0.004515	0.004698
Pri 2C	0.02703	0.02562	0.01079	0.007577	0.007027	0.0061	0.007459	0.007468
Pri 3A	0.02699	0.0224	0.007492	0.008783	0.005756	0.006207	0.004499	0.004986
Pri 3B	0.02095	0.0178	0.008526	0.009308	0.006134	0.006037	0.005672	0.006872
Pri 3C	0.03736	0.03344	0.01528	0.01078	0.01202	0.01093	0.006055	0.006965

Appendix 7: SOC stocks (tons/ha^{-1})

Equations used: R_1 (bulk density * %SOC * depth) = SOC stock (g cm^{-3})
SOC stock (g cm^{-3})* 100 = SOC stock (tons/ha^{-1})

Examples: 5yr1A 5 cm: (R_1 (0,92314023 * 0,01986 * 5) = 0.09166782 g cm^{-3}
0,09582165 * 100 = 9,58216462 tons/ha^{-1}

5yr1A 15 cm R1: 0.85824671 * 0.01841 * 10 = 0.15800322 (g cm^{-3})
0.15800322 *100 = 15.8003219 tons/ha^{-1}

5yr1A 30 cm R1: 0.93268207 * 0.009962 * 15 = 0.13691568 (g cm^{-3})
0.13691568 *100 = 13.6915685 tons/ha^{-1}

5yr1A 50 cm R1: 0.83799361 * 0.00763 * 20 = 0.12787782 (g cm^{-3})
0.12787782 *100 = 12.7877825 tons/ha^{-1}

	5 cm R_1	5 cm R_2	15 cm R_1	15 cm R_2	30 cm R_1	30 cm R_2	50 cm R_1	50 cm R_2
8 year 1A	2.8611724	3.5344896	6.0115735	7.6590462	10.4606883	11.5438784	15.1567942	13.8754065
8 year 1B	11.3265768	14.2598931	18.3090446	15.8524815	12.8748913	15.5311248	13.6851307	14.7315058
8 year 1C	7.2171175	5.5212396	11.1597184	8.8674265	13.1641262	9.9762472	14.6372442	10.4108178
8 year 2A	16.9315497	17.4512044	21.9186625	23.8465138	20.0686133	21.1442797	23.0543712	23.9401988
8 year 2B	10.1322565	7.2680921	14.6639236	14.892925	15.035478	16.9362133	23.0915531	15.4434362
8 year 2C	12.9055033	12.3590057	16.0214811	15.1943485	15.9532622	14.4132322	14.9030621	14.2183436
8 year 3A	6.0346415	7.2435739	3.8458642	5.3772601	4.7757151	5.0535223	3.1478709	3.5132805
8 year 3B	11.4449816	11.6679969	12.677508	11.700163	7.7838505	6.4949536	4.588836	4.719274
8 year 3C	5.8544828	5.3235919	4.4198739	4.64007	4.297138	4.5415692	5.3449314	5.1250109
5 year 1A	9.1667825	9.9975468	15.8003219	17.7156246	13.6915685	10.417519	12.7877825	24.3284642
5 year 1B	6.4711525	6.2900072	10.6712067	10.2717247	11.8439714	11.7021167	19.6138195	15.5459432
5 year 1C	5.439802	6.7011443	9.4278582	8.7650323	12.4745891	13.6274095	13.7071693	15.3149404
5 year 2A	6.6522501	7.7203841	9.6827427	10.6371696	13.9370682	12.2962192	14.4688215	14.9577057
5 year 2B	8.6317501	8.7769958	15.2425463	11.7148328	13.8734694	12.5166333	14.3712786	13.2061765
5 year 2C	6.2499236	7.648164	10.7926466	14.2884562	14.1400099	11.6636416	15.5957984	13.459878

5 year 3A	4.0955223	3.4294551	2.7947473	3.6671085	2.7057993	4.0737761	2.6533774	3.3705175
5 year 3B	2.5014758	4.7383171	3.9199736	5.4376237	14.7193629	11.0777695	8.7845137	7.8291899
5 year 3C	11.6227305	11.4822749	10.2827598	9.5370626	7.4227608	9.56185	5.6858343	5.591836
3 year 1A	16.1884381	17.5995327	21.6061577	27.7264316	21.1953556	23.4235609	15.9600903	15.437503
3 year 1B	13.374732	10.6802693	12.5598681	13.5125741	16.7070082	16.600668	18.3367555	14.7524397
3 year 1C	11.4542627	9.7828187	13.9853668	12.1850903	15.5783304	14.1893406	14.9000471	12.7999791
3 year 2A	7.606071	7.0025156	8.8181057	11.7118618	27.8766728	32.6107113	8.4257842	12.2110325
3 year 2B	2.6749384	2.9868676	8.0314249	8.8332606	12.4399905	12.6159684	12.5662075	14.1341797
3 year 2C	7.0541359	7.8827172	7.9813821	9.4787077	10.1014668	8.1464248	11.3282775	29.1520458
3 year 3A	7.8375737	6.9094152	11.4125719	10.6761298	13.2549115	11.3283186	16.8254182	13.0271699
3 year 3B	13.4430547	11.0470392	10.9449245	13.5242385	11.7193943	10.8916315	12.747587	14.0417019
3 year 3C	9.4543872	7.2066367	12.7288367	16.5996649	25.7207603	18.0350972	14.0767856	14.6004984
Clr 1A	11.7558962	8.9403603	14.5009639	18.5393743	13.5714821	12.9497697	12.6075971	12.4994177
Clr 1B	7.0946223	9.9378413	9.4303338	9.0739135	11.3437124	12.4742983	12.2005801	12.6850662
Clr 1C	7.5161912	9.2502515	9.3688685	9.4139684	13.6103434	13.4518478	18.2526425	15.2584599
Clr 2A	11.9849278	10.9157157	15.7481036	13.8439394	15.557995	14.4383217	14.7201272	13.3135066
Clr 2B	12.6666173	13.8090535	17.2496795	15.5266438	15.1321387	15.8974615	15.6508703	15.6692181
Clr 2C	6.9352326	8.1764296	8.8955083	1.4938171	11.3992933	11.4658921	14.207565	12.7703703
Clr 3A	13.756456	17.698966	18.2804008	16.0798729	10.5374546	12.650994	14.3085598	14.5475282
Clr 3B	11.8062643	14.749736	12.6040363	17.6664003	11.6768638	13.2243185	13.8714159	15.7479074
Clr 3C	15.101583	17.5830221	20.3010128	21.0533713	22.2675755	17.178008	17.5098563	17.455898
Sec 1A	11.0013798	7.1499186	9.6581305	8.3120956	12.6576553	11.7117292	10.4658927	8.4488082
Sec 1B	9.4122067	6.2410506	8.2344374	6.3162309	9.3290523	9.9556802	13.6617913	11.1074074
Sec 1C	8.6444917	4.8405133	21.3827343	14.3153046	16.4186875	13.2325222	10.7201881	13.6909298
Sec 2A	13.2427663	22.5297915	19.087353	22.8389715	16.2632697	18.3462107	19.7031779	19.8707237
Sec 2B	13.4156965	15.4933441	14.8764729	2.203793	15.8385474	14.2996015	13.0193322	16.2426052
Sec 2C	15.0509866	11.7778741	18.0058837	1.6728766	17.3164953	16.4832542	19.4606772	18.2282897
Sec 3A	14.8919592	9.7517985	20.3762809	22.7853795	18.6180674	23.5768056	18.1725032	17.8102523
Sec 3B	11.7594791	10.0726698	15.5692436	17.5938336	27.3118941	26.9365744	21.3186166	21.6852794

Sec 3C	14.1776804	14.0121959	22.4083375	18.1113081	19.2396771	18.6488619	13.3663697	14.3036278
Pri 1A	2.8484923	3.1558207	3.2921657	4.1263948	5.1532267	5.6665112	8.8121456	6.7127516
Pri 1B	6.3300056	9.2562757	3.9821001	5.8307446	8.3127071	8.1689963	9.2181874	11.1752356
Pri 1C	7.6827866	5.6424108	7.4004371	4.7897393	9.5792995	6.5752395	9.815172	11.0996939
Pri 2A	3.3736217	3.2755836	3.8738285	5.2062566	8.7344025	4.7576288	13.5831629	10.4172043
Pri 2B	14.9543267	23.3114647	13.4243242	16.8983836	7.7654746	8.8503633	8.1343467	8.5485017
Pri 2C	10.695393	10.3183723	9.0198432	6.5937085	9.4220173	8.1055884	12.9510784	13.1052898
Pri 3A	9.8608284	7.4649613	6.517003	6.1000652	7.163093	7.0184986	4.6960012	7.6289531
Pri 3B	8.5843777	6.1733168	4.9359607	5.8715215	5.4688192	4.7859803	9.9039572	11.4702308
Pri 3C	8.6079062	7.2119636	8.1168544	5.4813248	13.3728098	11.5813297	2.204251	10.061761

Appendix 8: %C in litter layer

Site	%SOC	Site	%SOC	Site	Site avg. %SOC	Landuse avg. %SOC
8yr-1A	45.51	**Clr-1A**	42.8	**8 year-1**	43.78	**42.05**
8yr-1B	39.38	**Clr-1B**	11.41	**8 year-2**	44.92	
8yr-1C	46.44	**Clr-1C**	15.55	**8 year-3**	37.46	
8yr-2A	44.22	**Clr-2A**	25.2			
8yr-2B	44.72	**Clr-2B**	31.67	**5 year-1**	32.41	**34.77**
8yr-2C	45.83	**Clr-2C**	33.29	**5 year-2**	37.27	
8yr-3A	43.11	**Clr-3A**	20.13	**5 year-3**	34.65	
8yr-3B	39.45	**Clr-3B**	21.83			
8yr-3C	29.81	**Clr-3C**	36.91			
				3 year-1	21.77	**21.62**
5yr-1A	39.91	**Sec-1A**	31.76	**3 year-2**	19.19	
5yr-1B	28.44	**Sec-1B**	41.2	**3 year-3**	23.89	
5yr-1C	28.87	**Sec-1C**	32.27			
5yr-1A	N/A	**Sec-2A**	28.84	**Cleared-1**	23.25	**26.53**
5yr-2B	44.48	**Sec-2B**	28.91	**Cleared-2**	30.05	
5yr-2C	30.05	**Sec-2C**	36.2	**Cleared-3**	26.29	
5yr-3A	36.63	**Sec-3A**	31.44			
5yr-3B	N/A	**Sec-3B**	25.65	**Sec. -1**	35.08	**31.29**
5yr-3C	32.67	**Sec-3C**	25.35	**Sec. -2**	31.32	
				Sec. -3	27.48	
3yr-1A	20.11	**Pri-1A**	23.82			
3yr-1B	22.78	**Pri-1B**	17.88	**Pri. -1**	20.45	**20.08**
3yr-1C	22.43	**Pri-1C**	19.65	**Pri. -2**	17.02	
3yr-2A	18.75	**Pri-2A**	14.89	**Pri. -3**	22.76	
3yr-2B	33.03	**Pri-2B**	21.42			
3yr-2C	5.83	**Pri-2C**	14.74			
3yr-3A	17.21	**Pri-3A**	14.35			
3yr-3B	26.77	**Pri-3B**	33.89			
3yr-3C	27.69	**Pri-3C**	20.04			

Appendix 9: Litter layer dry weight (g)

Site	Litter	Site	Litter
8 year 1A	58.125	Clear 1A	41.986
8 year 1B	99.632	Clear 1B	28.345
8 year 1C	84.623	Clear 1C	12.177
8 year 2A	41.624	Clear 2A	11.015
8 year 2B	34.123	Clear 2B	23.173
8 year 2C	45.963	Clear 2C	16.045
8 year 3A	70.545	Clear 3A	9.453
8 year 3B	68.145	Clear 3B	12.607
8 year 3C	65.334	Clear 3C	13.028
5 year 1A	20.917	Sec 1A	31.087
5 year 1B	40.402	Sec 1B	40.856
5 year 1C	40.692	Sec 1C	27.609
5 year 2A	32.632	Sec 2A	114.943
5 year 2B	45.344	Sec 2B	176.005
5 year 2C	40.962	Sec 2C	107.397
5 year 3A	59.434	Sec 3A	104.021
5 year 3B	53.452	Sec 3B	57.242
5 year 3C	39.778	Sec 3C	63.141
3 year 1A	49.613	Pri 1A	88.65
3 year 1B	49.975	Pri 1B	78.936
3 year 1C	81.997	Pri 1C	100.554
3 year 2A	24.964	Pri 2A	92.446
3 year 2B	45.683	Pri 2B	99.962
3 year 2C	72.516	Pri 2C	121.602
3 year 3A	36.787	Pri 3A	139.849
3 year 3B	43.508	Pri 3B	178.653
3 year 3C	42.487	Pri 3C	117.006

Appendix 10: Results from Kadeba & Aduayi (1985)

TABLE 4

Soil chemical analyses of *Pinus caribaea* stands of different ages (means of ten values)

Age (y)	Depth (cm)	pH		Org. C (%)	Total N (%)	P (ppm)	Exchangeable cations (meq/100 g)		
		H_2O	$CaCl_2$				K	Ca	Mg
4	0–10	6.0	5.1	1.09	0.070	5.8	0.20	2.02	1.34
	10–20	6.1	5.0	0.63	0.046	4.5	0.14	1.25	0.83
	20–30	5.6	4.8	0.47	0.038	3.0	0.11	1.03	0.65
6	0–10	6.1	4.9	0.98	0.061	5.4	0.17	1.90	1.21
	10–20	5.9	5.1	0.65	0.042	5.0	0.13	0.01	0.80
	20–30	5.9	5.0	0.41	0.034	2.9	0.11	0.93	0.67
8	0–10	5.9	5.0	0.74	0.056	5.7	0.15	1.72	1.08
	10–20	5.8	4.8	0.55	0.044	5.1	0.11	1.10	0.84
	20–30	5.8	4.7	0.46	0.035	3.5	0.12	0.96	0.72
10	0–10	6.1	4.9	0.70	0.051	5.6	0.15	1.54	1.12
	10–20	5.8	4.7	0.53	0.041	4.1	0.12	0.97	0.70
	20–30	5.7	4.8	0.39	0.037	3.7	0.11	0.89	0.61
14	0–10	6.0	5.2	0.87	0.055	4.6	0.16	1.66	1.18
	10–20	5.7	5.0	0.54	0.040	3.8	0.12	1.16	0.73
	20–30	5.8	4.9	0.41	0.035	3.1	0.12	0.99	0.81