Swedish University of Agricultural Sciences
Department of Soil and Environment

Impact of Eucalyptus plantations on pasture land on soil properties and carbon sequestration in Brazil

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Master's Thesis in Soil Science
Agriculture Programme – Soil and Plant Sciences

Examensarbeten, Institutionen för mark och miljö, SLU
2012:19

Uppsala 2012

SLU, Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
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EX0429, Independent project/degree project in Soil Science, 30 credits, Advanced level, A1E
Agriculture Programme – Soil and Plant Sciences, 270 credits (Agronomprogrammet – inriktning mark/växt, 270 hp)

Series title: Examensarbeten, Institutionen för mark och miljö, SLU
2012:19

Uppsala 2012

Keywords: Brazil, land use changes, Eucalyptus, reforestation, SOC, carbon sequestration

Online publication: http://stud.epsilon.slu.se

Abstract

Soil organic carbon (SOC) stocks and fluxes in forest ecosystems are influenced by natural and human disturbances. In the tropical regions the highest impacts on disturbance in forest C cycles are related to human activities such as conversion of natural lands to cropland and pasture areas and to forest plantations. The disturbances in the forest C cycles will release CO_2 emissions to the atmosphere triggering global warming. In this study the focus was set in subtropical soils in Brazil, south extreme region of Bahia. The aim of the study was to investigate whether reforestation of *Eucalyptus* plantations under former pasture areas will help mitigate climate change through carbon sequestration. Field measurements were made on the total SOC and nitrogen amount, along with soil physical and chemical attributes, between different land use systems , also to analyze if there will be any positive effect on soil chemical and physical properties with the reforestation. The study areas included the intact rainforest Mata Atlântica called Native Forest, as a reference, pasture areas, which have been settled in the past from deforestation of Mata Atlântica, and *Eucalyptus* plantations recently reforested under former pasture areas aimed for paper and pulp production. With the field measurements and simulated amounts of SOC using the CO-Fix V.3.2 programme it could be compared the effects on SOC sequestration in short and long term (max. 50 years) under the *Eucalyptus* reforestation. Our results show significant differences with lower SOC, higher pH and soil compaction under pasture areas after deforestation of the rain forest. Meanwhile reforestation with eucalypt plantations on former pasture areas did not lead to any significant total nitrogen and total SOC accumulations in short term. However, the simulated results showed that *Eucalyptus* reforestation will play a role on carbon sequestration in soils with time. After 20 years of production the *Eucalyptus* forests will gain higher SOC accumulations than in pasture systems. After 50 years the simulated SOC accumulation showed closer values to the amounts measured on field under the Native Forest areas. These results indicate that the *Eucalyptus* plantations are efficient at sequester carbon in the soil in the long term. However, the comparison with the Native Forest field measurements should be carefully interpret since the measurements on field were made within a certain depth while the program shows the total amount with no limited soil depth. For a complete comparison it remains to take deeper soil samples in the field measurements.

Keywords: Brazil, land use changes, *Eucalyptus* , reforestation, SOC, carbon sequestration

Sammanfattning

Markens organiska kol halter och flöden i skogliga ekosystem påverkas av både naturliga och mänskliga störningar. I tropiska områden påverkas den skogliga kol cykeln främst av mänskliga aktiviteter såsom förändringar av landskapssystem till jordbruk-, betes- och skogsplantager. Kolflöden i en balanserad skogssystem förändras när den blir störd och större mängder CO_2-halter släpps ut till atmosfären, som tros bidra till påskynding av växthuseffekten. Studien utfördes i Brasiliens subtropiska klimatregionen, i södra delen av Bahia. Målet innebar att iaktta om återplantering av *Eucalyptus* plantager på gamla betesmarksområden kunde bidra till kollagring i marken och därigenom lindra växthuseffekten med tiden. Fokus satts även på om återplantering av *Eucalyptus* bidrar till positiva effekter i kemiska och fysiska markegenskaper som förlorats genom landskapsskifte av naturlig regnskog till betesmark. Därmed jämfördes markvariabler mellan olika landskapssystem; Primär tropisk regnskog, betesmark och *Eucalyptus* planteringar som hade olika produktions längder inriktade till framställning av cellulosa. Markvariablerna som analyserades innebar markkol och kväve, katjonbyteskapacitet, pH och bulkdensitet.
Med hjälp av CO2-Fix V.3.2 programmet kunde även markkol simuleras och även få ut en långtidsperspektiv på hur mycket kol det kan lagras i marken med tiden (max. 50 år).
Våra resultat visade lägre mängder av kol, högre pH och bulkdensitet med landskift från primär skog till betesmark. Med *Eucalyptus* åteplantering påvisades inga signifikanta skillnader i kolmarken och kemiska egenskaper jämfört med betesmarksområden. Vid långsiktig jämförelse med simuleringen påvisas en högre kollagring i marken under *Eucalyptus* skogar efter 20 år av produktion. Därmed kan återplantering av skog med *Eucalyptus* lindra växthuseffekten långsiktigt. Efter 50 år påvisas en liknande stor kollagring i marken med *Eucalyptus* skogar jämfört med de mätta värden i regnskogen. Dock är det viktigt att poängtera att de mätta värdena är begränsade till ett specifikt djup i fält och för en mer komplett jämförelse med resultaten från simuleringsprogrammet skulle djupare provtagningar behövas.

Sökord: Brazil, land use changes, *Eucalyptus* , reforestation, SOC, carbon sequestration

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Introduction

The increase of green-house gas emissions such as carbon dioxide (CO_2) in the atmosphere is a big concern today and is believed to trigger global warming. One of the main causes of the gas emissions lies, apart from fossil fuel burning, in the deforestation around the world. With the increasing population the demand for agricultural land is increasing causing deforestation through accelerated food or fuel production. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) deforestation is estimated to account for approximately 17% of human induced carbon emissions. Global deforestation and land use change will affect several soil properties but mainly through an impact on the carbon flux between the soil and atmosphere (Smith *et al.*, 2007). The tropical timber will be the main focus of production in tropical regions for deforestation actions. Around two-thirds of the cleared land will be used for pasture while a third for arable farming. These types of land use are mainly managed by large enterprises and caused by the increased consumption of meat, soybean and oil palm products worldwide (Millstone and Lang, 2008; FAO,2010).

According to FAO'S Global Forest Resources Assessment (2010) the forests are globally storing more than 650 billion tonnes of carbon, 44 % in the biomass, 11 % in dead wood and litter, and 45 %in the soil. The amount of carbon stored in the biomass, dead wood, litter and soil together exceeds the amount of carbon found in the atmosphere by 50 %.

The Kyoto Protocol highlights the importance of forests for the decreasing CO_2 emissions through the capacity of carbon sequestration in the plant biomass and the soil. Developing and developed countries may participate together with reforestation or afforestation actions under the Kyoto Protocol's Clean Development Mechanism (CDM) and contribute by action plans of carbon credits to reduce deforestation and forest degradation (FAO, 2000). The UN Framework Convention on Climate Change (UNFCCC) also highlight the Reducing Emissions from Deforestation and Forest Degradation (REDD+) plan which is similar to the CDM incentive but also covers sustainable management of forests and enhancement of C stocks in forests (Parker et *al.*,2009).

While tropical forests act as the largest carbon sinks in the world, the tropical soils are less capable to store carbon than other biomes. This is mainly due to the rapid decomposition of dead biomass in the warm, humid climatic conditions which leads to rapid carbon and nutrient leaching (Trumper *et al.*, 2009). However, the degree of the change in soil organic carbon (SOC) content or whether if it remains stable for a certain period in the soil when land use is changed will depend on several factors; the type of land conversion, the intensity and the length of the new managed system, its initial SOC content and climate and physical characteristics of the soil (Lugo and Brown, 1986).

The total global forest area is estimated to be over 4 billion ha where more than half of the forest areas are accounted in the five countries: Russian Federation , Brazil, United States of America, Canada and China. Brazil possesses the second largest forest cover in the world with an area of 520 Mha. Brazil also reports the largest annual net loss of natural vegetation equivalent to 8% of the total native forest areas of the country. Meanwhile, the rates of the highest net losses of natural vegetation have decreased from 1990-2000 with 2.8 Mha to 2.3 Mha per year between 2005-2010 in the country (FAO,2010). Despite the rapid loss of global tropical forests during the past century there has also been an increase of forest plantations in the 1990´s with 20 Mha in tropical regions and 12 Mha in nontropical regions. They make up 7% of the total forest area. Three quarters will be afforestation/ reforestation with native species whereas one quarter will be of introduced species. Their importance is growing to meet the increasing global demand for wood pulp and energy (Carnus *et al*., 2006, FAO, 2010).Brazil has currently a forestry production with over 6.3 Mha, 0,6% of its forest territory, with mainly *Eucalyptus and Pinus* species. Over 4 Mha of *Eucalyptus* are planted designed for paper, pulpwood and charcoal production. In some areas there is also a multiple land use of agroforestry production (Brown *et al.,* 1997; ABRAF, 2010).

Aims

The aim of this study was mainly to analyse whether reforestation of *Eucalyptus* on former pasture areas will contribute to carbon sequestration in the soil in short-term and long-term. In addition it was also analysed whether reforestation will contribute to positive effects on soil physical and chemical properties. The study on these impacts of different land use systems were made in Bahia, Brazil. The soil properties analyzed comprised SOC and nitrogen content, pH, cation exchange capacity (CEC), exchangeable cations and bulk density. The different management systems for the comparison involved primary rainforest called Native Forest, used as a reference, Pasture areas and *Eucalyptus* plantation.

Background

In the southern region of the Bahia state the deforestation of the areas of Mata Atlântica rainforest started with establishment of agricultural crops (i.e. coffee, sugar-cane, cocoa, cotton) in 1930's. The deforestation took place by "slash and burn" practices, clearing extensive areas. In addition, the cleared areas were also used for raising livestock which became the main production of the region (Oliveira, 2008). Over the past 25 years more than 70 Mha of native vegetation in Brazil have been replaced by pastures for beef production. The commercial African grass species *Brachiaria* and *Andropogongayanus* are used for beef cattle production in the country (Rezende *et al*., 1999).

The pasture management in this region includes mainly *Brachiaria humidicola* for beef cattle production. The grass specie is known for providing good soil coverage, facilitate water infiltration and prevent soil erosion. The grass has a deep, dense rooting system which will sequester more atmospheric carbon than native pasture. Thereby *Brachiaria* species are suggested to be used as a sink of carbon from the atmosphere (Boddey *et al.*,2004). However, after about 5-10 years the productivity of the grass will decline leading to land degradation. The reasons involve gradual changes of the soil organic matter quality. The grass litter and decaying roots have high C/N values. This leads to a decrease in net nitrogen mineralization coupled with phosphor immobilization. There are also problems with soil compaction due to the intense grazing activity (Boddey *et al.*,2004; Rezende *et al.*, 1999; Fisher *et al.*, 2007).

While cattle production suffered from low production and land degradation, the land conversion to *Eucalyptus* forestry started in 1969 on former pasture land managed by private sectors (Oliveira, 2008). This reforestation has expanded in Brazil, especially with *Eucalyptus* and *Pinus*, during the 70's and 80's. It was supported by the governmental policy which subsidised reforestation programs to develop an internationally competitive industry on wood and paper production (IMA, 2009). A woody market for timber production was developed which triggered an expansive deforestation of the Atlantic forest (Oliveira, 2008). *Eucalyptus* forests in Brazil cover over 3 Mha. The reforestation in Bahia has to some extent replaced pasture areas, farmland and some areas of the Atlantic forest as well as other natural vegetation (Balieiro *et al.*, 2008). Plantations of E. *grandis*, E. *urophylla* and their hybrids and other *Eucalyptus* species were carried out in larger scales in the south region of Bahia leading to a drastic land use shift. The region is recognized to have an excellent adaption and productivity for forest management, due to its climatic conditions, soil properties and transport facilities. Today it covers the highest plantation concentrations at national level (IMA, 2009). The productivity and sustainability of the plantations remain an important topic .Currently the expansion of *Eucalyptus* covers 628 000 ha in this region (ABRAF, 2010).

The *Eucalyptus* plantations in southern Bahia are adapted to a fast growing short-rotation management for pulpwood production. The management includes three rotation crops whereby plantation of seedlings will take place in the first and third rotation. The first harvest will lie around 6-7 years and subsequent coppicing cycles of 6-7 years in a rotation length of max 21 years. After the first rotation stems are removed and harvest residues such as branches, twigs and foliage are left on the ground to decompose. The second rotation will then be developed as sprouts from the stumps. After harvest of the second rotation the third rotation will be done by planting new seedlings, see figure 2. Stumps and roots from the former rotation will be killed and left to decompose. The third rotation will be planted in new rows between the rows from the first plantation. This system is then planned to continue so that every second rotation is based on sprouting from stumps, followed by a rotation based on new planting. Moreover litter, roots, bark and crown slash remains on site after harvest. By this, carbon and nutrient losses are reduced. Nutrient deficiencies are the main constraints to the plantation growth in this region. Nutrient additions and good soil conditions are decisive for obtaining a well established production with high mean annual increments of the stems. This will ensure the economic viability of the industry.

The importance of Soil Organic Matter

Soil Organic Matter (SOM) normally constitutes a minor fraction of the soil matrix. Despite this it will influence the physical, chemical and biological soil conditions (Young, 1997). It is an important indicator on soil fertility and promote several soil properties as aggregate formation, soil stability, nutrient and soil moisture retention, soil pH, CEC, and improved soil structure and infiltration (Eriksson *et al.*, 2005; Young, 1997).

The carbon content normally is around 50% in SOM. The carbon released from the plant biomass will be either stored in the SOM, in living organisms during a certain time or released back to the atmosphere through soil and living plant respiration or lost through erosion, leaching, natural disturbances as wildfire or other anthropogenic disturbances as land conversion or deforestation. The combustion of biomass will also store carbon in the soil as charcoal (Liu *et al*., 2011; Eriksson *et al*., 2005). The turnover rate of the different organic compounds will depend on several factors such as the SOM chemical composition, soil chemical and physical conditions, e.g. soil texture, weathering state and CEC, and climatic conditions. The most stable parts of SOM have turnover times of centuries (Jandl *et al.*,2007, Brady & Weil, 2008).

The composition of the SOM is dominated by humus compounds. These are divided in humic and fulvic acids and humins, containing nitrogen, sulphur and phosphorous bound in organic form. The chemical composition of these will result in a slower decomposition rate due to their stability comparing with the non-humic components as cellulose, hemicellulose, proteins and lipids. The amount of clay minerals and silt found in the soils will influence the stabilisation of these fractions forming strong organo-complexes between the high charged surface clay mineral particles and the humus compounds. Also organic matter fractions are trapped in the micro pores of the clay aggregates forming physical barriers for decomposing soil organisms. In highly weathered soils positively charged cations or Fe-and Al-oxide components bind strongly to negatively charged clay, silt and humus particles making decomposition difficult for living soil organisms (Eriksson *et al*., 2005; Garten *et al.*, 1999; Post and Kwon, 2000).

Forests and the carbon cycle

Forests take up the CO_2 through photosynthesis and store carbon in woody biomass, dead wood, litter and in the soil (FAO, 2010). The soil organisms will decompose dead forest biomass to SOM which in turn will release carbon and nutrients through mineralization. The biological processes in the forest result in a closed C cycle between the atmosphere, the forest and the soil. If not disturbed by anthropogenic actions the cycle will remain in a steady state meaning there will be a C cycle where carbon input and output is balanced (Liu *et al.*, 2011) .The forest biomass which store carbon can be defined as living and dead allocated both above- and below-ground. The living above-ground biomass includes stem, stump, branches, seeds and foliage and the below-ground consists of all living roots. The litterfall is included in the fine dead biomass definition with leaves, roots and branches less than 10 cm of diameter (FAO, 2005; McClaugherty *et al.*, 1984). The dead woody biomass consist of dead roots and stumps larger or equal to 10cm of diameter (FAO,2005, Kueppers *et al.*, 2004).

In tropical forests the environmental conditions trigger a rapid decomposition of the forest litter and dead biomass to SOM compared to temperate and boreal forests. Favourable temperatures in the air and the soil will facilitate the microbial activity during the entire year leading to a rapid mineralisation of SOM. The periods with high precipitation accelerates the decomposition as well. These will be main factors inducing the process of decomposition in dead biomass. The oxygen availability is also important and depend on the water availability in the soil (O'Connel & Nambiar, 1997).

Carbon gains in the soil are mainly depending on the amount and types of residues added every year. According to Rasse *et al.*, (2005) the roots contribute with 30 % more of carbon than from above-ground biomass to the soil. In general forest systems will provide more SOM than agricultural systems due to the higher amount of litter input in the soil such as foliage, branches and roots (Lal, 2005; Lima *et al.*, 2006). Under pasture areas the amount of fine roots will be the most important factor for SOC accumulation. The growth of the grass species does not reach deeper than 40 cm in the soil (Tarré *et al*., 2001). Whereas in forest plantations the coarser tree roots have a longer life span and will reach deeper than the grass roots. This will benefit to the carbon storage in the soil in long term (Brady & Weil, 2008; Cerri *et al.*, 1991; Lima *et al.*, 2006; Silva, 2008). For short rotation plantations there will be finer roots than in the case of long rotations (Masera *et al.*, 2003).

The type of tree species found in the system also play an indirect role on the SOC accumulation through their production and allocation of above-and below-ground biomass (Aerts *et al.*,1997; Lugo and Brown, 1993; McCalugherty *et al.*, 1984; Lemenih *et al.*, 2004; Garay *et al.*, 2004). Forest plantations which are intensively managed have shown to accumulate higher amounts of litter than in natural forests and the accumulation is faster. The fast growth will lead to higher amounts of litter on the forest soil (Lugo *et al.*,1990; Eriksson *et al*., 2005). However, the turnover of the litter to SOM will depend on the quality of the litter. Litter rich in phenolics and lignin will have higher C/N values and contribute to slower decomposition rates leading to less SOM found in short term (Lugo and Brown, 1993; Eriksson *et al*., 2005; Gama-Rodrigues and Barros, 2002).

The carbon stored in the soil will occur in several forms having different degrees of protection from decomposition. It can be classified as labile and stable pools. Both pools will release carbon into the atmosphere and to groundwater with time. The labile carbon is mostly found in the O-horizon in forests and in the sand sized organic matter (Lugo and Brown, 1993; Marland *et al.*, 2004). Most of the total carbon, 5-40%, will be stored in the labile fraction which is more exposed to rapid decomposition. It is predicted that one-fifth to one-third of the carbon remains in the soil either as live biomass (~5%) or as humic (~20%) or non-humic (~5%) fractions of the soil humus (Brady & Weil, 2008).

Materials and Methods

Study Site characteristics

The study was performed in the municipality of Eunápolis , located in the extreme south of Bahía region, Brazil, at approximately 16˚17'34.04'S, 39˚12'35.67W and about 65km from the seaside of Porto Seguro, see figure 1. The climate of the region is classified by Köppen as Tropical wet with no drying season (Af) having a mean annual temperature of 23.2º C. The main annual rainfall is around 1433 mm and fairly evenly distributed over the year. The relief in this area is plane to undulating with an elevation about 60-200 m a.s,l. The native vegetation is classified as dense and shade tolerant vegetation (Mata Atlântica).The geology of this area is dissected plain (so called "Tabuleiro") which has been developed from Tertiary sediments of the so called "Barreiras" group. The parent material consists of conglomeratic sandstones with the highly weathered clay mineral kaolinite. The soils have naturally low pH, and low fertility. They are generally deep and well drained with no impediment for plant root growth.

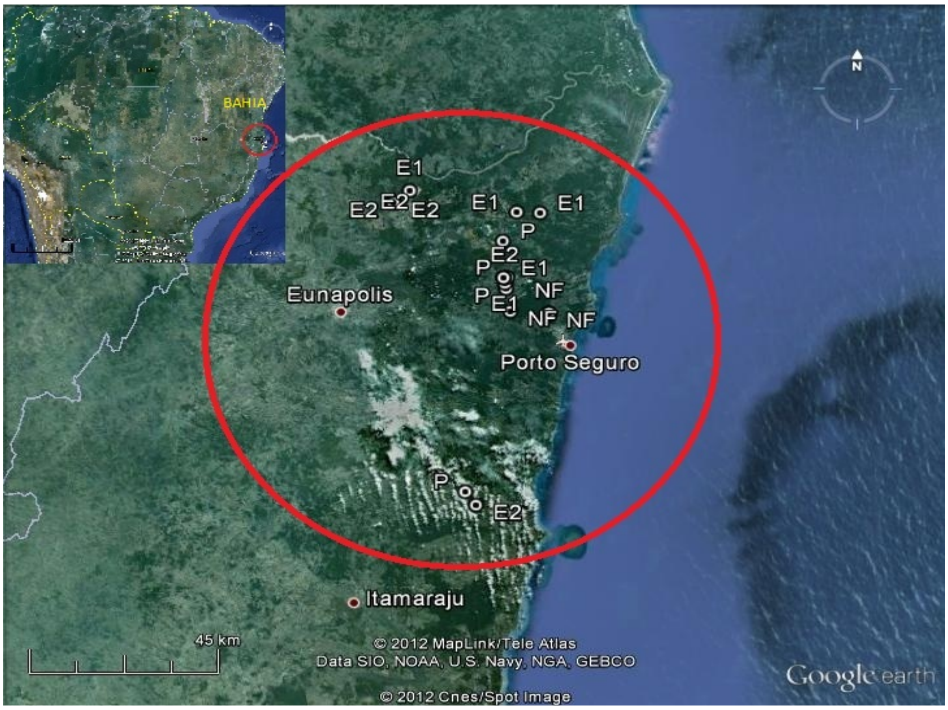

Figure 1. *Localization of the chosen areas in the extreme south region of Bahia, Brazil.E1=Eucalyptus 1, E2= Eucalyptus 2 , P= Pasture, NF= Native Forest.*

Site selection and description of the different land use systems of the region

For the selection of the study areas various field visits were made in the native forest, pasture and *Eucalyptus* areas. The variables observed in the field for site selection varied between the land use systems. For the native forest it was important to recognise an area as undisturbed as possible. The pasture sites included in the study were adjacent to the *Eucalyptus* plantations, see figure 2.To have pasture and *Eucalyptus* sites side by side minimized the risk of selecting sites with different soil parent material and climatic conditions. Also areas with high grazing activity were favoured. The grade of the grazing activity was followed after grass height on field and the presence of tracks from cattle. The grade for grazing activity ranged from value 0: no grazing activity to value 5: high grazing activity. The variables for the *Eucalyptus* stands included low failure and mortality percentage and a high mean annual increment of the stands. The variation found between each site for other vegetation grown under the trees was not taken into consideration while choosing similar *Eucalyptus* sites in this study.
Topography, previous land use, soil texture and colour as well as easy access to the areas were also taken in consideration for the selection of the study sites. For the estimation of soil texture and colour small pits were dug in all visited areas to estimate, by eye and touch, similar soil texture conditions.

Native Forest

The studied native forest was a Private Reserve of Natural Heritage embracing an area of 6.069 ha of the Mata Atlântica rainforest, located approximately 15 km from the seaside of Porto Seguro. The forest is classified as Dense Primary Natural Ombrophylle (Gama-Rodrigues *et al*., 2007) and the high abundance of naturally fallen tree stems, dense vegetation, a high biodiversity of flora and fauna and minimal tracks of anthropogenic disturbances were good indicators to justify the classification as primary forest. Furthermore no charcoal accumulations were found in the soil profile, indicating that this is a natural undisturbed area.

Grasslands

The chosen grasslands adjacent to the *Eucalyptus* forests had the main grazing grade of 3.2.
The areas have been established since 15 years. The use of fire has been implemented now and then as soil management practices. Further information on Net Primary Production of above-ground biomass and whether addition of fertilization has been implemented or if the areas have been under other types of management before pasture could not be compiled from this study. In addition the areas adjacent to the *Eucalyptus* plantations were estimated for being unmanaged by the appearance of weed growth in the management, low grass heigth, soil compaction and spots of land degradation.

Eucalyptus

Reforested areas with *Eucalyptus* plantations with clones of *E. globulus* E.urophylla* on former pasture land were selected for soil sampling. The selection included a total of 10 areas of plantations divided in two groups based on how long time the land has been exposed for reforestation. The first group (Eucalyptus 1) included plantations in soils with a mean length of 4.7 years since reforestation. The second group (Eucalyptus 2) included plantations in soils under 12-16 years of plantation with a mean length of 14 years of production. The main reason for selecting different rotation stands was to compare if differences are found with time in soil carbon storage and other variables as amount of dead organic matter, soil chemical properties, soil bulk density, CEC and nitrogen.

In the areas which included third rotation plantations in the Eucalyptus 2 group stumps were found left from the previous rotations on the field. The stumps were counted and measured by diameter and length to estimate how much carbon they contain and how this stock will change over time by degradation. Fallen trees and dead stumps found in the native forest were not taken into account.

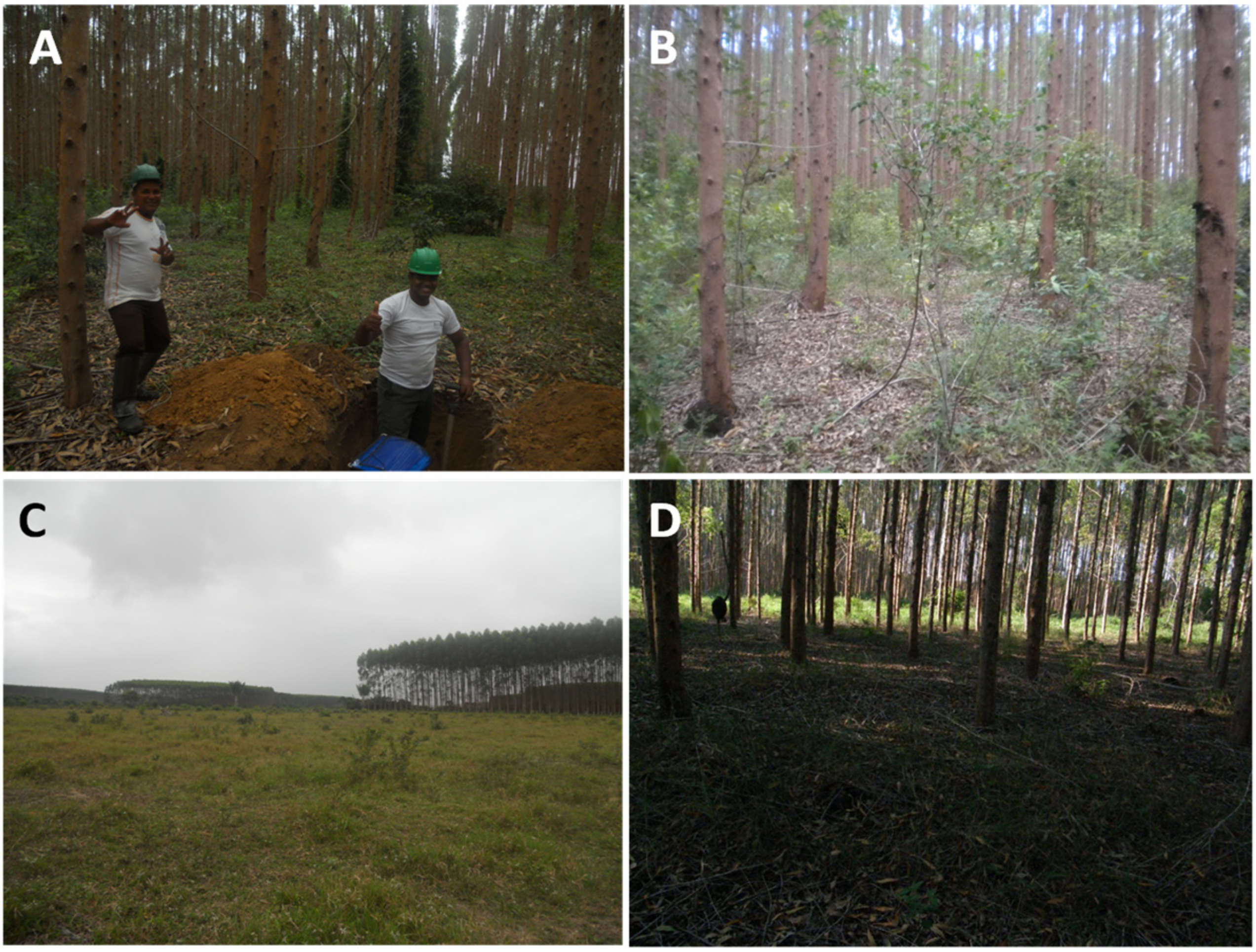

Figure 2. *Different land use systems used in the study performed in the south of Bahia region, Brazil. A- Planted eucalypt B- Re-sprouted eucalypt C- Pasture adjacent to eucalypt areas. D- Replanted eucalypt.Source: Manuela R. da Silva.*

Plantation Management

The field preparation start with herbicide treatment before plantation. Two litres per ha of glyphosate is distributed throughout the area 30 days before plantation for reduction of weed growth. The soil is mixed down to 60 cm or 90 cm depth with a riper leaving a distance of 4 meters between rows. During this process 350 kg ha^{-1} of natural reactive phosphate (source of phosphorus), containing 30 % P_2O_5 is applied at 20 cm depth. No liming is initially required since the soil already has proper values of calcium and magnesium. Thereafter 84 kg $ha^{-1}$of fertilizer with NPK 6-30-6 is added in the rows at 15cm soil depth and a hydrosorb gel is applied to avoid drought during the plant establishment. Hybrid clones of E.*urophylla* x E.*grandis* which have grown about 90 days in the nursery are thereafter planted. The spacing between the plants is 3 X 4 m, giving 833 trees per hectare. Furthermore, after planting, spraying with the pre-emergence herbicide Fordor (Isoxaflutol) is carried out in a 1.3 m wide band along the tree rows, for weed control. In addition is applied granulated bait formulated with sulfluramid (0.3% a.i.) for ant control (Atta and Agromyrmex). For maintaining a good production with high growth rates inputs of fertilizers and liming will be required in the subsequent rotations, see table 1 below for amounts.

Table 1. *Number of rotations and treatments applied on the Eucalyptus production in the study area*.

Rotation	Age yrs	Treatment
1	0-7	350 kg ha^{-1} Natural Fosfate Reactive +84 kg ha^{-1} NPK 06-30-06+ 200kg ha^{-1} NPK 10-00-30
2	7-14	1000 kg ha^{-1} calcium dolomite+ 350kg ha^{-1} Natural Fosfate Reactive+84 kg ha^{-1} NPK 06-30-06+ 500kg ha^{-1} NPK 10-00-30
3	14-21	1800kg ha^{-1} calcium dolomite + 350kg ha^{-1} Natural Fosfate Reactive+ 84 kg ha^{-1} NPK 06-30-06+600 kg ha^{-1} NPK 10-00-30

Sampling and analysis

Sampling Procedure

To enable statistical analyses five sites were used for each one of the different land use system; Native Forest, Pasture, Eucalyptus 1 and Eucalyptus 2. Soil, litter and root samples were collected within one randomly marked square sampling area of $100m^2$ at each site. In this sampling area five plots (size 50cm x 50cm) were sampled for soil and litter. For the purpose of the statistical analysis the plots were randomly selected within the $100m^2$ area.

At each plot two soil samples were collected at different depths down to 30cm depth (0-5 cm and 5-30cm).Two sharp edged cylinders with known dimensions were used for the mineral soil collections at different depths (height 5cm and diameter 6cm and height 25cm and diameter 6 cm).The O horizon was included in the upper soil sample. The bulk density was calculated from the dry weight of the soil for each of the collected samples. Since the soil bulk density showed little variation along the different soil depth no correction for soil compaction was made.

The litter was collected by hand within the entire plot (0.5 x 0.5m). The collected litter included dead leaves, seeds, twigs, bark and branches in the *Eucalyptus* and native forest. For the litter collection in the pasture areas the living grass was first cut within the plot to ground level and thrown outside of the plot. The remaining dead grass with yellow to brown colour found on the ground was thereafter collected by hand.

For soil profile description the FAO Guidelines for soil description (2006) was used and thereafter the equivalent to USD Soil Taxonomy was checked (USDA, 2010). One pit down to 60 cm depth was opened within each selected sampling area i.e five per site. However regarding the native forest site, and taking into consideration of being a high preserved area, only one pit down to 60cm was opened. Here the samples were collected at six depth intervals: 0-10, 10-20, 20-30, 30-40, 40-50, 50-60cm and used for pH, total elemental composition and CEC analyses.

In the other land uses systems a sample from 50cm depth was also taken in each area from the opened pits for pH and CEC analysis. In addition one sample from the *Eucalyptus* areas and one from the native forest from 60cm depth was brought to Sweden for analysis on total elemental composition. A general soil profile description was made after each soil description presenting thereby only one soil profile description per different land use systems.

The sampled soils were stored in polyethylene bags in refrigerator no longer than 14 days before the roots, decaying coarse organic material and charcoal was separated from the mineral soil samples by hand while still fresh. Also the roots were separated; living from dead.

Sample Preparation

After separation of live and dead organic residues the soil samples were dried at 65ºC for 48 hours and ground to pass a 2mm sieve. The gravel and charcoal remaining was separated by hand before and while grounding and thereafter weighted. The ten soil samples (five from 0-5cm depth and five from 5-30cm depth) within one selected area were weighed, pooled and homogenized. In total two pooled soil samples per area were handed in for pH, nitrogen and carbon analysis in <2mm fraction. Also one sample from 50cm depth per area was taken for CEC and pH analysis except for the native forest where six soil samples were analysed from 0-60cm depth. In addition, five pooled soil samples from different depths and areas were made for each different land use system; Native forest, Pasture, Eucalyptus 1 and Eucalyptus 2, for soil texture analysis. Furthermore, a sample from Sweden with known carbon and nitrogen content was also analysed as a reference and for evaluation of the values from the laboratory in Brazil.

The collected litter at each plot was dried at 70ºC for 48 hours. A pooled sample of the five study sites of each land use system was made. The pooled sample from the forest sites consisted of a mixture of dead branches, twigs and leaves and was weighted and grounded with laboratory mill. Litter from the pasture included only dead grass found on the ground. In total five pooled litter samples were handed in for carbon and nitrogen analysis.

The roots were separated living from dead based on colour and consistency. The separated roots and decaying coarse organic material (OM) were brushed to get rid of mineral soil particles and weighed separately. Also the gravels found in the dried soil samples were washed and dried and weighed. The density of living root was estimated to 1 g cm^{-3} D.M and the gravels to 2.5 g cm^{-3} based on standard values. A general sample of decaying coarse OM including dead roots was handed in from each land use system. In total five pooled decaying coarse OM samples from each land use system were handed in for carbon and nitrogen analysis.

Laboratory analysis

Ground samples of dried litter, decomposed litter and roots were sent to the Laboratory of Soil and Plant in the Federal University of Viçosa, situated in Minas Gerais state.The organic carbon in soil and plant samples was measured through the Walkley Black oxidation method. Total nitrogen was determined through the micro-Kjeldahl method (Schnitzer, 1982).The soil texture was determined by Bouyoucos hydrometer method.

The soil pH was measured in water (1:2.5 H_2O) with electronic pH meter and a glass electrode. Available P, Na and K was extracted with Mehlich 1 extractant. The CEC and exchengable cations were determined by extraction of 1 g mineral soil with 250 ml 1M-ammonium acetate at pH 7. Exchangable Ca, Mg and Al was measured with extraction of 1.0 mol l^{-1} KCl. The total acidity(H+Al) was measured in 0.5 mol l^{-1} calciumacetate extract at pH 7.0. The effective cation exchange capacity (CEC_{eff}) was calculated for the four different sites at the depth of 50cm, also the cation exchange capacity at pH 7 (CEC_{ph7}) and base saturation index (BSI) was calculated. CEC_{eff} was obtained as the sum of base cations (Ca+Mg+K+Na) and exchangable Al. Base saturation (%) was calculated dividing the sum of base cations(Ca+Mg+K+Na) by the CEC_{eff} of the soil and multiplied by hundred. Dry bulk density was determined by dividing oven-dry mass at 65 ºC of the <2mm fraction by the volume of the cylinder taking into account the volumes of the roots and gravel.

Statistics

Statistical comparisons were made on the variables between the different land use systems (native forest vs. pasture; native forest vs. Eucalyptus 1 ; native forest vs. Eucalyptus 2; pasture vs eucalyptus 1; pasture vs Eucalyptus 2; Eucalyptus 1 vs Eucalyptus 2); carbon, nitrogen, pH , soil pH , dry soil bulk density and CEC in the <2mm fraction samples. Analysis of variance (ANOVA) was used and multiple comparison of means using Tukey's honestly significant difference (HSD) method. The confidence level was set at 0.05. Linear regression analysis was used to compare strength of relationships between pH and base cation content with Microsoft Excel 2007. The statistical analysis was performed using JMP statistical program, release 10 (SAS Institute, 2012).

CO2-Fix and Yasso: Total SOC simulation with time

CO_2-Fix V 3.1 is a computer model based on simulation of stocks and fluxes of soil organic carbon in forest and farming ecosystems. The soil carbon inputs will be derived from the vegetation parameters of the ecosystem which are inserted in the CO2-Fix module. The simulation of carbon sequestered in soil is made together with the dynamic soil carbon module YASSO. This module is suited for well drained soils and used to calculate decomposition of various litter types from different biomes. With input on regional climatic data, chemical composition of the litter and amount of organic matter found in the soil it can illustrate the annual carbon flux in the ecosystem (Masera *et al*., 2003; Schelhaas *et al*., 2004). The model is mainly used for carbon balances in forest ecosystems. However since our case study involves pasture areas it was also used for simulation of the carbon storage in the pasture soils. The module was used to illustrate how reforestation will affect the soil organic carbon storage with time. An illustration of the net C effect (Total SOC) was made by summing up the soil carbon flux from the former pasture culture (Old SOC) and from the *Eucalyptus* reforestation (New *Eucalyptus* SOC) . The module predicted the soil carbon flux during a 50-year period.

Biomass Module

The litter produced in the biomass model is attained from inserting existing data on biomass parameters. The biomass will have a turnover to soil organic matter with time where carbon will be transported into the different organic matter fractions or released through respiration or erosion to the atmosphere. The biomass parameters for the *Eucalyptus* include stem, foliage, branches and roots. The dry wood density for the stems in *Eucalyptus* was obtained from Neves (2000) and was estimated to 480 to 550 kg D.M.m^{-3} for plantations aimed for cellulose production in the same region. The mean annual increment (m^3 $ha^{-1}yr^{-1}$) of the tree stems was calculated with the yield tables received from the forestry enterprise where the soil samples were taken, see table 2. For the mean annual increment calculation it was assumed that the growth followed a linear relation between the above-ground biomass and coppice shoot age (Zewdie, 2008).The carbon content in stems was estimated after the general parameter stating a content of 50% D.M. Data on carbon content, relative growth rates and turnover rate of foliage, branches and roots of *Eucalyptus* were found in Lemma *et al.*,(2006). Estimation on E.*grandis* parameters was based on Tegene (1999), Nabuurus and Mohren (1993) and Abate (2004),see table 3 and 4 for parameters.

Table 2. *Calculated mean annual increment (m^3 $ha^{-1}yr^{-1}$) of the Eucalyptus stems based on Zewdies (2008) assumption of a linear growth with time. Eucalyptus 1: planted eucalypt, Eucalyptus 2: re-sprouted eucalypt, Eucalyptus 2.1: replanted eucalypt.*

Age yrs	Eucalyptus 1	Eucalyptus 2	Ecualyptus 2.1.
1	17.5	18.7	18.3
2	35.0	37.5	36.5
3	52.5	56.2	54.8
4	70.0	75.0	73.0
5	87.5	93.7	91.3
6	105.0	112.4	109.5

For the biomass production in the pasture management (Old SOC) was the grass represented as a "tree" in the biomass model with very small stem volume, no branches and a high volume of foliage and roots. The parameters for pasture root and foliage growth and compartment were taken from the study case suggested by Schelhaas (2004) in the simulation program (Table 3). For the relative growth the stem compartment was set as small as possible implemented with an increment of 0.01. The foliage and root compartment were set with very high relative increment, above ground with 500 m^3 ha^{-1} $yr^{-1}$and below-ground 400 (table 4). The wood density was set to "1" and by this the above ground production was calculated to be 5T D.M. $ha^{-1}yr^{-1}$(500*1*0.01 T DM $ha^{-1}yr^{-1}$). The mortality of these parameters was set to a high level, 0.9, to avoid a large build-up of biomass in the stem parameter. The below-ground production was set to 4 T D.M. ha^{-1} yr^{-1}, see table 4. Since the case study involved unmanaged pasture areas, the harvest parameter was excluded.

Table 3.*Wood density (T D.M m^{-3}), carbon content (T C T^{-1} D.M) and turnover rate (1 yr^{-1}) used in this study.*

Variable	Biomass compartment	E.*grandis*	Pasture
Woody density T D.M m^{-3}		0.55	
Carbon content T C T^{-1} D.M	foliage	0.53	0.47
	branch	0.46	
	stem	0.50	0.47
	root	0.47	0.47
Turnover 1 yr^{-1}	foliage	0.49	0.80
	branch	0.05	
	root	0.10	0.90

Table 4.Relative growth values of different plant compartments used in the model for E.grandis and unmanaged grassland (pasture).

Age	E.*grandis*			Pasture		
	foliage	branch	root	stem	foliage	root
0	0	0	0	0.01	500	400
2	0.3	0.1	0.3			
4	0.3	0.1	0.3			
6	0.2	0.1	0.3			

Yasso Soil Model

The Yasso soil model compartments (Fig. 3) are divided in two categories 1) the different litter types and 2) the litter quality. In the litter compartment is the litter classified in three divisions; 1) the foliage and fine roots are included in the non-woody litter, 2) the branches and coarse roots in fine woody litter and 3) the stems and stumps included in the coarse woody litter group. In addition, the root litter will be separated in fine and coarse depending on the proportion of branches and foliage litter present. The litter compartments decompose to the decomposition compartments in a time rate which is set to 1. This means that all contents are released at once. For the woody litter the rate will be smaller than 1. The litter will decompose to the compartments depending on the chemical composition; extractives, celluloses and ligin-like compounds. Each decomposition compartment has also a decomposition rate which will determine the loss of its contents by time. The losses from decomposition will either be transferred into the next decomposition compartment which have slower decomposition rates, or be lost through respiration and removed from the system. These fractionation rates in both compartments depend on temperature and water availability (Masera *et al*., 2003). The values of the decomposition in the litter quality was followed from the models standard parameters (*Schelhaas et al., 2004)* see table 5 for the values.

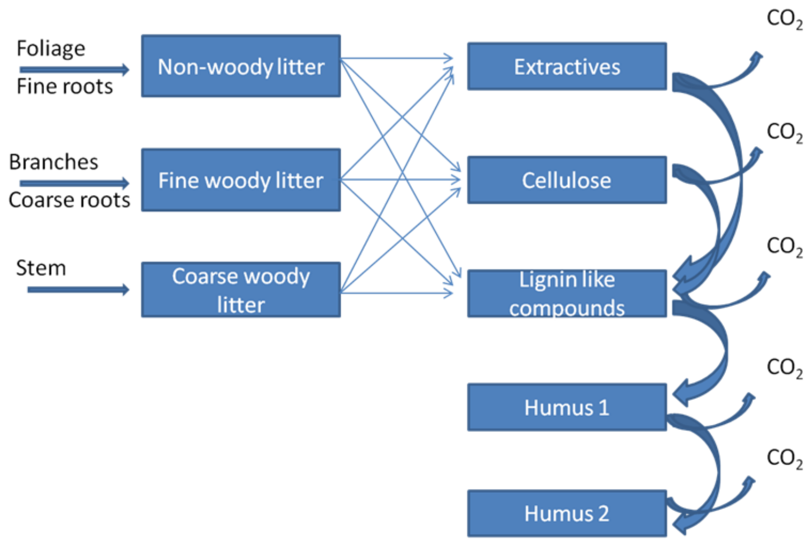

Figure 3. Litter *and decomposition compartments used in the YASSO model*.

Table 5. *Yasso model value parameters of litter quality used in this study*

Parameter	Value
Non woody litter quality	
Extractives	0.38
Holocellulose	0.36
Lignin-like compounds	0.26
Fine woody litter quality	
Extractives	0.03
Holocellulose	0.65
Lignin-like compounds	0.32
Coarse woody litter quality	
Extractives	0.03
Holocellulose	0.75
Lignin-like compounds	0.22

The main carbon input derived from biomass compartments was used to initialize the soil model. To simulate the initial carbon in the soil (T C ha^{-1}) before the reforestation of *Eucalyptus* (Old SOC) the mean SOC content measured from pasture field was used, 51.7 T C ha^{-1}. The initial carbon content under the *Eucalyptus* reforestation (New Eucalyptus SOC) was set to zero to discover the original amount of carbon sequestered in the soil with the plantation stands.

The climatic data (mean monthly temperature, effective temperature, mean sum and mean annual precipitation were ser after by Gama-Rodrigues (2003) study which used data from the meteorological station from the same region. The sum of the mean effective temperature (degree-days per year) was calculated by the model to 8576°C. The potential evapotranspiration was calculated by the model to 680.85mm.

Carbon release from stumps

The carbon release from the decaying stumps was also taken into account in the model. The volume of the stumps was measured in the field. By assuming the same density as for the stems, and the same carbon content, the carbon content in the stumps was assessed. The decomposition rate of the stumps by time was calculated with help of the the linear exponential equation (eq.1) used in Mackensen and Bauhus (2003) for E. *regnans* and E.*maculata,* which was the closest prediction we could find for *Eucalyptus* stump degradation with time. According to the authors the equation is based on the assumption that the decomposition rate is proportional to the amount of matter remaining.

$$X = X_0\, e^{-kt} \qquad \text{(eq.1)}$$

Where X stand for present wood density, X_0 initial wood density, k decomposition constant, and t is the time. Finally the carbon amount which will be released by time was calculated.

Results

The soils in the selected areas were classified according to the FAO Unesco Soil Units as Acrisols (FAO, 2001) equivalent in USDA Soil Taxonomy to Ultisols with subgroup Typic Haplustults (USDA,2010) and to Argissolo Amarelo Distrófico according to Brazilian Soil Classification System (Embrapa, 2006). Generally the soils of this study are highly weathered, acidic and low nutrient content. They can be described as having an upper mineral horizon with coarser texture and darker colour influenced by the OM with a transition to a B-horizon with a clay-rich accumulation. The clay accumulation in the B-horizon has yellowish-brown colour influenced by the presence of Al- oxides. For more detailed descriptions of the soils in the different land use systems see appendix 1-4.

The results of the granulometry laboratory showed a high percentage of sand in all soils, over 50 % between 0-30cm depth. The soil texture was classed as Sandy Clay Loam for the native forest and *Eucalyptus* areas. The *Eucalyptus* areas had a slight difference in percentage of clay between the Eucalyptus 1 and 2. The soil texture of pasture areas showed a higher percentage of sand than remaining areas. The soil texture was thereby classified as Sandy Loam.

The bulk density was for 0-5cm and 0-30cm significantly ($p<0.05$) higher in pasture and in the *Eucalyptus* stands comparing to the native forest (Table 6). The *Eucalyptus* stands tended to have a somewhat lower bulk density than pasture; however the difference was not significant. The Eucalyptus 2 tended to have a higher bulk density than Eucalyptus 1, although not significantly different.

Table 6.*Particle size distribution (%) and mean (standard error) bulk density (*g cm^{-3}) *in the different land use systems and depths, 0-5 and 5-30. Treatment means followed by the same letter in rows did not significantly differ at the 5% probability level(n=5)..*

Property	Soil depth cm	Native Forest	Pasture	Eucalyptus 1	Eucalyptus 2
Coarse sand %	0-30	56	69	65	50
Fine sand %	0-30	11	10	9	24
Silt %	0-30	3	4	2	5
Clay %	0-30	30	17	24	21
Bulk density g cm^{-3}	0-5	0.66 a (±0.07)	1.28 b (±0.07)	1.15 b (±0.08)	1.24 b (±0.05)
	5-30	1.22 a (±0.04)	1.46 b (±0.01)	1.38 b (±0.02)	1.44 b (±0.02)

The results on total elemental composition in the <2mm fraction had an uncertainty with ±2% .It showed a high percentage of SiO_2, 66-72% D.M. Also high amounts of aluminium oxide Al_2O_3 13.9-19% D.M. ,2.49-2.9% D.M. of Fe_2O_3 and 0.8 -1.16% D.M. TiO_2. MnO, MgO and P_2O_5 contents were <0,05%, K_2O was 0,09% D.M. , CaO 0.08% D.M and Na_2O <0.05% D.M.

Soil Chemical Properties in Native Forest

The samples taken from the pit of the undisturbed native forest from 0-60 cm depth interval showed a low soil pH-value increasing with depth. The exchangeable cation concentration was low and it decreased as well with depth. The CEC_{eff} had its highest content in the 0-10cm depth and also decreased with depth. The most outstanding properties were the Al^{3+} content and high total acidity content, see table 7.

Table 7. *Soil chemical properties at a soil profile in native forest from 0-60cm depth (n=1).*

Depth	pH	Ca^{2+}	Mg^{2+}	Al^{3+}	K^{+}	Na^{+}	Total Acidity	CEC_{pH7}	CEC_{eff}	BSI
cm				cmol$_c$ kg^{-1}				cmol$_c$ kg^{-1}		%
0-10	4.23	0.18	0.19	2.3	0.121	0.02	13.2	13.7	2.84	3.9
20-30	4.40	0.08	0.12	1.7	0.074	0.02	9.4	9.74	2.04	3.5
20-30	4.50	0.07	0.10	1.4	0.054	0.02	7.3	7.55	1.65	3.3
30-40	4.53	0.03	0.06	1.0	0.038	0.02	5.8	5.95	1.15	2.5
40-50	4.57	0.17	0.08	1.2	0.026	0.02	5.3	5.60	1.50	5.4
50-60	4.65	0.05	0.09	1.1	0.023	0.02	4.6	4.78	1.28	3.8

Soil chemical Properties in pasture and *Eucalyptus* land use systems

There were no significant differences found in the soil chemical properties between pasture and *Eucalyptus* areas. The measured pH in water and with the base saturation show a positive correlation, see figure 4, although not significantly proven(r=0.715). The pH decreases as an effect of low exchangeable cation availability in the soil. All samples had in general a low pH except one sample. The sequence was followed: pasture > Eucalyptus 2 > Eucalyptus 1 .For the BSI and exchangeable Ca^{2+}, Mg^{2+} and K^{+} the sequence followed: Eucalyptus 2 > Pasture > Eucalyptus 1. The exchangeable base cations with highest contents in the soil followed: Ca^{2+}> Mg^{2+}> K^{+}> Na^{+}. The total acidity and aluminium content was high in the soils following the sequence: Eucalyptus 1 > Eucalyptus 2 > pasture. Significant differences were found between the pasture and Eucalyptus 1 for total acidity but in aluminium content no significant differences were found. The content in the Eucalyptus 1 were similar to the native forest in its natural state at 50cm depth, 1.2cmol$_c$ kg^{-1}. Regarding CEC$_{eff}$ values the amount was lower than 5 cmol$_c$kg^{-1}. The sequence followed: Eucalyptus 1 > Eucalyptus 2 > Pasture. The values in the *Eucalyptus* plantations were somewhat higher than the values found in the native forest, 1.5 cmol$_c$kg^{-1} in 40-50 cm depth, see table 8 for mean values.

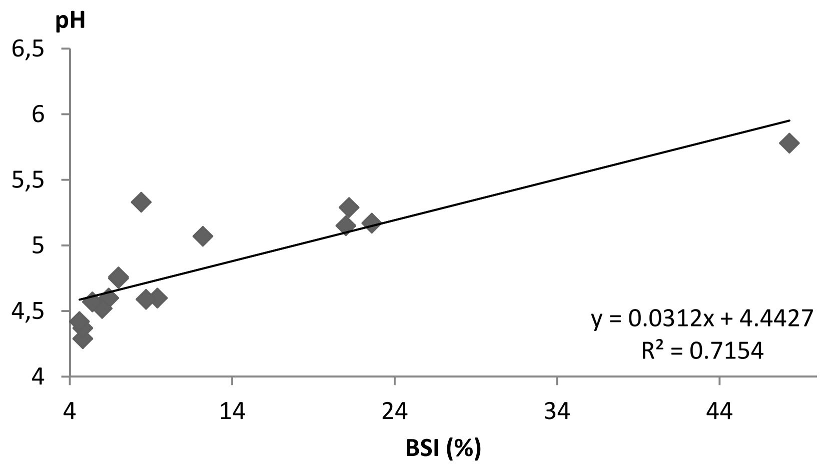

Figure 4. *Correlation between pH and base saturation index (BSI) at 50 cm depth in the soil (n=15).*

Table 8. *Mean (standard error) pH values and soil chemical content at 50cm depth in the different land use systems. Treatment means followed by the same letter did not significantly differ at the 5% probability (n=5.)*

Variable	Pasture	Eucalyptus 1	Eucalyptus 2
pH	5.00 a (±0.11)	4.57 a (±0.16)	4.96 a (±0.25)
Ca^{2+} $cmol_c$ kg^{-1}	0.48 a (±0.13)	0.35 a (±0.16)	0.55 a (±0.34)
Mg^{2+} $cmol_c$ kg^{-1}	0.12 a (±0.03)	0.10 a (±0.02)	0.16 a (±0.03)
Al^{3+} $cmol_c$ kg^{-1}	0.76 a (±0.12)	1.26 a (±0.18)	0.86 a (±0.24)
K^{+} $cmol_c$ kg^{-1}	0.016 a (±0.0)	0.015 a (±0.01)	0.03 a (±0.01)
Na^{+} $cmol_c$ kg^{-1}	0.008 a (±0)	0.017 a (±0.0)	0.012 a (±0)
Total acidity $cmol_c$ kg^{-1}	3.76 a (±0.14)	4.78 a (±0.28)	4.38 a (±0.62)
CEC_{pH7} $cmol_c$ kg^{-1}	4.39 a (±0.27)	5.27 a (±0.21)	5.12 a (±0.41)
CEC_{eff} $cmol_c$ kg^{-1}	1.39 a (±0.16)	1.75 a (±0.08)	1.60 a (±0.16)
BSI %	13.7 a (±3.17)	9.24 a (±3.46)	15.6 a (±8.20)

pH and Organic Carbon

The mean pH in the 0-5 cm depth followed the sequence: pasture > Eucalyptus 2 > native forest > Eucalyptus 1 . The pH increased significantly under the pasture areas comparing with native forest and a significant decrease took place under Eucalyptus 1. In the 5-30 cm soil depth it was followed the sequence: pasture > Eucalyptus 2 > Eucalyptus 1 > native forest. Significant differences were found between pasture and remaining land use systems, see table 9 for mean values.

Table 9. *Mean (standard error) pH values at 0-5 and 5-30cm depth in the different land use systems. Treatment means followed by the same letter did not significantly differ at the 5% probability level (n=5).*

Soil Depth cm	Native Forest	Pasture	Eucalyptus 1	Eucalyptus 2
0-5	4.8 a (±0.21)	5.9 ab (±0.32)	4.6 b (±0.05)	5.08 b (±0.23)
5-30	4.4 a (±0.10)	5.90 b (±0.40)	4.57 a (±0.06)	4.81 a (±0.31)

The mean carbon content in litter followed the sequence: Eucalyptus 2 > Eucalyptus 1 > native forest >pasture. In the 0-5cm depth <2mm fraction a significant decrease was found under the pasture and *Eucalyptus* areas compared with the native forest areas. The sequence followed: native forest > pasture > Eucalyptus 1 >Eucalyptus 2. However, there were no significant differences found between the pasture and *Eucalyptus* areas. In the 5-30 cm the carbon content decreased significantly under Eucalyptus 2 compared with native forest. The sequence followed: native forest > Eucalyptus 1 > pasture >Eucalyptus 2. For the carbon concentration in decaying coarse OM collected in the 0-30cm depth lead the following sequence: native forest>Eucalyptus 1> Eucalyptus 2 > pasture, see table 10.

Table 10. *Mean (standard error) C% in litter, 0-5cm, 5-30cm depth and decaying coarse organic material (OM) in the different land use systems. Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5).*

	Native Forest	Pasture	Eucalyptus 1	Eucalyptus 2
Litter	52.5	48.5	53.6	55.3
0-5 cm	4.46 a (±1.09)	1.98 b (±0.21)	1.81 b (±0.12)	1.74 b (±0.34)
5-30 cm	1.68 a (±0.29)	1.08 ab (±0.07)	1.16 ab (±0.05)	0.96 b (±0.08)
Decaying coarse OM	49.4	39.1	47.9	43.5

The mean amount of SOC in the <2mm fraction per unit area (kg m^{-2}) in the 0-5cm led to the following sequence: native forest > Eucalyptus 1 > Eucalyptus 2 > Pasture with no significant differences found between the different land use systems (Fig. 5). In the 5-30 cm depth the sequence followed: native forest > Eucalyptus 1> pasture> Eucalyptus 2. Significant differences were found between native forest and remaining land use systems. It can be observed, however not significantly proven, a tendency to a decrease of SOC from Eucalyptus 1 to Eucalyptus 2.

For the carbon present in the decaying coarse OM collected in the 0-30cm depth were higher amounts present under the native forest and *Eucalyptus* plantation following the sequence: native forest>Eucalyptus 1 >Eucalyptus 2> pasture (Fig.4). Eucalyptus 1 had a significant increase comparing with the pasture areas. For Eucalyptus 2 the amount tended to decrease comparing with Eucalyptus 1 but again no significant differences were achieved.

Regarding the total SOC amount in the <2mm fraction per unit area (kg m^{-2}) in 0-30cm depth together with the carbon amount in the decaying coarse OM found between 0-30cm depth the sequence followed native forest> Eucalyptus 1>pasture>Eucalyptus 2 (Fig.6). The content between pasture and *Eucalyptus* plantations did not show any significant differences when adding up the amount of decaying coarse OM. The gains or losses of carbon per unit area were slightly discrete with these land shifting systems if not comparing with native forest.

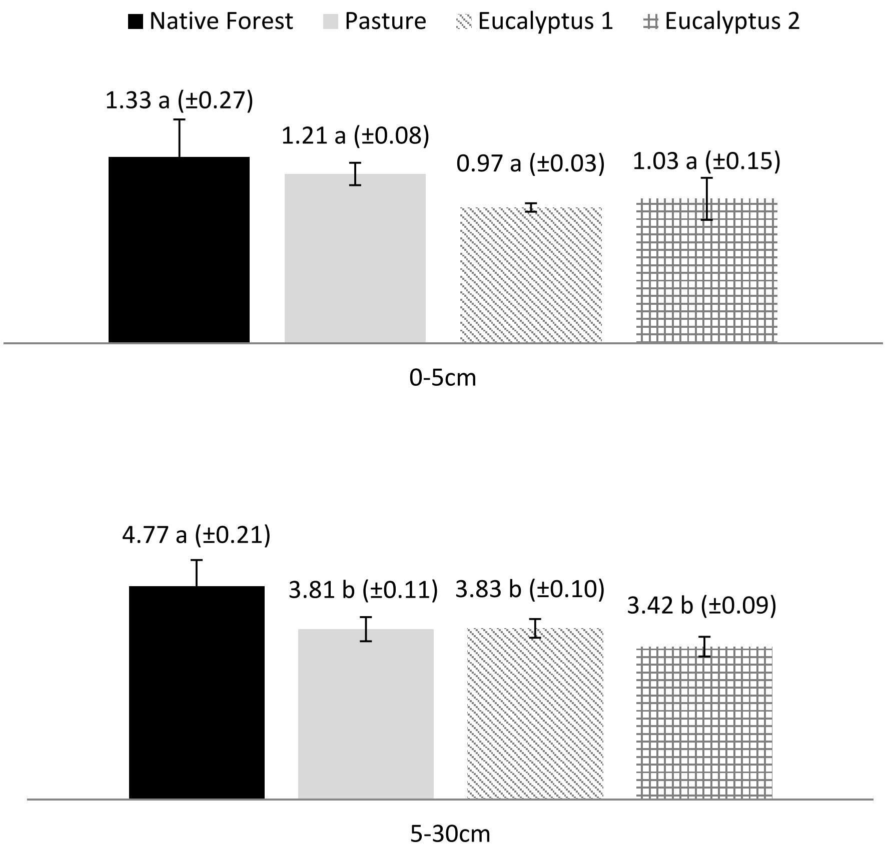

Figure 5. *Mean (standard error) content of soil organic carbon (SOC) amount per unit area (kg m^{-2}) in 0-5cm and 5-30 cm depth. Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5).*

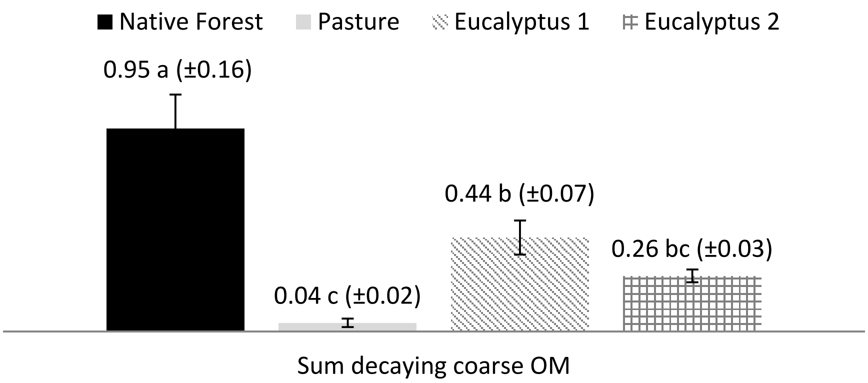

Figure 6. *Mean (standard error) carbon content of decaying coarse organic material (OM) in amount per unit area (kg m^{-2}) in 0-30cm depth . Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5).*

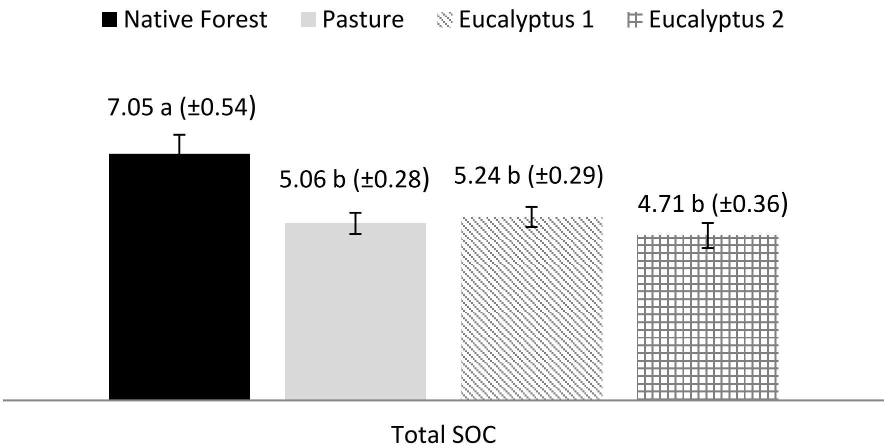

Figure 5. *Mean (standard error) content of total soil organic carbon (SOC) amount per unit area (kg m^{-2}). Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5).*

Nitrogen and C/N

The mean nitrogen concentration had its highest content in the litter following the sequence: native forest >pasture> Eucalyptus 2 > Eucalyptus1. In the <2mm fraction the mean concentrations were low and decreased significantly from native forest to remaining land uses systems in the 0-5 cm depth. The sequence followed: native forest > pasture> Eucalyptus. In the 5-30 cm depth only Eucalyptus 2 differed significantly from native forest showing a decrease. Between pasture and *Eucalyptus* areas no significant differences were found.

The mean nitrogen concentration found in the decaying coarse OM was not very high either and followed the sequence: native forest > Eucalyptus 1 > Eucalyptus 2> pasture , see table 11 for main concentrations.

Table 11. *Mean (Standard error) N concentration (%) in litter, 0-5cm, 5-30cm depth and decaying coarse organic material in the different land use systems. Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5).*

	Native Forest	Pasture	Eucalyptus 1	Eucalyptus 2
Litter	1.42	0.53	0.37	0.39
0-5 cm	0.23 a (±0.07)	0.14 b (±0.02)	0.10 b (±0.02)	0.10 b (±0.03)
5-30cm	0.11 a (±0.02)	0.08 ab (±0.00)	0.08 ab (±0.01)	0.07 b (±0.00)
Decaying coarse OM	1.04	0.51	0.80	0.79

The mean amount of nitrogen in the <2mm fraction per unit area (kg m^{-2}) in the 0-5cm depth showed to be higher under pasture following the sequence: pasture >native forest> Eucalyptus 2 > Eucalyptus 1. Significant differences were found between pasture and *Eucalyptus*

reforestation. In the 5-30 cm depth were significant differences found between native forest and the remaining land use systems having the native forest the highest content. The
total nitrogen in 0-30cm depth were significant differences found between the native forest and *Eucalyptus* areas. The sequence changed showing native forest with highest amount : native forest> pasture > Eucalyptus 1> Eucalyptus 2.Overall is the amount of nitrogen relatively low and the contents differ little between each land use system when regarding the total amount 0-30 cm, see figure 7.

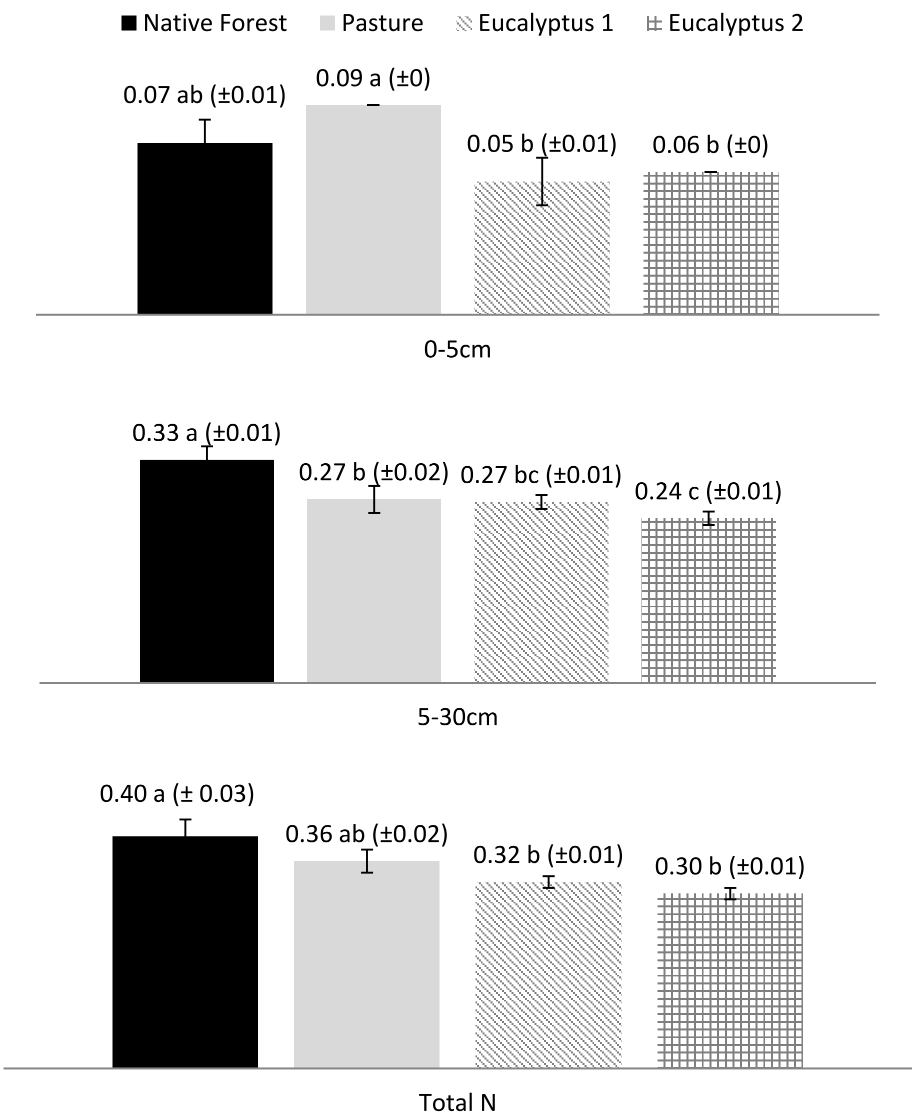

Figure 7. *Mean (standard error) of nitrogen (N) amount per unit area (kg m^{-2}) in 0-5, 5-30 and 0-30cm depth. Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5).*

The mean C/N values found in the litter were overall high following the sequence: Eucalyptus 2 > Eucalyptus 1 > pasture > native forest. In general the C/N value decreased with depth. For both the 0-5cm and 5-30 depth the sequence followed: native forest > Eucalyptus 1 >

Eucalyptus 2 > pasture, no significant differences were found. In the decaying coarse OM the sequence changed following: pasture > Eucalyptus 1> Eucalyptus 2 > native forest, see table 12 for mean values.

Table 12. *Mean (Standard error) C/N values in litter, 0-5cm, 5-30cm depth and decaying coarse organic material in the different land use systems Treatment means followed by the same letter did not significantly differ at 5% probability level (n=5)*

	Native Forest	Pasture	Eucalyptus 1	Eucalyptus 2
Litter	37	93.3	141	142
0-5 cm	18 a (±2.3)	14 a (±0.83)	18 a (±1.15)	17.5 a (±2.38)
5-30cm	14.6 a (±0.58)	14.3 a (±1.23)	14.4 a (±1.13)	14.2 a (±0.69)
Decaying coarse OM	47.6	76.6	59.6	55.2

Simulated soil carbon flux by time

The changes in SOC were simulated for the *Eucalyptus* plantations for a period of 50 years, see figure 8. The original content of SOC at year 0, called Old SOC, was set as the current SOC measured in the pasture soils and with the assumption of a steady state situation, i.e. the current content in the pasture is equal to that at the time of *Eucalyptus* plantation. The simulation showed that the content of Old SOC slowly decreased exponentially over time from 50.6 T ha^{-1} at year 0 to 33 T ha^{-1} at year 50. However, at the same time the *Eucalyptus* added new SOC originating from litter fall, root litter and harvest residues. The SOC from *Eucalyptus* showed a very irregular pattern due to that a substantial part of the carbon was added as harvest residues at intervals. Thus, at harvest the SOC increased instantaneously followed by a decrease due to decomposition losses. The curve with carbon amount released from stumps started after harvest of the 2^{nd} rotation when stumps were killed and left to decompose. Another set of stumps were killed and left to decompose after harvest of the 6^{th} rotation. Thus, with the applied management strategy there will be stumps added from two rotations out of eight. It can be observed that the amount of carbon in decomposing stumps slowly decreased with time. The time for the stump to completely degrade was calculated to be over 80 years.

The Total SOC, calculated as the sum of Old SOC, Eucalyptus SOC and Stump SOC showed an irregular pattern, very much depending on the irregular supply of *Eucalyptus* SOC. However, an initial decline was obvious during the first years following establishment of the first rotation. This was due to the losses of Old SOC that were not compensated by litter supplied from the still small *Eucalyptus* trees. It was also obvious that Total SOC was quite similar to the SOC content in the pasture during the first 20 years, except directly after harvest when there was a peak. However, after 20 years the simulation showed a higher increase in Total SOC with *Eucalyptus* reforestation.

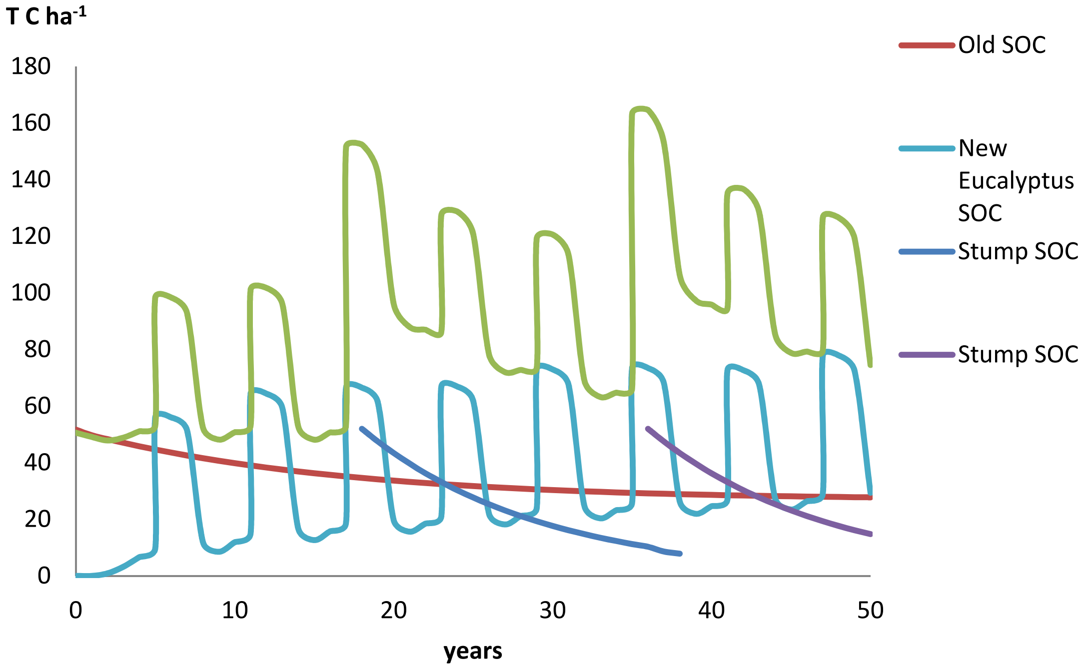

Figure 8. *Soil carbon changes of the different land use systems and total SOC over time from simulation.*

Comparing the simulated results with the measured on field in the amount on Total SOC per unit area (T ha^{-1}) were closely with *Eucalyptus* reforestation after 5 years. After 14 years of reforestation there was found a higher difference between the simulated and measured results showing higher amounts of SOC in the simulation, see table 13.

Table 13. *Simulated Total SOC) and measured under the pasture and Eucalyptus after 5 years (Eucalyptus 1) and 14 years (Eucalyptus 2) in T ha^{-1}.*

Land Use	Simulated Total SOC	Measured Total SOC
Eucalyptus 1	53.1	52.4
Eucalyptus 2	52.7	47.1
Pasture	50.6	50.6

Comparing the simulation of total SOC in *Eucalyptus* with the pasture and the measured values found in Native Forest with time 20 and 50 years it can be observed a higher gaining with the *Eucalyptus* reforestation after 20 years. However, this gaining does not reach the amount found in the undisturbed Native Forest. Meanwhile, after 50 years the amount of Total SOC in the *Eucalyptus* will reach to similar values of the measured amount found under Native Forest, see table 14. However, it is important to highlight that the field measurements were made only on the top soil whereas the program shows no limited soil depth.

Table 14. *Comparison between the different land use systems in amount of total SOC (T ha^{-1}) with time 20 and 50 years.*

Land Use	Time yrs	Total SOC T ha-1
Pasture	20	34
	50	29
Eucalyptus	20	52.7
	50	74.5
Native Forest	20	70.5
	50	70.5

Discussion

The results on the total elemental composition showed high amounts of silica , aluminium and iron oxides. The low CEC_{eff} indicated that kaolinite may be the dominant clay mineral which is highly weathered. Kaolinite is the most common mineral in the clay fraction of tropical soils. The mineral structure lack significant isomorphous substitutions and has small external surface area. From the soil texture analysis it can be observed that the soil types found in this area, Ultisols, Argic Acrisol or Argissolo Amarelo Distrófico, posess a sandy top soil. From the soil profile descriptions it could be observed that the top layer holds a higher percentage of sand sized particles than in 5-30 cm depth. The amount of decaying coarse OM will be also higher in this layer whereby the most carbon will be found there. Garay (2004) states that in these superficial sandy soils will the SOM be the most important factor to avoid leaching of carbon and nutrients. As it can be observed in the results the amount of nitrogen and carbon in % is higher in the top layer, 0-5cm, and decreasing with depth.

The soils are already poor in nutrients in this area. The results in the soil chemical properties under native forest show a low amount of exchangeable cations. The pH was also low as observed not exceeding 5. The higher amount of nutrients is stored in the living and dead biomass of the forest system instead of in the soil which is typical for tropical biomes (Leite, 2001). While shifting to pasture system the pH values have increased since the amount of organic acids produced by the forest systems are removed (Reiners *et al*., 1994). With *Eucalyptus* reforestation the pH decreased again. The amount of Ca^{2+} and Mg^{2+} increased with land use change from Native Forest to remaining land use systems down at 50 cm depth. For the pasture the changes in the chemical soil properties and pH may also have to do with the effect of the deforestation of previous natural forest. The deforestation contributes to an input of large amounts of ash in the soil which supplies higher amounts of bases (Silvana *et al*., 2002; Moraes *et al*., 1996; Reiners *et al*., 1994). Other factors that may have given rise to an increase in the base cations is less atmospheric acidic deposition and less base-cation uptake in the vegetation(Leite *et al*., 2010). Also we can not exclude that the pasture system has previously been fertilized. Reiners *et al*., (1994) point out that active pastures tend to be more fertile than forest soils.

Regarding the remaining soil chemical properties between pasture and *Eucalyptus* areas there were no significant differences among them. However, there was a tendency for higher amounts of Al^{3+}, Total Acidity and CEC_{eff} under *Eucalyptus* reforestation. With low pH the aluminum availability will increase in the soils. Enhanced soil acidity was also observed with *Eucalyptus* plantations in Hawaii (Rhoades and Binkley, 1996). The highest values of total acidity were found under native forest and also high contents were found under *Eucalyptus*. According to the authors, the soil acidification is a result of the high uptake of base cations of these species which will store it in the biomass. The same trend was followed for Leite (2001) comparing *Eucalyptus* and natural forest In Brazil indicating that possible effects of acidification with the plantations will also occur in natural vegetation.

The soil bulk density was higher under pasture than under native forest. This may be due to deforestation and active cattle trampling which decrease pore space distribution in the soil and infiltration (Silvana *et al*., 2002).The soil bulk density tended to decline with reforestation of *Eucalyptus* even though it did not lead to significant differences. The higher amount of roots contributes to improved physical soil conditions providing more air in the soil and decreasing soil compaction (Vogt *et al.*, 1997). However heavy machinery during forest operations can cause soil compaction and inhibit root growth (Brady and Weil, 2008). Since the management consists of several short rotations there may be a root growth restriction due to repeated mechanical management. It can be observed in Eucalyptus 2 an increase in the soil bulk density reaching to values closer to the pasture areas

Regarding the C/N values the native forest showed the lowest values in the litter. This is coupled to its higher nutrient quality which leads to a rapid turnover to SOM. As it can be observed the amount of decaying coarse OM in native forest was much higher than for the other land use systems. The C/N values in *Eucalyptus* plantation were highest in the litter. The plantations also deposit a higher proportion of woody litter with higher lignin content and more resistant to decomposition (Gama-Rodrigues and Barros, 2002). For the litter in the pasture areas our C/N values were also high. Despite these high values Cantarutti *et al*., (2002) stated the high turnover rates of this grass species which lead to high nitrogen turnover to the soil.

The results on nitrogen in the <2mm fraction from the laboratory differed from our measured reference samples having an underestimation of 19.5% from the values in the laboratory from Sweden. By this it should be taken into consideration that there is an underestimation of the nitrogen content results. The pasture areas showed higher nitrogen content in kg m^{-2} in the <2mm fraction comparing with the *Eucalyptus* plantations. The system involves a nitrogen cycle with the plants (growth, senescence) and cattle consumption (forage consumption, faeces and urine) (Boddey *et al*., 2004). The higher nitrogen content contributes to a rapid decomposition of SOM with help of the decomposing soil microorganisms. With higher respiration rates more carbon will be released to the atmosphere. In the Eucalyptus 2 the total nitrogen amount per unit area tended to decrease although it did not lead to any significant differences statistically. The fast growing short rotation plantations are highly nutrient demanding and cause depletion of soil nutrients after frequent harvest. Even if residues are left in the plantation and fertilizing take place the nutrients in the soil will decrease when frequent stem wood is harvested and taken away causing impacts on soil nutrients and carbon storage (Binkley *et al*., 1992; Fölster and Khanna, 1997).The Eucalyptus 2 also showed low C/N values in the soil as an effect of the fertilization and liming. Lundström *et al*. (2003) reviewed research on liming and ash application effects in the temperate forest soils and showed changes in BSI, pH, CEC and increase of carbon in the labile form. It will lead to higher turnover rates of soil organic matter including higher microbial activity and soil respiration.

The results obtained from field measurement show the potential of the soils to store carbon through reforestation practices established on former pasture areas of the region. Whether a change in SOC stocks will occur or not with land use change it will mostly depend on the previous land use management and its initial SOC stock (Lemenih, 2004; Garay *et al*., 2004). Overall deforestation of tropical forestland will lead to a decrease in SOC pool. Anthropogenic disturbances as slash and burn practices of above ground biomass and greater exposure of the SOM through forest clearing lead to a higher carbon output causing an unbalance in the system (Brady & Nyle, 2008). In our results the preserved native forest showed the highest SOC pools whereby the system has reached a steady state. On the other hand regarding the *Eucalyptus* plantations the system has recently been planted and no equilibrium of SOC has been reached yet. Thus it is crucial to analyse even the remaining decaying stumps in the plantation management which will contribute to SOC flux. This has not always been taken into consideration in other studies and we find it important to highlight its contribution to SOC pool accumulation with time.

The land use shift from native forest to pasture led to a significant total SOC decrease. According to several published papers the land use shifting from natural forests to pasture areas can also maintain or even increase SOC stocks with time (Fearnside and Barbosa, 1998; Neill *et al*., 1997; Fisher *et al*., 2007; Lima, 2006; Moraes *et al.*, 1996; Lugo and Brown, 1993). It is also important to highlight the grade of disturbance the native forest has had since it will affect whether there will be a gain or loss in SOC pool when comparing with a shifted land use system. In our case the native forest is an intact area whereby no major anthropogenic soil disturbances have taken place. Other reports also show a higher amount of carbon preserved in native forests comparing to pasture areas. The pasture areas are not well managed and overgrazed which will tend to land degradation leading to an unbalanced system regarding SOC pool (Desjardins *et al*., 1994; Trumbore *et al*., 1995). Meanwhile Costas results (2009) of a study performed in Bahia region showed no significant differences in SOC comparing primary forest with degraded or productive pasture areas. Moreover, it was proved that more than half of the carbon content found in the managed and unmanaged pastures was derived from the previous land use system meaning that the recently established pastures did not contribute so much to the SOC pools, this could also be the case in the pasture areas of our studies.

Our chosen areas for the field study did not show any significant differences in total SOC for *Eucalyptus* reforestation on former pasture areas. However a tendency to total carbon increase was noticed after five years of management. The higher amount of decaying coarse OM in the eucalypt will contribute to an increase in the total amount of SOC with time. This is important to highlight, since the recent reforestation with eucalypt plantations has not reached to a steady state yet. For other studies the reforestation or afforestation on previous deforested areas increase total soil carbon stocks with time. Certainly the higher carbon accumulation will take place once the trees mature and establish a steady state in the system (Jandl *et al*., 2007, Lugo and Brown, 1993). The SOC pool can even reach to similar conditions of the native forest in older established plantations (Davis and Condron, 2002). Cespedes (2007) study in Uruguay showed a decline with reforestation of *Eucalyptus* spp. on former pasture areas. Also 50% of the origin of the soil carbon in the 30 year old *Eucalyptus* came from the former pasture soils suggesting that the reforestation did not contribute as much as the pasture did for carbon accumulation in the soils. However the management of the pastures was not taken into account in the study. Sanchez *et al*. (1985) state that the benefit of reforestation on soil properties and carbon are primarily found when soils are degraded, usually due to poor management.

Comparing Ecualyptus 1 with Eucalyptus 2 there are no significant differences found. The trend show different results from Silvas (2008) study performed in the same region of Bahia. For Silva who made a comparison in different soil depths found no significant differences either between pasture and recent *Eucalyptus* reforestation in the 0-20 cm depth. However, when comparing with the re-sprouted eucalypt there was a significant increase. When comparing between 0-40cm depth there was no significant differences found but a trend showed an increase in the SOC stock under the re-sprouted eucalypt. The total carbon gaining was mainly noticed when taking into account 0-100 cm depth, showing a significant increase with re-sprouted eucalypt. Comparing with our study there was a difference in the management length. The re-sprouted eucalypt plantations in Silvas research were taken under soils with a length of 8 years of management. Our areas in Eucalyptus 2 have been exposed to more soil disturbances. Three areas were taken from their second rotation and two areas from their third rotation, with an average of 14 years of plantation. Samson *et al*.,(1999) state that short rotations (less than 10 years) do not lead to carbon sequestration and that most carbon is probably lost during the establishment phase of the plantation.Indeed higher decline of SOC pool take place in forest plantations during forestry management operations. These lead to soil disturbances in the top soil reducing mycorrhizal populations. When soil is disturbed it will cause changes in the microclimatic conditions of the soil as temperature and humidity. Through soil preparations it can trigger the mineralization of SOM when exposed to the air. The breakage of soil aggregates will expose the protected SOM to the soil microorganisms leading to a more rapid C mineralization(Jandl *et al*, 2007; Lal, 2005; Vogt *et al.*, 1997)

The amount of roots and decaying coarse OM found in the areas of Eucalyptus 2 soil samples were lower than in Eucalyptus 1. This is important to enhance since it can be a key factor to the decrease in SOC in our results. It is important to notice that our study included only the measurements of SOC content from the top soil 0-30 cm. Silvas (2008) stated the importance to take samples deeper for a complete comparison. The author concluded that it is difficult to detect changes in total SOC stock and total soil nitrogen in short term which are stated to be small and to have high variability in the soil. It was also concluded that evaluating the carbon in the labile fractions in soil organic matter will give more differences and results than in the stable fractions. Faria *et al.*, (2009) study in Bahia region prove a decrease in total SOC fractions of SOM in the layers 0-10 and 10-20 cm in *Eucalyptus* plantations when samples were taken from a longer horizontal distance from the tree rows. This indicates the importance that the root and stump cycling and rhizodeposition have for the soil organic matter accumulation. In addition, the soils under Eucalyptus 2 have been exposed for several treatments with herbicides than in the Eucalyptus 1. The herbicide application affects the belowground root health by inhibiting the short root growth and mycorrhizal formation, suggesting that the low presence of fine roots in some of the *Eucalyptus* areas has to do to the repeated glyphosate treatments with time (Vogt *et al.*, 1997). However, it is more likely that the lower presence in fine roots has to do with the soil structure in these areas.In two areas of Eucalyptus 2 the amount of fine roots were very low in the depth 0-30 cm. Witschoreck *et al.*, (2003) showed in a study of *E.urophylla* that the higher amount of finer roots are present in the first 30 cm of the soil depth. The increasing density in the soil with depth will difficult the root penetration and development. In our study these areas seemed already to have difficulty in root penetration within 5-30 cm depth.

The temperature, mean precipitation and topography are key factors for the mineralization of SOM and the amount of SOC losses and storage. Higher temperatures and precipitation will trigger the rapid decomposition of soil organic matter leading to a lower contribution to the SOC pool (Post, 1982). High temperature may also increase evapotranspiration and water stress with lower production of litter as a result. There are also differences in the amount of SOC and nitrogen under *Eucalyptus* plantations at different climatic conditions. The increased microbial activity lead to a more rapid decomposition in the samples taken in wet seasons (Gama-Rodrigues *et al*., 2005; Trumbore *et al*., 1995). Silva (2008) also evaluated the dynamics of eucalypt litter turnover and showed that rapid decomposition will take place in areas with higher mean precipitation. O'Connell and Nambiar (1997) state that the successive rotations of forest plantations established under soils which are naturally highly acidic and poor in nutrients will result in rapid mineralization of SOM.

Since the soils have a broad spatial variability in properties it is usually necessary to have a very large number of soil samples to prove statistical differences in soil carbon pools (Jandl *et al.*, 2007). Soil models can be used as an alternative for simulation on soil carbon sequestration in different land use systems. The computer simulation may give a reasonable idea on how the long-term SOC accumulation may look like, whereas our field measurements only showed the accumulation in short term, due to the fairly young plantations, and within a limited soil depth. With the simulation of the Old SOC content were several variables assumed and taken from literature review.

The differences on the simulated amount of SOC stored under *Eucalyptus* reforestation comparing with the measured were not very high, stating that there is no equilibrium between the input and output of SOC reached yet. The physical disturbances in *Eucalyptus* management are associated with site preparation and harvest. It is known when a plantation is growing the production of biomass will dominate over the decomposition of SOM. During harvest and site preparation the loss in SOM exceeds biomass production (Fölster and Khanna , 1997). After 20 years the differences are noticed in the simulation showing a higher amount of SOC with *Eucalyptus* reforestation. The implemented sustainable soil management in the plantations will help to increase SOC pool in long term. The higher amount of decaying OM and remaining of stumps after harvest found under *Eucalyptus* will trigger a gaining in the SOC stock by time. Thereby the plantations established for longer periods than 20 years will play an important role in SOC sequestration and mitigation on climate change. The results show that the undisturbed native forest is the optimal forest system for SOC sequestration in tropical environments. However, after deforestation the *Eucalyptus* reforestation will be an alternative to sequester carbon, but the gainings in SOC will only be noticed in the long term and not in the short term as it can be observed through the field measurements. After 50 years of *Eucalyptus* reforestation the amount of SOC accumulation is just as much as in the amounts measured on field under native forest. This gives a certain idea of the *Eucalyptus* capability to carbon sequestration. Furthermore, it is important to remind that the measured amounts have a limit in the soil depth, for a complete comparison deeper soil samples should have been taken under native forest.

Conclusions

- The intact native forest showed the lowest bulk density and highest SOC stock showing a steady state in the forest SOC cycle since no disturbance has taken place.

- The field measurements showed an increase in soil compaction and total SOC decrease with land use change to pasture. Higher pH and exchangeable cation concentrations show possible fertilization effects. The total nitrogen is not affected by the land use changes.

- The soil compaction decreased with *Eucalyptus* reforestation. The management after five years tend to increase the SOC stock.

- The field measurements showed that reforestation under longer periods , 14 years, and managed in a short rotation system, did not show higher differences in SOC stocks than the pasture areas. The C cycle in the forest system has not reached a steady state yet.

- The simulation on total SOC pool show similar results to the measured SOC amounts. In the long rung (>20 years) will the *Eucalyptus* result in increased C stocks in plantations, however these amounts will not reach to the SOC stock amounts under native forest.

Sources of errors

A number of errors were during collection and preparation of the samplings were attempted to be adjusted. During field visit the physical difficulty to use the cylinder in 5-30 cm of depth caused some soil compaction in some samplings. This may have been caused by the natural soil hardness and mechanical soil preparation and cattle trampling. In *Eucalyptus* the presence of bigger root disturbances when samples were near the tree row may also caused an impact in the soil collection. The cylinder in this case has been brought down between 0,5-4 cm deeper. For this error calculations have been made for correction to get the real contents of soil down to 30 cm.

During soil preparation before handing in to laboratory were some soil samplings mistakenly dried in the oven up to 105°C instead of 65°C. This may have affected the carbon content in the soil due to the soil water evaporation. For correction were one part of the soil samples dried at 65°C to 105°C. By this, a new soil mass was calculated with differences of water loss taken into account. Also the samples dried at 105°C formed strong clay aggregations. While homogenizing the soil samples, there was a risk that not all soil particles were completely homogenized in the samples. The gravel found in these samples displayed different ranges of weathering giving difficulties to distinguish between gravel or clay particle.

Since this area has a land use history with deforestation using slash and burn system the soil contained high amounts of charcoal both in the pasture and *Eucalyptus* areas. The charcoal was carefully sorted out of the samplings, since it is known that this will highly affect the results of total organic carbon in the laboratory. Although since the amount was high there might be a risk of some charcoal particle contamination was included in the pooled samples. These were well covered within clay aggregates and most likely crushed and mixed during the homogenization process.

Due to other impediments and circumstances outside the field study the samples were not handed in directly after the sample preparation. It took 2-4 weeks to hand in the samples to the laboratory for C and other chemical analysis, there is also the risk it may have changed the water status in the soil samples even though they were well sealed in polytechnic bags. The amounts may have been affected slightly in the chemical and carbon analysis.

Acknowledgments

First I would like to thank the Swedish International Development Cooperation (Sida) for funding the study through a Minor Field Study (MFS). Secondly, my dearest supervisors Prof. Mats Olsson and Prof. Jan-Erik Nylund from the Swedish University of Agricultural Sciences for facilitating me with contacts, suggestions, ideas, improvements and for always keeping up the good mood during my project. Also I want to give a big thank you to Prof. Agna Menezes and her colleagues in Soil Department from Universidade Estadual de Santa Cruz in Ilhéus for facilitating me with equipment, suggestions and ideas in the project, contacts and for support for the laboratory analysis. I want to thank several people from Eunápolis, Ivonete for facilitating me with logistic and helping me get to Brazil. In the forestry enterprise Sergio Ricardo Silva, Jose Henrique Bazani , Helton Maycon Lourenco and further staff members for the greatest support, suggestions, ideas ,facilitations and company during my visit in Eunápolis. I also want to express my thanks for the highest professional support on field: Nelsinei and Clayison and their remaining colleagues at Checon Paiva. Muito obrigada pelos bons momentos, apoio e muita risada, sem a vossa ajuda o projeto ia ser muito mais dificil de superar!

My warmest thanks for remaining people who also supported me emotionally and welcomed me in their homes and families and made feel like home so far away from Sweden: Frederico and Gizele, Daniela and Aline, Marcelo and Gabriel, Dona Ofelia, Jorge and his friends and family, Gil and Wellington, Anne and Everton and his family, my friends from UESC University who showed me the greatest time in Ilhéus. Muito obrigada a todos vocês por fazer o meu tempo na Bahia ser inesquecível!

I also want to thank all my friends in Stockholm and Uppsala for their emotional support during the writing of the project. Last but not least I would like to thank my family for all their support during my studying years and for always believing in me.

APPENDIX 1. SOIL PROFILE DESCRIPTION NATIVE FOREST

Source: Manuela R. da Silva

Soil Chemical Composition of the study area

pH	Ca^{2+} cmol$_c$ kg^{-1}	Mg^{2+}	Al^{3+}	K^+	Na^+	Total acidity	CEC_{pH7}	CEC_{eff}	BSI %
4.57	0.17	0.08	1.2	0.03	0.02	5.3	5.6	1.5	5.4

Depth cm	pH	C %	N %	C/N	Bulk density g cm^{-3}
0-5	4.75	4.46	0.23	5.15	0.66
5-30	4.42	1.68	0.11	1.32	1.22

General information of the study area

Location	RPPN Estação Veracel, 15 km from Porto Seguro, toward Eunápolis direction
Topography	Plain relief
Geomorphology	Dissected plain ("Tabuleiro") developed in Tertiary sediments of the "Barreiras" group.
Parent material	Conglomeratic sandstones with kaolinite
Climate	Tropical wet with no drying season (Af)
Vegetation	Dense and shade tolerant vegetation, rainforest Mata Atlântica
Soil type	Umbric Acrisol (FAO,2001), Typic Haplustus (USDA,2010), Argissolo Amarelo Distrófico(Embrapa, 2006)

Brief description of the profile

The soil horizon starts with a shallower A horizon with darker colour and coarser texture enriched with abundant fine roots and a high biological activity. The colour graduates weakly to a lighter brown E horizon with a weak granular structure. Further down the soil is a finer and yellowish texture consisted of sandy clay, some fine gravel can be found and soft grayish clay nodules originating from the with a mixture of surface horizon, the structure is developed to moderate and subangular blocky and there is still a high biological activity and fine to coarse roots present.

Profile description

Oe 4-2cm, moderately decomposed organic material

Oa 2-0cm, highly decomposed organic materia and mycelia

A 0-10cm, sandy loam, 10 YR (3/3) dark brown moist; weak granular structure, fine to coarse, loose, very friable, non-sticky, slightly plastic, high porosity, channels, vughs, fine and very fine common voids, abundant fine roots, many biological activity , earthworm channels, termite, ant channels and nests, diffuse smooth boundary

A/Bt 10-25cm, sandy loam, 10 YR (4/3) brown moist; weak granular structure, fine to coarse, loose, very friable, non-sticky, slightly plastic, high porosity, channels, vughs, fine and very fine common voids, many fine roots, many biological activity , earthworm channels, termite, ant channels and nests, diffuse smooth boundary

Bt 25- 60cm, sandy clay loam, 2,5 Y (5/6) light olive brown dry, 10 YR (5/4) yellowish brown moist, very few fine gravel, angular, fresh weathered, feldspar, very few mottles, coarse, distinct, sharp boundary, 10 YR (3/2) very dark grayish brown dry, 10 YR (3/1) very dark gray moist; moderate, subangular blocky, very fine to coarse, loose, very friable, slightly sticky, slightly plastic, high porosity, channels, vughs, common fine and medium, few coarse and very coarse voids, many very fine to coarse roots, many biological activity, earthworm channels, termite, ant channels and nests

APPENDIX 2. SOIL PROFILE DESCRIPTION PASTURE

Source: Manuela R. da Silva

Chemical compostion of the study area

pH	Ca^{2+} cmol$_c$ kg^{-1}	Mg^{2+}	Al^{3+}	K^+	Na^+	Total acidity	CEC_{pH7}	CEC_{eff}	BSI %
5.0	0.48	0.12	0.76	0.02	0.01	3.76	4.39	1.39	13.7

Depth cm	pH	C %	N %	C/N	Bulkdensity g cm^{-3}
0-5	5.91	1.98	0.14	14.1	1.28
5-30	5.90	1.08	0.076	14.2	1.46

General information of the study area

Location	Eunápolis, Bahía, Brazil
Topography	Plain relief
Geomorphology	Dissected plain ("Tabuleiro") developed in Tertiary sediments of the "Barreiras" group
Parent material:	Conglomeratic sandstones with kaolinite
Climate:	Tropical wet with no drying season (Af)
Vegetation:	Pasture, *Brachiaria humidicola*

Mean grazing grade (0-5 5: heavy graze) 3,2

Soil type Ochric Acrisol (FAO,2001), Typic Haplustus (USDA,2010), Argissolo Amarelo Distrófico (Embrapa, 2006)

Brief description of the profile

The profile consist of a deep A horizon down to 20cm of darker and coarser texture than the B-horizon, many fine gravel is found in A horizon and the structure varies from weak to moderate granular, there are many fine roots found and a high biological activity with common charcoal reaminings, the colour shifts gradually to yellowish with depth and the texture is finer changing to a sandy clay loam from 24 cm where the B horizon starts. The roots become fewer with depth and the structure is stronger with blocky subangular structure, common charcoal remainings are also found with depth.

Profile description

A 0-20cm, sandy loam, 10YR (4/2)dark grayish brown dry, 10 YR (4/1) dark gray moist, many fine gravel, angular, freshly weathered, quartz; weak granular to blocky subangular, , fine to medium, soft, very friable, slightly sticky, slightly plastic, medium porosity, channels, vughs, fine, few, common, soft concretion, rounded, soft, clay, greyish, , abundant very fine to fine roots, many charcoal, common earthworm, gradual broken boundary

B_t 24-60cm, sandy clay loam, 10YR(6/4) light yellowish brown dry, 10 YR (6/3) pale brown moist, common rock fragments, fine gravel, angular, freshly weathered,quartz; strong blocky subangular, medium to very coarse, soft, friable, sticky, slightly plastic, medium porosity, channels, common very fine to fine voids, common mineral concentration, soft concretion, medium, enlongated and rounded,grayish, soft, few fine roots, common charcoal

APPENDIX 3. SOIL PROFILE DESCRIPTION EUCALYPTUS 1

Source: Manuela R.da Silva

Soil chemical composition of the study area

pH	Ca^{2+}	Mg^{2+}	Al^{3+}	K^{+}	Na^{+}	Total acidity	CEC_{pH7}	CEC_{eff}	BSI
	$cmol_c\ kg^{-1}$								%
4.57	0.35	0.10	1.26	0.02	0.02	4.78	5.27	1.75	9.2

Depth cm	pH	C%	N%	C/N	Bulkdensity g cm^{-3}
0-5	4.6	1.8	0.1	17.4	1.15
5-30	4.6	1.2	0.1	14.2	1.38

General Information of the study area

Location	Eunápolis, Bahía, Brazil
Topography	Plain to weakly ondulate relief
Geomorphology	Dissected plain ("Tabuleiro") developed in Tertiary sediments of the "Barreiras" group
Parent material	Conglomeratic sandstones with kaolinite
Climate	Tropical wet with no drying season (Af)
Vegetation	*Eucalyptus* plantation, E.*grandis**E.*urophylla*, mean age 4,7 years
Soil Type	Argic Acrisol (FAO, 2001), Typic Haplustus (USDA,2010), Argissolo Amarelo Distrófico (Embrapa,2006)

Brief description of the soil profile

Sandy clay soils with coarser texture and dark brown colour in the upper 15cm of the surface, many fine gravel , weak granular structure, high biological activity, many fine roots and charcoal remainings, finer texture with depth with more clay accumulation, moderate structure, subangular blocky and yellowish colour, common soft concretion of clay mixed with organic matter from upper layer, fewer fine gravel, fewer fine roots ,more common medium roots and few charcoal.

Profile description

O_i 4-2 cm, non decomposed leaves and dry mycelia

O_e 2-0 cm, moderately decomposed organic material

A 0-15cm, sandy loam, 10YR(3/3) dark brown dry, (4/2) dark grayish brown moist, common coarse gravel and mottles, angular, slightly weathered quartz, 10 YR (6/3) pale brown dry, 10YR (5/2) grayish brown moist, prominent , sharp boundary; weak single grain, granular, fine to medium , loose dry and moist, non-sticky, non-plastic, very high porosity,channels,common fine to medium pores, abundant mineral concentration, soft concretion, medium and coarse, soft, clay, grayish, fine, both hard and soft, discontinuous irregular, common very fine to medium roots, common biological activity, charcoal, earthworm channels, diffuse irregular boundary

AE/B_t 15-28cm, sandy loam, 10 YR(5/6) yellowish brown dry and moist, sticky, plastic, very friable, slightly hard, common rock fragments, quartz, moderate blocky subangular medium to coarse, common mottle, distinct, clear boundary, 7,5YR (4/2) dark grayish brown dry, 10YR (4/3) brown moist , moderate granular and subangular blocky coarse, slightly hard, friable, slightly sticky, plastic, very high porosity, channels, vughs, common fine and medium voids, very fine few roots, common medium to coarse roots, few charcoal, gradual smooth boundary

B_t 28-60cm, sandy clay**,** 10 YR (6/6) brownish yellow dry, 2,5Y (6/4) light yellowish brown moist, very few fine gravel, angular, fresh or slightly weathered, quartz, few fine mottles, prominent, sharp, 10 YR (6/3) pale brown dry, 10YR (5/2) grayish brown moist; moderate , subangular blocky, coarse and very coarse, soft, very friable, non-sticky, slightly plastic, medium porosity , channels, fine to medium common pores, very fine few roots , common medium to coarse roots, few charcoal

APPENDIX 4. SOIL PROFILE DESCRIPTION EUCALYPTUS 2

Source: Manuela R. da Silva

Soil chemical composition of the study area

pH	Ca^{2+} cmol$_c$ kg^{-1}	Mg^{2+}	Al^{3+}	K^+	Na^+	Total acidity	CEC_{pH7}	CEC_{eff}	BSI %
4.96	0.55	0.16	1.86	0.03	0.01	4.38	5.12	1.60	15.6

Depth Cm	pH	C %	N%	C/N	Bulk density g cm^{-3}
0-5	5.08	1.74	0.10	17.4	1.24
5-30	4.81	0.96	0.07	14.1	1.44

General Information of the study area

Location	Eunápolis, Bahía, Brazil
Topography	Plain to weakly ondulate relief
Geomorphology	Dissected plain ("Tabuleiro") developed in Tertiary sediments of the "Barreiras" group
Parent material	Conglomeratic sandstones with kaolinite
Climate	Tropical wet with no drying season (Af)
Vegetation	*Eucalyptus* plantation, E.*grandis**E.*urophylla*, mean age 5,2 years, 1st cycle 2nd rotation and 2nd cycle 1st rotation
Soil Type	Argic Acrisol (FAO,2001), Typic Haplustus (USDA,2010), Argissolo Amarelo Distrófico (Embrapa,2006)

Brief description of the soil profile

The A horizon consists of a coarser texture of sandy loam comparing to the B horizon varying from sandy clay to sandy clay loam , the colour in A horizon is differed by being more darker, the content of fine gravel is few and some clay from B horizon is also dispersed through the A horizon which can be noticed by the common mottling, the structure varies from weak to moderate having a common biological activity, the boundary varies from abrupt to diffuse. The clay content is much higher in the B horizon giving a finer texture and yellowish colour starting from around 20cm. Here the structure is moderate to strong subangular blocky and fewer finer and coarser roots are found, also some tracks of few charcoal and some sesquioxides are found.

Profile description

O_i 2-0 cm, non decomposed dry leaves and mycelia

O_e 0-2 cm, moderately decomposed organic material

A 0-20cm, sandy loam, 10 YR (3/2) very dark grayish brown dry,10 YR (4/2) dark grayish brown moist, few fine gravel, angular, freshly weathered, quartz, common mottle, 10YR (4/4) dark yellowish brown, moist, 10YR(5/4) yellowish brown dry, fine, distinct, sharp ;weak to moderate granular, fine to coarse, soft, very friable, slightly sticky, non-plastic, high porosity, channels,common fine roots few medium to coarse roots, common earthworm channels, termite, ant channels and nests, clear irregular boundary

B_t 20-60cm, sandy clay loam, 10 YR (6/6) brownish yellow dry, 2,5Y (6/4) light yellowish brown moist, very few mottling 10 YR (3/2) very dark grayish brown dry,10 YR (4/2) dark grayish brown moist, fine, prominent, sharp, few clay-sesquioxides, grayish and reddish; strong, blocky subangular, coarse to very coarse, slightly hard, friable, non sticky, plastic, high porosity, channels very fine to very coarse, few very fine to coarse roots, few charcoal

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