SOIL-PLANT CARBON STOCKS IN THE WEATHERLEY CATCHMENT AFTER CONVERSION FROM GRASSLAND TO FORESTRY

by

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DECLARATION

I declare that the dissertation hereby submitted by me for the degree Magister Scientiae Agriculturae at the University of the Free State is my own work and that I have not previously submitted the same work at another University. I therefore concede copyright of this dissertation in favour of the University of the Free State.

Signature:..Date..

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DEDICATION

I dedicate this dissertation to my family and my husband Mr Zwelinzima Mavuso. Thank you for being the best family throughout my studies.

ABSTRACT

Soil and vegetation play a vital role in the global C cycle because C exchange is affected by both. Thus a change in land use may result in either a loss or gain of C in the soil-plant system. This study was conducted in the Weatherley catchment in the northerly Eastern Cape Province, a former grassland area. Approximately half of the 160 ha in the catchment was afforested with three tree species, viz. *P. elliottii*, *P. patula*, and *E. nitens* in 2002. Before afforestation, a baseline study (Le Roux *et al*., 2005) on soil organic matter was conducted on the areas designated for the above mentioned tree species. Therefore, this study was a continuation of the mentioned study with the aim to quantify the soil and biomass C stocks (in some instances N stocks also) eight years after afforestation.

For comparable purposes the same 27 sites studied by Le Roux *et al*. (2005) were investigated, viz. 25 afforested sites and two control sites. Soil samples were collected in 2010 at various depths from the 27 sites: 0-50, 0-100, 0-150, 0-200, 0-250, 0-300, 0-400, 0-500, 0-600, 0-700, 0-800, 0-900, 0-1000, 0-1100, and 0-1200 mm and analysed for organic C and total N as organic matter indices. At each site, three sub-samples were taken per depth interval and mixed together to give a composite sample. The procedure was replicated four times at each site.

At each of the 27 sites, fallen litter and undergrowth were collected simultaneously with the soil sampling, also in four replicates. After being dried in a glasshouse, the litter was milled and analysed for C and N contents. A year after soil and litter sampling, when trees were eight years old, the height and diameter at breast height of 12 trees were measured at each of the 25 afforested sites. The measured data were used to calculate the utilisable stem volume, and hence the tree C stocks.

Afforestation of the former grassland areas influenced soil organic matter in the upper 300 mm layer, resulting in either increases or decreases in soil C stocks, N stocks and C:N ratios. Soil C stocks decreased by 0.9 Mg ha^{-1} at site 235 (Katsptuit soil with grass) to 23.6 Mg ha^{-1} at site 232 (Katspruit soil with *P. elliottii* trees). The rate of decrease ranged between 0.11 and 2.95 Mg C ha^{-1} yr^{-1}. The soil C stocks increased by 0.9 Mg ha^{-1} at site 244 (Pinedene soil with *P. patula* trees) to 11.3 Mg ha^{-1} at site 242 (Longlands soil with *P. patula* trees). The rate of increase ranged from 0.11 Mg C ha^{-1} yr^{-1} to 1.41 Mg C ha^{-1} yr^{-1}. Soil C stocks decreased significantly by 5.5 Mg ha^{-1}, 10.0 Mg ha^{-1}, and 12.4 Mg ha^{-1} for grass, *E. nitens*, and *P. elliottii* areas, respectively. Soils under *P. patula* showed an increase in C stocks of 1.9 Mg ha^{-1}. When soils were grouped according to mapping units, drainage classes or first subsoil (B1 or E1) horizons there was generally a significant decrease in soil

C stocks due to afforestation. The soil N stocks to a large extent behaved like the soil C stocks.

The aboveground biomass C stocks were obtained by adding the litter C stocks and the tree C stocks together. These aboveground biomass C stocks varied from 3.71 Mg ha^{-1} at site 209 (Katspruit soil with grass) to 167.2 Mg ha^{-1} at site 246 (Pinedene soil with *E. nitens* trees). On average the aboveground biomass C stocks for the 27 sites was 64.9 Mg ha^{-1}. However, aboveground biomass C stocks averaged 69.7 Mg ha^{-1} for the 25 afforested sites and only 4.8 Mg ha^{-1} for the two control sites. The aboveground biomass C stocks varied significantly from 4.8 Mg C ha^{-1} for the grass to 41.2 Mg ha^{-1} for the *P. elliottii* and 67.3 Mg ha^{-1} for the *P. patula* and 113.2 Mg ha^{-1} for the *E. nitens* areas. Based on the soil mapping units, aboveground biomass C stocks varied from 45.6 Mg ha^{-1} for the C soil group to 83.3 Mg ha^{-1} for the A soil group. In the drainage class soil group, the aboveground biomass C stocks varied significantly from 44.1 Mg ha^{-1} for the poorly drained soils to 81.8 Mg ha^{-1} for the moderately drained soils and 74.4 Mg ha^{-1} for the freely drained soils. The aboveground biomass C stocks varied significantly from 44.7 Mg ha^{-1} for the G horizon soils to 86.2 Mg ha^{-1} for the red apedal B horizon soils. In general, the tree C stocks contributed the greatest portion to the aboveground biomass C stocks, which in turn contributed more to the total C stocks in the catchment. The C (undifferentiated hydromorphic), poorly drained, and G horizon soil groups had the lowest aboveground biomass C stocks because the conditions in these soil groups limited tree growth and hence C sequestration.

Total C stocks in the catchment before afforestation were estimated to be 7 209 Mg. After eight years of afforestation C stocks were estimated to be 11 912 Mg. Therefore the trees added 4 702 Mg C to the catchment, at a rate of 588 Mg C yr^{-1} or 3.67 Mg C ha^{-1} yr^{-1}. The rate of C sequestration in the afforested areas was 7.74 Mg ha^{-1} yr^{-1}.

Keywords: Afforestation, biomass, carbon stocks, nitrogen stocks, soil organic matter

UITTREKSEL

Grond en plantegroei speel 'n belangrike rol in die globale C siklus omdat C uitruiling deur beide beïnvloed word. 'n Verandering in die landgebruik kan dus n wins of verlies van C in die grond-plant sisteem veroorsaak. Hierdie studie is in die Weatherley opvanggebied in die noordelike Oos-Kaapprovinsie, wat voorheen deur gras bedek was, uitgevoer. Ongeveer die helfte van die 160 ha in die opvanggebied is in 2002 met drie boomspesies, te wete *P. elliottii*, *P. patula*, en *E. nitens* geplant. Voor boomaanplanting is 'n basislynstudie (Le Roux *et al*., 2005) uitgevoer om die grondorganiese materiaal in die gebiede wat vir bosbou geoormerk is te bepaal. Hierdie studie is dus 'n opvolg van die bogenoemde studie met die doel om die grond en biomassa C voorraad (en in sommige gevalle ook N voorraad) agt jaar na die aanvang van bosbou te bepaal.

Vir vergelyking is dieselfde 27 punte wat deur Le Roux *et al*. (2005) bestudeer is, te wete 25 bosboupunte en twee kontrole punte, ondersoek. Grondmonsters is in 2010 op verskeie dieptes by die 27 punte ingesamel: 0-50, 0-100, 0-150, 0-200, 0-250, 0-300, 0-400, 0-500, 0-600, 0-700, 0-800, 0-900, 0-1000, 0-1100, en 0-1200 mm en vir organiese C en totale N, as indikatore van organiese materiaal, ontleed. By elke punt is drie submonsters per diepte-interval geneem en gemeng om 'n saamgestelde monster te gee. Die proses is vier keer by elke punt herhaal.

By al 27 punte is die plantreste en ondergroei tydens grondmonsterneming, ook in vier herhalings, geneem. Na droging in die glashuis is die materiaal gemaal en vir C- en N-inhoud ontleed. 'n Jaar na grond en plantreste versamel is, toe die bome agt jaar oud was, is die hoogte en borshoogte diameter van 12 bome by elk van die 25 bosboupunte gemeet. Hierdie data is gebruik om die bruikbare stamvolume en dus boom C voorraad te bereken.

Bosbou in die grasgebiede het die grondorganiese materiaal in die boonste 300 mm laag beïnvloed. Dit het tot 'n verhoging of 'n verlaging in die C voorraad, N voorraad en C:N verhouding gelei. Grond C voorraad het met van 0.9 Mg ha^{-1} by punt 235 (Katspruit grond met gras) tot 23.6 Mg ha^{-1} by punt 232 (Katspruit grond met *P. elliottii* bome) afgeneem. Die tempo van afname het tussen 0.11 en 2.95 Mg C ha^{-1} j^{-1} gevarieer. Die C voorraad het met tussen 0.9 Mg ha^{-1} by punt 244 (Pinedene grond met *P. patula* bome) tot 11.3 Mg ha^{-1} by punt 242 (Longlands grond met *P. patula* bome) toegeneem. Die tempo van toename het dus vanaf 0.11 Mg C ha^{-1} j^{-1} tot 1.41 Mg C ha^{-1} j^{-1} gevarieer. Grond C voorraad het betekenisvol met 5.5 Mg ha^{-1}, 10.0 Mg ha^{-1}, en 12.4 Mg ha^{-1} vir onderskeidelik die gras, *E. nitens*, en *P. elliottii* areas afgeneem. Gronde met *P. patula* het 'n toename in C voorraad van 1.9 Mg ha^{-1} gehad. Nadat die gronde volgens karteereenhede, dreineringsklasse of die eerste ondergrondhorison (B1 of E1) gegroepeer is, was daar oor die algemeen ‘n betekenisvolle afname in grond C voorraad as gevolg van bosbou. Die grond N voorraad het min of meer soos die grond C voorraad reageer.

Die bogrond biomassa C voorraad is bereken deur die plantreste C voorraad en die boom C voorraad bymekaar te tel. Die bogrond biomassa C voorraad het van 3.71 Mg ha^{-1} by punt 209 (Katspruit grond met gras) tot 167.2 Mg ha^{-1} by punt 246 (Pinedene grond met *E. nitens* bome) gevarieer. Die gemiddelde bogrond biomassa C voorraad vir die 27 punte was 64.9 Mg ha^{-1}. Aan die ander kant was die gemiddelde bogrond biomassa C voorraad 69.7 Mg ha^{-1} vir die 25 bosboupunte en slegs 4.8 Mg ha^{-1} vir die kontrole punte. Die bogrond biomassa C voorraad het betekenisvol vanaf 4.8 Mg C ha^{-1} vir die gras, 41.2 Mg ha^{-1} vir die *P. elliottii*, 67.3 Mg ha^{-1} vir die *P. patula* tot 113.2 Mg ha^{-1} vir die *E. nitens* areas verskil. Volgens die karteringseenhede het bogrond biomassa C voorraad vanaf 45.6 Mg ha^{-1} vir die C grond groep tot 83.3 Mg ha^{-1} vir die A grond groep gevarieer. In die dreineringsgroepering het die bogrond biomassa C voorraad betekenisvol vanaf 44.1 Mg ha^{-1} vir die swak gedreineerde gronde tot 81.8 Mg ha^{-1} vir die matig gedreineerde gronde en 74.4 Mg ha^{-1} vir die goed gedreineerde gronde gevarieer. Die bogrond biomassa C voorraad het betekenisvol vanaf 44.7 Mg ha^{-1} vir die G horison gronde tot 86.2 Mg ha^{-1} vir die rooi apedale B horison gronde verskil. Oor die algemeen het boom C voorraad die grootste bydrae tot die bogrond biomassa gemaak, wat op sy beurt weer die grootste bydrae tot die C voorraad in die opvanggebied gemaak het. Die C (ongedifferensieerde hidromorfe), swak gedreineerde, en G horison grond groepe het die laagste bogrond biomassa C voorraad omdat die toestande in die gronde boom groei en daarom C vaslegging beperk het.

Totale C voorraad in die opvanggebied voor bosbou is op 7 209 Mg geraam. Na agt jaar van bosbou is die C voorraad op 11 912 Mg geraam. Die bome het dus 4 702 Mg C tot die opvanggebiedg teen ‘n tempo van 588 Mg C j^{-1} of 3.67 Mg C ha^{-1} j^{-1} by gedra. Die tempo van C vaslegging in slegs die bosbou gebiede was 7.74 Mg ha^{-1} j^{-1}.

Sleutelwoorde: Bosbou, biomassa, koolstof voorraad, stikstof voorraad, grondorganiese materiaal

CHAPTER 1

INTRODUCTION

1.1 Background

Carbon (C) in the atmosphere and biosphere is of great importance for the functioning of the global C cycle. The carbon concentration in the atmosphere is controlled by gains and losses in the C cycle. In the cycle soils are an important sink for C and therefore play a vital role in the dynamics controlling atmospheric carbon dioxide (CO_2). A change in land use may result in either a loss or gain of C in soils (Jenkins, 2002).

The research reported in this dissertation describes the soil-plant C stocks in the Weatherley catchment eight years after conversion from grassland to forestry. This study is a continuation of the WRC project KV 170/05 on soil organic matter in the Weatherley catchment in the northerly Eastern Cape Province (Le Roux *et al.*, 2005). The authors present important baseline data on C stocks for the catchment before afforestation.

1.2 Motivation

Allison (1973) indicated that soil organic matter has been regarded to be important for plant life for a long period of time. Organic matter plays a major part in the microbiological, chemical, and physical aspects of soil fertility and it is related to the productivity of a soil. Organic matter includes plant and animal material in various stages of decomposition (Cooperband, 2002). Among others organic matter plays a major role in nutrient cycling, increasing the water holding capacity of soil, improving water infiltration, encouraging root development, and reducing crusting, especially in fine textured soils. Because of this fact, maintaining soil organic matter is an objective of many sustainable crop production systems.

Soils play a vital role in C (one of the indices of organic matter) storage. According to Lorenz and Lal (2010) forest ecosystems form the biggest part of terrestrial ecosystems and are capable of absorbing large amounts of CO_2 from the atmosphere through the process of photosynthesis. This CO_2 is returned back to the atmosphere *via* auto and heterotrophic respiration. Only a small amount of C is stored in above and belowground biomass, litter, and soil. Forests contain half of the terrestrial C sink (Canadell *et al.*, 2007). According to FAO statistics, 234 petagrams (Pg) C are stored aboveground in forests, 62 Pg C below ground, 41 Pg C in dead wood, 23 Pg C in litter, while a total of 968 Pg is in stored forest soils (Kindermann *et al.*, 2008).

From the figures given by Kindermann *et al*. (2008) it is clear that forest soils store a large amount of C. This C is subject to loss from soils, due to *inter alia* land use change. However, according to Lorenz and Lal (2010) the C cycle plays an important role in controlling the concentration of C in the atmosphere as it escapes from the terrestrial ecosystem. Any disturbance in the C cycle or in the ecosystem influences the imbalance of the gains and losses of C. These imbalances may result into high emissions of CO_2 to the atmosphere.

However, due to the high greenhouse gas concentration, Engelbrecht *et al*. (2004) highlighted that the potential for sequestration of CO_2 internationally and nationally is receiving more attention. Therefore, knowledge of the potential for CO_2 sequestration in South Africa is important. The carbon dioxide and other greenhouse gases act as a protective layer in the earth's atmosphere, preventing excessive warming of the earth. Any rise in levels of CO_2, increases mean global temperatures, because it increases the amounts of solar radiation trapped by the greenhouse gasses (Stavins & Richards, 2005). According to Lal and Singh (2000) the atmospheric CO_2 concentration increased from 280 ppmv in 1800 to 315 ppmv in 1957 to 358 ppmv in 1996. Therefore, nations are forced to assess their contributions to sources and sinks of CO_2. They are also forced to evaluate the processes that control CO_2 accumulation in the atmosphere.

Another reason why C is important is because of the growing population and the demand for food production. Soil and forest resources were managed by each individual country. Nowadays, there is growing global awareness in which people begin to realise that global climate can be changed by human activities. The increase in CO_2 concentration in the atmosphere from 280 ppm to 340 ppm since the industrial revolution, due to fossil fuel burning, deforestation, and agriculture, is an example of this. The rate of increase is approximately 1 to 5 ppm CO_2 per annum (Coleman *et al*., 1989).

The Weatherley catchment was selected for this study, because of the amount of work that is continuously being carried out at this site (Roberts *et al*., 1996; Le Roux *et al*., 2003; Le Roux *et al*., 2005; Van Huyssteen *et al*., 2005). This offered the opportunity to contribute and build on to the previous research. This study therefore aims to quantify the status and contribution of the Weatherley catchment to South Africa's and the world's organic C stocks.

1.3 Hypothesis

Soil-plant carbon stocks will increase on account of afforestation of grassland areas in the Weatherley catchment.

1.4 Objectives

- The first objective of this study was to quantify whether soil-plant carbon stocks in the Weatherley catchment changed markedly within eight years of afforestation of the grassland.

- The second objective was to establish whether changes in soil-carbon stocks in the Weatherley catchment are related either to the tree species or to soil types

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Carbon is available in the air as CO_2, as carbonates in the earth's crust, in the sea as carbonate ions, and in many organic compounds in soil. In the sea it is dependent amongst others on gases that escape from the interior of the earth (Bolin *et al.*, 1979). In soil, the degradation of dead plant and animal materials is an important biological process because of circulation of C to the atmosphere as CO_2. During this process nitrogen is converted into ammonium (NH_4^+) and nitrate (NO_3^-). Elements like phosphorus and sulphur are made available in forms required by plants (Stevenson & Cole, 1999). Therefore, carbon is an important element of life on earth.

In the C cycle (Figure 2.1) the Soil-Plant-Atmosphere system is very important because it determines the balance of C. The carbon cycle involves a number of processes that take anything from hours to millions of years. Processes such as photosynthesis, respiration, and humus accumulation occur over a short period. The long term processes are responsible for exchange of C between rocks and surficial systems (ocean, atmosphere, biosphere, and soils; Berner 2003). Therefore it is essential to understand the factors and processes in the cycling and balance of C (Lal & Singh, 2000; Brady & Weil, 2002; Garcia-Pausas *et al.*, 2007) to manage soil organic matter properly. With well managed organic matter, soil quality and plant production, as well as reduced greenhouse emissions could be reached. Therefore, the gains and losses of C determine soil organic matter build up (Brady & Weil, 2002). The following discussion will focus on the flow of C through the plant into the soil and its subsequent transformation in the soil by microorganisms.

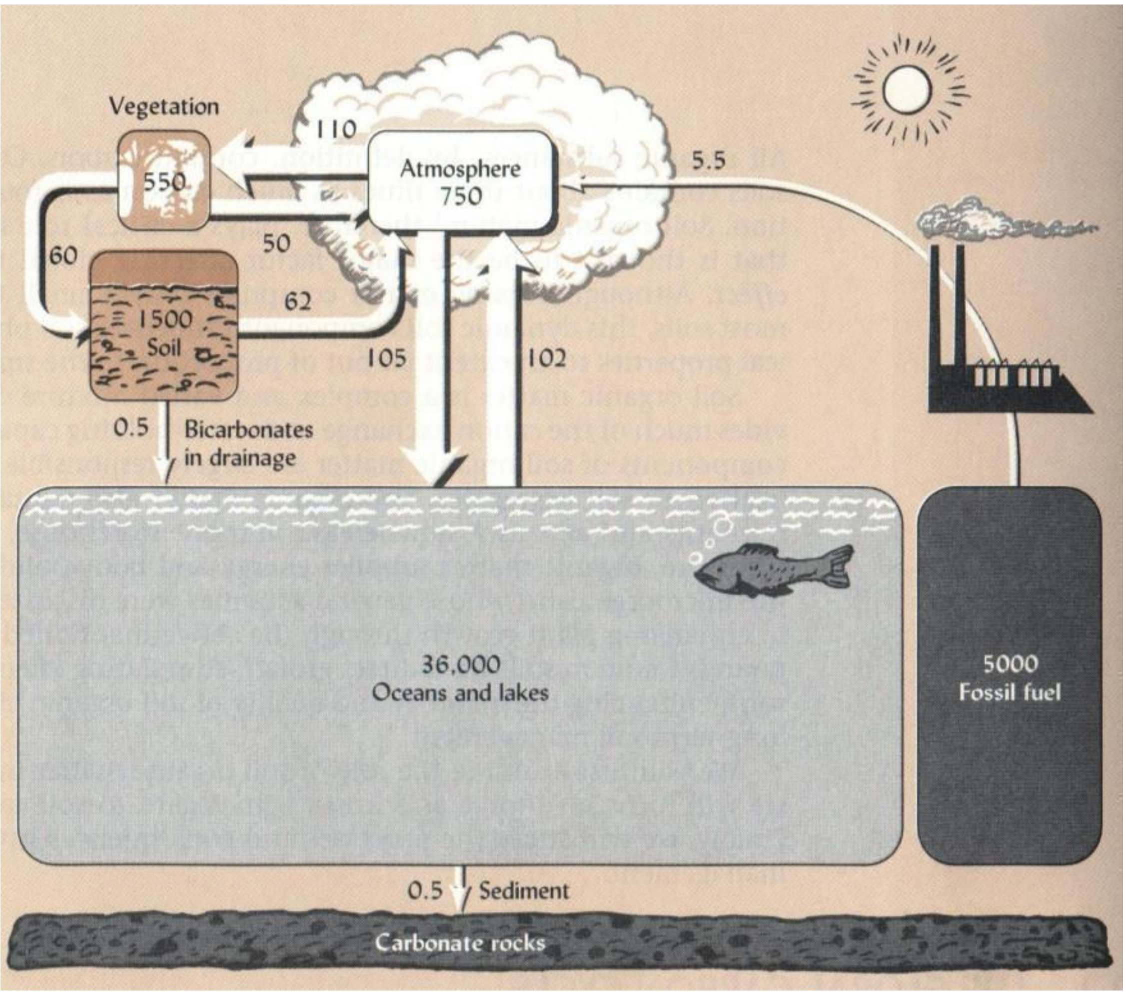

Figure 2.1 The global C cycle indicating the annual C flux in Pg (Brady & Weil, 2002). 1 Pg = 10^{15}

2.2 Carbon sequestration

The global C (Figure 2.1) cycle highlights the pools of C which interact with the atmosphere. Numbers in the boxes denote the petagrams (Pg = 10^{15} g) of C stored in the major pools. The numbers and arrows show the amount of C flowing annually (Pg yr^{-1}) by various pathways between the pools. Soil contains approximately twice as much C as the vegetation and the atmosphere combined. The flow of C to the atmosphere from fossil fuel burning (5.5 Pg) and more C that is leaving (62 + 0.5 Pg) than entering (60 Pg) the soil indicate imbalances caused by human activities. These imbalances are partly offset by increased absorption of C by the oceans (Brady & Weil, 2002).

Jones and Donnelly (2004) define carbon sequestration as "the process of removing CO_2 from the atmosphere and storing it in C pools of varying lifetime" and it is therefore a natural process (Lorenz & Lal, 2010). Carbon enters terrestrial ecosystems mainly by photosynthesising plants. In the process of photosynthesis CO_2 and water are both substrates and solar energy from the sun is trapped and stored as chemical energy in C compounds. The CO_2 is then used as source of C (Trumbore, 2006). According to Stevenson and Cole (1999) the photosynthetic process is important in providing raw material for microbial growth and humus synthesis. Plants use solar energy and nutrients from the soil to produce lignin, cellulose, protein, and other organic substances that make up their structures. In particular, forests are known as major terrestrial C sinks. They sequester larger amounts of atmospheric CO_2 than grasslands. When C enters the forest ecosystem, it is stored and sequestered in different pools, viz. vegetation, detritus, and soil (Lorenz & Lal, 2010).

In the forest ecosystem, C is transferred and distributed among plants, animal, and microbial biomass and in soil organic matter. The stem wood is the part within trees with the largest C pool. The major pathways for C to enter the soil organic C pools are litter, root exudates, and microbial metabolism (Figure 2.2). In forest ecosystems, the forest floor and mineral soil horizons in particular, have large C pools (Lorenz & Lal, 2010). However, grassland ecosystems also play a vital role in the C cycle, but receive less attention compared to forests (Hall & Scurlock, 1991; Hall *et al.*, 1995). Nevertheless, the flow of C is more or less similar in both ecosystems. Grassland soils' carbon pool is considerably from 200 to 300 Pg (Scurlock & Hall, 1998). Moreover, Hungate *et al*. (1997) indicate that grasslands sequester about 98% of C belowground. However, roots' contribution to soil C is mainly through their death and decomposition as well as exudation, mucilage production, and living roots sloughing off (Van Veen *et al*., 1991). Although some studies (Lieth, 1978; Hall & Scurlock, 1991) indicate that both grasslands and forests almost occupy equal land area and productivity, especially in the tropics, the variation between the two lies in standing biomass (7 to 10 times more biomass in forests than in grasslands).

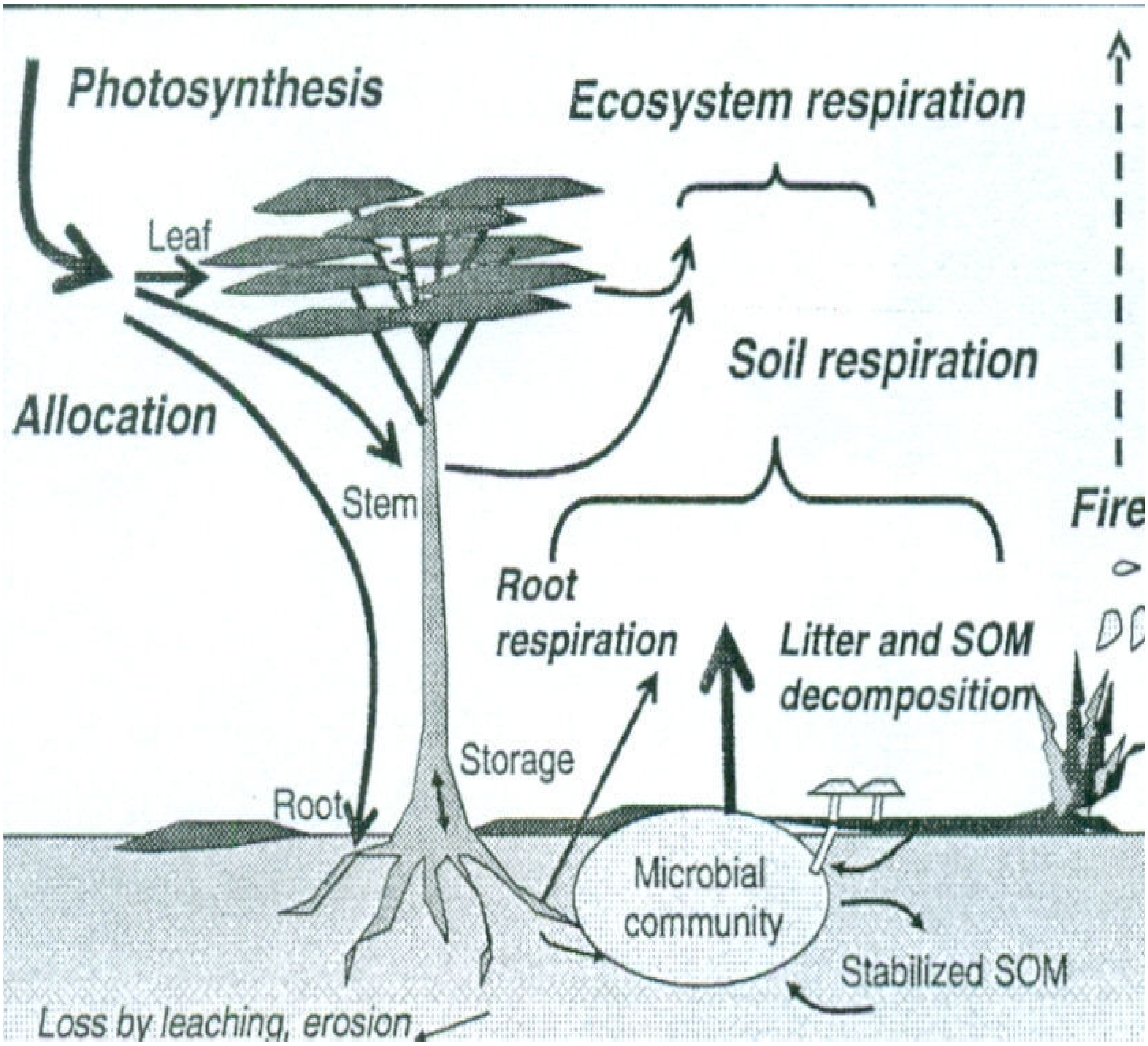

Figure 2.2 Pathways of carbon flow through ecosystems (Trumbore, 2006).

In the C cycle the two major pathways for C losses (to the atmosphere) from ecosystems are respiration via living plant leaves and stems and soil respiration via plant roots and microbial respiration during decomposition of litter and soil organic matter (Trumbore, 2006; Lorenz & Lal, 2010). Loss of C through fire is also important in returning C to the atmosphere, especially where drought or cold is a limiting factor for decomposition (Harden *et al.*, 2000). Minor losses include leaching of dissolved organic or inorganic C or losses through erosion. Therefore, the net land surface C depends on the balance of photosynthesis and respiration as well as other minor losses (Trumbore, 2006).

As mentioned earlier, water also plays a vital role in photosynthesis. Water is important in all types of vegetation. Vegetation controls precipitation once it has fallen. The vegetation intercepts precipitation which through evaporation goes back to the atmosphere before it reaches the ground. Interception is more pronounced in forests than in grassland, because trees have a larger surface area available to store water (interception storage capacity). The interception storage capacity is between 0.25 and 7.5 mm of rain in forests. The rainfall intensity determines the amount of rain lost by interception. For example, all water from light showers of rain may evaporate from tree foliage before reaching the ground. The interception in showers of less than 20 mm of rain is 50-90%, while in heavier downpours it is 10-30%. For deciduous trees the interception loss is 20-25% and for conifers it is 15-40%. The vegetation also loses water through transpiration (evaporation from inside the leaves and through the bark; Thomas & Packham, 2007). Therefore, the intensity of rainfall or the interception rate can influence how much water is available for photosynthesis in forests.

The availability of water plus the CO_2 concentration inside the leaf control the stomatal conductance, which influences the rate of photosynthesis (Lorentz & Lal, 2010). Trees differ in drought tolerance, for example the differences observed in the reduction of biomass accumulation among *populous* genotypes (Monclus *et al.*, 2005). Therefore, C allocation into different parts, viz. foliage, stems, roots, and reproductive organs, primary productivity and evapotranspiration are affected largely by the water availability (Webb *et al.*, 1978; Korner, 2006).

The increases in forest productivity will come at the cost of increased water use. Alam and Starr (2009) estimated C sequestration and water use of woodlands and observed a variation in stem biomass C density (from 4-380 g C m^{-2}) and soil C density (from 1323 to 8172 g C m^{-2}). Mean annual rainfall varied between 35 mm and 768 mm and mean annual temperature varied between 22.1°C and 29.9°C. Both stem biomass C and soil C densities were correlated with annual rainfall rather than with temperature.

2.2.1 Plant biomass

Thomas and Packham (2007) define biomass as “the weight of organic material in a standing crop”. They indicate that this definition may or may not include deadwood and litter. Brown *et al*. (1996) define forest biomass as “the amount of C that can be returned to the atmosphere or sequestered or conserved on the land to meet greenhouse gas (GHG) emission targets”. These greenhouse emission targets were established by the Kyoto Protocol (Read & May, 2001), resulting from the 1997 meeting on climate change. To meet these targets, forestry activities that aim at offsetting C emissions are considered. The Kyoto Protocol states clearly the significance of forest budgets and factors influencing them (Brown & Schroeder, 1999).

The importance of tree biomass can be quantified by the ability of forests in the global C cycle. Forests store large amounts of C in both vegetation and soil. They also exchange C with the atmosphere through photosynthesis and respiration processes, hence they are sources of atmospheric C when disturbed either by human or natural causes. During regrowth after disturbance they can become atmospheric C sinks (Brown *et al*., 1996).

The aboveground part of woody plants contains more than 85% of the biomass in most forests. This, in most studies, does not include the biomass in roots. The total biomass of forests include the bole, branches, bark leaves, and roots. Forests can store large amounts of C on the surface of the soil as litter, especially under pine plantations. The litter can accumulate up to 150 Mg DM ha^{-1} or close to half of the stem biomass in the Eastern Transvaal (Mpumalanga) of South Africa. On the other hand, grasslands are assumed to have higher soil C than forests, because a larger fraction of C is translocated by grasses belowground than forests do (Christie & Scholes, 1995).

The difference brought upon by production through photosynthesis and consumption through factors such as respiration and harvest influence the quality of biomass in a forest. Other factors that change forests include human activities, like harvesting and clearing of forest land for non forest use, wildfires, pest outbreaks, changes in climate, and atmospheric pollutants. This means biomass is a vital tool in assessing any structural changes in forests and also important in measuring the qualities of forest ecosystems in a wide range of environmental conditions (Brown *et al*., 1999). In their study, Brown *et al*. (1999) found the biomass densities for softwood forests (pine) ranging from 2 to 346 Mg ha^{-1}, with weighted average of 110 Mg ha^{-1}.

Houghton (2005) indicated that it is important to know the spatial distribution of forest biomass because biomass is important in the calculation of sources and sinks of C resulting from conversion of forest to non forest land or *vice versa* and for the measurement of change over time. However, Houghton (2005) concentrated more on deforestation than on afforested lands (standing crop). Moreover, knowledge of the biomass of forests depends on the distribution of the sources and sinks of C over the land surface.

The forest biomass differs from region to region and between tropical and temperate zones. The average aboveground biomass in temperate zones is known as a result of forest sampling inventories. However, the spatial distribution of biomass, that is the biomass of individual stands or plots, is not known. In tropical forests both the average and spatial distribution of biomass are not known. The general reason for lack of this knowledge is because forest inventories are few in numbers and do not exist at all in tropical countries (Houghton, 2005).

In their study on storage of organic matter in tropical and subtropical life zones (areas with similar plant and animal communities), Brown and Lugo (1982) observed a rapid accumulation of aboveground biomass during the first 10 to 20 years of forest life. Life zones seemed to be the influencing factor for the rate of biomass accumulation. A higher biomass was reached earlier by moist forest life zones and even at maturity they had higher biomass than other life zones. In both young and mature stands dry life zones accumulated lower biomass.

The rate of biomass accumulation was compared in tropical and temperate forests. In temperate forests aboveground biomass accumulated linearly from 1 to 40 years. This was at a slower rate as compared to tropical forests. The time the temperate forests took to reach 100 t ha^{-1} biomass was double that of tropical forests. It was only after 50 years that the temperate forests reached a similar range of biomass as tropical forests (Brown & Lugo, 1982). Pregitzer and Euskirchen (2004) observed an increase of C with age in living biomass of boreal, temperate, and tropical forests.

Other studies such as that of Luyssaert *et al*. (2007) estimated above and belowground biomass in forests. Aboveground biomass for humid evergreen, semi-arid evergreen, and deciduous semi-arid forests was 5761 g C m^{-2}, 4766 g C m^{-2}, and 7609 g C m^{-2} respectively. Carbon ranged from 1.352 g C m^{-2} in semi-arid deciduous to 1.604 g C m^{-2} in semi-arid evergreen forests. In grasslands belowground production exceeds aboveground annual production, but belowground biomass is less than aboveground standing crop (five to ten times of the aboveground biomass). However, most grasslands contain aboveground biomass of 7 to 1974 g m^{-2} and belowground biomass of 139 to 3871 g m^{-2} (Lieth, 1978). The production of biomass is influenced by atmospheric CO_2 concentration, temperature, water stress, and nitrogen availability (Hall & Scurlock, 1991).

Even though biomass is useful, it is just a measure that gives how much there is and does not indicate the rate of growth or any loss in vegetative growth. It does not give the amount of new growth added or lost, hence there is no indication on the functioning of the forest. Therefore, an estimate of the productivity is more useful as it gives the amount of new material that is added. To evaluate the total standing biomass of forest, there must be an increase in annual forest productivity and hence an increase in forest C uptake (Thomas & Packham, 2007). Lal and Singh (2000) indicated that in developing countries like India, people who live in rural areas rely heavily on forest products. More than 70% of the people rely on forests for fuel wood, cattle feed, food, and shelter. From 1951 to 2000, India has increased its forest plantation rate from 1. 67 Mha yr^{-1} to 2 Mha $yr^{-}1$ to meet their basic demand. Consequently, India is considered as one of the leading among tropical countries due to its rate of afforestation.

Productivity is a broad term, which encompasses terms such as net primary production (NPP) and gross primary production (GPP). Primary production results from the use of sunlight in photosynthesis by green plants. In this process, CO_2 is fixed and sugars are created. Therefore, GPP can be obtained from the fixed carbon or sugars. Forest components (foliage, wood, and roots) use some of the energy for growth and maintenance and for synthesis of other plant tissue from CO_2 or respiration. Hence, GPP minus respiratory losses gives the NPP. The NPP represents the exact increase in growth. To obtain a positive NPP, the GPP of forest must be bigger than the respiratory losses. It is not easy to measure GPP because of the complexity of forest ecosystems in accounting for all carbon uses and losses (Thomas & Packham, 2007).

However, according to Luyssaert *et al.* (2007) climatic variables affect GPP and NPP. The GPP and NPP were correlated very well with mean annual temperature and annual precipitation globally. Any increases in temperature and precipitation, increased primary production but a saturation point was reached beyond 1500 mm precipitation and 10°C mean annual temperature. Even though lower NPP values were found with low precipitation, quantification at precipitation above 1500 mm still has to be made.

2.3 Soil organic matter

According to Van Veen *et al.* (1991) for most soils, the source of organic matter is aboveground primary production. Carbon is transferred from the aboveground parts of living plants to the soil via litter fall and roots. Carbon derived from roots is utilised mainly by microbes for energy. The microbes' activity promotes nutrient cycling in soil. Therefore organic matter is composed of many organic substances in various stages of decomposition. It is produced when living organisms (plant or animal) die and it is incorporated into the soil through decomposition processes (Cooperband, 2002). In the process, soil organisms such as earthworms and beetles break large pieces of organic material into smaller pieces. Smaller organisms take the process further. When this happens, the number of microorganisms also increases. The microorganisms are, in turn, added to the soil when they die. When plants are harvested, the remaining part of the plant material on the soil surface is incorporated into the soil by earthworms and other organisms (Cooperband, 2002).

Soil organic matter is mostly concentrated in the topsoil (Sitaula *et al.*, 2004). It is a key soil component in the soil's ability to supply essential nutrients. These nutrients play a major role in soil fertility and thus need to be maintained for sustainable production purposes. According to Bot and Benites (2005), soil organic matter mostly originates from plant tissue. The water content in plant residues is approximately 60-90%. The remainder is made up by C, oxygen, hydrogen, sulphur, nitrogen, phosphorus, potassium, calcium, magnesium, and other elements. Moreover, litter input and decomposition are important in soil organic matter accumulation.

2.3.1 Litter input and decomposition

Soil organic matter accumulation is a slow process which continues over time. It is therefore difficult to follow organic matter build up and the mechanisms controlling it. Commonly, the build up is explained by faster accumulation of litter than its decomposition. Therefore, the rate of soil organic matter build up depends on the amount and quality of litter as well as the rate of its decomposition (Berg *et al*., 1995). The importance of litter in an ecosystem is highly evident. Litter acts as a protective layer for soil from the effects of moisture and temperature changes. Litter is a source of energy and nutrients for heterotrophic organisms (e.g. bacteria, actinomycetes, fungi, protozoa, and nematodes). These organisms metabolise litter and release nutrients to the soil for use by plants. Nevertheless within ecosystems, the amount and quality of litter gives information about the dynamics of nutrient cycling (Ukonmaanaho *et al*., 2008). Hence, litter fall is the main pathway of nutrient return to the soil (Melillo *et al*., 1982; Lemma *et al*., 2007a) which is controlled by decomposition.

The rate of decomposition decreases as decomposition continues. This is because more easily digestible materials are decomposed first leaving the more resistant ones (Berg *et al*., 1995). Therefore, the rate of nutrient release is dependent on the type of species in question. Hence the rate of decomposition is affected by both plant material and its environment (Singh & Gupta, 1977). Olson (1963) reported decomposition rates of 6.25% yr^{-1} in pine forests. The decomposition rate varies within and between species. There may also be differences between woody and non-woody tissues. However, in fresh litter, decomposition rate is from 0.1% to 0.0001% per day (Aerts, 1997; Berg, 2000; Berg & Meentemeyer, 2002).

However, with higher amounts of litter fall, species like *Pinus* accumulated more litter, which was related to slower rates of litter decomposition. These low rates of decomposition were associated with less organic C transfer to the soil. Hence *Pinus patula* with its characteristic branch litter that decomposes slowly is expected to be inefficient for C sequestration in soil (Lemma *et al*., 2007a). Lemma *et al*. (2007a) observed almost the same total litter (foliage, branches, stem, and roots) input in *Pinus* and *Eucalyptus* stands. The only difference was that the *Pinus* had more fine woody litter than the *Eucalyptus* indicating that total litter input and the proportion of fine woody litter best described the interspecific differences in SOC accumulation. Cuevas and Lugo (1998) found considerable N concentrations of 38 kg N ha$-^{1}$ yr^{-1} in *Pinus elliottii* with low nutrient return to the soil. However higher N amounts were re-translocated within the species. Thus, it was concluded that *Pinus elliottii* can return low quantities of nutrients while its production of organic matter is high. Therefore, this species can do well in nutrient poor soils. This indicated that species performance should be understood prior to planting.

In a study on newly shed leaf litter versus decomposed litter, Lemma *et al*. (2007b) indicated the elemental composition (mg g^{-1}) on both litters in different stands. The *Pinus patula* had less C, N, and C:N ratio in the decomposed litter, 533 mg g^{-1}, 16 mg g^{-1}, and 32.7 respectively. The *Eucalyptus* stands decomposed layer had 530 mg g^{-1} , 17 mg g^{-1}, and 31.7 of C, N, and C:N ratios respectively. For both stands, the C:N ratios and the elemental compositions were higher in leaf litter compared to the decomposed litter. Thus, SOC was more pronounced at an earlier age under *Eucalyptus* while under *Pinus* SOC did not level off in 30 years. Therefore, this implied that in order to maximise SOC sequestration *Eucalyptus* should be harvested at about 13 years.

According to Almendros *et al*. (2000), the rate of decomposition is influenced by the chemical characteristics of plant biomass. Plant extractives such as tannins, lignin concentration, and the quality and quantity of water soluble sugars as well as nitrogen compounds affect the biodegradation of litter. For example, Lorenz *et al*. (2004) found lower N contents in pine trees and a higher C:N ratio. However, the pine trees had lower tannins and phenolics, thus causing the pine litter to decompose faster.

Berg and Staff (1980) divided decomposition into an early stage and later stage. In the early stage, the plant extractives such as holocellulose and lignin behaved differently. The free holocelluse was highly susceptible to microbial decomposition while lignin did not decompose at all. Therefore lignin concentration increased as the other compounds were decomposed (Lemma *et al*., 2007b). According to Singh and Gupta (1977) factors such as water-soluble or leachable substances, initial N content and water content affect the early stages of decomposition. The organic matter is lost rapidly due to microbial activity and leaching. Decomposers use C as an energy source during decomposition and N is assimilated into the cell proteins. Therefore, the higher the N contents in the original material, the faster the decomposition. Water availability is important in accelerating microbial activity and therefore the rate of decomposition. Therefore rainfall and freeze-thaw cycles are important in the release of nutrients (Berg *et al*., 2010).

In the later phase lignin concentration influences the decomposition of litter (Berg *et al.*, 2010), while climate has a lesser effect (Berg & Meentemeyer, 2002). In determining the influence of plant nutrient levels on the decomposition rate and pattern of chemical changes of Scots pine needle litter, Berg and Staff (1980) observed that with 25% lignin concentrations in litter, the influence of plant nutrients on the decomposition rate levelled out. Therefore, small amounts of N and other nutrients were released from the litter. When the lignin concentration was only 10%, the influence of lignin was retarded until the concentration reached 30%. Berg (2000) indicated that the N concentration is significant for lignin degradation. Berg *et al*. (1982) observed a negative relationship between N concentration and lignin mass-loss rate. For N rich litters, the lignin decomposition was low while for N poor litter it was high.

On the other hand, grassland's decomposition is complex and it is best explained by understanding the impact of climate on decomposition. Bontti *et al*. (2009) indicated that root decomposition is influenced by precipitation because higher temperatures with adequate soil moisture, promote higher rates of decomposition. However, decomposition in grasslands is complicated by contrasting results (Melillo *et al*., 1982; Moore *et al*., 1999; Berg, 2000). The idea is to study decomposition both aboveground and belowground (Bontti *et al*., 2009).

The decomposition in grasslands is also controlled by litter quality. Litter quality affects roots more than leaves. The variables lignin content, C to N ratio, and lignin to N ratio influence decomposition (Silver & Miya, 2001). With lower lignin percentage in leaves, decomposition was faster in leaves than in roots. However, decomposition can vary depending on the role of precipitation and temperature on different regions (Bontti *et al*., 2009).

Furthermore, Bontti *et al*. (2009) claimed that more attention has been paid to aboveground than to belowground decomposition. There are large belowground C inputs in grasslands. Therefore it is imperative to understand the differences between leaves and roots in grasslands to come up with the correct total ecosystem decomposition (Long *et al*., 1989; Hall & Scurlock, 1991; Bontti *et al*., 2009).

2.3.2 Organic constituents of soil

Soil organic matter or humus, is characterised by dark brown to black colour and is highly resistant to decomposition (Cooperband, 2002). Humus is the part of organic matter that has been altered by different soil organisms into stable components. This humus is the most wide-spread organic carbon-containing material in terrestrial and aquatic environments. The chemical composition of humus makes it difficult for use by microorganisms and its intimate interactions with the soil mineral phases explains why humus cannot be decomposed readily (Bot & Benites, 2005). Humus contains two major compounds: non-humic and humic substances.

2.3.2.1 Non-humic substances

Non-humic substances are easily decomposable SOM which are obtained from the fresh organic residues including proteins, amino acids, sugars, and starches. The weather conditions, water content of the soil, growth stage of the vegetation, addition of organic residues, and cultivation practices including tillage, highly influence the non-humic substances. The various organisms in the soil obtain their food primarily from non-humic substances (Bot & Benites, 2005).

Lipids are characterised by a common property of being able to dissolve in solvents such as benzene, acetone, chloroform, hexane, methanol, and ethanol. They include organic acids, fats, waxes, and resins. They constitute 1.2 to 6.3% of the soil organic matter (Stevenson & Cole, 1999) and are important due to their ability to act as growth hormones on plant growth (Bot & Benites, 2005).

The carbohydrates in soil are contributed by plant remains such as simple sugars, hemicelluloses, and cellulose which are decomposed by bacteria, actinomycetes, and fungi. These microorganisms in turn produce polysaccharides and their own carbohydrates. The carbohydrates make up the main polysaccharides found in soil (Stevenson, 1986).

Carbohydrates are significant in binding soil particles into stable aggregates. They also form complexes with metal ions. Several factors like structural complexity combine together for the stability of polysaccharides. This makes them resistant to enzymatic attack and adsorption on clay minerals or oxide surfaces (Stevenson, 1986).

2.3.2.2 Humic substances

The most stable fraction of SOM is the humic substances. This stability is due to their chemical structure, heterogeneity, their ability to be bound in soil aggregates as well as their interactions with metal cations and clay minerals. Humic substances are the reservoir of soil C and nutrients. They are a source of food to microorganisms and thus are involved in the survival means of microorganisms (Theng *et al*., 1989).

The humic substances are classified into humic acids (HA), fulvic acids (FA), and humins according to their solubility in alkali and acid. They are part of OM that is precipitated from aqueous solution at pH below 2. Fulvic acids are fractions that are soluble under all pH conditions. Humin is not soluble in water. Humic acids are found wherever there is decomposition of OM (Hayes *et al*., 1989). Humic substances are good for soil structural formation and maintenance, serve as slow release sources of nitrogen, sulphur, and phosphorus for plant nutrition and microbial growth. They retain plant nutrients by cation exchange processes and enhance the soil's buffering capacity. Organic constituents in the humic substances act as plant growth stimulants. Their dark colour increases the absorption of energy from the sun and heating of the soil (Hayes *et al*., 1989; MaCarthy *et al*., 1990).

The three humic substances contain the same structure, but differ in molecular weight, ultimate analysis, and functional groups. Humic acids are easily extracted components of humus. Their colour range from dark brown to black. They are insoluble in acidic water. Fulvic acids have a lower molecular weight and higher content of oxygen-containing functional groups per unit weight than the humic acids or humins. Other characteristics include resistance to microbial attack, ability to form water-soluble and water insoluble salts and complexes with metal ions and hydrous oxide, and their interaction with clay minerals and organic chemicals. Humins are characterised by a black colour, high C content and low oxygen content. The ratio of humic acids to fulvic acids in forest soils is less than one while in grasslands is more than two (Schnitzer & Khan, 1972; Thomas & Packham, 2007).

2.3.3 Soil organic carbon, amounts and distribution

Soil is considered to contain the largest C pool of terrestrial ecosystems (Wang *et al*., 2004) and contains a stock of C that is three times as large as that in the vegetation and twice that in atmosphere (Smith *et al*., 2008). According to Buringh (1984) the estimated total organic C (in prehistoric times) in the soils of the world was $2014 * 10^{15}$ g. The current estimates of organic C in these soils has been reduced to $1477 * 10^{15}$ g with an annual loss of $4.6 * 10^{15}$ g organic C. This decline is mainly brought by changes in land use. Measures like forest plantations are therefore needed to conserve soil organic C.

The organic matter content in soils varies from 1 to 5% of the dry weight in soils and has an inverse relationship with soil depth. The C content is approximately 58% of the organic matter content (Buringh, 1984). About 60% of South African soils contain a low soil organic C content of less than 2%, "conducive to low soil productivity and soil degradation" (De Villiers *et al*., 2002) with the latter being the most serious threat to agricultural productivity and biodiversity (Buringh, 1984).

Rantoa (2009) estimated organic C stocks in the soils of South Africa. In these soils, the soil forming factors (climate, parent material, land cover, vegetation, and topography) and the human induced factors (land use, management, and degradation) influenced the soil organic

C content. The study of Rantoa (2009) serves as baseline data for South African soils, which determines the potential for C sequestration. An average of 73 726 kg ha^{-1} organic C was observed, when using a 1.50 g cm^{-3} bulk density. The results obtained indicated that the South African soils have C stocks that increase from the warmer, drier western to cooler, wetter eastern parts of the country.

Measures are being taken worldwide to reduce C emissions and to increase C sequestration. Le Roux *et al*. (2005) therefore quantified the C sequestered by grassland soils destined for afforestation in the Weatherley catchment. A linear decrease of organic C was observed from an average of 1.7 * 10^{-3} Mg m^{-3} in the top 50 mm layer to about 0.5 * 10^{-3} Mg m^{-3} in the 600 to 700 mm layer (Figure 2.3). The organic matter was quantified to a depth of 1200 mm in 27 soil profiles. These data are useful, especially to determine whether there have been changes in organic matter contents in the different soils and soil layers after afforestation of the catchment.

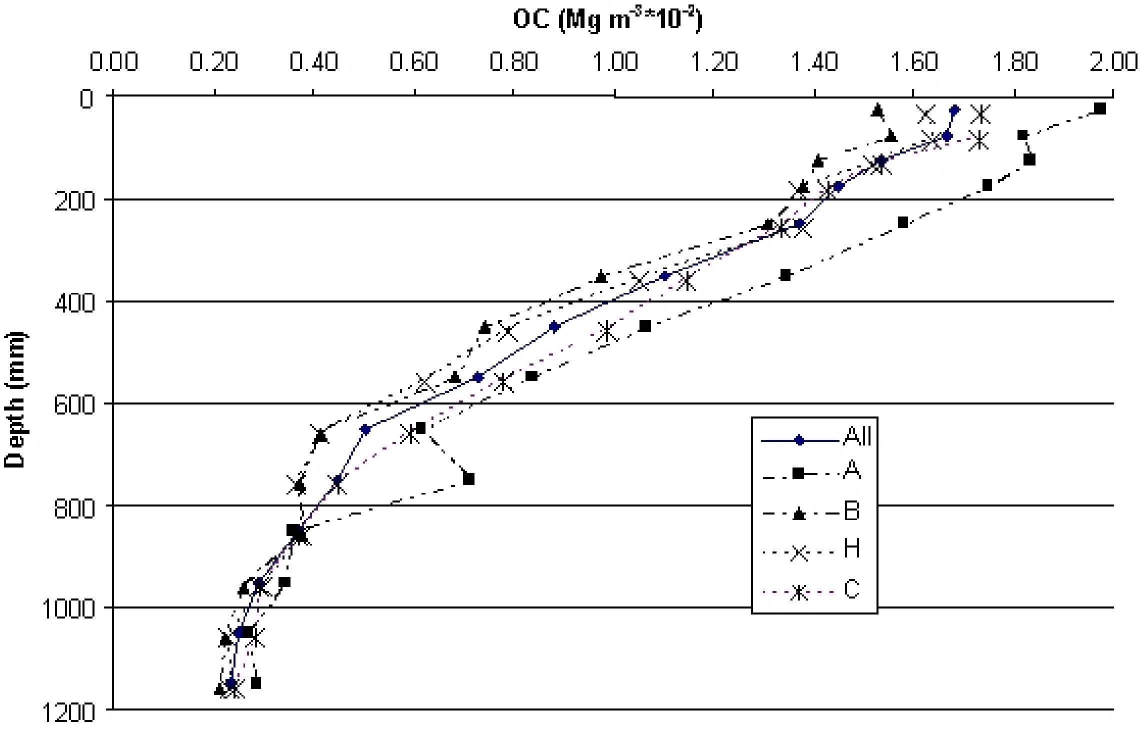

Figure 2.3 Organic carbon content of different soil layers for each of the groups of similar soils in the area of the Weatherley catchment destined for afforestation (Le Roux *et al*., 2005). All = A, B, C, and H, A = apedal mesotrophic, B = plinthic mesotrophic, C = undifferentiated hydromorphic, and H = mostly neocutanic B horizon soils

2.3.4 Factors influencing organic carbon stocks

The South African Forestry industry is concerned with the production of wood and wood fibre. According to Fairbacks and Scholes (1999), under the current climate in South Africa, only 1.5% of the country is suitable for forestry and much of this land is relatively marginal. Trees are important in South Africa as they supply local wood and paper, while some are exported, contributing to the country's economy. Tree plantations take a long time between planting and harvesting, thus making them vulnerable to environmental changes. Fairbacks and Scholes (1999) pointed out that the concentration of CO_2 in the atmosphere is increasing and is therefore affecting the climate. The changes in the climate are expected to affect the forestry industry. Stevenson and Cole (1999) cited Jenny (1930) who indicated that the factors of soil formation decrease in order of importance: climate > vegetation> topography = parent material > time on their influence on C sequestration. In this study only the factors that affect grassland and forestry soils will be considered.

2.3.4.1 Climate

The key components of climate, water and temperature, are the two most important parameters in organic matter accumulation and turnover (Alvarez & Lavado, 1998). The amount of vegetation cover, quantity, and quality of organic residues added to the soil, and the rate of organic matter mineralisation and decomposition are regulated by climate (Hontoria *et al*., 1999).

In South Africa, forestry species of economic importance are *Eucalyptus*, *Pinus*, and other tree species like *Acacia*. The forestry industry in South Africa is facing soil nutrient depletion (Hawley *et al*., 2008). Mills and Fey (2003) indicated that the rate of soil organic matter depletion is largely dependent on climate. Bot and Benites (2005) relate an increase in mean annual precipitation to increases in soil organic matter levels. Adequate soil moisture conditions result in greater biomass production hence more plant residues and more food for soil organisms. The activity of the microorganisms is influenced by oxygen and water. Under water saturated conditions there is poor aeration. The activity of microorganisms is therefore reduced because of reduction in oxygen levels in soil. This also leads to a reduction in mineralisation rates. Anaerobic conditions also reduce some of the transformation processes and plant roots can be subjected to damage. Therefore, with continued production and slow decomposition a large OM content in soils is expected especially under long periods of water saturation such as in peat soils.

Brown and Lugo (1982) used a ratio of mean and annual air temperature to annual precipitation (T/P) to relate storage of organic matter to climate in tropical forests. This ratio was used rather than the ratio of evapotranspiration to precipitation or actual evapotranspiration because the interest was to measure the environmental conditions to which plants adapt in the long term. Areas of study had different soil moisture regimes. A decrease in soil C storage was related to an increasing T/P ratio. Litter storage had no correlation with T/P, but total litter production had significant relationship with T/P. Total biomass decreased with increasing T/P.

2.3.4.2 Vegetation

The quality and quantity of organic matter inputs influence the rate of soil organic matter accumulation. The carbon content of grassland soils is usually higher than that of forest soils. This is because of higher production of biomass under grassland and due to less air circulation and because the activity of microbes is reduced (Stevenson & Cole, 1999). The presence of materials such as lignin, especially under forest ecosystems retards decomposition. On the other hand, materials with a higher C:N ratio like cereal straw and grasses favour nutrient mineralisation, organic accumulation, and humus formation (Bot & Benites, 2005).

Organic matter accumulation may differ, based on the type of vegetation (Texeira *et al*., 2008). Even within the same type of vegetation for example grassland, there may be differences in soil organic matter content between plant species. In a study conducted by Wedin and Tilman (1990) where monocultures of five perennial grasses (*Apopyron repens*, *Agorstis scabra*, *Poa pratensis*, *Schizachyrium scoparium*, and *Andropogon gerardi*) were planted, differences in grassland vegetation led to differences in N cycling where *Agrostis scabra* gave higher annual net nitrogen mineralisation of 12 kg N m^{-2} yr^{-1}.

In their study Giardina *et al*. (2001) evaluated the effects of tree litter quality and soil clay content on C and net N mineralisation rates in mineral soils sampled from subalpine forest types of the central Rocky Mountains. Two types of trees were used, *Pinus contorta* and *Populous tremuloides* (aspen) with soils that varied in clay content from 70 to 390 g kg^{-1} soil. In this study pine soils released 238 g kg^{-1} soil C while aspen soils released 103 g C kg^{-1} soil C. The pine soils had lower C content due to faster mineralisation of pine and the opposite was true with aspen soils. The C mineralisation rates were not related to soil clay content. The pine soil C was of higher quality than aspen soil C as indicated by higher microbial biomass.

2.3.4.3 Topography

Topography or relief influences climate, runoff, evaporation, and transpiration. Variations in topography include knolls, slopes, and depressions. The soil C content is higher in soils occurring in depressions than those on the knolls (Stevenson, 1986). Organic matter accumulation is often favoured at the bottom of hills. There are two reasons for this accumulation: conditions are wetter than at mid or upper-slope positions and organic matter is transported to the lowest point in the landscape through runoff and erosion. On the other hand, because of lower temperatures, soil organic matter levels may be higher on north-facing slopes compared with south-facing slopes in the northern hemisphere.

In water logged conditions, plant remains are not completely decomposed. Hence, organic matter levels are usually higher in naturally moist and poorly drained soils because the destruction of organic matter is protected by anaerobic conditions prevailing during wet periods (Stevenson, 1986).

2.3.4.4 Parent material

The effect of parent material on soil texture alters the C content of the soil. Other things being constant (vegetation and topography), under varied climatic zones, the soil textural properties affect C and N. The organic matter is preserved by the fixation of humic substances to clay particles. Therefore the C content in different soil textures decreases in the order: heavy-textured soils, loamy soils, and sandy soils (Stevenson, 1986).

Soil texture plays an important role in C storage in ecosystems and strongly affects the nutrient availability and retention (Silver *et al.*, 2000). The amount of organic residues returned to the soil is generally higher in fine-textured soils, because the greater nutrient and water holding capacities of these soils promotes greater plant production. At the same time, the generally wetter conditions of the fine-textured soils may restrict aeration and therefore reduce the rate of organic matter oxidation. Organic matter also binds to the finer particles, preventing microbial oxidation (Stevenson & Cole, 1999).

Hanegraaf *et al*. (2009) found C accumulation was about 39 g C m^{-2} yr^{-1} in the top 0-50 mm of grassland sandy soils. The results possibly fall below the expected C sequestration, because the highest C sequestration was obtained after a period of 20 years (Hanegraaf *et al*., 2009). In contrast, McLauchlan *et al*. (2006) found soil organic C in the top 100 mm of soil accumulated at a constant rate of 62 g C m^{-2} yr^{-1} after 40 years.

The effect of afforestation on change in C within soils where clay content was low (sand, sandy, and loams), medium (silty loams or silty clay loams), and high (clays and clay loams) is shown in Figure 2.4 (Paul *et al*., 2002). Clay tended to decrease the storage of soil C for the 0-100 mm depth layer while the opposite is true for the greater than 100 mm or less than 300 mm depth where C increases with increase in clay content (Paul *et al*., 2002). The study conducted by Lugo and Sanchez (1986) confirmed this and indicated that the organic C content and soil C accumulation were negatively correlated with the sand content of soil and were directly related to clay content. Moreover, Bird *et al*. (2002) observed that sandy soils under trees contained 35-50% lower C in the 0-50 mm layer than clay soils. The presence of large amounts of soil organic C in fine textured compared to coarse textured soils under the same climatic conditions relates to the higher nutrient and water holding capacities of fine textured soils and greater ability of clay to protect C against microbial mineralisation. In contrast, research conducted by Silver *et al.* (2000) showed that sandy soils stored approximately 113 Mg C ha^{-1} to a 1 m depth versus 101 Mg C ha^{-1} in clay soils. The sandy soils also had a higher forest floor than the clay soils.

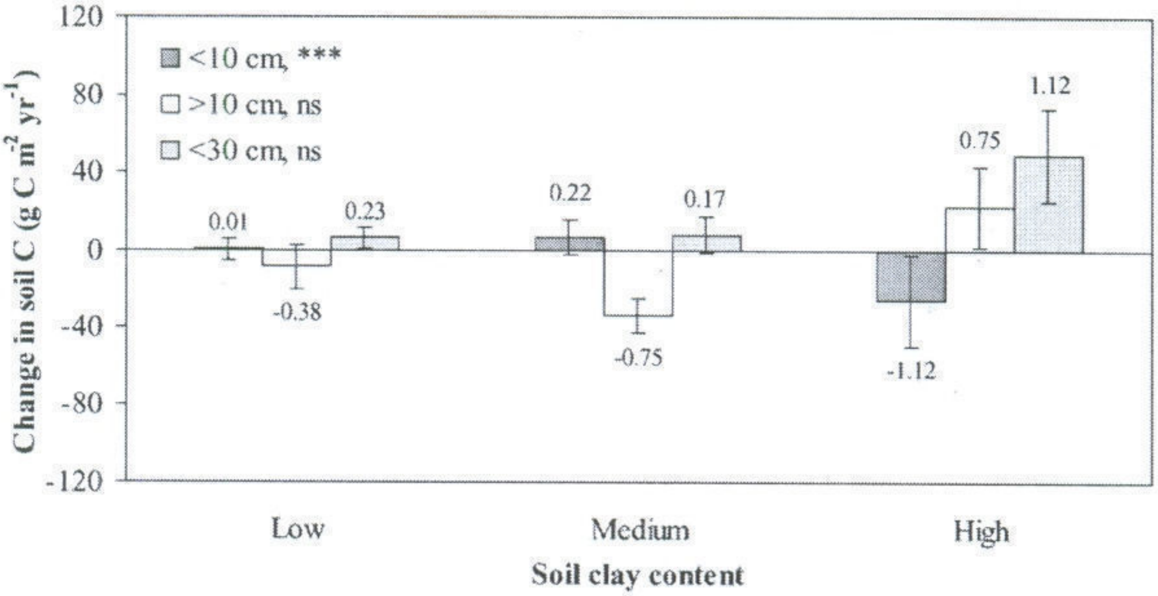

Figure 2.4 The weighted-average change in soil C from <100, >100, and <300 mm for three categories of soil clay content (Paul *et al*., 2002).

2.3.4.5 Land use

In the following discussion on land use, grassland versus forestry is considered. With conversion of an ecosystem with a low C density, that is the amount of organic C per unit of land area in Mg ha^{-1}, to an ecosystem with a high C density, a net increase in C storage is expected (Christie & Scholes, 1995). South Africa contributes only 1.2% to the plantations in Africa. Plantations consist of fast-growing trees such as *Pinus* and *Eucalyptus* species. These plantations are grown on a rotational basis. They are clear felled when their growth rate begins to decline and then another tree plantation is introduced. The rotation length ranges from 6 to 25 years and depends on the objective of the final product. Therefore, the plantation will only contribute to a net C storage if the mean C density over the rotation is greater than that of the vegetation it replaces (Christie & Scholes, 1995).

Moreover, the process of photosynthesis as mentioned earlier, plays an important role in the amount of C stored by vegetation. The reduction in atmospheric CO_2 concentrations can be through forest plantations and modification of agricultural practices so as to increase the quantity of C stored in soil organic matter (Christie & Scholes, 1995). In a study conducted by Olsen and Van Miegroet (2009), forest soils produced more CO_2 in summer compared with the rangelands.

Le Roux *et al*. (2005) conducted a baseline study in the Weatherley catchment on soil organic matter. The study was on grassland soils which were later afforested. Differences in the amounts and distribution of organic carbon content occurred in all four groups of soils studied. The group A, Hutton and Clovelly forms (excessively drained soils) had the largest amounts of organic C in all the soil layers (53-111.1 Mg C ha^{-1}). This was followed by the group C soils, Longlands, Katspruit, Westleigh, Kroonstad, and Klapmus forms (poorly drained soils) with 46-97 Mg C ha^{-1}. The group B and H, Bloemdal, Pinedene, and Tukulu forms soils (moderately well drained soils, and freely drained soils respectively) had similar amounts of organic C and distribution pattern, 43-88 Mg C ha^{-1}.(

The total nitrogen as observed by Le Roux *et al.* (2005) was found to have accumulated in the subsoils of the strongly hydromorphic soils. This accumulation was related to the long periods of anaerobic conditions in these horizons. For each tree species area, the mean values of organic C content in the 0-1200 mm layer ranged between 74.1 and 97.3 Mg ha^{-1}. Le Roux *et al.* (2005) further claimed that, under grassland soils, organic matter accumulation is likely to be highest in the topsoil, however, under afforestation a different accumulation can be expected. The reason could be because the tree roots can penetrate deeper and translocate more organic matter deeper into the soil. Therefore afforestation plays an important role in the soil organic matter contents because soil organic matter is lost mostly within 10 years after clearing of forests or grassland. The amount of organic matter lost depends on the type of soil (Gregorich, *et al.*, 1994).

2.3.4.6 Others

Other factors like burning also play an important role in C storage. Tainton (1999) regarded fire, as used by livestock farmers and wildlife managers, as a vital tool in both African savannah and grassland systems by controlling bush encroachment and removing dead and dying vegetation that has low forage suitability and is not palatable to animals. Burning of grassland gives greater annual dry matter production as a result of earlier grass growth at the beginning of growing season (Ojima *et al*., 1994). During burning dead surface litter is removed and greater light penetration as well as higher soil temperatures in spring are encouraged. On the other hand, large amounts of nutrients including C and N are lost via volatilisation during burning and as a result there may be larger decrease in soil N than C and increase in the C:N ratio depending on the fire intensity (Hall & Scurlock, 1991; Fynn *et al*., 2003).

Fynn *et al*. (2003) investigated the effects of burning native grassland on soil organic matter status in a long-term (50 years) field experiment where different times and frequencies of burning were compared. It was observed that regular burning of the grasslands led to a relatively higher loss of N than C from the soil-plant system. The organic C loss occurred only in the top few cm of the soil under repeated burning as has also been reported in other studies (Ojima *et al*., 1994). The addition of the leaf litter material on the surface had an impact in the first few cm of soil and therefore its removal by fire decreased the organic matter content close to the surface. At deeper layers, there were insignificant results because mostly the organic matter in grassland soils came from the root turnover. The loss of C was less pronounced in spring burning than in either winter or autumn burning. When burning was practiced in spring, the opportunity existed during the previous winter for litter to decompose and/or became incorporated into the soil through the activity of soil microorganisms. Similar studies indicated that repeated annual burning resulted in greater inputs of lower quality plant residues causing a significant reduction in soil organic N and higher C:N ratios in soil organic matter (Ojima *et al*., 1994).

In a study conducted by Gimeno-Garcia *et al*. (2000), burning resulted in the losses of organic matter and total N. The organic matter and nutrients removed were closely associated with quantity of fire. Soil subjected to high intensity fires was easily eroded and as a result of organic matter and nutrients were lost. Bird *et al*. (2000) observed an increase of 40% to 50% in C from tree plots which were not subjected to fire in the 0-5 cm interval when compared with plots put under fire. The C increase was related to higher C inputs per unit area from trees.

CHAPTER 3

MATERIAL AND METHODS

3.1 Description of the Weatherley catchment

The School of Bioresources Engineering and Environmental Hydrology (BEEH, 2003) of the University of KwaZulu-Natal together with North East Cape Forests and Mondi selected the Weatherley catchment in 1995 for hydrological studies. These studies were undertaken in two phases. The first phase involved characterisation of the hydrology of the catchment over a six year period, under its natural grassland vegetation. Different tree species were planted in spring 2002 on selected soils in the catchment, while continuing the hydrological studies to evaluate the influence of the afforestation on the hydrology. During this conversion period the University of the Free State research team was requested to monitor the influence of afforestation on the organic C content of the soil, hence the first baseline study was conducted (Le Roux *et al*., 2005). This study is a continuation of the mentioned baseline study.

3.1.1 Location

The Weatherley catchment is located in the north-eastern corner of the Eastern Cape Province. It occupies about 160 ha and is situated 4 km south-west of Maclear, on the road to Ugie (Figure 3.1). The catchment is covered by the 1:50 000 topocadastral sheet 3128AB Maclear (Chief Director of Surveys and Mapping, 1993).

3.1.2 Relief

Weatherley is the upper-most catchment of one of the very small branches of the Mooi River. Water does not flow into the catchment and this characteristic makes it very suitable for hydrological studies (Figure 3.2). It drains in a north-easterly direction and is closed on the eastern, southern, and western slopes (Van Huyssteen *et al*., 2005).

Molteno and Elliot sandstone shelves are prominent at approximately 1 316 -1 318 m above mean sea level in the eastern and southern slopes. This is because of the resistance of Molteno and Elliot sandstone against weathering. The south-western corner of the catchment constitutes the highest point in the catchment at 1 352 m. The stream runs in a north easterly direction and occurs at a height of between 1 254 and 1 286 m (Le Roux *et al*., 2005; Van Huyssteen *et al*., 2005).

The catchment supports a large population of moles and earthworms due to the moist conditions prevailing in the soils. This leads to the formation of many surface moun ds thus making walking very difficult. This gives an impression that macro faunal activity is correlated with changing water regimes in the soil. In summer rainy periods moles and earthworms will move to drier soil and to the wetter soils in the dry winter months (Le Roux *et al*., 2005; Van Huyssteen *et al*., 2005).

3.1.3 Geology

The catchment is characterised by Elliot sandstone and mudstone found higher than 1 320 m above mean sea level, covering the upper slopes on the eastern and southern slopes (Figure 3.3). The sandstone and mudstone of the Molteno formation are found lower than 1 320 m above mean sea level. Two dolerite dykes, one in the south-western corner and one in the north-western corner form part of the catchment (Le Roux *et al*., 2005).

3.1.4 Climate

Some climatic data of a weather station at Maclear, roughly 4 km from Weatherly is given in Table 3.1. The catchment has warm wet summers with annual mean maximum temperatures of 25°C and cold dry winters with mean annual minimum temperatures of 4°C. Snow is common on the surrounding higher lying areas of the catchment. Large amounts of rainfall are experienced in summer months. This characteristic feature plays a vital role in the hydromorphic nature of the soils dominating the catchment (Le Roux *et al*., 2005; Van Huyssteen *et al*., 2005). The annual mean rainfall at Weatherley from 1996 to 2010 was 1 026 mm (Table 3.2).

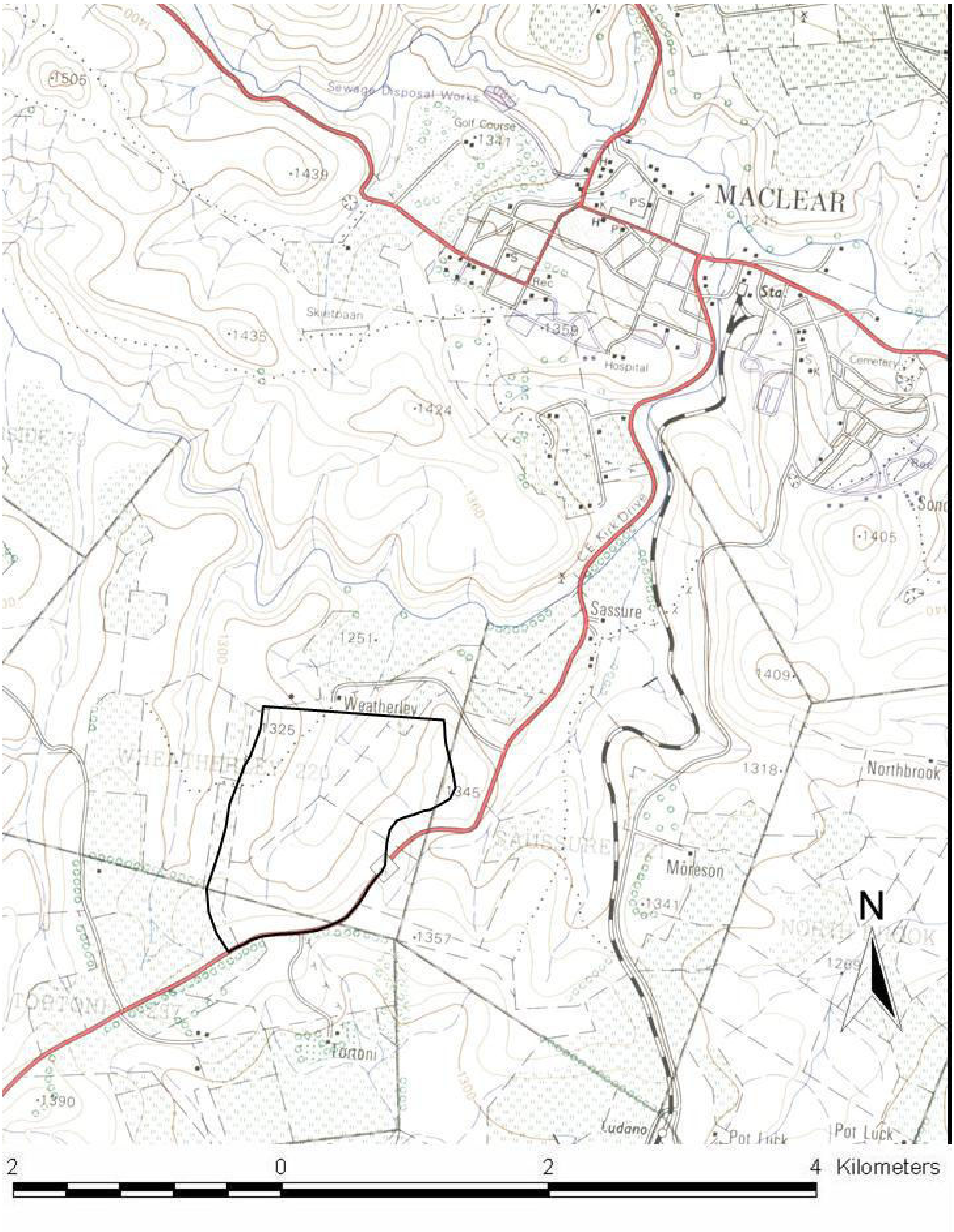

Figure 3.1 Location of the Weatherley catchment, 4 km south of Maclear on the road to Ugie (Chief Director of Surveys and Mapping, 1993).

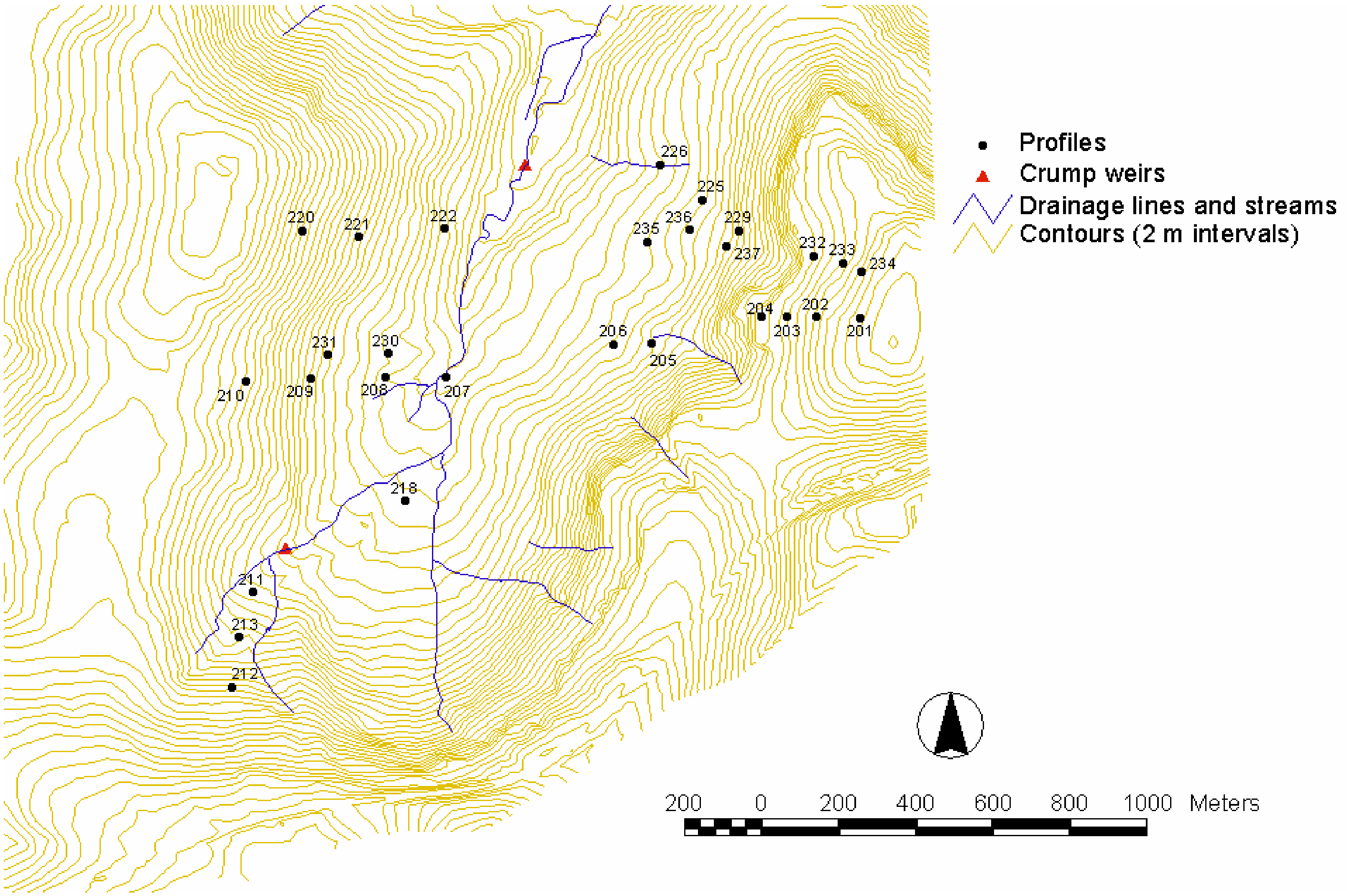

Figure 3.2 Geography of the Weatherley catchment, including the location of the sampling sites (Van Huyssteen *et al*., 2005)

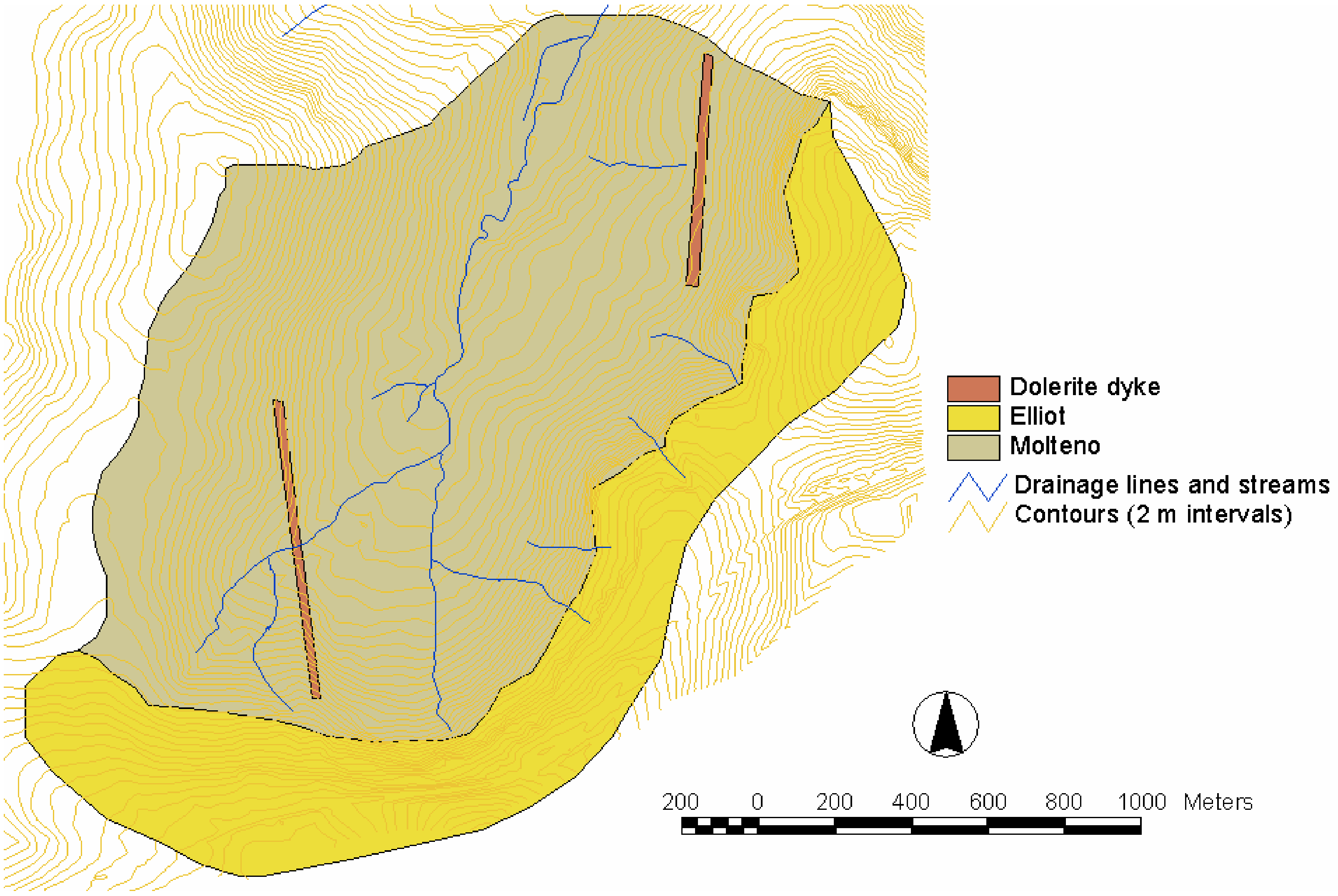

Figure 3.3 Simplified geology of the Weatherley catchment (De Decker, 1981)

Table 3.1 Climatic data from a weather station at Maclear, located roughly 4 km from Weatherley (Roberts *et al*., 1996).

Month	P (mm)	E (mm)	P/E	T (°C)*		
				T_{mx}	T_{mn}	$(T_{mx}+T_{mn})/2$
January	195.3	142.1	1.37	25	14	20
February	154.3	120.6	1.28	25	14	20
March	140.4	116.9	1.20	24	12	18
April	61.6	97.1	0.63	24	11	18
May	30.3	84.2	0.36	21	7	14
June	24.9	71.6	0.35	18	4	11
July	15.2	73.5	0.21	19	4	11
August	28.8	98.2	0.29	19	6	11
September	36.6	111.4	0.33	21	8	14
October	65.2	134.0	0.49	21	10	15
November	131.3	137.0	0.96	24	12	18
December	180.5	141.6	1.27	24	13	19
Total	1064.3	1328.1	0.80			

*mx and mn stand for maximum and minimum respectively; P = monthly mean rainfall, E =evaporation, T = temperature.

Table 3.2 Yearly rainfall, measured at Weatherley from 1996 to 2010 (BEEH, 2003)

Year	Rainfall (mm)
1996	1 196
1997	952
1998	1 187
1999	956
2000	1 304
2001	1 092
2002	896
2003	714
2004	1 005
2005	794
2006	1 100
2010	1 117
Mean	1 026

3.1.5 Soils

The soils in the catchment are highly acidic and have a low cation exchange capacity. Generallised soil patterns from a soil survey are shown in Figure 3.4. The wet Katspruit (Map unit Ca), dry Hutton (Map unit Af), and Oakleaf (Map unit He) soil forms (Soil Classification Working Group, 1991) constitute the major part of the catchment. Most of the soils do, however, show clear signs of water saturation. These signs are characterised by clay depletions, ranging from faint grey mottles to continuous grey zones (Le Roux *et al.*, 2003). The northwest facing slopes in the southern part of the catchment also have strongly structured Sepane soils (Van Huyssteen *et al.*, 2005).

3.1.6 Vegetation

The native vegetation at Weatherley is known as moist upland grassland, which is typical of veld type 42 (Low & Rebelo, 1996). This veld type occurs between 600 and 1 400 m above mean sea level and is most commonly found in the Drakensberg foothills of the Eastern Cape and KwaZulu-Natal provinces. The vegetation was dense, sour grassland with *Themeda triandra* (Redgrass), *Heteropogon contortus* (Speragrass), *Tristachya leucothrix* (Hairy Tridentgrass), *Eragrostis curvula*, *Elionurus muticus*, *Digitaria setifera* and *Andropogon appendiculatus* as the dominant species. Diagnostic species included hardy forbs such as *Walafrida densiflora*, *Cucumis zeyheri* (Spiky Cucumber), *C. ahirsutus* (Wild Cucumber), *Berkheya onopordifolia*, *Spermacoce natalensis*, *Kohautia cynanchica*, *Tephrosia macropoda*, *T. multijuga*, *Conyza obscura*, *Corchorus confuses*, *Phyllanthus glacophyllus*, *Richardia brasiliensis*, *Gomphrena celosioides*, *Aster bakerianus*, *Alysicarpus rugosus*, *Helichrysum coriaceum* and *H. rugulosum*. Unpalatable species such as *Elionurus muticus* (Wire grass) and herbaceous weeds like *Senecio retrorsus* (Staggersweed) and *Helichrysum argyphyllum* (Doll rose) were present due to overgrazing. All these mentioned species occurred in large numbers. Other species which occurred in lower numbers, but with high frequencies include *Alloteropsis semialata*, *Aristida junciformis*, *Blepharis integrifolia*, *Bulbostylis schoenoides*, *Helichrysum aureonitens*, and *Zornia capensis*. The mean biomass yield for the four groups of soils in the grassland was 3 400 kg ha^{-1} yr^{-1} (Le Roux *et al*., 2005).

About 76 ha of the grassland was afforested in 2002 (Figure 3.5). Three tree species, *Pinus patula*, *Pinus elliottii*, and *Eucalyptus nitens* were planted. These species have different soil requirements for optimum growth. Specific areas of the catchment were therefore selected for each species. However, the normal criteria were deliberately transgressed at some of the sites to study interactions between trees and soils.

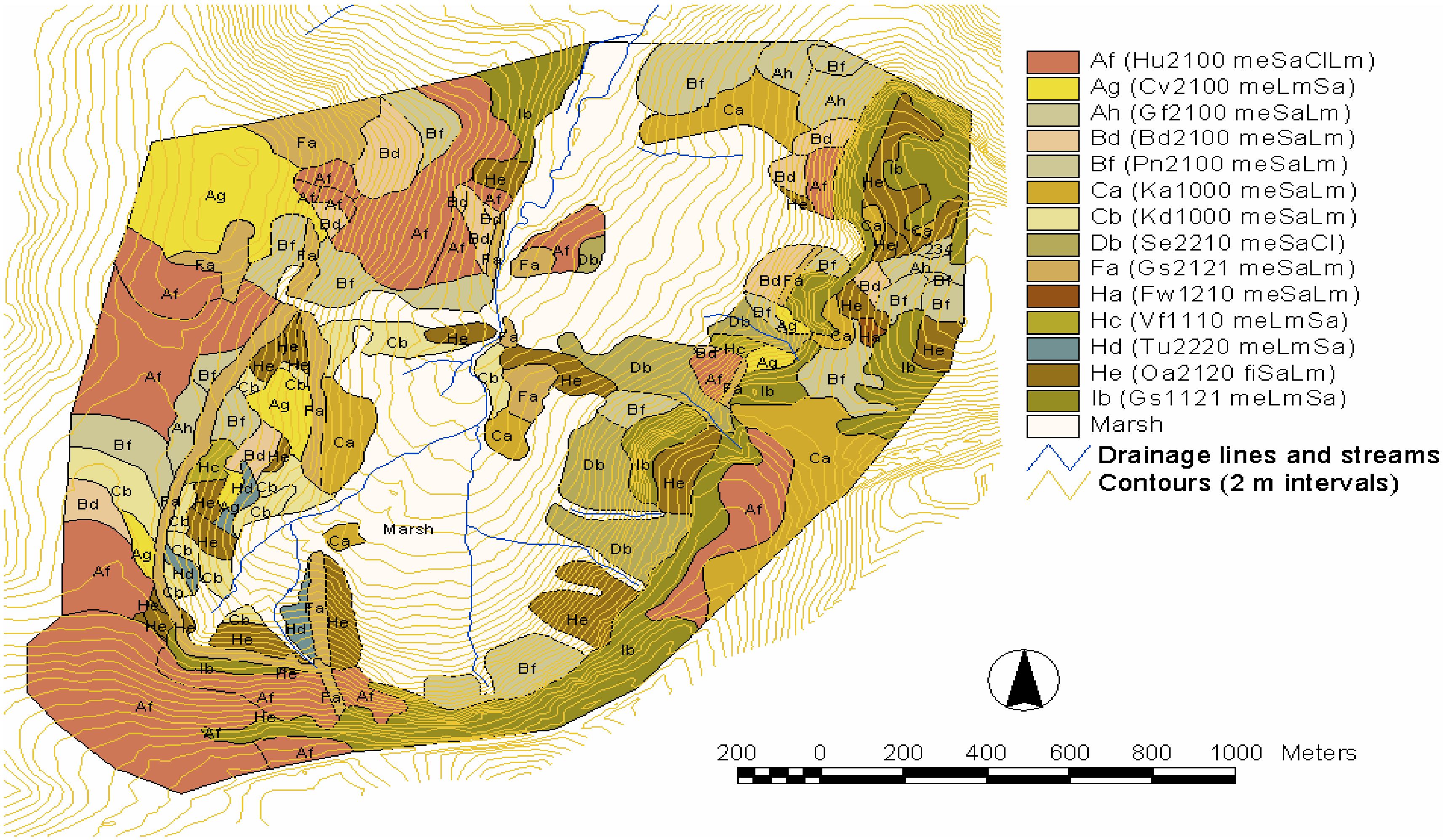

Figure 3.4 Generalised soil patterns according to Roberts *et al.* (1996)

Figure 3.5 Planting strategy in the Weatherley catchment (BEEH, 2003)

3.1.7 Hydrology

The catchment experiences high runoff during summer months after large rain storms. There is, however, little low flow. The variation in annual runoff is showmn in Figure 3.6 (BEEH, 2003).

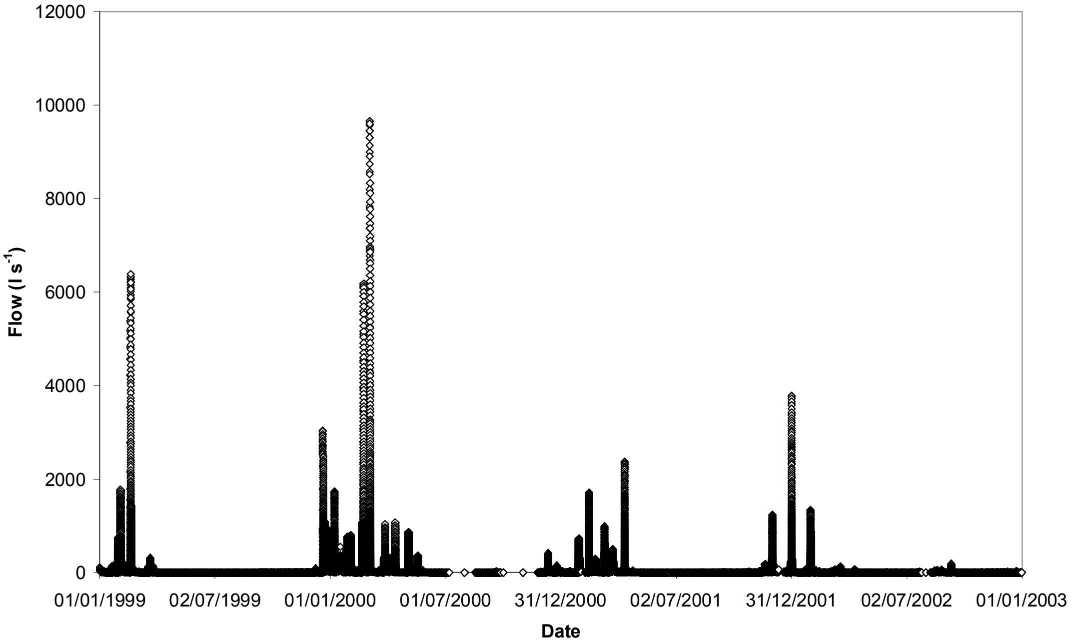

Figure 3.6 Hydrograph, showing runoff at the lower weir in the Weatherley catchment (BEEH, 2003).

3.2 Methodology

3.2.1 Experimental site

As mentioned earlier, parts of the catchment was afforested in 2002 according to a planting strategy (Figure 3.5), which was based on the generalised soil pattern (Figure 3.4). Five broad soil groups could be used for this purpose. Each group with its map unit subdivisions and relevant total areas is listed in Table 3.3. The areas of each of these groups actually planted to the different tree species are given in Table 3.4.

For comparative purposes the same 27 sites used by Le Roux *et al.* (2005) in their baseline study were investigated in this study (Figure 3.7). In their selection of sampling sites an attempt was made to select replicates from every broad soil group allocated to each of the tree species (Table 3.5). 25 sites were selected, ten for the *Pinus elliottii* area, eight for the *Pinus patula* area, and seven for the *Eucalyptus nitens* area. Two control sites outside the afforested area were also sampled. This sampling sites selection used 13 soil profiles (all numbers 235 and lower), which were described in detail by Van Huyssteen *et al.* (2005). The other 14 soil profiles (all numbers 240 and higher) were described in lesser detail by Le Roux *et al.* (2005).

Table 3.3 Areas of soils which could be used for afforestation in the Weatherley catchment according to the survey by Roberts *et al.* (1996)

Soil groups, map units and soil forms	**Area (ha)**
Group A: Apedal mesotrophic soils	
Af: Hutton	38
Ag: Clovelly and some Griffin	8
Ah: Hutton/Clovelly/Griffin	4
Group B: Plinthic mesotrophic soils	
Bd: Bloemdal	6
Bf: Pinedene and some Avalon	16
Group C: Undifferentiated hydromorphic soils	
Ca: Westleigh, Katspruit, Longlands	10
Cb: Kroonstad, Longlands	7
Group D: Non-red duplex soils	
Db: Sepane and some Escourt	8
Group H: Mostly neocutanic B horizons	
Ha: Pale topsoil sands	<1
Hc: Vilafontes	1
Hd: Tukulu	1
He: Tukulu, Oakleaf	13
Total	112

Table 3.4 Areas of the different groups of similar soils in each tree species area (Le Roux *et al.*, 2005)

Tree species	**Soil groups and areas (ha)**[1]				**Total (ha)**
	A	B	C	H	
Pinus elliottii	4.2	7.6	6.6	7.9	26.3
Pinus patula	18.4	3.3	0.2	5.0	26.9
Eucalyptus nitens	15.0	7.2	0	0.6	22.8
Total	37.6	18.1	6.8	13.5	76.0

[1] A = *apedal mesotrophic*, B = *plinthic mesotrophic*, C = *undifferentiated hydromorphic*, and H = mostly *neocutanic* B horizon soils

3.2.2 Quantification of carbon stocks

For this study the C (N in some instances also) stocks in soil, litter, and trees were quantified. The C (N in some instances also) stocks quantified by Le Roux *et al.* (2005) for soil and grassland were also used. Details for both studies are therefore given for completeness.

3.2.2.1 Soil

Soil samples for the baseline study (Le Roux *et al.*, 2005) were taken at five depths, viz. 0-50 mm, 50-100, 100-150, 150-200, and 200-300 mm. At each sample site three sub-samples were taken at each depth and mixed together to give a composite sample. This procedure was replicated four times at each site. For the remaining layers up to 1 200 mm, single soil samples were taken at 100 mm depth intervals.

For the current study, soil samples were taken at 15 depths, viz. 0-50, 50-100, 100-150, 150-200, 200-250, 250-300, 300-400, 400-500, 500-600, 600-700, 700-800, 800-900, 900-1 000, 1 000-1 100, and 1 100-1 200 mm. At each sample site, three sub-samples were taken at each depth and mixed together to give a composite sample. The procedure was replicated four times at each site.

The 783 soil samples for the baseline study and the 1 620 soil samples for this study were dried at room temperature, crushed, sieved to pass a 2 mm screen, and stored until analysed. Both sets of soil samples were analysed for organic C and total N as indices of organic matter. Organic C and total N were determined following Mebius and Kjelhahl procedures as described by Nelson & Sommers (1982) and Bremner & Mulvaney (1982), respectively. The organic C and total N contents (%) were converted to organic C and total N stocks (Mg ha^{-1}), using the bulk density data of the baseline study (Le Roux *et al.*, 2005).

3.2.2.2 Litter

At each of the 27 sites, fallen litter and undergrowth (if present) was collected from four 1 m^2 areas in April 2010. A 1 m^2 square, made of iron rod, was used to ensure the size of the sample area. The sample areas were randomly selected. This sampling was done simultaneously with the soil sampling. The litter fall included small branches, twigs, leaves, needles, and flowers, but not fallen trees and root litter. All the litter samples were dried in a glasshouse and weighed. The complete litter sample of a site was then ground in a commercial shredder (Bosch 2 500 HP). A subsample of the shredded sample was then finely ground in a laboratory mill (Retsch GmbH 5657 HAAN). The C and N contents were then determined on a dry combustion analysing system (Leco Truspec CN analyser).

In the baseline study aboveground biomass yield of the grass was measured at most sites without any replications (Le Roux *et al.*, 2005). Unfortunately, neither the C content nor the N content of the biomass were determined.

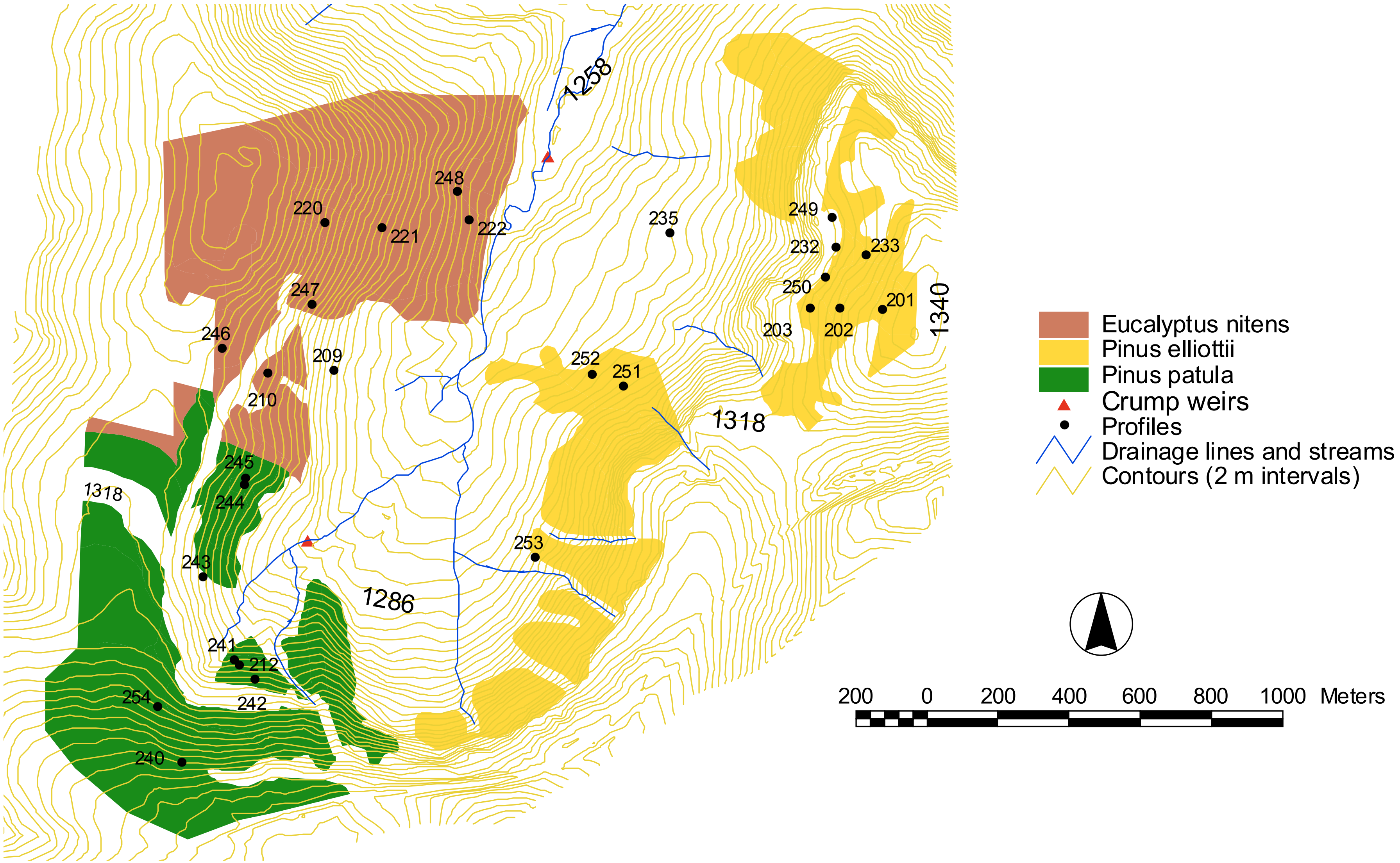

Figure 3.7 Distribution of the 27 sampling sites for this study (Le Roux *et al.*, 2005)

Table 3.5 Soil map units where three tree species were established (Le Roux *et al.*, 2005)

Soil map unit	Profile No	Soil form*	Latitude & Longitude	Terrain unit	%Slope
Pinus elliottii area					
Ah4	250	Pinedene (Pn)	31° 06' 06.2" / 28° 20' 23.5"	Upper foot slope	10
Af13	251	Clovelly (Cv)	31° 06' 19.0" / 28° 19' 99.8"	Upper foot slope	10
Bf16	201	Longlands (Lo)	31° 06’ 06.0” / 28° 20’ 18.0”	Upper midslope	4
Bf15	202	Pinedene (Pn)	31° 06' 06.0" / 28° 20' 15.1"	Upper midslope	4
Ca5	232	Westleigh (We)	31° 06' 01.6" / 28° 20' 14.8"	Crest / Footslope	2
Ca5	249	Kroonstad (Kd)	31° 06' 02.0" / 28° 20' 21.0"	Upper foot slope	7
Db3	252	Kroonstad (Kd)	31° 06' 17.6" / 28° 19' 96.1"	Upper foot slope	7
Db5	253	Klapmuts (Km)	31° 06' 39.0" / 28° 19' 89.5"	Upper foot slope	10
He18	203	Tukulu (Tu)	31° 06' 05.9" / 28° 20' 13.0"	Upper mid slope	8
He17	233	Pinedene (Pn)	31° 06' 02.1" / 28° 20' 16.9"	Footslope	2
Pinus *patula* area					
Af10	240	Hutton (Hu)	31° 06’ 37.7” / 28° 19’ 28.0”	Upper foot slope	10
Af10	254	Hutton (Hu)	31° 06' 16.7" / 28° 19' 53.3"	Upper mid slope	8
Bf6	245	Pinedene (Pn)	31° 06' 28.6" / 28° 19' 56.7"	Upper mid slope	8
Bd7	244	Pinedene (Pn)	31° 06' 30.6" / 28° 19' 55.4"	Upper mid slope	8
Cb12b	241	Longlands (Lo)	31° 06' 51.0" / 28° 19' 543"	Upper foot slope	4
Cb12a	242	Longlands (Lo)	31° 06' 51.6" / 28° 19' 54.9"	Upper foot slope	4
He11	212	Tukulu (Tu)	31° 06' 32.0" / 28° 19' 34.0"	Upper mid slope	4
He8	243	Tukulu (Tu)	31° 06' 41.3" / 28° 19' 50.6"	Upper mid slope	10
Eucalyptus nitens area					
Af4	221	Hutton (Hu)	31° 06' 00.3" / 28° 19' 42.9"	Upper foot slope	8
Af9	246	Pinedene (Pn)	31° 06' 14.6" / 28° 19' 52.9"	Upper middle slope	5
Bd2	220	Bloemdal (Bd)	31° 06' 59.9" / 28° 19' 38.9"	Upper mid slope	16
Bd4	222	Tukulu (Tu)	31° 05' 59.7" / 28° 19' 49.0"	Lower mid slope	7
He1	248	Tukulu (Tu)	31° 05' 96.2" / 28° 19' 80.3"	Upper foot slope	10
He 3	210	Bloemdal (Bd)	31° 06' 10.5" / 28° 19' 34.9"	Upper mid slope	5
Bf3	247	Pinedene (Pn)	31° 06' 08.3" / 28° 19' 64.4"	Upper middle slope	13
Control sites					
Cb2	209	Katspruit (Ka)	31° 06' 10.3" / 28° 19' 39.6"	Upper mid slope	8
Marsh	235	Katspruit (Ka)	31° 05' 57.8" / 28° 20' 02.4"	Lower foot slope	3

*Soil classification Working Group (1991)

3.2.2.3 Trees

A year after soil and litter sampling (April 2011), when trees were eight years old, the height (H, m) and diameter at breast height (DBH, m) of twelve trees were measured at each site. These measured data were used to calculate the utilisable stem volume (USV, m^3) of each tree (Equation 3.1). A tape measure was used to measure the DBH, 1.2 m above the soil, while a vertex was used for height measurements.

$$USV = 10^{\wedge} (-8.28929+ (2.43963*\log (DBH +80)) + (1.32537*(\log ((H)/10)))) \qquad (3.1)$$

The mass of the stems (individual tree C mass) was calculated by multiplying the USV with a mean bulk density of 0.93 for *Pinus elliottii*, 0.88 for *Pinus patula*, and 0.99 for *Eucalyptus nitens* in Mg m^{-3} (Van Vuuren *et al.*, 1978) and fraction of oven-dry mass that is C (assumed 0.5 for all species), then divided by the fraction that stemwood contributes to whole tree biomass ha^{-1}; 0.67 for Eucalypt and 0.70 for pinus (Equation 3.2; Christie & Scholes, 1995). This mass was then used to calculate the total tree C mass on a hectae basis for each site taking into account the tree spacing of 3 m x 3 m for the pine species and 3 m x 2 m for the *E. nitens*.

$$C_i = V_{stem}\, P_{wood}\, F_{carbon}\, F^{-1}{}_{stem} \qquad (3.2)$$

Where;

C = tree biomass C density (Mg C ha^{-1})

V_{stem} = stem wood volume (m^3 ha^{-1})

P_{wood} = mean density of wood (0.99, 0.93, and 0.88 Mg m^{-3} for *E. nitens*, *P. ellilttii*, and *P. patula* respectively; Van Vuuren *et al.*, 1978)

F_{carbon} = fraction of oven-dry mass that is C (assumed 0.5 for all species; Christie & Scholes, 1995)

F_{stem} = fraction that stemwood contributes to whole tree biomass ha^{-1} (0.67 for *Ecalypt* and 0.70 for *Pinus*; Christie & Scholes, 1995).

3.2.3 Statistical analysis

Analyses of variance were computed at a 95% confidence limit level using SAS (SAS Institute, 1985). Firstly, one way of analysis was computed to establish whether the soil C contents and stocks of the groups of sites earmarked respectively for *Pinus elliottii* (201, 202, 203, 232, 233, 249, 250, 251, 252, and 253) *Pinus patula* (212, 240, 241, 242, 243, 244, 245, and 254), and *Eucalyptus nitens* (210, 220, 221, 222, 246, 247, and 248) differed from one another just before afforestation and eight years after afforestation.

Secondly, a two way analysis was computed to determine whether afforestation had an effect on the C contents and stocks of soil groups irrespective of tree species. Three approaches were employed in the grouping of the sites. The grouping of Roberts *et al.* (1996) was accepted as an initial approach, namely apedal mesotrophic soils (sites, 221, 240, 246, 250, 251, and 254), plinthic mesotrophic soils (sites 201, 202, 220, 222, 244, 245, and 247), undifferentiated hydromorphic soils (sites 232, 241, 242, 249, 252, and 253), and mostly neocutanic B horizon soils (sites 203, 210, 212, 233, 243, and 248). For the second approach the sites were grouped as freely drained soils (sites 221, 222, 240, 251, and 254), moderately drained soils (sites 202, 203, 210, 212, 220, 233, 243, 244, 245, 246, 247, 248, and 250), and poorly drained soils (sites 201, 232, 241, 242, 249, 252, and 253). In the third approach the sites were grouped, based on the second horizon, as red apedal B horizon soils (sites 210, 220, 221, 240, and 254), yellow-brown apedal B horizon soils (sites 202, 233, 244, 245, 246, 247, 250, and 251), neocutanic B horizon soils (sites 203, 212, 222, 243, and 248), and G horizon soils (sites 201, 241, 242, 249, 252, and 253). Details on the sites were given earlier. These groupings were an attempt to group soils into similar wetness classes based on the classification.

CHAPTER 4

EFFECTS OF AFFORESTATION ON SOIL ORGANIC MATTER

4.1 Introduction

Soil organic matter includes plant and animal material in various stages of decomposition, living organisms, and dark-coloured humus consisting of non-humic and humic substances (Cooperband, 2002). The most important of these is humus because of its substantial influence on several soil properties and processes essential in the functioning of soil (Stevenson & Cole, 1999). Therefore not surprising organic matter among others plays a major role in enhancing nutrient cycling, increasing water holding capacity, improving water infiltration, and encouraging aggregation and hence roots development. Soil organic matter is also important because of the vital role it plays in the global C cycle by serving either as a sink or source for C. Sequestration of C in soil organic matter has the advantage of maintaining or even decreasing the alarming CO_2 concentration in the atmosphere. The estimation is that globally the soil stores twice as much C as the vegetation and the atmosphere combined (Brady & Weil, 2002).

The organic matter content in soils is widely variable. However, in a soil organic matter accumulates over time until an equilibrium is reached. As mentioned earlier, Stevenson and Cole (1999) cited Jenny (1930) who indicated that the factors of soil formation (climate > vegetation > topography = parent material > time) are therefore responsible for the extent of this equilibrium and variability in the organic matter content in a soil. Soil organic matter is mostly concentrated in the topsoil (Sitaula *et al*., 2004) and it is a key soil component in the soil's ability to supply essential plant nutrients. These nutrients play a major role in soil fertility and need to be maintained for sustainable production purposes.

Land use practices such as the conversion of grassland to forest can pose a serious impact on the indices of soil organic matter, viz. organic C (OC) and total N (TN). The concentration of these indices in soils as shown by literature can be manipulated by several factors including land use history, climate and type of species, plant productivity, soil physical and biological properties, and site preparation (Post & Known, 2000; Paul *et al*., 2002).

However, several studies reported either decrease (Farley *et al*., 2004; Guo *et al*., 2007) or increase (Grunzweig *et al*., 2007) in these indices of soil's organic matter while other studies found negligible changes (Davis *et al*., 2007; Smal & Olszewska, 2008) after afforestation. Most studies argue that grassland areas sequester more soil OC than forested areas due to large amounts of biomass and high rate of biomass turnover (Brand & Pfund, 1998; Kuzyakov & Domanski, 2000).

As mentioned in the previous chapter some grassland areas in the Weatherley catchment were afforested with different tree species. This provided an opportunity to study changes in the organic matter content of several soil types in the catchment eight years after afforestation. Therefore, the effects of afforestation of grassland areas on soil C and N stocks in the Weatherely catchment are reported in this chapter.

4.2 Procedure

This chapter presents results on the effects of afforestation on soil organic matter as manifested in C and N stocks. Although soil and data analysis was made up to 1200 mm in 2003 (grassland soils) and 2010 (forest soils), the stocks presented here are only for the 0-300 mm layer, because in grassland soils replicates were taken only to 300 mm depth. Moreover, this layer showed the biggest differences in C and N stocks that resulted from afforestation.

As mentioned in the previous chapter, soils for the 27 sites were sampled and analysed for C and N concentrations (%). These data were then used to calculate the C and N stocks (Mg ha^{-1}). Bulk density values determined by Le Roux *et al*. (2005) were used to convert C and N concentrations to stocks. The stock values were used for the calculation of C:N ratios.

One way analysis of variance was computed to establish, at every site, the effect of afforestation on the indices of soil organic matter mentioned above. These indices were also subjected to two way analysis of variance with afforestation and either tree species and grass areas (Table 4.1) or soil groups (Table 4.2) as main effects. The MSD-test of Tukey was applied for comparison of means when main effects were significant. In instances where significant interactions between main effects were found multiple comparisons of means were done with Fischer's t-test. All statistical computations were done with the SAS package at 95% confidence level (SAS Institute, 1985).

Table 4.1 Grouping of sampling sites per tree species and grass areas as well as soil group (Roberts *et al*., 1996)

Land cover	**Soil groups**			
	A	**B**	**C**	**H**
Pinus elliottii	250 (Pinedene) 251 (Clovelly)	201 (Longlands) 202 (Pinedene)	232 (Katspruit) 249 (Kroonstad) 252 (Kroonstad) 253 (Klapmuts)	203 (Tukulu) 233 (Pinedene)
Pinus patula	240 (Hutton) 254 (Hutton)	244 (Pinedene) 245 (Pinedene)	241 (Longlands) 242 (Longlands)	212 (Tukulu) 243 (Tukulu)
Eucalyptus nitens	221 (Hutton) 246 (Pinedene)	220 (Bloemdal) 222 (Oakleaf) 247 (Pinedene)		210 (Bloemdal) 248 (Tukulu)
Grass			209 (Katspruit) 235 (Katspruit)	

Table 4.2 Measurement sites grouped according to Roberts *et al*. (1996) Approach 1 - differenciation degree; Approach 2 - drainage capacity; and , Approach 3 - classification

of the first subsoil and diagnostic horizon (B1or E1).

Approach 1				
Group A *(Apedal mesotrophic soils)*		**Group B** *(Plinthic mesotrophic soils)*	**Group C** *(Undifferentiated hydromorphic soils)*	**Group H** *(Mostly neocutanic B horizons soils)*
Sitess	221, 240, 246, 250, 251, 254	201, 202, 220, 222, 244, 245, 247	232, 241, 242, 249, 252, 253	203, 210, 212, 233, 243, 248
Approach 2				
Poorly drained soils		**Moderately drained soils**	**Freely drained soils**	
Sites	201, 232, 241, 242, 249, 252, 253	202, 203, 210, 212, 220, 233, 243, 244, 245, 246, 247, 248, 250	221, 222, 240, 251, 254	
Approach 3[1]				
G horizon soils (gs)		**Neocutanic B horizon soils (ne)**	**Yellow-brown apedal B horizon soils (ye)**	**Red apedal B horizon soils (re)**
Sitess	201, 241, 242, 249, 252, 253	203, 212, 222, 243, 248	202, 233, 244, 245, 246, 247, 250, 251	210, 220, 221, 240, 254

[1] 232 was excluded in approach 3 because it does not have either a B1 or E1 horizon.

4.3 Results and discussion

Analytical results in concentration (%) of all the replicated samples after afforestation for the 0-50, 50-100, 100-150, 150-200, 200-250, and 250-300 mm layers at each test site are presented in Appendix A. Analytical results before afforestation are from Le Roux *et al*. (2005). Diagrams showing OC (%) and TN (%) values at each depth interval to 300 mm before afforestation and after afforestation are presented in Appendix B. Bulk density values for the 0-50, 50-100, 100-150, 150-200, and 200-300 mm layers, used in the calculation of C and N stocks are presented in Table 4.3 (Mg m^{-3}) and Table 4.4 (Mg ha^{-1}). It should be noted that, the means before and after afforestation, reported in Table 4.8 to Table 4.18, are weighted means because of the different number of sites allocated per tree species and grass area, and per soil group. For the purpose of discussion, the focus will be on the stock (Mg ha^{-1}) and not on the concentration (%) values.

4.3.1 Sites

Of the 27 sites sampled, two (209 and 235) were control sites. Tables 4.5 and 4.6 present average results per site for OC and TN (in both concentrations and stocks) in the 0-300 mm layer for each of the sampled sites.

4.3.1.1 Organic C stocks

In the 0-300 mm layer before afforestation, the OC stocks ranged from 31.3 Mg ha^{-1} at site 242 to 60.2 Mg ha^{-1} at site 240 (Table 4.5). The average OC stock for all the 27 sites was 45.4 Mg ha^{-1}. After afforestation the OC stocks varied between 22.9 Mg ha^{-1} at site 203 and 60.7 Mg ha^{-1} at site 254 (Table 4.5). The average OC stock was 38.6 Mg ha^{-1}. However, in the control sites, the OC stocks also decreased by 10.2 Mg ha^{-1} at site 209 and by 0.9 Mg ha^{-1} at site 235 between the 2003 and 2010 samplings.

In general, eight years of afforestation decreased OC stocks by anything from 0.9 Mg ha^{-1} at site 235 to 23.6 Mg ha^{-1} at site 232. The rate of decrease therefore ranged between 0.11 and 2.95 Mg C ha^{-1} yr^{-1}. Although after eight years of afforestation most of the sites (201, 203, 209, 210, 220, 221, 222, 232, 233, 240, 246, 248, 249, 252) showed significant decreases in OC stocks, a few sites (242, 243, 244, 245, and 254) showed increases in OC stocks. These increases ranged from 0.9 Mg C ha^{-1} (244) to 11.3 Mg C ha^{-1} (242) but were only significant at sites 242, 245, and 254. The rate of increase ranged between 0.11 Mg C ha^{-1} yr^{-1} to 1.41 Mg C ha^{-1} yr^{-1} somewhat similar to that reported by Lugo & Sanchez (1986) in subtropical forest soils.

These results do not support the hypothesis that afforestation of grassland leads to increased C stock in the soils of the Weatherley catchment. Organic C (Mg ha^{-1}) after afforestation was on average lower (Table 4.5) than before afforestation in the 0-300 mm layer probably because during the first years of afforestation, trees were young and contributed little litter fall to the soil surface and aboveground C input was therefore relatively low (Wilde, 1964). Another reason could be attributed to low input of organic matter to the soil and associated decomposition, which occurs in the period when vegetation is still building biomass (Brand & Pfund, 1998). Paul *et al*. (2002) and Richter *et al.* (1999) also indicated that after afforestation, an initial decrease in soil C is expected and increases can only be seen after 30 years in the top 300 mm of soil. On the other hand, before afforestation more OC was expected, because grassland areas are usually grazed under their natural conditions, resulting in increasing manure input into the soil (Lantz *et al*., 2001; Shimizu *et al*., 2010). Bashkin and Binkley (1998) also indicated that total OC following afforestation, depends on C gained and C lost from previous land use. Therefore, grassland soils are best in accelerating soil OC stock recovery (Lugo & Sanchez, 1986), while higher OC stock in forest soils can only be achieved after several years of afforestation.

4.3.1.2 Total N stocks

The TN stocks before afforestation varied from 2.12 Mg ha^{-1} at site 202 to 4.57 Mg ha^{-1} at site 246 (Table 4.6). On average the TN stock was 3.16 Mg ha^{-1} for all 27 sites. After afforestation the TN stocks ranged between 1.87 Mg ha^{-1} at sites 202 and 203, and 5.11 Mg ha^{-1} at site 245 (Table 4.6) with an average of 2.87 Mg ha^{-1} for all 27 sites.

After afforestation TN stocks in the control sites decreased significantly by 0.78 Mg ha^{-1} at site 209 and increased significantly by 0.43 Mg ha^{-1} at site 235. In general significant decreases in TN stocks ranged from 0.25 Mg ha^{-1} at site 240 to 1.88 Mg ha^{-1} at site 246 after afforestation. Significant increases in TN stocks ranged from 0.43 Mg ha^{-1} at site 235 to 2.90 Mg ha^{-1} at site 245.

The effects of afforestation of grassland on TN (and OC) have been studied by several authors (Dupouey *et al*., 2002; Jackson *et al*., 2002; Martens *et al*., 2003; Powers, 2004; Macedo *et al*., 2008). Variable results have been documented by them showing either TN increases or decreases after afforestation. The reason why there was lower average TN stock after afforestation than before afforestation could possibly be explained by the fact that in the latter, the land was dominated by different grass species. Therefore, the grass could have contributed a lower risk of N leaching, because grass excretes substances that inhibit the nitrification process (Stevenson & Cole, 1999). The forest in this study was established on grassland soil which was assumed to have reached an equilibrium in terms of C and N cycles (Le Roux *et al*., 2005). The grassland soil had undergone pitting and was disc ploughed in preparation for afforestation. Therefore N (and C) inputs were disturbed during the initial years of establishment. This suggests that it is imperative to establish forest growth on a permanent grass cover (Martens *et al*., 2003) to minimise the risk of soil N loss, because the nitrogen content of the soil regulates C retained in the soil. Therefore, any increase in soil C also implies an increase in soil N.

4.3.1.3 C:N ratios

The C:N ratio before afforestation varied from 11.7 at site 209 to 17.2 at site 244 and from 8.0 at site 245 to 17.5 at site 202 after afforestation (Table 4.7). The average C:N ratio was 13.8 before afforestation and 15.0 after afforestation. Following afforestation, the C:N ratio declined in most of the sites. About half of the sites (201, 203, 210, 221, 222, 232, 233, 235, 240, 243, 245, 252) showed significant decreases in C:N ratios. In these sites the decrease in C:N ratio ranged between 1.20 at site 240 and 8.60 at site 245. Significant increases in the C:N ratio ranging between 1.00 at site 248 and 3.50 at site 250 were observed in a few sites (220, 247, 248, 250).

For forest, Gunderson *et al.* (1998) highlighted that soil C:N ratio is inversely related to nitrate (NO_3^-) leaching which is correlated to rates of soil N transformations (Willard *et al*., 1997). Furthermore, Gunderson *et al*. (1998) indicated that soils with C:N ratios above 30 have limited inorganic N and

Table 4.3 Mean bulk density (Mg m^{-3}) for the 27 sites at each depth in the Weatherley catchment (Le Roux *et al.*, 2005)

Depth (mm)	201	202	203	209	210	212	220	221	222	232	233	235	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254
0-50	1.22	1.36	1.45	1.25	1.30	1.47	1.41	1.31	1.35	1.25	1.30	1.39	1.45	1.46	1.34	1.51	1.45	1.50	1.36	1.46	1.19	1.12	1.38	1.46	1.17	1.35	1.29
50-100	1.38	1.49	1.48	1.30	1.45	1.62	1.68	1.48	1.45	1.36	1.45	1.52	1.41	1.53	1.55	1.60	1.56	1.52	1.54	1.62	1.32	1.32	1.48	1.59	1.38	1.46	1.31
100-150	1.45	1.50	1.60	1.36	1.53	1.59	1.62	1.60	1.56	1.44	1.49	1.55	1.47	1.62	1.62	1.59	1.61	1.59	1.52	1.62	1.54	1.34	1.54	1.63	1.36	1.50	1.47
150-200	1.53	1.51	1.54	1.39	1.52	1.61	1.69	1.68	1.50	1.52	1.48	1.56	1.48	1.63	1.65	1.64	1.64	1.62	1.59	1.64	1.52	1.46	1.61	1.66	1.51	1.52	1.53
200-300	1.52	1.56	1.58	1.44	1.62	1.66	1.71	1.65	1.48	1.56	1.59	1.66	1.41	1.62	1.70	1.65	1.63	1.66	1.58	1.67	1.60	1.51	1.59	1.68	1.54	1.58	1.56

Table 4.4 Mean bulk density (Mg ha^{-1}) for the 27 sites at each depth in the Weatherley catchment (Le Roux *et al.*, 2005)

Depth (mm)	201	202	203	209	210	212	220	221	222	232	233	235	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254
0-50	610	680	725	625	650	735	705	655	675	625	650	695	725	730	670	755	725	750	680	730	595	560	690	730	585	675	645
50-100	690	745	740	650	725	810	840	740	725	680	725	760	705	765	775	800	780	760	770	810	660	660	740	795	690	730	655
100-150	725	750	800	680	765	795	810	800	780	720	745	775	735	810	810	795	805	795	760	810	770	670	770	815	680	750	735
150-200	765	755	770	695	760	805	845	840	750	760	740	780	740	815	825	820	820	810	795	820	760	730	805	830	755	760	765
200-300	1520	1560	1580	1440	1620	1660	1710	1650	1480	1560	1590	1660	1410	1620	1700	1650	1630	1660	1580	1670	1600	1510	1590	1680	1540	1580	1560

Table 4.5 Mean organic carbon (OC) for 27 sites in the 0-300 mm layer before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

OC (%)[1]																											
Years	**201**	**202**	**203**	**209**	**210**	**212**	**220**	**221**	**222**	**232**	**233**	**235**	**240**	**241**	**242**	**243**	**244**	**245**	**246**	**247**	**248**	**249**	**250**	**251**	**252**	**253**	**254**
2003	0.88a	0.78a	0.83a	1.14a	1.24a	0.85a	0.84a	1.03a	1.04a	1.36a	0.99a	0.82a	1.39a	0.95a	0.67b	0.95b	0.82a	0.77b	1.03a	0.80a	1.22a	1.35a	1.01a	1.10a	1.17a	1.15a	1.16b
2010	0.69b	0.80a	0.55b	0.98b	0.94b	0.83a	0.76a	0.71b	0.79b	0.89b	0.76b	0.88a	1.31b	0.92a	0.99a	1.11a	0.92a	0.95a	0.89b	0.85a	0.84b	1.32a	1.02a	1.09a	0.91b	1.15a	1.56a
OC (Mg ha^{-1})[1]																											
2003	37.6a	35.0a	38.2a	46.2a	55.6a	40.9a	41.0a	47.8a	45.3a	58.4a	43.6a	37.9a	60.2a	43.2a	31.3b	45.7a	38.6a	36.5b	46.9a	38.8a	52.6a	55.0a	46.4a	52.9a	48.8a	51.4a	50.0b
2010	26.5b	32.7a	22.9b	36.0b	38.3b	36.1a	34.0b	30.1b	31.9b	34.8b	30.5b	37.0a	51.9b	40.9a	42.6a	48.6a	39.5a	41.1a	37.0b	37.3a	33.0b	49.0b	42.2a	47.9a	34.0b	46.7a	60.7a

[1] Means with the same letter are not significantly different.

Table 4.6 Mean total nitrogen (TN) for 27 sites in the 0-300 mm layer before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

TN (%)[1]																											
Years	**201**	**202**	**203**	**209**	**210**	**212**	**220**	**221**	**222**	**232**	**233**	**235**	**240**	**241**	**242**	**243**	**244**	**245**	**246**	**247**	**248**	**249**	**250**	**251**	**252**	**253**	**254**
2003	0.05b	0.05a	0.05a	0.10a	0.07a	0.05a	0.06a	0.06a	0.07a	0.08a	0.06a	0.05b	0.09a	0.08a	0.06a	0.06b	0.05b	0.05b	0.10a	0.06a	0.09a	0.10a	0.07a	0.08a	0.09a	0.10a	0.08b
2010	0.06a	0.05a	0.04b	0.09b	0.07b	0.05a	0.04b	0.07a	0.06a	0.07b	0.05a	0.07a	0.10a	0.07a	0.06a	0.09a	0.06a	0.12a	0.06a	0.05a	0.06b	0.10a	0.05b	0.08a	0.08a	0.09a	0.11a
TN (Mg ha^{-1})[1]																											
2003	2.21a	2.12a	2.34a	3.96a	3.33a	2.44a	2.77a	2.89a	2.84a	3.44a	2.60a	2.37b	4.03a	4.02a	2.93a	2.97b	2.23b	2.21b	4.57a	2.78a	4.01a	3.97a	3.07a	3.77a	3.79a	4.26a	3.38b
2010	2.23a	1.87a	1.87b	3.18b	2.68b	2.30b	1.96b	2.81a	2.44a	2.68b	2.12b	2.80a	3.78b	2.88a	2.67a	3.74a	2.72a	5.11a	2.69a	2.32b	2.34b	3.56a	2.27b	3.32b	3.21b	3.76a	4.20a

[1] Means with the same letter are not significantly different.

Table 4.7 Mean C:N ratios for 27 sites in the 0-300 mm layer before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

C:N ratio[1]																											
Years	**201**	**202**	**203**	**209**	**210**	**212**	**220**	**221**	**222**	**232**	**233**	**235**	**240**	**241**	**242**	**243**	**244**	**245**	**246**	**247**	**248**	**249**	**250**	**251**	**252**	**253**	**254**
2003	17.0a	16.8a	16.3a	11.7a	16.7a	16.7a	14.8b	16.6a	16.0a	17.1a	16.8a	16.0a	14.9a	13.5a	11.7a	15.4a	17.2a	16.6a	12.0a	14.0b	13.1b	13.9a	15.1b	14.0a	12.9a	12.04a	14.9a
2010	11.8b	17.5a	12.3b	11.3a	14.3b	15.7a	17.4a	10.7b	13.1b	13.0b	14.4b	13.2b	13.7b	14.2a	16.0a	13.0b	14.5a	8.0b	13.8a	16.1a	14.1a	13.8a	18.6a	14.4a	10.6b	12.5a	14.4a

[1] Means with the same letter are not significantly different.

the risk of NO_3^- leaching is relatively low. On the other hand, soils with C:N ratios below 25 leach more NO_3^-. In the present study soils before and after afforestation had mean C:N ratios below 25 (but slightly higher before than after afforestation) suggesting that the risk for NO_3^- leaching is high.

4.3.2 Tree species and grass areas

Results presented in this section are from soils grouped per tree species and grass allocation areas (Table 4.8 to 4.10). It should be noted that for comparison of significance between means the Tuckey and Fischer tests were used at 95% confidence level for main effects and interactions, respectively (Section 4.2). The discussion in this section will also be on stocks.

4.3.2.1 Organic C stocks

As illustrated in Table 4.8, OC stocks in soils of the Weatherley catchment were affected by the introduction of different tree species in grassland areas. The OC stocks before afforestation varied between 42.0 Mg ha^{-1} for the grass areas and 46.9 Mg ha^{-1} for *E. nitens* areas. Although before afforestation soils designated for *E. nitens* had higher OC stocks, there was no significant difference in OC stocks between the tree species and the grass areas. Eight years after afforestation OC stocks ranged from 34.5 Mg ha^{-1} for *E. nitens* to 45.2 Mg ha^{-1} for *P. patula* areas. Following afforestation, soils under *P. patula* had significantly higher OC stocks compared to *P. elliotti*, *E. nitens*, and grass areas which had almost similar amounts of OC stocks. The interaction between afforestation and the areas was therefore significant. When considering only the areas, soil OC stocks decreased significantly by 5.5 Mg ha^{-1}, 10.0 Mg ha^{-1}, and 12.4 Mg ha^{-1} for grass, *E. nitens*, and *P. elliottii* areas respectively. Correspondingly, the rates of decrease were 0.69 Mg C ha^{-1} yr^{-1}, 1.25 Mg C ha^{-1} yr^{-1}, and 1.55 Mg C ha^{-1} yr^{-1}. Afforestation of grassland areas in general resulted in a decrease of soil OC stocks. These rates are very close to what Paul *et al.* (2003) reported after afforestation using conifer species in eastern North America soils.

However, after afforestation OC stocks under *P. elliottii* areas were significantly lower (36.7 Mg ha^{-1}) than OC stock in areas designated for *P. elliottii*, *P. patula*, and *E. nitens* before afforestation. After afforestation, OC stocks under *P. patula* areas were significantly higher than OC stocks under grass areas before afforestation. Soils under *P. patula* showed an increase of 1.9 Mg C ha^{-1}, but it was not significant. Several studies have been conducted to determine the effect of afforestation on soil OC stocks and contrary findings were reported. Afforestation either resulted in a decrease (Parfitt *et al.*, 1997; Ross *et al.*, 1999; Turner & Lambert, 2000; Farley *et al.*, 2004; Guo *et al.*, 2007) or an increase in soil OC stocks

(Lemma *et al*., 2006; Grunzweig *et al*., 2007). In some studies, (Chen *et al*., 2000; Davis *et al*., 2007; Smal & Olszewska, 2008) negligible changes were documented. However, observations made indicated that an initial soil OC loss in the first few years of afforestation is expected (Davis, *et al*., 2007) and with time gradual increases in soil OC stocks are expected. Other authors (Post & Known, 2000; Paul *et al*., 2002) concluded that land use change, climate and type of species, plant productivity, soil physical and biological properties, history of C inputs, and soil disturbance determine soil OC stocks. Results from this study are consistent with the findings from Guo and Gifford (2002) and Guo *et al*. (2007), that after afforestation, soil C stocks usually decrease. The planting of forests on former pasture land usually results in decline in C stocks despite greater amounts of woody residues deposited by forests that are resistant to decomposition (Davis & Condrom, 2002). Carbon allocation and changes in cycling are associated with low effectiveness of tree species in preserving soil organic matter. With pasture species, 30-50% of fixed C is used in formation and maintenance of the root system (Kuzyakov & Domanski, 2000), resulting in high turnover compared to tree roots which are enduring (Lima *et al*., 2006). However, contrasting results in literature following afforestation of grassland are probably due to previous land use, climate, and type of tree species (Paul *et al*., 2002).

After afforestation, OC stocks under *E. nitens* were significantly lower than OC stocks in areas designated for *P. elliottii*, *P. patula*, *E. nitens*, or grass areas. After afforestation the OC stocks under grass areas decreased significantly and were different from OC stocks in any of the areas designated for tree species.

Table 4.8 Mean organic C (OC) concentration and stock in the topsoil (0-300 mm layer), grouped per tree species and grass designated areas in 2003 (Le Roux *et al*., 2005) and actual tree species and grass areas in 2010

OC (%)[1]					
Area					
Afforestation	***P. elliottii***	***P. patula***	***E. nitens***	**Grass**	**Mean**
Before	1.06^{def}	0.92^{abc}	1.03^{def}	0.98^{abcde}	1.01
After	0.92^{ab}	1.08^{def}	0.83^{a}	0.93^{abcd}	0.94
Mean	0.99	1.00	0.93	0.96	0.98
Afforestation: $MSD_{T(0.05)} = 0.05$ Area: $MSD_{T(0.05)} = 0.12$ Afforestation x Area: $p \leq 0.05$					
OC (Mg ha^{-1})[1]					
Before	46.7^{d}	43.3^{d}	46.9^{d}	42.0^{bcd}	45.4
After	36.7^{abc}	45.2^{d}	34.5^{a}	36.5^{ab}	38.6
Mean	41.7	44.2	40.7	39.3	42.0
Afforestation: $MSD_{T(0.05)} = 2.05$ Area: $MSD_{T(0.05)} = 4.6$ Afforestation x Area: $p \leq 0.05$					

[1] Significant differences were noted only with interactions. Means with the same letter are not significantly different.

4.3.2.2 Total N stocks

Data on TN stocks are presented in Table 4.9. In the soils before afforestation, TN stocks varied between 3.03 Mg ha^{-1} under *P. patula* designated areas and 3.16 Mg ha^{-1} under *P. elliottii* and grass designated areas. In afforested soils, TN stocks ranged from 2.46 Mg ha^{-1} under the *E. nitens* areas to 3.43 Mg ha^{-1} under the *P. patula* areas. Before afforestation, there was no significant difference in TN stocks between soils under the different areas as expected because all were grass. After afforestation as in the case of OC stocks, TN stocks under the *P. patula* areas were significantly higher than TN stocks under the other tree species and grass areas. More variation in TN stocks under the different species areas after afforestation were possibly due to the nature of forests which are widespread and coarser in root system compared to grassland vegetation (Partel *et al*., 2008), which have a dense and homogenous root system resulting in more homogeneous soil nutrients (Partel & Wilson, 2002).

Table 4.9 Mean total N (TN) concentration and stock in the topsoil (0-300 mm layer), grouped per tree species and grass designated areas in 2003 (Le Roux *et al*., 2005) and actual tree species and grass areas in 2010

TN (%)[1]					
	Area				
Afforestation	***P. elliottii***	***P. patula***	***E. nitens***	**Grass**	**Mean**
Before	0.07^{bcde}	0.06^{ab}	0.07^{bcd}	0.07^{bcdef}	0.07
After	0.07^{abc}	0.08^{fg}	0.06^{a}	0.08^{bcdef}	0.07
Mean	0.07	0.07	0.06	0.08	0.07
Afforestation: $MSD_{T(0.05)} = 0.005$ Area: $MSD_{T(0.05)} = 0.01$ Afforestation x Area: $p \leq 0.05$					
TN (Mg ha^{-1})[1]					
Before	3.16^{cdef}	3.03^{bcd}	3.15^{cde}	3.16^{cdefg}	3.12
After	2.69^{ab}	3.43^{cefg}	2.46^{a}	2.99^{abc}	2.87
Mean	2.92	3.22	2.81	3.08	3.00
Afforestation: $MSD_{T(0.05)} = 0.21$ Area: $MSD_{T(0.05)} = 0.47$ Afforestation x Area: $p \leq 0.05$					

[1] Significant differences were noted only for interactions. Means with the same letter are not significantly different.

Soil TN stocks decreased significantly by 0.47 Mg ha^{-1} under *P. elliottii* areas and 0.69 Mg ha^{-1} under *E. nitens* areas. The rates of decrease were 0.06 Mg N ha^{-1} yr^{-1} and 0.09 Mg N ha^{-1} yr^{-1} for *P. elliottii* and *E. nitens*, respectively. Although TN stocks under grass areas decreased by 0.17 Mg ha^{-1}, the decrease was not significant. However, under *P. patula* an increase of 0.40 Mg N ha^{-1} was observed, though it was not significant. The rate of increase was 0.05 Mg N ha^{-1} yr^{-1}. One possible reason for high TN stocks under *P. patula* could be that N was not a limiting nutrient in those areas or it could be due to high input of biomass.

With respect to tree species and grass areas, soils under *P. elliottii*, after afforestation, had significantly lower TN stock compared to soils under either *P. elliottii*, *E. nitens*, or grass areas before afforestation which were not significantly different. Despite having higher amounts of TN stocks, TN stocks under *P. patula* after afforestation were not significantly different from TN stocks before afforestation. The TN stocks under afforested *E. nitens* areas were significantly lower than TN stocks under the tree species and grass designated areas. After afforestation the TN stocks under grass were lower, but not significantly different from TN stocks under the grass designated area (before afforetation). Nitrogen availability in soil depends on the type of species in question. Therefore, the decrease in TN stocks after afforestation can be related to differences in species composition of forest and grass, which regulates N and/or C turnover.

4.3.2.3 C:N ratios

In Table 4.10 the data show no significant interaction between afforestation and tree species and grass areas. The C:N ratio before afforestation was around 15.0 under tree species designated areas and 13.8 under the grass areas. After afforestation the C:N ratio varied from 13.0 under the grass areas to 14.6 under the *E. nitens* areas. The C:N ratio decreased by 0.8 under the *E. nitens*, 1.3 under *P. elliottii*, 1.4 under *P. patula*, and 1.5 under the grass areas. In general the C:N ratio decreased after afforestation. Studies in New Zealand (Parfitt *et al*., 1997; Yeats *et al*., 2000) reported higher C:N ratios after afforestation of former pasture land. Peichl *et al*. (2011) observed no change in C:N ratio after afforestation of grassland. Our results show a general decline in C:N ratio, which may be associated with both a decline in OC and in TN stocks, with the former being relatively smaller.

Table 4.10 Mean C:N ratio in the topsoil (0-300 mm layer), grouped per tree species and grass designated areas in 2003 (Le Roux *et al*., 2005) and actual tree species and grass areas in 2010

C:N					
	Area				
Afforestation	***P. elliottii***	***P. patula***	***E. nitens***	**Grass**	**Mean**
Before	15.2	15.1	15.0	13.8	15.0
After	13.9	13.7	14.2	12.3	13.8
Mean	14.5	14.4	14.6	13.0	14.4
Afforestation: $MSD_{T(0.05)} = 0.62$ Area: $MSD_{T(0.05)} = 1.39$ Afforestation x Area: $p > 0.05$					

4.3.3 A, B, C, and H soils

In the first approach the soils were grouped into *apedal mesotrophic* (Group A), *plinthic mesotrophic* (Group B), *undifferentiated hydromorphic* (Group C), and mostly *neocutanic B horizon* (Group H) soils (Table 4.2). This approach was employed by Roberts *et al*. (1996) in mapping the soils in the Weatherley catchment

4.3.3.1 Organic C stocks

Organic C data for this soil grouping are presented in Table 4.11. There was no significant interaction between afforestation and soil groups. Organic C stocks before afforestation varied between 39.0 Mg ha^{-1} in the B soil group and 50.7 Mg ha^{-1} in the A soil group. After afforestation the OC stocks ranged from 34.7 Mg ha^{-1} in the B soil group to 45.0 Mg ha^{-1} in the A soil group. The OC stocks in the B soil group decreased significantly by 4.3 Mg ha^{-1} in the B soil group, 5.7 Mg ha^{-1} in the A soil group, 6.7 Mg ha^{-1} in the C soil group, and 11.2 Mg ha^{-1} in the H soil group. The rates of decrease were 0.54, 0.71, 0.84, and 1.4 Mg C ha^{-1} yr^{-1} for the B, A, C, and H soil groups respectively. Regardless of a decline in OC stocks within soil groups following afforestation, our results show much higher OC stocks under A soil group compared to other soil groups before and after afforestation. The A group is dominated by the Hutton soil form. These oxidic soils contain apedal B horizons found in the upper and mid footslopes of the Weatherley catchment. The results of this study correspond with those reported by Rantoa (2009) where the highest OC content in the oxidic soils was found in the upper footslopes and upper midslopes. The soils in B group are generally found in regions of medium rainfall and therefore have low organic matter levels (Fey, 2010). Relatively similar amounts of OC stocks in the B and H soil groups were observed. These two groups contain soils with similar pedological characteristics with B group having a red or yellow-brown apedal B horizon, with signs of wetness in both soil groups below the B horizon. The results were therefore expected.

Before afforestation, soils in the A and B groups had significantly different OC stocks compared to soils in the C and H groups which were not significantly different. After afforestation the OC stocks in the B group and H group were not different and had lower OC stocks compared to soils in the A group and the C group which were also not significantly different.

Table 4.11 Mean organic C (OC) concentration and stock in the topsoils (0-300 mm), grouped per A, B, C, and H mapping unit (Roberts *et al.*, 1996) before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

OC (%)					
Soil group[1]					
Afforestation	**A**	**B**	**C**	**H**	**Mean**
Before	1.12	0.85	1.10	1.01	1.01
After	1.10	0.82	1.04	0.84	0.94
Mean	1.11	0.83	1.07	0.93	0.98
Afforestation: $MSD_{T(0.05)}$ = 0.05 Soil group: $MSD_{T(0.05)}$ = 0.10 Afforestation X Soil group: $p > 0.05$					
OC (Mg ha^{-1})					
Before	50.7	39.0	48.0	46.1	45.7
After	45.0	34.7	41.3	34.9	38.8
Mean	47.8	36.8	44.7	40.5	42.2
Afforestation: $MSD_{T(0.05)}$ = 2.04 Soil group: $MSD_{T(0.05)}$ = 3.81 Afforestation X Soil group: $p > 0.05$					

[1] A = *apedal mesotrophic*, B = *plinthic mesotrophic*, C = *undifferentiated hydromorphic*, and H = mostly *neocutanic* B horizon soils

4.3.3.2 Total N stocks

Table 4.12 shows that the interaction between afforestation and soil groups on TN stocks was significant. Total N stocks before afforestation ranged from 2.45 Mg ha^{-1} in the B soil group to 3.73 Mg ha^{-1} in the C soil group. After afforestation TN stocks varied between 2.51 Mg ha^{-1} in the H soil group and 3.18 Mg ha^{-1} in the A soil group. Eight years of afforestation significantly decreased the TN stocks by 0.25 Mg ha^{-1} in the A soil group, 0.44 Mg ha^{-1} in the H soil group, and 0.60 Mg ha^{-1} in the C soil group. The rates of decrease were 0.03 Mg N ha^{-1} yr^{-1}, 0.06 Mg N ha^{-1}yr^{-1}, and 0.08 Mg N ha^{-1}yr^{-1} for the A, H, and C soil groups respectively. However, there was a slight increase of 0.22 Mg ha^{-1} in TN stocks in the B group soils, but it was not significant.

In soils before afforestation, the B group and the H group had significantly lower TN stocks compared to soils in the A group and the C group which had significantly different amounts of TN stocks. A similar trend applied to soils after afforestation but in this case, the B soil group and the H soil group were not significantly different in TN stocks as in the case of OC stocks. An interesting observation after afforestation was in the A soil group which had significantly different TN stocks (3.18 Mg N ha^{-1}) compared to the B soil group and the C soil group before afforestation. The B soil group after afforestation had significantly different TN stocks (2.67 Mg ha^{-1}) compared to the A and the C soil groups before afforestation. The C soil group after afforestation had significantly different TN stocks (3.13 Mg ha^{-1}) compared to the B and the C soil groups before afforestation. Lastly, the H soil group had significantly different TN stocks compared to the A, C, and H soil groups before afforestation.

Table 4.12 Mean total N (TN) concentration and stock in the topsoils (0-300 mm), grouped per A, B, C, and H mapping unit (Roberts *et al.*, 1995) before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

TN (%)					
Soil group[1]					
Afforestation	**A**	**B**	**C**	**H**	**Mean**
Before	0.08	0.05	0.08	0.06	0.07
After	0.08	0.06	0.08	0.06	0.07
Mean	0.08	0.06	0.08	0.06	0.07
Afforestation: $MSD_{T(0.05)} = 0.005$ Soil group: $MSD_{T(0.05)} = 0.01$ Afforestation x Soil group: $p > 0.05$					
TN (Mg ha^{-1})[2,]					
Before	3.43^{efg}	2.45^{a}	3.73^{g}	2.95^{cd}	3.11
After	3.18^{def}	2.67^{abc}	3.13^{de}	2.51^{ab}	2.86
Mean	3.30	2.56	3.43	2.73	3.01
Afforestation: $MSD_{T(0.05)} = 0.21$ Soil group: $MSD_{T(0.05)} = 0.38$ Afforestation x Soil group: $p \leq 0.05$					

[1] A = *apedal mesotrophic*, B = *plinthic mesotrophic*, C = *undifferentiated hydromorphic*, and H = mostly *neocutanic* B horizon soils. [2] Significant differences were noted only for the interactions. Means with the same letter are not significantly different

4.3.3.3 C:N ratios

The data for C:N ratio are displayed in Table 4.13. There was no significant interaction between afforestation and the soil groups. The C:N ratio before afforestation varied between 13.5 in the C soil group and 16.1 in the B soil group. The C:N ratio in the C soil group differed significantly compared to the C:N ratio in other soil groups in the same year. After afforestation, the C:N ratio ranged from 13.3 in the C soil group to 14.3 in the A soil group. However, there were no significant differences in C:N ratios between the soil groups. There was again similarity in C:N ratios between the B soil group and the H soil group after afforestation in 2010. In this year, the C:N ratios in all soil groups were significantly different from the C:N ratios in B soil group and H soil group before afforestation.

Table 4.13 Mean C:N ratio in the topsoils (0-300 mm), grouped per A, B, C, and H mapping unit (Roberts *et al.*, 1995) before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

C:N					
	Soil group[1]				
Afforestation	**A**	**B**	**C**	**H**	**Mean**
Before	14.9	16.1	13.5	15.8	15.1
After	14.3	14.0	13.3	14.0	13.9
Mean	14.6	15.0	13.4	14.9	14.5
Afforestation: $MSD_{T(0.05)} = 0.62$ Soil group: $MSD_{T(0.05)} = 1.15$ Afforestation x Soil group: $p > 0.05$					

[1] A = *apedal mesotrophic*, B = *plinthic mesotrophic*, C = *undifferentiated hydromorphic*, and H = mostly *neocutanic* B horizon soils

4.3.4 Poorly, moderately, and freely drained soils

In the second approach soils were grouped into the different drainage classes: poorly, moderately, and freely drained soils (Table 4.2). As earlier the OC and TN are discussed in terms of stocks.

4.3.4.1 Organic C stocks

The effect of afforestation and soil grouping on OC stocks is shown in Table 4.14. The OC stocks before afforestation ranged from 43.0 Mg ha^{-1} in poorly drained soils to 51.2 Mg ha^{-1} in freely drained soils. In the latter soils, the OC stocks were significantly higher than the OC stocks in either the moderately or the poorly drained soils. After afforestation, the OC stocks varied between 36.4 Mg ha^{-1} in the poorly drained soils and 44.5 Mg ha^{-1} in the freely drained soils. Like before afforestation, the OC stocks in the freely drained soils were significantly higher than the OC stocks in the moderately and the poorly drained soils. Normally poorly drained soils are associated with higher amounts of OC (Davidson, 1995; Davis *et al.*, 2004; Ju *et al.*, 2006) than well drained soils, because in these wet soils oxygen supply is not enough to enhance decomposition (Davidson, 1995). Surprisingly the opposite is true with the soils of the Weatherley catchment where the freely drained soils had much higher OC stocks before and after afforestation. In the freely drained soils, oxidation of stored C is promoted. However, other factors such as organic matter production, climate, depth to water table, and soil characteristics might have limited oxidation rates in these soils (Armentano, 1980).

The OC stocks within the soil groups over the years decreased significantly. In the poorly drained soils OC stocks decreased by 6.6 Mg ha^{-1}, 6.7 Mg ha^{-1} in the freely drained soils, and 7.3 Mg ha^{-1} in the moderately drained soils. Although the freely drained soils had the highest OC stocks in both years, after afforestation they lost as much OC as the poorly drained soils.

Table 4.14 Mean organic C (OC) concentration and stock in the topsoils (0-300 mm), grouped per soil drainage class before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

OC (%)				
	Soil group			
Afforestation	**Poorly drained Soils**	**Moderately drained soils**	**Freely drained soils**	**Mean**
Before	0.93	1.07	1.14	1.01
After	0.86	0.99	1.09	0.94
Mean	0.90	1.03	1.12	0.98
Afforestation: $MSD_{T(0.05)} = 0.06$ Soil group: $MSD_{T(0.05)} = 0.09$ Afforestation x Soil group: $p > 0.05$				
OC (Mg ha^{-1})				
Before	43.0	46.5	51.2	45.7
After	36.4	39.2	44.5	38.8
Mean	39.7	42.9	47.9	42.3
Afforestation: $MSD_{T(0.05)} = 2.22$ Soil group: $MSD_{T(0.05)} = 3.51$ Afforestation x Soil group: $p > 0.05$				

4.3.4.2 Total N stocks

Total N stocks before afforestation ranged from 2.79 Mg ha^{-1} in the poorly drained soils to 3.38 Mg ha^{-1} in the freely drained soils with poorly drained soils having a significantly lower TN stocks compared to the moderately and the freely drained soils which were not different (Table 4.15). After afforestation the same pattern was observed. The TN stocks varied between 2.61 Mg ha^{-1} in the poorly drained soils and 3.31 Mg ha^{-1} in the freely drained soils. The poorly drained soils had significantly lower TN stocks compared to the freely drained soils before and after afforestation.

Due to afforestation, the TN stocks decreased within the soil groups. The TN stocks decreased by 0.07 Mg ha^{-1} in the freely drained soils, 0.18 Mg ha^{-1} in the poorly drained soils and 0.34 Mg ha^{-1} in the moderately drained soils. These results therefore show that soil drainage class also controls TN stocks in soils of the Weatherley catchment. The findings in this study of higher TN stocks in well drained than in poorly drained soils, suggests that N transformation rates were faster in freely drained soils than in poorly drained soils and with regard to mineral N, production rates were faster than consumption rates (Ullah & Moore, 2009). The lower TN in the poorly drained soils may be associated with higher emissions of

N_2O from these soils than in the freely drained soils. According to Ullah and Zinati (2006) in poorly drained soils, higher denitrifier activities reduce NO_3 to NO_2 and N_2 gases.

Table 4.15 Mean total N (TN) concentration and stock in the topsoils (0-300 mm), grouped per soil drainage class before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

TN (%)				
Afforestation	**Poorly drained soils**	**Moderately drained soils**	**Freely drained soils**	**Mean**
Before	0.06	0.08	0.08	0.07
After	0.06	0.08	0.08	0.07
Mean	0.06	0.08	0.08	0.07
Afforetation: $MSD_{T(0.05)}$ = 0.005 Soil group: $MSD_{T(0.05)}$ = 0.008 Afforestation x Soil group: $p > 0.05$				
TN (Mg ha^{-1})				
Before	2.79	3.34	3.38	3.06
After	2.61	3.00	3.31	2.86
Mean	2.70	3.17	3.35	2.96
Afforetation: $MSD_{T(0.05)}$ = 0.20 Soil group: $MSD_{T(0.05)}$ = 0.31 Afforestation x Soil group: $p > 0.05$				

4.3.4.3 C:N ratios

Unlike OC and TN, C:N ratio was highest in the poorly drained soils with both samplings. Before afforestation, the C:N ratio ranged from 14.3 in the moderately drained soils to 15.6 in the poorly drained soils (Table 4.16). However, though the C:N ratio in the poorly drained soils was higher, it was not significantly different from the C:N ratio in the freely drained soils which had a significantly larger C:N ratio than the moderately drained soils. After afforestation, the C:N ratio varied between 13.1 in the moderately drained soils and 14.6 in the poorly drained soils. The C:N ratio in the poorly drained soils was significantly higher than the C:N ratio in either the moderately or freely drained soils which were not significantly different. In general the C:N ratio decreased significantly within soil groups due to afforestation. The units of decrease were 1.0, 1.2, and 2.0 in the poorly drained, moderately drained, and freely drained soils, respectively.

Table 4.16 Mean C:N ratio in the topsoils (0-300 mm), grouped per soil drainage class before afforestation in 2003 (Le Roux *et al*., 2005) and after afforestation in 2010

C:N				
Afforetation	**Poorly drained soils**	**Moderately drained soils**	**Freely drained soils**	**Mean**
Before	15.6	14.3	15.3	15.2
After	14.6	13.1	13.3	13.9
Mean	15.1	13.7	14.3	14.6
Afforestation: $MSD_{T(0.05)} = 0.60$ Soil group: $MSD_{T(0.05)} = 0.94$ Afforestation x Soil group: $p > 0.05$				

4.3.5 G, neocutanic B, yellow-brown apedal B, and red apedal B horizon soils

In this approach soils were grouped based on the classification of the first subsoil (B1 or E1) horizon in the profile (Table 4.2). The focus of discussion will also be on OC and TN stocks.

4.3.5.1 Organic C stocks

Organic C stocks data for this grouping are presented in Table 4.17. Before afforestation, OC stocks ranged from 42.3 Mg ha^{-1} in the yellow-brown apedal B horizon soils to 50.9 Mg ha^{-1} in the red apedal B horizon soils. After afforestation, OC stocks varied between 34.5 Mg ha^{-1} in the neocutanic B horizon soils and 43.0 Mg ha^{-1} in the red apedal B horizon soils. On account of afforestation the OC stocks decreased significantly in all soil groups. The OC stocks decreased in the order: 3.8 Mg ha^{-1} in the yellow-brown apedal B horizon soils, 4.5 Mg ha^{-1} in the G horizon soils, 7.9 Mg ha^{-1} in the red apedal B horizon soils, and 10.0 Mg ha^{-1} in the neocutanic B horizon soils. The corresponding rates of OC stocks decreases were 0.48, 0.56, 0.99, and 1.25 Mg ha^{-1} yr^{-1} for the respective soil groups. Although the interaction between afforestation and the soil groups was not significant, before afforestation the red apedal B horizon soils had a significantly higher OC stocks compared to other soil groups. After afforestation, the neocutanic B horizon soils had significantly lower OC stocks than the G horizon and the red apedal B horizon soils. Red apedal B horizon soils are found in the driest diagnostic horizons (Van Huyssteen *et al*., 2005) opposed to the G horizon, neocutanic B horizon, and yellow-brown apedal B horizon soils. High amounts of OC stocks were not expected in these soils because usually the lower degree of water saturation coupled with better aeration would have lead to high rates of organic matter mineralisation and as a result a low OC content. Therefore factors other than water saturation might have contributed to the low contents of OC.

Table 4.17 Mean organic C (OC) concentration and stock in the topsoils (0-300 mm), grouped per classification of the first subsoil (B1 or E1) horizon before afforestation in 2003 (Le Roux *et al*., 2005) after afforestation in 2010

OC (%)					
Soil group[1]					
Afforestation	**gs**	**ne**	**ye**	**re**	**Mean**
Before	1.02	0.98	0.91	1.13	1.00
After	1.00	0.82	0.91	1.06	0.95
Mean	1.01	0.90	0.91	1.09	0.98
Afforetation: MSD$_{T(0.05)}$ = 0.06 Soil group: MSD$_{T(0.05)}$ = 0.11 Afforestation x Soil group: $p > 0.05$					
OC (Mg ha^{-1})					
Before	44.5	44.5	42.3	50.9	45.1
After	40.0	34.5	38.5	43.0	39.0
Mean	42.3	39.5	40.4	47.0	42.1
Afforestation: MSD$_{T(0.05)}$ = 2.27 Soil group: MSD$_{T(0.05)}$ = 4.30 Afforestation x Soil group: $p > 0.05$					

[1] gs =G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils.

4.3.5.2 Total N stocks

The stocks data on TN are presented in Table 4.18. As with OC there was no significant interaction between afforestation and soil groups. Before afforestation the TN stocks varied between 2.78 Mg ha^{-1} in the yellow-brown apedal B horizon soils and 3.53 Mg ha^{-1} in the G horizon soils. After afforestation the TN stocks ranged from 2.54 Mg ha^{-1} in the neocutanic B horizon soils to 3.09 Mg ha^{-1} in the red apedal B horizon soils. The neocutanic B horizon soils had significantly lower TN stocks (2.54 Mg ha^{-1}) compared to the G horizon and the red apedal B horizon soils. Generally, the TN stocks declined within soil groups due to afforestation: 0.38 Mg ha^{-1} in the neocutanic B horizon soils, 0.47 Mg ha^{-1} in the G horizon soils, and 0.19 Mg ha^{-1} in the red apedal B horizon soils. Nevertheless, soils in the yellow-brown apedal B horizon had a slight increase of 0.02 Mg ha^{-1} in TN stock. The rates of decrease in TN stocks were very low ranging between 0.02 Mg ha^{-1} yr^{-1} in the red apedal B horizon soils to 0.06 Mg ha^{-1} yr^{-1} in the G horizon soils.

Table 4.18 Mean total N (TN) concentration and stock in the topsoils (0-300 mm), grouped per classification of the first subsoil (B1 or E1) horizon before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

<table>
<tr><td colspan="6">TN (%)</td></tr>
<tr><td colspan="6">Soil group^1</td></tr>
<tr><td>Afforestation</td><td>**gs**</td><td>**ne**</td><td>**ye**</td><td>**re**</td><td>**Mean**</td></tr>
<tr><td>Before</td><td>0.08</td><td>0.06</td><td>0.06</td><td>0.07</td><td>0.07</td></tr>
<tr><td>After</td><td>0.08</td><td>0.06</td><td>0.07</td><td>0.08</td><td>0.07</td></tr>
<tr><td>**Mean**</td><td>0.08</td><td>0.06</td><td>0.06</td><td>0.07</td><td>0.07</td></tr>
<tr><td colspan="6">Afforestation: MSD$_{T(0.05)}$ = 0.006
Soil group: MSD$_{T(0.05)}$ = 0.01
Afforestation x Soil group: $p > 0.05$</td></tr>
<tr><td colspan="6">TN (Mg ha^{-1})</td></tr>
<tr><td>Before</td><td>3.53</td><td>2.92</td><td>2.78</td><td>3.28</td><td>3.10</td></tr>
<tr><td>After</td><td>3.06</td><td>2.54</td><td>2.80</td><td>3.09</td><td>2.87</td></tr>
<tr><td>**Mean**</td><td>3.29</td><td>2.73</td><td>2.79</td><td>3.18</td><td>3.00</td></tr>
<tr><td colspan="6">Afforestation: MSD$_{T(0.05)}$ = 0.23
Soil group: MSD$_{T(0.05)}$ = 0.44
Afforestation x Soil group: $p > 0.05$</td></tr>
</table>

[1] gs =G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils.

4.3.5.3 C:N ratios

The C:N ratio data are presented in Table 4.19. There was no significant interaction between afforestation and soil groups. The C:N ratio ranged from 13.5 in the G horizon soils to around 15.5 in the neocutanic B horizon, yellow-brown apedal B horizon, and red apedal B horizon soils before afforestation. After afforestation the C:N ratio varied between 13.1 in the G horizon soils and 14.7 in the yellow-brown apedal B horizon soils. There was also a marked decrease in C:N ratio due to afforestation, as with the OC and the TN stocks. These decreases were 0.4 in the G horizon soils, 0.8 in the yellow-brown apedal B horizon soils, 1.5 in the red apedal B horizon soils and 1.9 in the neocutanic B horizon soils.

Table 4.19 Mean C:N ratio in the topsoils (0-300 mm), grouped per classification of the first subsoil (B1 or E1) horizon before afforestation in 2003 (Le Roux *et al.*, 2005) and after afforestation in 2010

<table>
<tr><td colspan="6">C:N ratio</td></tr>
<tr><td colspan="6">Soil group^1</td></tr>
<tr><td>Afforetation</td><td>**gs**</td><td>**ne**</td><td>**ye**</td><td>**re**</td><td>**Mean**</td></tr>
<tr><td>Before</td><td>13.5</td><td>15.5</td><td>15.5</td><td>15.6</td><td>15.0</td></tr>
<tr><td>After</td><td>13.1</td><td>13.6</td><td>14.7</td><td>14.1</td><td>13.9</td></tr>
<tr><td>**Mean**</td><td>13.3</td><td>14.6</td><td>15.1</td><td>14.9</td><td>14.5</td></tr>
<tr><td colspan="6">afforestation: MSD$_{T(0.05)}$ = 0.64
Soil group: MSD$_{T(0.05)}$ = 1.21
Afforestation x Soil group: $p > 0.05$</td></tr>
</table>

[1] gs =G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils.

4.3.6 Conclusion

The soil OC stocks in the Weatherley catchment did not increase on account of afforestation in 14 of the 27 sites studied. These sites showed significant decreases in soil OC stocks after afforestation. Only three sites showed significant increases in soil OC stocks, implying that soils in the Weatherley catchment to some extent have potential to accumulate OC stocks due to afforestation. With regard to TN 13 sites showed significant decreases and 5 sites significant increases in TN stocks. The rest of the sites showed either decreases or increases in OC and TN stocks that were not significant. The introduction of different tree species especially *P. elliottii* and *E. nitens* resulted in significant decreases in soil OC stocks, while *P. patula* resulted into a slight increase in soil OC stocks which was not significant. The TN stocks followed the same trend as the OC stocks. However, these initial decreases in soil OC and TN stocks are according to literature because the trees are still young. Higher OC and TN stocks in these soils can be expected only after more years of afforestation.

Grouping of the measurement sites into different soil groups showed that when soils were grouped according to Roberts *et al*. (1996) mapping units, drainage classes or first subsoil (B1 or E1) horizons there was generally a significant decrease in soil OC stocks due to afforestation. The TN stocks to a large extent behaved like OC stocks except for the B soil group and in the red apedal B horizon soils. In the mentioned two groups TN stocks increased slightly following afforestation. These results suggest that the soil types also control the soil OC and TN stocks in the Weatherley catchment.

CHAPTER 5

CARBON STOCKS IN THE ABOVEGROUND BIOMASS

5.1 Introduction

In the global C cycle, forests play a vital role and are therefore the major terrestrial C sinks (Masera *et al*., 2003). Worldwide, forests sequester larger amounts of atmospheric CO_2 than grasslands (Lorenz & Lal, 2010). Carbon enters forests ecosystems mainly by the process of photosynthesis which takes place in the plant leaves. In the process the CO_2 is used as source of C (Trumbore, 2006) and converted to carbohydrates. The rates of photosynthesis vary greatly among tree species due to factors such as light intensity, temperature, water, canopy development, stomatal behaviour, and soil conditions (Kozlowski *et al*., 1991). The stem wood is the part within trees with the largest C pool (Lorenz & Lal, 2010).

Land use conversion from grassland to forestry can affect C sequestration in vegetation and consequently in litter. However, the soil is disturbed during site preparation for tree planting. As such some nutrients as well as soil C are lost from the soil through volatilisation. The trees would then receive fewer nutrients from the soil to maintain growth which would in turn sult in reduced biomass production and less C sequestration, and consequently less litter fall can be expected from these forest stands. The litter is important for nutrient retention in the soil, because it protects the soil from the effects of moisture and temperature changes (Ukonmaanaho *et al*., 2008).

The litter is a source of energy and nutrients for soil microorganisms. These organisms metabolise litter and release nutrients to the soil for use by plants (Ukonmaanaho *et al*., 2008). The rate of nutrient release to the soil is governed by the rate of litter decomposition, and it varies with vegetation type. Hence the rate of decomposition is affected by both plant material and its environment (Singh & Gupta, 1977). As indicated earlier Almendros *et al*. (2000) claimed that the chemical characteristics of plant biomass also influence the rate of decomposition. Plant extractants such as tannins, lignin, and the quality and quantity of water soluble sugars as well as N compounds affect the biodegradation of litter.

Berg and Staaf (1980) divided decomposition into an early stage and later stage. In the early stage of decomposition the initial N content affected the decomposition. In the later stage, lignin concentration influenced decomposition of litter (Berg *et al*., 2010). For example Berg and Staaf (1980) observed that with 25% lignin concentration in litter, decomposition levelled out. This chapter focuses on the litter, tree, and the biomass C stocks.

This chapter presents results on C stocks in the aboveground biomass, viz. the litter and the trees. In the previous chapter, soil organic C and total N stocks were presented and discussed for 2003 (before afforestation) and 2010 (after afforestation). However, before afforestation the C and N contents of the aboveground biomass components were not determined in sufficient detail to enable statistical comparison between the two samplings. Therefore, this chapter will focus mainly on the results after afforestation in 2010. The aboveground C stocks will be discussed separately for the litter and for the trees. However, for the litter N stocks will be considered also. The tree species areas and soil groupings used in the previous chapter were also employed in this chapter.

5.2 Procedure

For the litter, C and N concentrations (%) were analysed for the 25 sites (excluding the two control sites). These data were then used to calculate the C and N stocks (Mg ha^{-1}) by multiplying the mass of litter (Mg ha^{-1}) by the C or N concentrations. For the trees, no C concentrations were determined. The C stocks were calculated with equation 3.2 as adapted from Christie and Scholes (1995). In this equation assumptions on density of wood, fraction of oven – dry mass and stem wood contribution to the whole tree biomass were made as discussed in chapter three.

A one way analysis of variance was then computed to establish differences between sites, tree species areas, or soil groups concerning C stocks (and N stocks if appropriate) for the litter, trees and aboveground biomass. The MSD-test of Tukey was applied for comparison of means. Statistical analyses were computed with the SAS package at a 95% confidence level (SAS Institute, 1985).

5.3 Results and discussion

Firstly, results concerning C stocks, N stocks, and C:N ratio for the litter are presented and discussed. Thereafter the focus is shifted to the C stocks of the trees. Finally, results on C stocks of the aboveground biomass, viz. that of the litter plus trees are presented and discussed.

5.3.1 Litter

The litter data on C stocks, N stocks and C:N ratio presented in this section for discussion are the means per site, per tree species areas, and per soil groups. Data for the replicates are given in Appendix C. As mentioned earlier, data of the two control sites were excluded in this section.

5.3.1.1 Sites

5.3.1.1.1 Litter C stocks

Litter C stocks varied from 4.24 Mg C ha^{-1} at site 203 (Tukulu soil with *P. elliottii* trees) to 11.5 Mg C ha^{-1} at site 240 (Hutton soil with *P. patula* trees; Table 5.1). The litter C stocks differed significantly amongst the sites. On average litter C stock for the 25 sites was 7.95 Mg C ha^{-1}. It was not possible to say whether there had been an increase or decrease in litter C stocks following eight years of afforestation of the catchment, because only grass C stocks were measured before afforestation. However, the range of C stocks recorded in this study is substantially higher than those from Ordonez *et al*. (2008) in Central Highlands of Mexico and Mohanraj *et al*. (2010) in Indian tropical forests, who reported a range of 0.29 to 3.26 Mg C ha^{-1} in the litter of pine plantations. The C in litter depends on the amount of the aboveground biomass which is expected to be higher in older plantations (Goma-Tchimbakala & Bernhard-Roversat, 2006). Therefore the aboveground biomass is expected only to increase in the Weatherley catchment following afforestation.

5.3.1.1.2 Litter N stocks

Data on litter N stocks are presented in Table 5.1. As expected, the lowest and highest litter N stocks were recorded also at site 203 and 240, viz. 0.06 Mg N ha^{-1} and 0.32 Mg N ha^{-1}, respectively. The litter N stocks amongst the sites differed significantly similar to the litter C stocks. On average litter N stock for the 25 sites was 0.16 Mg N ha^{-1}. The small amounts of litter N stocks found in this study may be related to the fact that the trees are still young and contributed little litter N. Dames *et al*. (1998) indicated that litter N concentrations increase with increasing stand age. Other than that, the small amounts of litter N stocks could also be linked to the rates of litter decomposition which is also determined by among others temperature, climate, and litter chemical characteristics. Higher decomposition rates are expected to lead to more N being transferred to the soil, leaving small quantities in the litter.

5.3.1.1.3 Litter C:N ratios

The litter C:N ratios varied from 36.5 at site 240 with the highest C and N stocks to 74.6 at site 203 with the lowest C and N stocks (Table 5.1). Significant differences in litter C:N ratios were also observed between sites. However, according to Augusto *et al*. (2002) litter decomposition rate is affected by the C:N ratio. Litter with a high C:N ratio have a low decomposition rate, while the opposite is true for litter with a low C:N ratio.

Table 5.1 Mean litter C stocks, N stocks, and C:N ratios for the 25 sites after afforestation in 2010

Sites	C stocks[1] (Mg ha^{-1})	N stocks[1] (Mg ha^{-1})	C:N ratios[1]
201	5.96^{edgcf}	0.12^{efhijk}	51.0^{efghij}
202	4.62^{efg}	0.07^{ikj}	70.1^{bc}
203	4.24^{fg}	0.06^{jk}	74.6^{b}
210	8.86^{abcde}	0.13^{defhij}	66.8^{bcd}
212	8.78^{abcde}	0.20^{bcdef}	44.2^{ghij}
220	9.43^{abcd}	$0.18^{bcdefgh}$	53.6^{defghi}
221	8.46^{abcde}	$0.15^{bcdefghi}$	55.9^{cdefgh}
222	5.21^{defg}	$0.12^{efghijk}$	44.5^{ghij}
232	$7.87^{abcdefg}$	$0.13^{defghij}$	61.5^{bcde}
233	6.30^{bcdefg}	0.11^{fghijk}	58.4^{cdefg}
240	11.5^{a}	0.32^{a}	36.5^{j}
241	8.57^{abde}	$0.18^{bcdefgh}$	48.8^{efghij}
242	10.6^{ab}	0.24^{abc}	44.6^{ghij}
243	10.4^{ab}	0.24^{ab}	42.4^{hij}
244	9.89^{abc}	0.22^{bcd}	46.0^{fghij}
245	8.29^{abcde}	0.20^{bcde}	40.5^{ij}
246	10.6^{ab}	0.19^{bcdefg}	56.5^{cdefgh}
247	9.15^{abcd}	$0.15^{cdefghi}$	60.9^{bcdef}
248	$7.28^{abcdefg}$	$0.13^{defghij}$	$55.8^{cdefghi}$
249	6.94^{bcdefg}	$0.13^{defghij}$	53.1^{defghi}
250	6.67^{bcdefg}	$0.13^{defghij}$	52.4^{defghi}
251	6.31^{bcdefg}	0.11^{ghijk}	59.5^{bcdefg}
252	6.74^{bcdefg}	$0.12^{efghijk}$	56.5^{cdefgh}
253	5.68^{cdefg}	0.11^{ghijk}	54.0^{defghi}
254	10.5^{ab}	0.24^{abc}	44.7^{ghij}

[1] Means with the same letter in the same column are not significantly different

5.3.1.2 Tree species areas

As mentioned earlier, results on C stocks, N stocks, and C:N ratios presented in this section are from litter at the 25 afforested sites, grouped per tree species allocation areas (Section 4.1).

5.3.1.2.1 Litter C stocks

Eight years after afforestation the litter C stocks differed significantly from 6.13 Mg ha^{-1} for the *P. elliottii* areas to 8.43 Mg ha^{-1} for *E. nitens* areas to 9.82 Mg ha^{-1} for the *P. patula* areas (Table 5.2). This implied that the three tree species had different influences on the litter C stocks. The amounts for the litter C stocks in this study are in line with those reported by Laclau (2003) and Ordonez *et al*. (2008) for pine plantations in Patagonia and the Central

Highlands of Mixico respectively. Therefore, differences in litter produced by the different tree species might explain the differences in the litter C stocks.

Table 5.2 Mean litter C stocks, N stocks, and C:N ratios, grouped per tree species areas after afforestation in 2010

	Tree species[1]		
	P. elliottii	***P. patula***	***E. nitens***
C stocks (Mg ha^{-1})	6.13^c	9.82^a	8.43^b
N stocks (Mg ha^{-1})	0.11^c	0.23^a	0.15^b
C:N ratios	59.1^a	43.5^b	56.3^a

[1] Means in the same row with the same letter are not significantly different

5.3.1.2.2 Litter N stocks

In Table 5.2 the litter N stocks varied from 0.11 Mg ha^{-1} for *P. elliottii* areas, 0.15 Mg ha^{-1} for the *E. nitens* areas and 0.23 Mg ha^{-1} for the *P. patula* areas due to afforestation. The relative difference in N stocks between the *E. nitens* areas and the *P. elliottii* was almost similar to that of C stocks, viz. 36% and 38% respectively. This was not the case between the *P. patula* areas and *E. nitens* areas with relative differences of 17% in C stocks and 53% in N stocks. Generally the litter N stocks found under the different tree species were very small. Kozlowski *et al*. (1991) indicated that trees usually suffer from N deficiency because they have a longer growing season and are slow in growth. Further, the litter under *P. patula* stands had comparatively higher N stocks. This might be because pine trees have high N content in leaves. However, factors such as age, development stage and physiological activity determine the litter N content. On the other hand with increasing age the N content in tree leaves decreases because of leaching and increase in cell wall components which dilute the N (Kozlowski *et al.*, 1991). In this study the tree's leaves probably had low N contents which could be related to the low N content in litter.

5.3.1.2.3 Litter C:N ratios

The litter C:N ratios differed significantly from 43.5 for the *P. patula* areas to 56.3 and 59.1 for the *E. nitens* and the *P. elliottii* areas, respectively (Table 5.2). Thus like for the sites, the tree species areas with the lowest C and N stocks had the highest C:N ratio and vice versa. The litter C:N ratio recorded under the *P. elliottii* stands compared well with the C:N ratio of 69 reported by Priha and Smolander (1997) in litter of Pinus needles. According to Berg (20000 the high litter C:N ratio under the *P. elliottii* can probably be due to the low litter N stocks.

5.3.1.3 A, B, C, and H soils

As in the previous chapter, the litter C stocks, N stocks and C:N ratios were grouped into apedal mesotrophic (Group A), plinthic mesotrophic (Group B), undifferentiated hydromorphic (Group C), and mostly neocutanic B horizon (Group H) soils (Table 4.2). This approach was employed by Roberts *et al*. (1996) in mapping of the soils in the Weatherley catchment.

5.3.1.3.1 Litter C stocks

Litter C stocks data for this grouping are presented in Table 5.3. Due to afforestation, the litter C stocks ranged from 7.50 Mg ha^{-1} for the B soil group to 9.02 Mg ha^{-1} for the A soil group, but these differences were not significant. Despite this, the A group soil produced 14% to 20% more litter C stocks compared to the rest of the soil groups, which had almost similar amounts of C stocks. This difference in the amounts of litter C stocks could probably be related to the differences in the litter types due to varying tree species.

5.3.1.3.2 Litter N stocks

In Table 5.3, the litter N stocks ranged from 0.15 Mg ha^{-1} for the B, C, and H soil groups to 0.19 Mg ha^{-1} for the A soil group, but there was no significant difference between the litter N stocks for the different soil groups. On a relative basis the difference in N stock between the A soil group and the other three soil groups was 27%. This is larger than the 14 to 20% observed with C stocks.

5.3.1.3.3 Litter C:N ratios

Data in Table 5.3 show that the litter C:N ratios varied from 50.9 for the A soil group to 57.1 for the H soil group. Similar to the C or N stocks there was no significant difference between the litter C:N ratios for the different soil groups. Unlike the litter C and N stocks, that varied little if at all between the B, C and H soil groups, the litter C:N ratio of the H soil group exceeded that of the B and C soil groups by 8 to 9%.

Table 5.3 Mean litter C stocks, N stocks, and C:N ratios, grouped per A, B, C, and H mapping unit (Roberts *et al.*, 1996) after afforestation in 2010

Soil groups[1]				
	A	**B**	**C**	**H**
C stocks (Mg ha^{-1})	9.02^{a}	7.50^{a}	7.74^{a}	7.64^{a}
N stocks (Mg ha^{-1})	0.19^{a}	0.15^{a}	0.15^{a}	0.15^{a}
C:N ratios	50.9^{a}	52.3^{a}	53.1^{a}	57.1^{a}

[1] Means in the same row with the same letter are not significantly different. A = apedal mesotrophic, B = plinthic mesotrophic, C = undifferentiated hydromorphic, and H =mostly neocutanic B horizon soils.

5.3.1.4 Poorly, moderately, and freely drained soils

Litter C stocks, N stocks, and C:N ratios were grouped into the different soil drainage classes: poorly, moderately, and freely drained soils (Table 4.2).

5.3.1.4.1 Litter C stocks

The litter C stocks ranged from 7.48 Mg ha^{-1} for the poorly drained soils to 8.41 Mg ha^{-1} for the freely drained soils (Table 5.4), but these differences were not significant. However, the poorly drained soils produced 9% to 12% less litter C stocks than the moderately and freely drained soils, respectively. The lower litter C stocks in the poorly drained soils might be due to either poorer quality litter or less litter produced by the trees.

Table 5.4 Mean litter C stocks, N stocks, and C:N ratios, grouped per soil drainage class after afforestation in 2010

Soil groups[1]			
	Poorly drained soils	**Moderately drained soils**	**Freely drained soils**
C stocks (Mg ha^{-1})	7.48^{a}	8.04^{a}	8.41^{a}
N stocks (Mg ha^{-1})	0.15^{a}	0.15^{a}	0.19^{a}
C:N ratios	52.8^{ab}	55.6^{a}	48.2^{b}

[1] Means in the same row with the same letter are not significantly different

5.3.1.4.2 Litter N stocks

In Table 5.4 the litter N stocks ranged from 0.15 Mg ha^{-1} for the poorly and moderately drained soil groups to 0.19 Mg ha^{-1} for the freely drained soil group. Despite this 27% difference, analysis of variance indicated that the soil groups had no significant influence on the litter N stocks. In comparison with this N stock difference of 27% between the soil groups, the difference in C stocks was only 9% to 12%.

5.3.1.4.3 Litter C:N ratios

Table 5.4 also contains the data on litter C:N ratios. These ratios varied from 48.2 for the freely drained soils to 55.6 for the moderately drained soils. The litter C:N ratio for the moderately drained soils was significantly higher than the litter C:N ratio for the freely drained soils. However, the litter C:N ratios of these two soil groups did not differ significantly from that of the poorly drained soils.

5.3.1.5 G, neocutanic B, yellow-brown apedal B, and red apedal B horizon soils

The grouping of the soils based on the classification of the first subsoil (B1 or E1) horizon in the profile (Table 4.2) was also employed for litter C stocks, N stocks and C:N ratios.

5.3.1.5.1 Litter C stocks

Data in Table 5.5 show that the litter C stocks varied from 7.17 Mg ha^{-1} for the neocutanic B horizon soils to 9.76 Mg ha^{-1} for the red apedal B horizon soils after eight years of afforestation. The red apedal B horizon soils had significantly higher litter C stocks than the other three soil groups which did not differ significantly from one another. It could be deduced that in these four groups of soils, only the red apedal B horizon soils had a pertinent influence on the litter C stocks. The higher amounts of litter C stocks for the red apedal B horizon soils were not expected, because of the drier conditions prevailing in this soil group (Van Huyssteen *et al*., 2005) which may be thought to have a negative influence on the litter C stocks. However, other factors such as differences in the litter production and composition might explain these higher C stocks.

5.3.1.5.2 Litter N stocks

The litter N stocks ranged from 0.15 Mg ha^{-1} for G horizon, neocutanic B horizon and yellow-brown apedal B horizon soils to 0.20 Mg ha^{-1} for the red apedal B horizon soils (Table 5.5). Despite this difference, analysis of variance indicated that the soil groups had no significant influence on the litter N stocks.

5.3.1.5.3 Litter C:N ratios

The litter C:N ratios varied from 51.3 for the G horizon soil group to 55.5 for the yellow-brown apedal B horizon soil group (Table 5.5), but these differences were not significant. However, litter C:N ratio of the yellow-brown apedal B horizon soils was 6% to 8% higher than the litter C:N ratio of the other soil groups.

Table 5.5 Mean litter C stocks, N stocks, and C:N ratios, grouped per classification of the first subsoil (B1 or E1) horizon after afforestation in 2010

	Soil groups[1]			
	gh	**ne**	**ye**	**re**
C stocks (Mg ha^{-1})	7.42^{b}	7.17^{b}	7.73^{b}	9.76^{a}
N stocks (Mg ha^{-1})	0.15^{a}	0.15^{a}	0.15^{a}	0.20^{a}
C:N ratios	1.3^{a}	52.3^{a}	55.5^{a}	51.5^{a}

[1] Means in the same row with the same letter are not significantly different. gh = G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils.

5.3.2 Tree C stocks

The tree C stocks data presented in this section are grouped per site, per tree species area, and per soil group. Data of the two control sites are excluded due to the absence of trees. Data for the repetitions are given in Appendix D.

5.3.2.1 Sites

In Table 5.6 the C stocks for the trees varied significantly from 25.2 Mg ha^{-1} at site 252 (Kroonstad soil with *P. elliotti* trees) to 156.5 Mg ha^{-1} at site 246 (Pinedene soil with *E. nitens* trees). The average tree C stock for the 25 sites was 61.8 Mg ha^{-1}. This variation in tree C stocks could be related to differences in tree species and site conditions, and management (Del Rio *et al*., 2008). In the Weatherley catchment soils vary from site to site and even within sites. Gower *et al*. (2001) indicated that the net primary productivity, viz. increase in forest growth, is controlled by environmental conditions such as topography and soil quality, suggesting that these conditions can affect the final forest biomass and hence the tree C stocks. Slope aspect is an important topographic factor because it determines the amount of solar radiation received. This regulates soil air, temperature, water availability, and consequently forest growth (McNab, 1993). Additionally, Kozlowski *et al*. (1991) pointed out that growth of trees varies widely because of differences in the productive capacity of land. The variation depends on the soil's capacity to supply nutrients, water, and oxygen, its physical properties that affect root growth and the topography and slope.

5.3.2.2 Tree species areas

Data for tree C stocks in the different tree species areas are given in Table 5.7. The tree C stocks varied significantly from 35.1 Mg ha^{-1} for the *P. elliottii*, to 57.5 Mg ha^{-1} for the *P. patula*, to 104.8 Mg ha^{-1} for the *E. nitens* sites. The *Pinus* stands had low C stocks compared to *E. nitens* stands. The low C stocks in the *Pinus* stands could be as a result of limitations to tree growth due to a lack of nutrients such as N (Kozlowski *et al*., 1991) and consequently less biomass production or species differences. Oren *et al*. (2001) indicated that the tree growth as well as C sequestration is limited by N. Nitrogen availability affects photosynthesis, foliar biomass, canopy characteristics and woody tissue growth and hence C sequestration (Novaes *et al*., 2009).

However, C stocks estimated for pine stands in the Weatherley catchment are in line with those reported by Laclau (2003) for pine plantations in northwest Patagonia and by Ordonez *et al*. (2008) for pine plantations in the central highlands of Michoacan, Mexico. Moreover, *E. nitens* stands probably had higher C stocks than the *Pinus* stands, because as opposed to the *Pinus* species, the *E. nitens* have broad leaves which encourage more photosynthesis or greater light use efficiency. Gower *et al*. (1997) pointed out that the accumulation of C stocks differs significantly between forest stand types.

Table 5.6 Mean tree C stocks for the 25 sites after afforestation in 2010

Sites	**C stocks[1] (Mg ha^{-1})**
201	29.0^{c}
202	34.5^{c}
203	39.6^{c}
210	95.6^{abc}
212	60.6^{bc}
220	65.5^{bc}
221	82.3^{abc}
222	76.3^{abc}
232	36.4^{c}
233	49.0^{c}
240	67.8^{abc}
241	45.5^{c}
242	51.2^{c}
243	50.0^{c}
244	57.0^{bc}
245	56.8^{c}
246	56.5^{a}
247	147.4^{ab}
248	110.0^{abc}
249	35.7^{c}
250	36.0^{c}
251	32.5^{c}
252	25.2^{c}
253	33.2^{c}
254	70.9^{abc}

[1] Means with the same letter are not significantly different.

5.3.2.3 A, B, C, and H soils

Tree C stocks varied significantly from 37.9 Mg ha^{-1} for the C soil group to 74.3 Mg ha^{-1} for the A soil group (Table 5.8). Although the trees growing in the A soil group had the highest tree C stocks, there was no significant difference between this and the B and H soil groups. The trees growing in the C soil group performed poorly and had almost half the C stocks of the A soil group. The C soil group is associated with swampy, poorly drained soils. These soils are saturated with water, have low oxygen supply, and support hydromorphic vegetation. Therefore it was not surprising to observe low C stocks in trees growing in the C soil group because the prevailing conditions in these soils probably limited tree growth, resulting into lower biomass production.

Table 5.7 Mean tree C stocks, grouped per tree species areas after afforestation in 2010

	Tree species[1]		
	P. elliottii	***P. patula***	***E. nitens***
C stocks (Mg ha^{-1})	35.1^c	57.5^b	104.8^a

[1]Means with the same letter are not significantly different

Table 5.8 Mean tree C stocks, grouped per A, B, C, and H mapping unit (Roberts *et al.*, 1995) after afforestation in 2010

	Soil groups[1]			
	A	**B**	**C**	**H**
C stocks (Mg ha^{-1})	74.3^a	66.6^a	37.9^b	67.5^a

[1]Means with the same letter are not significantly different. A = apedal mesotrophic, B = plinthic mesotrophic, C = undifferentiated hydromorphic, and H =mostly neocutanic B horizon soils

5.3.2.4 Poorly, moderately, and freely drained soils

The tree C stocks varied significantly from 36.6 Mg ha^{-1} for the poorly drained soils to 73.7 Mg ha^{-1} for the moderately drained soils and 65.9 Mg ha^{-1} for the freely drained soils (Table 5.9). These results imply that the conditions in the poorly drained soils did not encourage production of high tree biomass and hence tree C stocks, as observed in either the moderately or freely drained soil. Wang *et al.* (2003) and Grant (2004) found that soil drainage affects C dynamics. Grant (2004) observed much higher C accumulation in upslope stands than in lowland areas (three times that of lowland stands). The higher productivity that coincides with higher C stocks was associated with decreased soil moisture coupled with better soil aeration (Wang *et al.*, 2003), higher soil temperatures, and higher soil nutrient availability (Grant, 2004). In addition, Grant (2004) cited Macdonald and Lieffers (1990) who indicated that forest growth is accelerated on soils with lower water tables because of rapid mineralisation and nutrient uptake. These authors measured higher foliar nutrient concentrations and CO_2 assimilation rates in Black spruce forest growing on drained versus undrained soils.

Table 5.9 Mean tree C stocks, grouped per drainage class after afforestation in 2010

	Soil groups[1]		
	Poorly drained soils	**Moderately drained soils**	**Freely drained soils**
C stocks (Mg ha^{-1})	36.6^b	73.7^a	65.9^a

[1]Means with the same letter are not significantly different

5.3.2.5 G, neocutanic B, yellow-brown apedal B, and red apedal B horizon soils

In this soil grouping, the tree C stocks ranged significantly from 37.3 Mg ha^{-1} for the G horizon soil group to 76.4 Mg ha^{-1} for the red apedal B horizon soil group (Table 5.10). Although the red apedal soil group had the highest tree C stocks, the difference was not significant between this soil group and the tree C stocks of the neocutanic and the yellow-brown apedal B horizon soil groups. The C stock in trees growing in the G horizon soils was significantly lower than those of trees growing in the neocutanic B and red apedal B horizon soils. This implied that the G horizon soils had a severely limiting influence on the tree C stocks. The G horizon soils are normally saturated with water for long periods of time (Soil Classification Working Group, 1991) and these conditions normally do not support plant growth, due to the reduced oxygen supply. Moreover, trees growing under such conditions are likely to grow slowly, produce less biomass, resulting in less C stocks.

Table 5.10 Mean tree C stocks, grouped per classification of the first subsoil (B1 or E1) horizon after afforestation in 2010

	Soil groups[1]			
	gh	**ne**	**ye**	**re**
C stocks (Mg ha^{-1})	37.3^b	67.3^a	67.0^{ab}	76.4^a

[1]Means with the same letter are not significantly different. gh = G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils.

5.3.3 Biomass C stocks

As mentioned earlier the biomass C stocks for the 25 afforested sites were obtained by adding the litter C stocks and the tree C stocks. The biomass C stocks for the two control sites incorporated the grass and its litter. Results on the biomass C stocks are presented and discussed per sites, tree species and grass areas, and for the different soil groupings.

5.3.3.1 Sites

The biomass C stocks presented in this section are for all 27 sites studied in the Weatherly catchment, including the two control sites (Table 5.11). These biomass C stocks varied from

3.71 Mg ha^{-1} at site 209 (Katspruit soil with grass) to 167.2 Mg ha^{-1} at site 246 (Pinedene soil with *E. nitens* trees). On average the biomass C stock for the 27 sites was 64.9 Mg ha^{-1}. However, biomass C stocks averaged 69.7 Mg ha^{-1} for the 25 afforested sites and 4.8 Mg ha^{-1}for the two control sites. The low biomass C stocks of the control sites (209 and 235) compared to the afforested sites is because grassland areas have usually lower biomass than afforested areas (Hall & Scurlock, 1991). The biomass C stocks reported here for the afforested sites fall within the range reported by Ordenez *et al*. (2008) in plantations and forest classes in the central highlands of Michoacan, Mexico, although their results included the C stocks of roots. For all the afforested sites, the tree C stocks contributed most to the biomass C stocks.

Table 5.11 Mean biomass C stocks for the 27 sites after afforestation in 2010

Sites	Litter C stocks[1] (Mg ha^{-1})	Tree C stocks[1] (Mg ha^{-1})	Biomass C stocks[1] (Mg ha^{-1})
201	5.96^{edgcf}	29.0^{c}	34.9^{cd}
202	4.62^{efg}	34.5^{c}	39.1^{cd}
203	4.23^{fg}	39.6^{c}	43.9^{cd}
209	3.71^{g}	nd	3.71^{d}
210	8.86^{abcde}	95.6^{abc}	104.5^{abc}
212	8.78^{abcde}	60.6^{bc}	69.4^{bcd}
220	9.43^{abcd}	65.5^{bc}	74.9^{bcd}
221	8.46^{abcde}	82.3^{abc}	90.7^{abcd}
222	5.21^{defg}	76.3^{abc}	81.5^{abcd}
232	7.87^{abcdefg}	36.4^{c}	44.3^{cd}
233	6.30^{bcdefg}	49.0^{c}	55.3^{cd}
235	5.80^{cdefg}	nd	5.80^{d}
240	11.5^{a}	67.8^{abc}	79.3^{abcd}
241	8.57^{abde}	45.5^{c}	54.1^{cd}
242	10.6^{ab}	51.2^{c}	61.9^{cd}
243	10.4^{ab}	50.0^{c}	60.4^{cd}
244	9.89^{abc}	57.0^{bc}	66.9^{bcd}
245	8.29^{abcde}	56.8^{c}	65.1^{cd}
246	10.6^{ab}	156.5^{a}	167.2^{a}
247	9.15^{abcd}	147.4^{ab}	156.6^{ab}
248	7.28^{abcdefg}	110.0^{abc}	117.3^{abc}
249	6.94^{bcdefg}	35.7^{c}	42.7^{cd}
250	6.67^{bcdefg}	36.0^{c}	42.7^{cd}
251	6.31^{bcdefg}	32.5^{c}	38.8^{cd}
252	6.74^{bcdefg}	25.2^{c}	31.9^{cd}
253	5.68^{cdefg}	33.2^{c}	38.9^{cd}
254	10.5^{ab}	70.9^{abc}	81.4^{abcd7}

[1] Means in the same column with the same letter are not significantly different. nd = not determined.

5.3.3.2 Tree species and grass areas

Data for the biomass C stocks in this grouping are presented in Table 5.12. The biomass C stocks varied significantly from 4.8 Mg ha^{-1} for the grass to 41.2 Mg ha^{-1} for the *P. elliottii,* 67.3 Mg ha^{-1} for the *P. patula,* and 113.2 Mg ha^{-1} for the *E. nitens* areas. The biomass C stocks for the *E. nitens* area were significantly higher than for the two *Pinus* species areas that differed non significantly. This could be related to the higher contribution of the tree C stocks of the *E. nitens* species, possibly associated with the higher leaf area index of the *E. nitens*, which allowed more C fixation (Usuga *et al*., 2010), while the *Pinus* have needle like leaves. Moreover, Laclau (2003) found mean biomass C stock of 44.0 Mg C ha^{-1} (stand age varied from 15 to 60 years) in pine plantations of northwest Patagonia which is in line with these results. However, their results included the C stocks in stems, branches, and foliage. The biomass C stock for the grass was markedly lower, due to lower C sequestration.

Table 5.12 Mean biomass C stocks, grouped per tree species and grass areas after afforestation in 2010

	Tree species^{1}			
	P. elliottii	***P. patula***	***E. nitens***	**Grass**
Litter C stocks (Mg ha^{-1})	6.13^{c}	9.82^{a}	8.43^{b}	nd
Tree C stocks (Mg ha^{-1})	35.1^{c}	57.5^{b}	104.8^{a}	nd
Biomass C stocks (Mg ha^{-1})	41.2^{b}	67.3^{b}	113.2^{a}	4.8^{c}

^{1}Means with the same letter in the same row are not significantly different. nd = not determined.

5.3.3.3 A, B, C, and H soils

Biomass C stocks data for this soil grouping are presented in Table 5.13. The biomass C stocks varied from 45.6 Mg ha^{-1} for the C soil group to 83.3 Mg ha^{-1} for the A soil group. The biomass C stock for the C soil group was significantly lower than that for the A soil group, primarily due to the poorer performance of trees in the C soil group than in the A soil group. The B and the H soil groups had almost similar biomass C stocks also reflected in their litter C and tree C stocks.

Table 5.13 Mean biomass C stocks, grouped per A, B, C, and H mapping unit (Roberts *et al*., 1995) after afforestation in 2010

	Soil groups^{1}			
	A	**B**	**C**	**H**
Litter C stocks (Mg ha^{-1})	9.02^{a}	7.50^{a}	7.74^{a}	7.64^{a}
Tree C stocks (Mg ha^{-1})	74.3^{a}	66.6^{a}	37.9^{b}	67.5^{a}
Biomass C stocks (Mg ha^{-1})	83.3^{a}	74.1^{ab}	45.6^{b}	75.1^{ab}

^{1}Means with the same letter in the same row are not significantly different. A = apedal mesotrophic, B = plinthic mesotrophic, C = undifferentiated hydromorphic, and H = mostly neocutanic B horizon soils.

5.3.3.4 Poorly, moderately, and freely drained soils

Table 5.14 presents the biomass C stock data for this soil grouping. The biomass C stocks varied significantly from 44.1 Mg ha^{-1} for the poorly drained soils to 81.8 Mg ha^{-1} for the moderately drained soils and 74.4 Mg ha^{-1} for the freely drained soils. This variation in biomass C stocks is in line with tree biomass C stocks because the latter contributed 90% of biomass C stocks regardless of the group.

Table 5.14 Mean biomass C stocks, grouped per drainage class after afforestation in 2010

	Soil groups[1]		
	Poorly drained soils	**Moderately drained soils**	**Freely drained soils**
Litter C stocks (Mg ha^{-1})	7.48^{a}	8.04^{a}	8.41^{a}
Tree C stocks (Mg ha^{-1})	36.6^{b}	73.7^{a}	65.9^{a}
Biomass C stocks (Mg ha^{-1})	44.1^{b}	81.8^{a}	74.4^{a}

[1]Means with the same letter in the same row are not significantly different

5.3.3.5 G, neocutanic B, yellow-brown apedal B, and red apedal B horizon soils

The biomass C stocks varied significantly from 44.7 Mg ha^{-1} for the G horizon soils to 86.2 Mg ha^{-1} for the red apedal B horizon soils (Table 5.15). Trees on the G horizon soils performed poorly in terms of biomass C stocks since both the litter and tree C stocks were low for reasons given earlier. The biomass C stocks of the neocutanic B horizon soils and the yellow-brown apedal B horizon soils were neither significantly higher than those of the G horizon soils nor significantly lower than those of the red apedal B horizon soils.

Table 5.15 Mean biomass C stocks, grouped per classification of the first subsoil (B1 or E1) horizon after afforestation in 2010

	Soil groups[1]			
	gh	**ne**	**ye**	**re**
Litter C stocks (Mg ha^{-1})	7.42^{b}	7.17^{b}	7.73^{b}	9.76^{a}
Tree C stocks (Mg ha^{-1})	37.3^{b}	67.3^{a}	67.0^{ab}	76.4^{a}
Biomass C stocks (Mg ha^{-1})	44.7^{b}	74.5^{ab}	74.7^{ab}	86.2^{a}

[1]Means with the same letter in the same row are not significantly different. gh = G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils.

5.4 Conclusion

Generally, the different sites had different litter C and N stocks. Site 203 (Tukulu soil with *P. elliottii* trees) had the lowest C and N stocks and the highest C:N ratio compared to the rest of the sites. The different tree species also influenced the litter C and N stocks and C:N ratios. The litter under *P. patula* stands had the highest C (9.82 Mg ha^{-1}) and N (0.23 Mg ha^{-1}) stocks while *P. elliottii* had the highest litter C:N (59.1) ratio. When litter was grouped according to the Roberts *et al*. (1996) mapping units, the soil groups had no influence on the litter C and N stocks, or on the C:N ratios. However, the A (apedal mesotrophic) soil group had the highest litter C (9.02 Mg ha^{-1}) and N (0.19 Mg ha^{-1}) stocks with the H (mostly neocutanic B horizon soils) soil group having the highest C:N (57.1) ratio. In the grouping according to drainage class, the soil groups influenced only the litter C:N ratios. However, the freely drained soils had higher litter C (8.41 Mg ha^{-1}) and N (0.19 Mg ha^{-1}) stocks, although not significant. In the last grouping according to the first subsoil (B1 or E1) horizon the soil groups influenced the litter C stocks with the red apedal B horizon soils having significantly higher litter C (9.76 Mg ha^{-1}) stocks than the other three soil groups, and the highest N (0.20 Mg ha^{-1}) stocks.

Of the 25 sites, site 252 (Kroonstad soil with *P. elliottii* trees) had the lowest tree C (25.2 Mg ha^{-1}) stocks and site 246 (Pinedene soil with *E. nitens* trees) had the highest tree C (156.5 Mg ha^{-1}) stocks. The average C stock for the 25 sites was 61.8 Mg C ha^{-1}. The *E. nitens* stands performed significantly better than the *Pinus* species and had comparatively higher C stocks (104.8 Mg ha^{-1}). The C soil group (undifferentiated hydromorphic) performed poorly and had significantly lower C stocks (37.9 Mg ha^{-1}) than other soil groups. Similarly the poorly drained soils had the lowest C stocks (36.6 Mg ha^{-1}) compared to other soil groups and the tree C (37.3 Mg ha^{-1}) stocks for the G horizon soils were significantly lower compared to other soil groups. The poorly drained soils therefore always had the lowest tree C stocks, due to the poor tree growth on these soils.

In the biomass C stocks the two control sites were included. Site 209 (Katspruit soil with grass) had the lowest biomass C stocks (3.71 Mg ha^{-1}) and site 246 (Pinedene soil with *E. nitens* trees) had the highest biomass C stocks (167.2 Mg ha^{-1}). The average biomass C stocks for the 25 afforested sites was 69.7 Mg ha^{-1}. The grass areas had the lowest biomass C stocks (4.8 Mg ha^{-1}). It was not surprising to see these results because according to literature the grassland areas have lower biomass and consequently lower C stocks. The *P. elliottii* stands had the lowest biomass C stocks (41.2 Mg ha^{-1}) compared to the other tree species stands. The C soil group (undifferentiated hydromorphic) had significantly lower biomass C stocks (45.6 Mg ha^{-1}). The poorly drained soils also performed badly and had the lowest biomass C stocks (44.1 Mg ha^{-1}). Finally, the G horizon soils also performed poorly and had the lowest biomass C stocks (44.1 Mg ha^{-1}). As with the tree C stocks, the poorly drained soils also had the lowest biomass C stocks

In general, the biomass C stocks were mainly affected by the tree C stocks because comparatively, the tree C stocks were much higher than the litter C stocks. Also *E. nitens* sequestered significantly more C stocks (113.2 Mg ha^{-1}) than *P. patula* (67.3 Mg ha^{-1}), *P. elliottii* (41.2 Mg ha^{-1}), or the native grass (4.8 Mg ha^{-1}). The rate of C sequestration for *E. nitens* therefore equated to 14.2 Mg ha^{-1} yr^{-1}.

CHAPTER 6

TOTAL CARBON STOCKS IN THE WEATHERLEY CATCHMENT

6.1 Introduction

Vegetation and soil are very important components in the global C cycle. Forest ecosystems store C in the biomass, soil, litter, and coarse debris pools (Tolunay, 2011). Of the total ecosystem C accumulation, 80-90% is found in the forest vegetation, followed by the forest floor and the mineral soil. The greatest C storage for aboveground biomass is found in tree stems, branches, and foliage. Forests absorb C from the atmosphere through the process of photosynthesis. The ability of forests to sequester C is regarded as one way of addressing the global increases in atmospheric CO_2 (Jach *et al*., 2000). Forest ecosystems can either be a sink or source of C (Lasco & Pulhin, 2003). Therefore in order to lessen the concentration of atmospheric CO_2, increasing forest plantation can assist to reduce global warming.

Apart from aboveground vegetation, belowground C storage is also important. Carbon that is distributed among the different plant parts is stored or is preserved in litter which finally enters into the soil. The litter in soils is either transformed into organic matter which is oxidised to CO_2 (Cao & Woodward, 1998). Changes in land use and management can therefore affect the amount of C in plant biomass and in soils.

There is a possibility that C can be stored in forest biomass and in soils, either on a long term basis or temporarily (Gower, 2003; Houghton, 2005). Processes such as photosynthesis and respiration that result inter alia in litter production and decomposition are responsible for the exchange of C between vegetation, soils, and the atmosphere. However, these factors are governed by both environmental conditions and vegetation characteristics.

As mentioned in the previous chapters, the Weatherley catchment was afforested with three different tree species. This chapter focuses on the total C stocks in the Weatherley catchment before and eight years after afforestation, 2003 and 2010 respectively.

6.2 Procedure

This chapter presents results on total C stocks, incorporating the soil C stocks and C stocks in the aboveground litter, trees and grass biomass, for the Weatherley catchment. As with the other chapters, the results are given per site, per tree species and grass areas, and per soil group. A one way analysis of variance was computed to establish differences between sites, tree species and grass areas, and soil groups. The MSD-test of Tuckey was applied for comparisons of means. Statistical analyses were computed with the SAS package at a 95% confidence level (SAS Institute, 1985).

6.3 Results and discussion

The data on total C stocks presented here are mainly those after afforestation in 2010 because limited data on the C stocks in the aboveground biomass were recorded before afforestation in 2003. Therefore the data covers all 27 sites studied, including the two control sites.

6.3.1 Sites

The data on the total C stocks for the 27 sites are presented in Table 6.1. These C stocks varied significantly from 39.7 Mg ha^{-1} at site 209 (Katspruit soil with grass) to 204.2 Mg ha^{-1} at site 246 (Pinedene soil with *E. nitens* trees). The average total C stock for the 27 sites was 103.6 Mg C ha^{-1}, and that for the 25 afforested sites 108.6 Mg ha^{-1} and two control sites 41.3 Mg ha^{-1}.

However, because of the uneven distribution in species composition and the period since abandonment of former land use, the C stocks among the afforested sites were expected to vary (Wang *et al*., 2009). In the Weatherley catchment the soil contributed only 37.3% to the total C stocks. This could be related to several factors: first, in preparation to tree plantations, the soil was disturbed through disc ploughing and pitting, resulting in much C loss through volatilisation. Secondly, due to the young age of the studied plantations, there was slow C incorporation in to the soil (Singh *et al*., 2007) and lastly previous land use might also explain these low soil C stocks. Guo and Gifford (2002) indicated that after afforestation on grassland sites (sites with high soil C) there might initially be a decrease in soil C.

The low total C stocks of the two control sites,namely 209 and 235 may be attributed to lower aboveground C stocks on account of the absence of trees and their litter. Generally, in the Weatherley catchment forest ecosystem, the tree biomass contributed 59.7% of the total C stocks, followed by soil with 37.3%, and litter with 7.5% of the total C stocks. This implied that an important portion of total C stocks were in the tree biomass. The results for this study fall within the range reported by Fonseca *et al*. (2011). They reported a range of 88.7 to 204.3 Mg C ha^{-1} for plantations between 0.5 and 16 years old after land use change from pasture to forest. It should be kept in mind that there might have been over or under estimation in the tree C stocks because, as mentioned in chapter 3 in the calculation of the tree C stocks, some assumptions were made.

Table 6.1 Mean C stocks for the 27 sites after afforestation in 2010

Carbon stocks (Mg ha^{-1})				
Sites	**Soil**	**Litter**	**Trees**	**Total**
201	26.5^{b}	5.96^{cdefg}	29.0^{c}	61.4^{cde}
202	32.7^{a}	4.62^{efg}	34.5^{c}	71.7^{cde}
203	22.9^{b}	4.23^{fg}	39.6^{c}	66.8^{cde}
209	36.0^{b}	3.71^{g}	nd	39.7^{e}
210	38.3^{b}	8.86^{abcde}	95.6^{abc}	142.8^{abc}
212	36.1^{a}	8.78^{abcde}	60.6^{bc}	105.4^{bcde}
220	34.0^{b}	9.43^{abcd}	65.5^{bc}	108.9^{bcde}
221	30.1^{b}	8.46^{abcde}	82.3^{abc}	120.8^{abcde}
222	31.9^{b}	5.21^{defg}	76.3^{abc}	113.4^{abcde}
232	34.8^{b}	$7.87^{abcdefg}$	36.4^{c}	79.1^{cde}
233	30.5^{b}	6.30^{bcdefg}	49.0^{c}	85.9^{cde}
235	37.0^{a}	5.80^{cdefg}	nd	42.8^{de}
240	51.9^{b}	11.5^{a}	67.8^{abc}	131.3^{abcd}
241	40.9^{a}	8.57^{abde}	45.5^{c}	95.0^{cde}
242	42.6^{a}	10.6^{ab}	51.2^{c}	104.5^{bcde}
243	48.6^{a}	10.4^{ab}	50.0^{c}	108.9^{bcde}
244	39.5^{a}	9.89^{abc}	57.0^{bc}	106.4^{bcde}
245	41.1^{a}	8.29^{abcde}	56.8^{c}	106.2^{bcde}
246	37.0^{b}	10.6^{ab}	156.5^{a}	204.2^{a}
247	37.3^{a}	9.15^{abcd}	147.4^{ab}	193.9^{ab}
248	33.0^{b}	$7.28^{abcdefg}$	110.0^{abc}	150.2^{abc}
249	49.0^{b}	6.94^{bcdefg}	35.7^{c}	91.7^{cde}
250	42.2^{a}	6.67^{bcdefg}	36.0^{c}	84.9^{cde}
251	47.9^{a}	6.31^{bcdefg}	32.5^{c}	86.6^{cde}
252	34.0^{b}	6.74^{bcdefg}	25.2^{c}	66.0^{cde}
253	46.7^{a}	5.68^{cdefg}	33.2^{c}	85.6^{cde}
254	60.7^{a}	10.5^{ab}	70.9^{abc}	142.1^{abc}

[1] Means with the same letter in the same column are not significantly different

6.3.2 Tree species and grass areas

Data for the total C stocks for the different tree species and grass areas are presented in Table 6.2. These stocks varied significantly from 41.2 Mg C ha^{-1} for the grass areas to 78.0 Mg C ha^{-1} for the *P. elliottii* area to 112.5 Mg C ha^{-1} for the *P. patula* area to 147.8 Mg C ha^{-1} for the *E. nitens* area. As mentioned, the low total C stocks in the grass area were because of the absence of trees and litter. The total C stocks for the *E. nitens* area was higher than that for the other tree species areas. This was mainly because of the larger C contribution by the total aboveground biomass. Generally, total aboveground biomass was the major contributor to the total C stocks for the tree species areas, as opposed to the grass area where soil was the major contributor.

Table 6.2 Mean C stocks grouped per tree species and grass areas after afforestation in 2010

Carbon stocks (Mg ha^{-1})				
	Tree species[1]			
	P. elliottii	***P. patula***	***E. nitens***	**Grass**
Belowground: Soil	36.7^{abc}	45.2^{d}	34.5^{a}	36.5^{ab}
Aboveground: Litter	6.13^{c}	9.82^{a}	8.43^{b}	nd
Trees	35.1^{c}	57.5^{b}	104.8^{a}	nd
Total Aboveground	41.2^{b}	67.3^{b}	113.2^{a}	4.8^{c}
Total	78.0^{c}	112.5^{b}	147.8^{a}	41.2^{d}

[1] Means with the same letter in the same row are not significantly different. nd = not determined

The total C stocks between the tree species and grass areas were remarkably variable because of the differences amongst the contributing components, especially litter and tree C stocks. Of the total C stocks, 88.6% was stored belowground for grass areas, and 47.1% for *P. elliottii*, 40.2% for *P. patula*, and 23.3% for *E. nitens* areas. These results suggested that the forest C pool depends on the type of vegetation or tree species. The results of this study fall within the range reported by Martin *et al*. (2005) for mixed boreal forest (including *Pinus* and *Populus* tree species) in northern Manitoba, Canada; Mendoza-Ponce and Galicia (2010) for a highland temperate landscape in Central Mexico in 12 years old *P. patula* areas, and Ordonez *et al*. (2008) who found total C stocks varying from 83 to 439.4 Mg C ha^{-1} for pine forest in the Central Highlands of Michoacan, Mexico.

6.3.3 A, B, C, and H soils

Data for this soil grouping are presented in Table 6.3. The total C stocks varied significantly from 87.0 Mg ha^{-1} for the C soil group (undifferentiated hydromorphic) to 128.3 Mg ha^{-1} for the A soil group (apedal mesotrophic). The C soil group had the lowest total C stocks, but it was not significantly different from the B (plinthic mesotrophic) and H (mostly neocutanic) soil groups. Although the A soil group had the highest total C stock, it was not significantly different from the B and H soil groups. For the B and H soil groups, the aboveground biomass contributed 68.0%, for the A soil group 64.9%, and for the C soil group 52.4% of the total C stocks. In general, for all the soil groups aboveground biomass was the major contributor the total C stocks, because of the large tree C stocks.

Table 6.3 Mean C stocks, grouped per A, B, C, and H mapping units (Roberts *et al.*, 1996) after afforestation in 2010

Carbon stocks (Mg ha^{-1})				
Soil groups[1]				
	A	**B**	**C**	**H**
Belowground: Soil	45.0^{a}	34.7^{b}	41.3^{a}	34.9^{b}
Aboveground: Litter	9.02^{a}	7.50^{a}	7.74^{a}	7.64^{a}
Trees	74.3^{a}	66.6^{a}	37.9^{b}	67.5^{a}
Total Aboveground	83.3^{a}	74.1^{ab}	45.6^{b}	75.1^{ab}
Total	128.3^{a}	108.9^{ab}	87.0^{b}	110.0^{ab}

[1] Means with the same letter in the same row are not significantly different. A = apedal mesotrophic, B = plinthic mesotrophic, C = undifferentiated hydromorphic, and H =mostly neocutanic B horizon soils

6.3.4 Poorly, moderately, and freely drained soils

Data for this soil grouping are presented in Table 6.4. The total C stocks varied significantly from 80.5 Mg ha^{-1} for the poorly drained soils to 121.0 Mg ha^{-1} for the moderately drained soils. Although the moderately drained soil group had the highest C stocks, it was not significantly different from the freely drained soil group. The aboveground biomass C stocks contributed most to the total C stocks for all the soil groups.

Table 6.4 Mean C stocks, grouped per drainage class after afforestation in 2010

Carbon stocks (Mg ha^{-1})			
Soil groups[1]			
	Poorly drained soils	**Moderately drained soils**	**Freely drained soils**
Belowground: Soil	36.4^{b}	39.2^{b}	44.5^{a}
Aboveground: Litter	7.48^{a}	8.04^{a}	8.41^{a}
Trees	36.6^{b}	73.7^{a}	65.9^{a}
Total Aboveground	44.1^{b}	81.8^{a}	74.4^{a}
Total	80.5^{b}	121.0^{a}	118.8^{a}

[1] Means with the same letter in the same row are not significantly different

6.3.5 G, neocutanic B, yellow-brown apedal B, and red apedal B horizon soils

Data for the total C stocks in this soil grouping are presented in Table 6.5. These stocks varied significantly from 84.7 Mg C ha^{-1} for the G horizon soil group to 129.2 Mg C ha^{-1} for the red apedal B horizon soil group. The G horizon soil group performed poorly and had the lowest total C stocks but it was not significantly different from the neocutanic and the yellow-brown apedal B horizon soil groups. Although the red apedal B horizon soil group had the highest total C stocks, they were also not significantly different from the neocutanic and the yellow-brown apedal B horizon soil groups. As in the other groupings, the aboveground C stocks contributed the greatest portion of the total C stocks for all the soil groups: 53% for the G horizon soils and approximately 68% for the other soil groups.

Table 6.5 Mean C stocks, grouped per classification of the first subsoil (B1 or E1) horizon after afforestation in 2010

Carbon stocks (Mg ha^{-1})				
	Soil groups[1]			
	gh	**ne**	**ye**	**re**
Belowground: Soil	40.0^{ab}	34.5^{c}	38.5^{bc}	43.0^{a}
Aboveground: Litter	7.42^{b}	7.17^{b}	7.73^{b}	9.76^{a}
Trees	37.3^{b}	67.3^{a}	67.0^{ab}	76.4^{a}
Total Aboveground	44.7^{b}	74.5^{ab}	74.7^{ab}	86.2^{a}
Total	84.7^{b}	109.0^{ab}	113.2^{ab}	129.2^{a}

[1] Means with the same letter in the same row are not significantly different. gh = G horizon soils, ne = neocutanic B horizon soils, ye = yellow-brown apedal B horizon soils, re = red apedal B horizon soils

The C stocks data from this study and the earlier baseline study (Le Roux *et al.*, 2005) were used to estimate C sequestration in the Weatherley catchment before (Table 6.6) and after (Table 6.7) afforestation. In order to estimate the most representative biomass C stocks for the grassland area in 2003 the average biomass recorded for the designated areas (*P. elliottii*: 3.48 Mg ha^{-1} for 10 sites; *P. patula*: 3.84 Mg ha^{-1} for 8 sites; *E. nitens*: 2.68 Mg ha^{-1} for 4 sites; grass: 3.39 Mg ha^{-1} for 24 sites) in the baseline study and the average C concentration (38.7% for 2 sites) measured in this study were applied. It must be noted that 2003 biomass yield referred to the biomass regrowth of one year and excludes the litter, while the 2010 biomass referred to the biomass on the control sites that included the litter.

Table 6.6 Carbon stocks in the Weatherley catchment per designated tree species and grass areas in 2003

Species	***P.elliottii***	***P. patula***	***E. nitens***	**Grass**	**Total**
Area (ha)	26.3	26.9	22.8	84.0	160
Soil C (Mg ha^{-1})	46.7	43.3	46.9	42.0	
Biomass C (Mg ha$^{-1)}$	1.35	1.49	1.04	1.32	
Soil C (Mg)	1228	1165	1069	3528	6990
Biomass C (Mg)	35	40	34	110	219
Total C stocks (Mg)	1263	1205	1103	3638	7209

Table 6.7 Carbon stocks in the Weatherley catchment per actual tree species and grass areas in 2010

Species	***P.elliottii***	***P. patula***	***E. nitens***	**Grass**	**Total**
Area (ha)	26.3	26.9	22.8	84.0	160
Soil C (Mg ha^{-1})	36.7	45.2	34.5	36.5	
Biomass C (Mg ha$^{-1)}$	41.2	67.3	113.2	4.8	
Soil C (Mg)	965	1216	787	3066	6034
Biomass C (Mg)	1084	1810	2581	403	5878
Total C stocks (Mg)	2049	3026	3368	3469	11912

The total C stocks in the catchment amounted to 7 209 Mg (Table 6.6) and after eight years of afforestation to 11 912 Mg (Table 6.7). This implies a 4 703 Mg gain in C stocks on the 76 ha that was afforested. The rate of C sequestration in the whole Weatherley catchment on account of afforestation was therefore 588 Mg yr^{-1} or 3.67 Mg ha^{-1} yr^{-1}. The rate of C sequestration in the afforested areas only was 7.74 Mg ha^{-1} yr^{-1}.

6.4 Conclusion

Of the 27 sites studied, the two control sites (Katspruit soils with grass) had the lowest total C stocks, 39.7 Mg ha^{-1} and 42.8 Mg ha^{-1} for sites 209 and 235 respectively because of the lower contribution of the aboveground biomass to the total C stocks at these sites. Site 246 (Pinedene soil with *E. nitens* trees) had the highest total C stocks (204.2 Mg ha^{-1}). The total C stocks for the different tree species and grass areas were lowest for the grass area (41.2 Mg ha^{-1}) and highest for the *E. nitens* area (147.8 Mg ha^{-1}).

In grouping of the soils according to the Roberts *et al*. (1996) mapping units, the C (undifferentiated hydromorphic) soil group performed worst and had the lowest total C stocks (87.0 Mg ha^{-1}), while the A (apedal mesotrophic) soil group had the highest total C stocks (128.3 Mg ha^{-1}). In the grouping according to drainage class, the poorly drained soils had the lowest total C stocks (80.5 Mg ha^{-1}) as opposed to the moderately drained soil group which had 121.0 Mg ha^{-1}. In the last grouping according to the first subsoil (B1 or E1) horizon the G horizon soil group had the lowest total C stocks (84.7 Mg ha^{-1}) while the red apedal B horizon soil group had the highest total C stocks of 129.2 Mg ha^{-1}. It therefore seemed that poorly drained soil conditions limited tree growth and therefore C sequestration while tree growth and hence C sequestration were promoted on the freely drained soils. In general, the total aboveground C stocks contributed the greatest portion to the total C stocks.

The total C stocks in the Weatherley catchment were 7 209 Mg before afforestation and 11 912 Mg eight years after afforestation. Only 76 ha of the 160 ha was afforested. Therefore the trees contributed 4 702 Mg C to the catchment, at a rate of 588 Mg C yr^{-1} or 3.67 Mg C ha^{-1} yr^{-1} for the whole catchment. The rate of C sequestration for the afforested area only was 7.74 Mg ha^{-1} yr^{-1}. The *E. nitens* trees sequestered more C stocks (113.2 Mg ha^{-1}) than other experimented tree species, therefore afforestation of the catchment or other similar areas with this species should continue in order to maximise C sequestration.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS

Soil and vegetation play a vital role in the global C cycle because C exchange is affected by both. Thus a change in land use may result in either a loss or gain of C from the soil-plant system. The objectives of this study were therefore, to quantify whether soil-plant C stocks in the Weatherley catchment changed markedly eight years after afforestation of grassland. The second objective was to establish whether changes in soil C stocks in the Weatherley catchment were related to either the tree species or soil types.

The Weatherley catchment is located in the Eastern Cape Province of South Africa. This 160 ha catchment was covered with grassland before 76 ha was afforested in 2002 with three tree species, viz. *P. elliottii*, *P. patula*, and *E. nitens*. Before afforestation, a baseline study on soil organic matter was conducted on the areas designated for the above mentioned tree species. In this study, the same 27 sites used by Le Roux *et al*. (2005) were investigated. These sites included two controls. Soil sampling was done in May 2010 and tree sampling in March 2011 when the trees were eight years old.

Afforestation influenced the soil organic matter in the Weatherley catchment in the 0-300 mm layer. After afforestation, 14 sites showed significant decreases and 3 sites showed significant increases in soil C stocks. Organic C stocks decreased by 0.9 Mg ha^{-1} at site 235 (Katspruit soil with grass) and 23.6 Mg ha^{-1} at site 232 (Katspruit soil with *P. elliottii* trees). The rate of decrease therefore ranged between 0.11 and 2.95 Mg C ha^{-1} yr^{-1}. On the other hand, soil C stocks increased by 0.9 Mg ha^{-1} at site 244 (Pinedene soil with *P.patula* trees) and 11.3 Mg ha^{-1} at site 242 (Longlands soil *with P. patula* trees). The rate of increase in soil C stocks ranged thus from 0.11 Mg ha^{-1} yr^{-1} to 1.41 Mg ha^{-1} yr^{-1}. All remaining 10 sites showed insignificant decreases or increases in soil C stocks. For soil N stocks, 13 sites showed significant decreases and 5 sites showed significant increases. The significant decreases in soil N stocks ranged from 0.25 Mg ha^{-1} at site 240 (Hutton soil with *P.patula* trees) and 1.88 Mg ha^{-1} at site 246 (Pinedene soil with *E. nitens* trees). Significant increases in soil N stocks ranged from 0.43 Mg ha^{-1} at site 235 (Katspruit soil with grass) and 2.90 Mg ha^{-1} at site 245 (Pinedene soil with *P. patula* trees). Soil C stocks decreased significantly by 5.5 Mg ha^{-1}, 10.0 Mg ha^{-1}, and 12.4 Mg ha^{-1} for grass, *E. nitens*, and *P. elliottii* areas, respectively. Soils under *P. patula* showed an insignificant increase of 1.9 Mg ha^{-1} in soil C stocks. The soil N stocks followed the same trend as the soil C stocks. These initial decreases in soil C and N stocks are probably because the trees are still young.

When the soils were grouped according to the Roberts *et al*. (1996) mapping units, drainage classes or first subsoil (B1 or E1) horizons there was generally a significant decrease in soil C stocks due to afforestation. The decreases in soil C stocks ranged from 43.0 Mg ha^{-1} in the B soil group to 11.2 Mg ha^{-1} in the H soil group, 6.6 Mg ha^{-1} in the poorly drained soils to 7.3 Mg ha^{-1} in the moderately drained soils, and 3.8 Mg ha^{-1} in the yellow-brown apedal B horizon soils to 10.0 Mg ha^{-1} in the neocutanic B horizon soils. The soil N stocks to a large extent behaved similarly to the soil C stocks except for the B soil group and for the red apedal B horizon soils. In these two groups soil N stocks increased slightly following afforestation. These results suggest that soil type also controls the soil C and N stocks in the Weatherley catchment.

With regard to litter, site 203 (Tukulu soil with *P. elliottii* trees) had the lowest litter C and N stocks and the highest C:N ratio compared to the rest of the sites. The litter under *P. patula* stands resulted in the highest C stocks (9.82 Mg ha^{-1}) and N stocks (0.23 Mg ha^{-1}) while *P. elliottii* areas had the highest litter C:N ratio (59.1). When litter data were grouped according to the Roberts *et al*. (1996) mapping units, drainage classes or first subsoil (B1 or E1) horizons, the soil groups influenced only the litter C:N ratios for the drainage class soil group, and the C stocks for the latter soil group. However, the A (apedal mesotrophic) soil group had the highest litter C stocks (9.02 Mg ha^{-1}) and N stocks (0.19 Mg ha^{-1}) with the H soil group (mostly neocutanic B horizon soils) having the highest C:N ratio (57.1). The freely drained soils had higher litter C (8.41 Mg ha^{-1}) and N (0.19 Mg ha^{-1}) stocks, although these differences were not significant. On the red apedal B horizon soils significantly higher litter C (9.76 Mg ha^{-1}) and N (0.20 Mg ha^{-1}) stocks were recorded than on the other three soil groups.

For the tree biomass, only the C stocks were considered. Of the 25 sites, site 252 (Kroonstad soil with *P. elliottii* trees) had the lowest tree C stocks (25.2 Mg ha^{-1}) and site 246 (Pinedene soil with *E. nitens* trees) had the highest tree C stocks (156.5 Mg ha^{-1}). On average the C stocks for the 25 sites was 61.8 Mg ha^{-1}. The *E. nitens* stands had the highest C stocks (104.8 Mg ha^{-1}). The C (undifferentiated hydromorphic), the poorly drained, and the G horizon soil groups had significantly lower C stocks, viz 37.9 Mg ha^{-1}, 36.6 Mg ha^{-1}, and 37.3 Mg ha^{-1} than the other soil groups. It therefore seems that the poorly drained soils led to poor performance of tree growth.

Concerning the aboveground biomass, site 209 (Katspruit soil with grass) had the lowest aboveground biomass C stocks (3.71 Mg ha^{-1}) and site 246 (Pinedene soil with *E. nitens* trees) had the highest C stocks (167.2 Mg ha^{-1}). The average aboveground biomass C stock for the 25 afforested sites was 69.7 Mg ha^{-1}. For the two grass sites the average aboveground biomass C stock was 4.8 Mg ha^{-1}. These results were not surprising because the grassland areas have lower aboveground biomass and consequently lower C stocks. For example, the *E. nitens* sequestered significantly more aboveground biomass C stocks (113.2 Mg ha^{-1}) than *P. patula* (67.3 Mg ha^{-1}), *P. elliottii* (41.2 Mg ha^{-1}), or the native grass (4.8 Mg ha^{-1}). The rate of C sequestration therefore equated to 14.2 Mg ha^{-1} yr^{-1} for *E. nitens*. The C soil group (undifferentiated hydromorphic), the poorly drained soils, and the G horizon soils had the lowest aboveground biomass C stocks, viz 45.6 Mg ha^{-1}, 44.1 Mg ha^{-1}, and 44.7 Mg ha^{-1} respectively.

Of the 27 sites studied, the two control sites (Katspruit soil with grass) had the lowest total C stocks (41.3 Mg ha^{-1} on average) because of the lower contribution of aboveground biomass to the total C stocks at these sites. Site 246 that comprises of Pinedene soil with *E. nitens* trees had the highest total C stocks (204.2 Mg ha^{-1}). The total C stocks for the different tree species and grass areas were lowest for the grass (41.2 Mg ha^{-1}) and highest for the *E. nitens* (147.8 Mg ha^{-1}) areas.

The C (undifferentiated hydromorphic) soil group had the lowest total C stocks (87.0 Mg ha^{-1}), and the A (apedal mesotrophic) soil group had the highest total C stocks (128.3 Mg ha^{-1}). For the next grouping, the poorly drained soils had the lowest C stocks (80.5 Mg ha^{-1}) as opposed to the moderately drained soil group (121.0 Mg ha^{-1}). The G horizon soil group had the lowest total C stocks (84.7 Mg ha^{-1}) and the red apedal B horizon soil group had the highest total C stocks (129.2 Mg ha^{-1}). As the lowest C stocks were recorded in the C soil group, poorly drained soils, and the G horizon soil group, it could possibly be related to the poor growth conditions in these soils which could not support good tree growth. In general, the aboveground biomass C stocks contributed the greatest portion to the total C stocks.

Total C stocks in the catchment before afforestation were estimated to be 7 209 Mg. After eight years of afforestation the C stocks were estimated to be 11 912 Mg. Therefore the trees contributed 4 702 Mg C to the catchment, at a rate of 588 Mg C yr^{-1} or 3.67 Mg C ha^{-1} yr^{-1}. Considering only the afforested areas, the rate of C sequestration was 7.74 Mg ha^{-1} yr^{-1}. The *E. nitens* trees sequestered more C stocks (113.2 Mg ha^{-1}) than other experimented tree species, therefore afforestation of the catchment or other similar areas with this species should continue in order to maximise C sequestration.

The following recommendations were drawn from the results of this study:

- Soil sampling at the same sites should be repeated at five year intervals and measuring of the standing trees when they are a bit older is also essential to get an overall view on the C stocks in the catchment as recommended from the baseline study and also in this study.

- The inclusion of tree components (roots, branches) other than the stems has been ignored in this first study after the baseline one and, it would be interesting to include them in future investigations.
- It would be of great value to include some of the nutritional elements such as phosphorus, potassium, calcium, magnesium, and sulphur because these elements have some influence on tree growth and hence the production of C stocks.
- In future an effort should be made to estimate the amount of C sequestered per mm of rain used for the tree species and grass or soil grouping.

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APPENDIX A

Organic C (OC, %) and total N (TN, %) of the replicated soil (0-1200 mm) samples and their means for the 27 profiles/sites in the Weatherley catchment eight years after afforestation, in April 2010.

Profile/Site 201

Depth (mm)	**Replication**	**C (%)**	**N (%)**	**C:N**
0-50	1	1.01	0.07	15.14
	2	0.83	0.07	12.55
	3	0.97	0.07	14.72
	4	1.01	0.06	15.58
	Mean	0.95	0.07	14.50
50-100	1	0.73	0.06	11.55
	2	0.71	0.05	13.83
	3	0.72	0.06	12.01
	4	0.72	0.06	11.42
	Mean	0.72	0.06	9.79
100-150	1	0.62	0.06	9.79
	2	0.72	0.06	13.94
	3	0.61	0.06	9.77
	4	0.62	0.06	11.42
	Mean	0.64	0.06	11.04
150-200	1	0.63	0.05	12.28
	2	0.67	0.05	12.53
	3	0.68	0.06	10.52
	4	0.56	0.05	10.31
	Mean	0.64	0.06	11.41
200-250	1	0.58	0.06	10.56
	2	0.56	0.05	10.28
	3	0.53	0.05	10.27
	4	0.55	0.05	10.28
	Mean	0.55	0.05	10.35
250-300	1	0.52	0.05	10.57
	2	0.51	0.04	12.35
	3	0.52	0.05	10.18
	4	0.53	0.05	10.73
	Mean	0.52	0.05	10.96
300-400	1	0.39	0.04	9.85
	2	0.37	0.04	9.70
	3	0.36	0.04	9.00
	4	0.41	0.04	10.33
	Mean	0.38	0.04	9.72
400-500	1	0.21	0.03	8.11
	2	0.23	0.04	6.59
	3	0.21	0.04	4.96
	4	0.23	0.04	6.26
	Mean	0.22	0.04	6.48
500-600	1	0.19	0.02	9.30
	2	0.22	0.03	7.81
	3	0.21	0.04	5.67
	4	0.24	0.03	9.56
	Mean	0.21	0.03	8.09
600-700	1	0.19	0.03	7.48
	2	0.18	0.02	7.65
	3	0.21	0.03	7.31
	4	0.21	0.02	8.59
	Mean	0.20	0.03	7.76
700-800	1	0.19	0.02	8.88
	2	0.18	0.02	8.26
	3	0.25	0.03	9.78
	4	0.25	0.03	9.93
	Mean	0.22	0.02	9.21
800-900	1	0.19	0.02	9.52
	2	0.18	0.02	11.99
	3	0.23	0.03	8.77
	4	0.23	0.02	15.44
	Mean	0.21	0.02	11.43
900-1000	1	0.13	0.02	7.46
	2	0.12	0.02	7.96
	3	0.22	0.03	8.90
	4	0.13	0.01	11.3
	Mean	0.15	0.02	8.92
1000-1100	1	0.14	0.01	11.90
	2			
	3	0.21	0.02	10.24
	4	0.10	0.02	6.65
	Mean	0.15	0.02	9.60
1100-1200	1	0.15	0.03	5.73
	2			
	3	0.13	0.02	8.55
	4	0.08	0.01	5.89
	Mean	0.12	0.02	6.72

Profile/Site 202

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.12	0.04	31.29
	2	1.02	0.05	20.83
	3	0.91	0.06	15.89
	4	0.89	0.05	19.53
	Mean	0.98	0.05	21.88
50-100	1	0.88	0.05	18.33
	2	0.78	0.05	14.40
	3	0.84	0.05	17.22
	4	0.84	0.05	17.15
	Mean	0.84	0.05	16.77
100-150	1	0.89	0.04	20.90
	2	0.64	0.05	13.26
	3	0.73	0.04	17.86
	4	0.72	0.05	14.96
	Mean	0.75	0.05	16.74
150-200	1	0.83	0.05	17.03
	2	0.70	0.04	16.25
	3	0.72	0.04	17.04
	4	0.77	0.04	19.72
	Mean	0.76	0.04	17.51
200-250	1	0.74	0.05	15.66
	2	0.76	0.05	15.84
	3	0.68	0.04	17.11
	4	0.68	0.04	16.07
	Mean	0.71	0.04	16.17
250-300	1	0.67	0.05	14.26
	2	0.83	0.04	19.22
	3	0.66	0.04	16.25
	4	0.65	0.04	17.09
	Mean	0.70	0.04	16.71
300-400	**1**	0.53	0.04	15.12
	2	0.49	0.03	14.10
	3	0.41	0.03	12.56
	4	0.45	0.04	12.89
	Mean	0.47	0.03	13.67
400-500	**1**	0.37	0.03	11.53
	2	0.38	0.03	15.02
	3	0.26	0.02	12.81
	4	0.39	0.03	13.41
	Mean	0.35	0.03	13.19
500-600	**1**	0.29	0.02	13.44
	2	0.31	0.02	15.38
	3	0.23	0.02	13.22
	4	0.24	0.02	11.54
	Mean	0.27	0.02	13.39
600-700	**1**	0.23	0.02	15.04
	2	0.26	0.02	13.44
	3	0.18	0.02	11.59
	4	0.21	0.02	12.09
	Mean	0.22	0.02	13.04
700-800	**1**	0.19	0.02	9.94
	2	0.21	0.02	10.75
	3	0.17	0.02	9.16
	4	0.19	0.02	8.62
	Mean	0.19	0.02	9.62
800-900	**1**	0.20	0.02	8.76
	2	0.23	0.02	11.11
	3	0.17	0.02	9.14
	4	0.22	0.03	8.81
	Mean	0.21	0.02	9.46
900-1000	**1**	0.19	0.02	10.94
	2	0.19	0.02	10.92
	3	0.15	0.01	12.13
	4	0.19	0.02	8.50
	Mean	0.18	0.02	10.63
1000-1100	**1**	0.14	0.02	8.75
	2	0.18	0.02	9.34
	3	0.11	0.02	7.80
	4	0.15	0.02	8.73
	Mean	0.15	0.02	8.66
1100-1200	**1**	0.11	0.01	8.01
	2	0.17	0.02	9.03
	3	0.14	0.02	8.07
	4	0.10	0.02	6.06
	Mean	0.13	0.02	7.79

Profile/Site 203

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	0.60	0.04	16.46
	2	0.64	0.05	13.84
	3	0.68	0.05	13.65
	4	0.74	0.05	15.78
	Mean	0.67	0.04	14.93
50-100	1	0.65	0.05	12.15
	2	0.58	0.05	11.17
	3	0.58	0.05	11.72
	4	0.54	0.05	11.79
	Mean	0.59	0.05	11.71
100-150	1	0.55	0.05	12.10
	2	0.62	0.04	13.68
	3	0.52	0.04	12.33
	4	0.74	0.04	15.07
	Mean	0.60	0.05	13.29
150-200	1	0.47	0.05	9.37
	2	0.54	0.04	12.18
	3	0.47	0.05	9.56
	4	0.49	0.04	12.17
	Mean	0.49	0.05	10.89
200-250	1	0.48	0.04	13.00
	2	0.40	0.04	10.28
	3	0.38	0.04	9.02
	4	0.53	0.04	12.18
	Mean	0.44	0.04	11.12
250-300	1		0.04	10.16
	2	0.38	0.03	11.38
	3	0.39	0.03	12.67
	4	0.51	0.04	12.63
	Mean	0.41	0.04	11.71
300-400	1	0.41	0.03	12.98
	2	0.41	0.03	12.36
	3	0.28	0.03	10.20
	4	0.36	0.03	11.41
	Mean	0.37	0.03	11.74
400-500	1	0.19	0.02	9.06
	2	0.19	0.03	7.03
	3	0.16	0.02	6.77
	4	0.19	0.02	9.19
	Mean	0.18	0.02	8.01
500-600	1	0.14	0.01	8.38
	2	0.14	0.02	8.35
	3	0.14	0.02	8.44
	4	0.13	0.02	6.98
	Mean	0.14	0.02	8.04
600-700	1	0.14	0.02	7.12
	2	0.12	0.02	6.44
	3	0.11	0.02	6.21
	4	0.15	0.02	8.20
	Mean	0.13	0.02	6.99
700-800	1	0.14	0.02	7.11
	2	0.15	0.02	9.71
	3	0.11	0.02	5.88
	4	0.10	0.02	6.55
	Mean	0.13	0.02	7.31
800-900	1	0.15	0.02	9.00
	2	0.10	0.01	6.96
	3	0.09	0.02	6.21
	4	0.06	0.01	5.05
	Mean	0.10	0.01	6.80
900-1000	1	0.11	0.01	8.16
	2	0.09	0.01	5.39
	3	0.04	0.01	3.86
	4	0.04	0.01	3.92
	Mean	0.07	0.01	5.33
1000-1100	1	0.07	0.01	5.19
	2	0.09	0.02	5.11
	3	0.06	0.01	4.26
	4	0.04	0.01	4.63
	Mean	0.06	0.01	4.80
1100-1200	1	0.08	0.01	5.95
	2	0.07	0.01	5.03
	3	0.06	0.01	4.08
	4	0.06	0.01	5.86
	Mean	0.07	0.01	5.23

Profile/Site 209

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.25	0.10	12.49
	2	1.47	0.11	13.21
	3	1.46	0.13	11.64
	4	1.41	0.10	13.82
	Mean	1.40	0.11	12.79
50-100	1	1.08	0.09	11.63
	2	1.24	0.10	12.24
	3	1.20	0.10	11.78
	4	1.07	0.09	11.36
	Mean	1.15	0.10	11.75
100-150	1	1.05	0.09	11.93
	2	1.09	0.10	11.09
	3	0.99	0.08	11.80
	4	1.16	0.09	12.39
	Mean	1.07	0.09	11.80
150-200	1	0.74	0.07	10.10
	2	0.89	0.08	10.59
	3	0.73	0.07	11.01
	4	0.71	0.08	9.43
	Mean	0.77	0.07	10.28
200-250	1	0.72	0.07	10.05
	2	0.65	0.07	9.34
	3	0.66	0.06	10.72
	4	0.69	0.07	10.17
	Mean	0.68	0.07	10.07
250-300	1	0.64	0.07	9.30
	2	0.63	0.07	9.28
	3	0.63	0.06	9.70
	4	0.61	0.05	11.57
	Mean	0.63	0.06	9.96
300-400	**1**	0.57	0.06	9.66
	2	0.51	0.06	8.26
	3	0.45	0.05	8.74
	4	0.45	0.04	10.28
	Mean	0.49	0.05	9.23
400-500	**1**	0.50	0.06	8.85
	2	0.45	0.05	9.96
	3	0.45	0.05	9.45
	4	0.38	0.04	9.62
	Mean	0.44	0.05	9.47
500-600	**1**	0.41	0.05	8.51
	2	0.31	0.04	8.47
	3	0.33	0.05	6.95
	4	0.29	0.04	7.94
	Mean	0.34	0.04	7.97
600-700	**1**	0.31	0.04	7.27
	2	0.26	0.04	6.62
	3	0.29	0.04	7.52
	4	0.23	0.04	5.80
	Mean	0.27	0.04	6.80
700-800	**1**	0.22	0.04	5.80
	2	0.20	0.03	6.23
	3	0.25	0.04	6.52
	4	0.20	0.03	6.15
	Mean	0.22	0.04	6.18
800-900	**1**	0.21	0.03	6.95
	2	0.19	0.02	8.31
	3	0.23	0.04	6.36
	4	0.18	0.03	5.79
	Mean	0.20	0.03	6.85
900-1000	**1**	0.21	0.04	5.70
	2	0.17	0.02	9.41
	3	0.21	0.04	5.77
	4	0.16	0.03	5.38
	Mean	0.19	0.03	6.56
1000-1100	**1**	0.18	0.04	4.98
	2	0.13	0.03	4.50
	3	0.19	0.04	4.87
	4	0.17	0.03	5.59
	Mean	0.17	0.03	4.99
1100-1200	**1**	0.18	0.04	5.07
	2	0.10	0.02	4.12
	3	0.20	0.04	5.20
	4	0.14	0.03	5.00
	Mean	0.16	0.03	4.85

Profile/Site 210

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.00	0.06	16.43
	2	1.18	0.09	13.36
	3	1.27	0.09	14.25
	4	1.06	0.08	13.66
	Mean	1.13	0.08	14.42
50-100	1	0.91	0.06	14.24
	2	0.97	0.06	17.21
	3	1.13	0.07	16.88
	4	0.89	0.06	14.96
	Mean	0.98	0.06	15.82
100-150	1	0.80	0.07	11.54
	2	0.80	0.07	12.14
	3	1.05	0.07	15.77
	4	0.96	0.06	16.10
	Mean	0.90	0.07	13.89
150-200	1	0.69	0.07	9.77
	2	0.87	0.06	14.19
	3	1.03	0.06	17.87
	4	0.92	0.07	13.25
	Mean	0.88	0.06	13.77
200-250	1	0.78	0.08	10.39
	2	0.88	0.06	15.77
	3	0.83	0.06	14.17
	4	0.89	0.06	15.90
	Mean	0.85	0.06	14.05
250-300	1	0.79	0.05	15.45
	2	0.81	0.06	14.53
	3	0.98	0.06	16.93
	4	0.89	0.06	14.10
	Mean	0.87	0.06	15.25
300-400	1	0.70	0.05	12.92
	2	0.72	0.05	13.96
	3	0.73	0.05	16.28
	4	0.71	0.06	12.81
	Mean	0.71	0.05	13.99
400-500	1	0.69	0.04	16.73
	2	0.64	0.04	15.63
	3	0.70	0.04	16.99
	4	0.67	0.05	13.54
	Mean	0.67	0.04	15.72
500-600	1	0.62	0.04	14.44
	2	0.61	0.05	13.48
	3	0.61	0.04	14.90
	4	0.56	0.04	13.54
	Mean	0.60	0.04	14.09
600-700	1	0.55	0.03	16.06
	2	0.47	0.04	12.42
	3	0.46	0.04	12.99
	4	0.45	0.04	12.20
	Mean	0.48	0.04	13.42
700-800	1	0.37	0.03	13.34
	2	0.45	0.04	11.24
	3	0.43	0.04	11.33
	4	0.31	0.03	11.18
	Mean	0.39	0.03	11.77
800-900	1	0.27	0.03	8.73
	2	0.26	0.03	8.98
	3	0.26	0.03	8.00
	4	0.36	0.03	11.17
	Mean	0.29	0.03	9.22
900-1000	1	0.24	0.03	9.54
	2	0.23	0.03	8.07
	3	0.22	0.04	5.79
	4			
	Mean	0.23	0.03	7.80
1000-1100	1			
	2	0.20	0.03	6.88
	3	0.19	0.03	7.08
	4			
	Mean	0.19	0.03	6.98
1100-1200	1			
	2	0.13	0.02	6.02
	3	0.17	0.05	3.83
	4			
	Mean	0.15	0.03	4.92

Profile/Site 212

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.20	0.07	17.43
	2	1.14	0.06	19.60
	3	1.06	0.06	17.37
	4	1.03	0.07	15.81
	Mean	1.11	0.06	17.55
50-100	1	0.91	0.05	18.07
	2	0.91	0.06	16.00
	3	0.84	0.06	14.67
	4	0.81	0.05	16.96
	Mean	0.87	0.05	15.77
100-150	1	0.81	0.05	14.41
	2	0.78	0.05	13.76
	3	0.77	0.06	12.70
	4	0.68	0.05	14.16
	Mean	0.76	0.05	15.73
150-200	1	0.83	0.05	12.93
	2	0.66	0.05	16.18
	3	0.80	0.05	14.96
	4	0.72	0.05	14.95
	Mean	0.75	0.05	15.20
200-250	1	0.82	0.05	15.20
	2	0.68	0.04	15.96
	3	0.76	0.04	17.69
	4	0.65	0.05	14.20
	Mean	0.73	0.05	15.76
250-300	1	0.74	0.05	16.29
	2	0.68	0.04	15.41
	3	0.64	0.05	12.44
	4	0.62	0.04	14.73
	Mean	0.67	0.05	14.72
300-400	1	0.57	0.04	13.43
	2	0.57	0.04	15.22
	3	0.58	0.04	13.77
	4	0.53	0.03	16.55
	Mean	0.56	0.04	14.74
400-500	1	0.51	0.04	14.27
	2	0.50	0.03	14.56
	3	0.47	0.03	13.84
	4	0.44	0.03	13.77
	Mean	0.48	0.03	14.11
500-600	1	0.39	0.03	13.22
	2	0.48	0.03	14.02
	3	0.44	0.03	14.24
	4	0.36	0.03	14.76
	Mean	0.42	0.03	14.06
600-700	1	0.32	0.03	12.51
	2	0.41	0.03	15.71
	3	0.33	0.03	13.07
	4	0.30	0.02	13.13
	Mean	0.34	0.02	13.61
700-800	1	0.25	0.02	11.26
	2	0.30	0.02	13.39
	3	0.30	0.02	13.79
	4	0.23	0.02	10.84
	Mean	0.27	0.02	12.32
800-900	1	0.25	0.02	13.29
	2	0.27	0.02	13.28
	3	0.28	0.02	12.99
	4	0.18	0.02	9.43
	Mean	0.25	0.02	12.25
900-1000	1	0.20	0.02	10.91
	2	0.24	0.02	12.50
	3	0.22	0.02	10.97
	4	0.16	0.02	9.32
	Mean	0.20	0.02	10.92
1000-1100	1	0.15	0.02	8.18
	2	0.21	0.02	10.48
	3	0.18	0.02	12.10
	4	0.16	0.12	9.19
	Mean	0.18	0.02	9.99
1100-1200	1	0.12	0.02	7.11
	2	0.15	0.02	8.64
	3	0.15	0.02	7.59
	4	0.10	0.02	6.39
	Mean	0.13	0.02	7.43

Profile/Site 220

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	0.85	0.04	19.44
	2	0.92	0.06	16.58
	3	1.05	0.07	15.84
	4	0.86	0.05	15.73
	Mean	0.92	0.06	16.90
50-100	1	0.91	0.04	24.72
	2	0.85	0.05	18.09
	3	0.89	0.05	17.23
	4	0.76	0.04	18.11
	Mean	0.85	0.04	19.53
100-150	1	0.69	0.04	16.96
	2	0.76	0.05	15.45
	3	0.80	0.04	22.25
	4	0.72	0.04	2020
	Mean	0.74	0.04	18.71
150-200	1	0.66	0.04	16.61
	2	0.64	0.04	15.05
	3	0.73	0.05	15.60
	4	0.71	0.05	15.33
	Mean	0.68	0.04	15.65
200-250	1	0.65	0.04	17.69
	2	0.67	0.04	17.15
	3	0.71	0.04	16.32
	4	0.70	0.04	17.54
	Mean	0.68	0.04	17.17
250-300	1	0.58	0.04	14.87
	2	0.63	0.03	19.27
	3	0.64	0.04	17.31
	4	0.68	0.05	14.89
	Mean	0.63	0.04	16.59
300-400	1	0.55	0.04	14.56
	2	0.54	0.04	15.07
	3	0.57	0.04	13.86
	4	0.53	0.04	13.45
	Mean	0.55	0.04	14.23
400-500	1	0.52	0.04	13.97
	2	0.50	0.03	14.66
	3	0.50	0.03	15.36
	4	0.51	0.04	13.71
	Mean	0.51	0.04	14.43
500-600	1	0.36	0.03	13.04
	2	0.41	0.03	14.75
	3	0.40	0.03	14.38
	4	0.43	0.03	13.97
	Mean	0.40	0.03	14.03
600-700	1	0.23	0.02	9.99
	2	0.29	0.03	11.24
	3	0.25	0.02	10.51
	4	0.30	0.02	14.19
	Mean	0.27	0.02	11.48
700-800	1	0.16	0.02	8.69
	2	0.21	0.02	9.90
	3	0.18	0.02	9.46
	4	0.21	0.02	11.03
	Mean	0.19	0.02	9.77
800-900	1	0.16	0.02	9.13
	2	0.16	0.02	9.10
	3	0.17	0.02	10.89
	4	0.19	0.02	9.47
	Mean	0.17	0.02	9.65
900-1000	1	0.11	0.01	8.37
	2	0.12	0.01	8.50
	3	0.15	0.01	10.67
	4	0.14	0.02	9.15
	Mean	0.13	0.01	9.17
1000-1100	1	0.09	0.01	8.13
	2	0.10	0.01	7.20
	3	0.12	0.02	7.83
	4	0.12	0.01	12.52
	Mean	0.11	0.01	8.92
1100-1200	1	0.11	0.01	10.36
	2	0.12	0.02	6.54
	3	0.11	0.02	5.51
	4	0.10	0.01	7..87
	Mean	0.11	0.02	7.57

Profile/Site 221

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	0.83	0.07	12.54
	2	0.85	0.07	11.59
	3	0.87	0.08	11.06
	4	0.95	0.07	13.23
	Mean	0.87	0.07	12.11
50-100	1	0.68	0.07	10.40
	2	0.66	0.07	9.28
	3	0.74	0.07	10.51
	4	0.84	0.07	11.58
	Mean	0.73	0.07	10.44
100-150	1	0.69	0.07	10.16
	2	0.63	0.06	10.24
	3	0.68	0.07	9.62
	4	0.79	0.07	11.35
	Mean	0.70	0.07	10.34
150-200	1	0.65	0.06	10.12
	2	0.59	0.06	10.24
	3	0.65	0.06	10.57
	4	0.82	0.07	11.23
	Mean	0.68	0.06	10.54
200-250	1	0.64	0.06	10.49
	2	0.62	0.06	9.97
	3	0.70	0.06	11.77
	4	0.68	0.06	11.00
	Mean	0.66	0.06	10.81
250-300	1	0.61	0.06	10.20
	2	0.54	0.06	9.83
	3	0.46	0.06	7.70
	4	0.57	0.05	11.13
	Mean	0.54	0.06	9.71
300-400	1	0.54	0.06	9.68
	2	0.53	0.05	11.20
	3	0.56	0.05	11.13
	4	0.49	0.05	10.89
	Mean	0.53	0.05	10.73
400-500	1	0.44	0.05	9.24
	2	0.47	0.46	10.27
	3	0.50	0.05	9.97
	4	0.39	0.04	9.92
	Mean	0.45	0.05	9.85
500-600	1	0.38	0.04	9.27
	2	0.34	0.04	9.35
	3	0.39	0.04	9.97
	4	0.23	0.03	8.07
	Mean	0.34	0.04	9.16
600-700	1	0.24	0.03	7.14
	2	0.21	0.03	7.03
	3	0.25	0.03	7.36
	4	0.17	0.03	6.03
	Mean	0.21	0.03	6.89
700-800	1	0.16	0.03	5.85
	2	0.20	0.03	6.56
	3	0.21	0.03	7.00
	4	0.14	0.02	5.82
	Mean	0.18	0.03	6.30
800-900	1	0.15	0.03	5.87
	2	0.14	0.03	5.00
	3	0.17	0.03	5.65
	4	0.14	0.03	5.19
	Mean	0.15	0.03	5.43
900-1000	1	0.15	0.03	5.16
	2	0.18	0.03	6.32
	3	0.16	0.03	5.71
	4	0.14	0.03	4.51
	Mean	0.16	0.03	5.43
1000-1100	1	0.14	0.03	5.67
	2	0.14	0.03	4.96
	3	0.16	0.03	5.59
	4	0.12	0.03	4.25
	Mean	0.14	0.03	5.12
1100-1200	1	0.14	0.03	5.15
	2	0.13	0.03	4.18
	3	0.15	0.03	4.74
	4	0.16	0.03	5.19
	Mean	0.15	0.03	4.81

Profile/Site 222

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.14	0.07	15.28
	2	0.99	0.09	10.79
	3	0.92	0.08	11.43
	4	0.68	0.05	12.55
	Mean	0.93	0.08	12.51
50-100	1	0.83	0.06	13.25
	2	0.86	0.06	15.02
	3	0.90	0.07	13.14
	4	0.61	0.04	13.79
	Mean	0.80	0.06	13.80
100-150	1	0.77	0.06	12.68
	2	0.73	0.05	14.53
	3	0.81	0.07	12.06
	4	0.62	0.05	13.16
	Mean	0.73	0.06	13.11
150-200	1	0.77	0.06	13.02
	2	0.76	0.06	12.43
	3	0.79	0.05	15.02
	4	0.71	0.06	11.97
	Mean	0.76	0.06	13.11
200-250	1	0.76	0.06	12.92
	2	0.78	0.06	13.83
	3	0.76	0.06	13.20
	4	0.81	0.06	12.92
	Mean	0.78	0.06	13.22
250-300	1	0.76	0.06	13.05
	2	0.68	0.05	12.85
	3	0.70	0.06	12.34
	4	0.76	0.05	14.39
	Mean	0.73	0.06	13.16
300-400	**1**	0.51	0.05	10.69
	2	0.65	0.05	11.88
	3	0.63	0.05	12.41
	4	0.62	0.05	11.35
	Mean	0.60	0.05	11.58
400-500	**1**	0.35	0.03	11.02
	2	0.46	0.05	9.96
	3	0.53	0.05	11.17
	4	0.48	0.04	12.76
	Mean	0.45	0.04	11.23
500-600	**1**	0.26	0.04	7.28
	2	0.36	0.04	8.93
	3	0.32	0.03	9.48
	4	0.29	0.03	10.17
	Mean	0.31	0.03	8.96
600-700	**1**	0.15	0.03	5.36
	2	0.20	0.03	6.26
	3	0.22	0.03	8.82
	4	0.18	0.02	7.76
	Mean	0.19	0.03	7.05
700-800	**1**	0.16	0.04	3.71
	2	0.16	0.04	3.86
	3	0.17	0.02	7.10
	4	0.11	0.02	5.27
	Mean	0.15	0.03	4.98
800-900	**1**	0.10	0.04	2.49
	2	0.14	0.04	3.30
	3			
	4	0.10	0.02	4.73
	Mean	0.11	0.03	3.50
900-1000	**1**	0.07	0.04	1.55
	2	0.12	0.05	2.58
	3			
	4	0.05	0.02	2.58
	Mean	0.08	0.04	2.24
1000-1100	**1**			
	2			
	3			
	4			
	Mean			
1100-1200	**1**			
	2			
	3			
	4			
	Mean			

Profile/Site 232

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.34	0.10	14.14
	2	1.21	0.09	14.09
	3	1.06	0.08	13.84
	4	0.98	0.08	12.92
	Mean	1.15	0.08	13.75
50-100	1	1.05	0.09	12.09
	2	1.00	0.08	13.22
	3	0.93	0.08	12.33
	4	0.97	0.07	13.80
	Mean	0.99	0.08	12.86
100-150	1	0.94	0.07	12.84
	2	0.80	0.06	12.41
	3	0.75	0.07	10.95
	4	1.01	0.07	14.14
	Mean	0.88	0.07	12.59
150-200	1	0.85	0.07	12.52
	2	0.79	0.06	12.84
	3	0.70	0.07	10.73
	4	0.82	0.06	13.08
	Mean	0.72	0.06	12.73
200-250	1	0.74	0.06	12.61
	2	0.72	0.06	12.99
	3	0.68	0.06	12.24
	4	0.74	0.06	13.08
	Mean	0.72	0.06	12.73
250-300	1	0.82	0.06	14.50
	2	0.76	0.05	15.14
	3	0.80	0.06	14.19
	4	0.71	0.05	14.62
	Mean	0.77	0.05	14..61
300-400	1	0.59	0.05	11.74
	2	0.60	0.05	11.10
	3	0.59	0.05	11.07
	4	0.61	0.06	10.74
	Mean	0.60	0.05	11.16
400-500	1	0.48	0.04	12.16
	2	0.51	0.04	11.68
	3	0.54	0.05	10.66
	4	0.51	0.05	11.32
	Mean	0.51	0.04	11.46
500-600	1	0.40	0.04	11.12
	2	0.40	0.04	10.18
	3	0.44	0.05	9.52
	4	0.43	0.04	12.29
	Mean	0.42	0.04	10.78
600-700	1	0.20	0.03	7.57
	2	0.21	0.03	8.43
	3	0.33	0.03	10.02
	4	0.25	0.03	9.01
	Mean	0.25	0.03	8.76
700-800	1	0.18	0.02	7.91
	2	0.15	0.02	7.56
	3	0.18	0.02	8.40
	4	0.19	0.02	8.40
	Mean	0.18	0.02	8.07
800-900	1	0.22	0.03	8.37
	2	0.16	0.02	8.76
	3	0.18	0.02	8.01
	4	0.15	0.02	7.21
	Mean	0.18	0.02	8.09
900-1000	1	0.16	0.02	8.56
	2	0.16	0.02	7.69
	3	0.16	0.02	7.66
	4	0.12	0.02	6.78
	Mean	0.15	0.02	7.67
1000-1100	1	0.18	0.02	8.75
	2	0.19	0.02	8.36
	3	0.15	0.02	7.63
	4	0.13	0.02	6.60
	Mean	0.16	0.02	7.83
1100-1200	1	0.12	0.02	5.87
	2	0.14	0.03	5.69
	3	0.15	0.02	6.54
	4	0.17	0.03	6.83
	Mean	0.15	0.02	6.23

Profile/Site 233

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	0.75	0.05	14.34
	2	1.22	0.07	17.21
	3	1.02	0.07	14.37
	4	0.76	0.05	15.40
	Mean	0.94	0.06	15.33
50-100	1	0.77	0.06	13.76
	2	0.92	0.06	16.52
	3	0.96	0.06	16.21
	4	0.77	0.06	13.45
	Mean	0.85	0.06	14.98
100-150	1	0.72	0.05	14.64
	2	0.72	0.05	14.16
	3	0.73	0.05	14.34
	4	0.73	0.06	13.23
	Mean	0.73	0.05	14.09
150-200	1	0.66	0.05	13.62
	2	0.65	0.05	12.61
	3	0.69	0.04	16.67
	4	0.64	0.05	13.02
	Mean	0.66	0.05	13.98
200-250	1	0.67	0.05	13.60
	2	0.69	0.05	14.11
	3	0.65	0.05	14.18
	4	0.70	0.05	13.52
	Mean	0.68	0.05	13.85
250-300	1	0.70	0.05	14.29
	2	0.69	0.05	14.74
	3	0.60	0.05	13.21
	4	0.60	0.04	14.08
	Mean	0.65	0.05	14.08
300-400	1	0.56	0.05	12.10
	2	0.57	0.05	12.52
	3	0.55	0.04	15.15
	4	0.51	0.04	14.70
	Mean	0.55	0.04	13.62
400-500	1	0.47	0.04	10.77
	2	0.49	0.04	13.07
	3	0.38	0.03	13.18
	4	0.28	0.03	11.23
	Mean	0.41	0.03	12.06
500-600	1	0.35	0.03	11.14
	2	0.41	0.04	11.12
	3	0.26	0.02	10.96
	4	0.17	0.02	11.06
	Mean	0.30	0.03	11.07
600-700	1	0.27	0.02	11.32
	2	0.33	0.03	11.00
	3	0.18	0.02	10.38
	4	0.15	0.02	9.92
	Mean	0.23	0.02	10.88
700-800	1	0.17	0.02	9.98
	2	0.31	0.02	13.22
	3	0.25	0.03	9.76
	4	0.25	0.03	8.11
	Mean	0.24	0.02	10.27
800-900	1	0.27	0.04	7.49
	2	0.26	0.02	11.01
	3	0.28	0.05	5.55
	4	0.33	0.05	7.35
	Mean	0.28	0.04	7.85
900-1000	1	0.32	0.05	6.84
	2	0.38	0.04	9.22
	3	0.40	0.04	9.29
	4	0.26	0.04	6.62
	Mean	0.34	0.04	7.99
1000-1100	1	0.26	0.04	6.91
	2	0.39	0.05	8.84
	3	0.35	0.05	7.56
	4	0.22	0.04	6.40
	Mean	0.31	0.04	7.43
1100-1200	1	0.22	0.04	6.35
	2	0.28	0.04	7.21
	3	0.28	0.04	6.95
	4	0.19	0.03	5.85
	Mean	0.25	0.04	6.59

Profile/Site 235

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.13	0.07	16.13
	2	1.09	0.08	13.63
	3	1.36	0.09	15.54
	4	1.30	0.08	15.55
	Mean	1.22	0.08	15.21
50-100	1	0.99	0.08	13.18
	2	1.02	0.07	13.78
	3	1.00	0.08	12.05
	4	1.06	0.07	14.43
	Mean	1.02	0.08	13.36
100-150	1	0.76	0.06	11.97
	2	0.85	0.06	13.73
	3	0.94	0.07	13.61
	4	0.86	0.07	12.89
	Mean	0.85	0.07	13.05
150-200	1	0.77	0.06	12.66
	2	0.78	0.06	12.19
	3	0.87	0.07	13.09
	4	0.76	0.06	12.75
	Mean	0.79	0.06	12.67
200-250	1	0.62	0.05	12.64
	2	0.62	0.05	12.02
	3	0.74	0.06	11.10
	4	0.69	0.06	10.74
	Mean	0.67	0.06	11.85
250-300	1	0.60	0.05	13.19
	2	0.61	0.05	13.55
	3	0.54	0.05	10.61
	4	0.59	0.05	11.13
	Mean	0.59	0.05	12.12
300-400	1	0.53	0.05	10.44
	2	0.56	0.05	12.07
	3	0.60	0.05	11.72
	4	0.54	0.05	11.01
	Mean	0.56	0.05	11.31
400-500	1	0.45	0.04	11.03
	2	0.48	0.05	10.21
	3	0.56	0.05	11.45
	4	0.47	0.04	11.08
	Mean	0.49	0.04	10.94
500-600	1	0.34	0.04	8.78
	2	0.49	0.05	10.19
	3	0.55	0.05	12.48
	4	0.32	0.04	8.35
	Mean	0.42	0.04	9.95
600-700	1	0.32	0.05	7.06
	2	0.40	0.05	8.55
	3	0.44	0.04	11.11
	4	0.34	0.04	8.32
	Mean	0.38	0.04	8.76
700-800	1	0.26	0.04	6.37
	2	0.32	0.04	7.32
	3	0.37	0.05	7.66
	4	0.27	0.04	7.79
	Mean	0.31	0.04	7.28
800-900	1	0.22	0.04	5.81
	2	0.21	0.04	6.10
	3	0.30	0.05	6.62
	4	0.23	0.04	5.37
	Mean	0.24	0.04	5.98
900-1000	1	0.18	0.04	4.95
	2	0.15	0.03	4.52
	3	0.20	0.04	5.58
	4	0.21	0.04	5.60
	Mean	0.18	0.04	5.16
1000-1100	1	0.15	0.03	5.71
	2	0.14	0.03	4.66
	3	0.18	0.04	5.03
	4	0.20	0.03	5.86
	Mean	0.17	0.03	5.31
1100-1200	1	0.12	0.03	4.08
	2	0.14	0.03	4.22
	3	0.15	0.03	5.08
	4	0.30	0.04	8.01
	Mean	0.18	0.03	5.35

Profile/Site 240

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.52	0.11	13.30
	2	1.56	0.13	11.99
	3	1.55	0.13	11.63
	4	1.56	0.12	12.48
	Mean	1.55	0.13	12.35
50-100	1	1.41	0.10	14.73
	2	1.45	0.10	14.78
	3	1.26	0.11	11.94
	4	1.50	0.10	14.30
	Mean	1.40	0.10	13.94
100-150	1	1.33	0.10	13.64
	2	1.30	0.09	14.68
	3	1.45	0.11	13.24
	4	1.54	0.09	16.74
	Mean	1.40	0.10	14.58
150-200	1	1.14	0.08	13.73
	2	1.13	0.08	14.50
	3	1.29	0.08	15.54
	4	1.22	0.08	15.17
	Mean	1.19	0.08	14.73
200-250	1	1.07	0.08	12.85
	2	1.04	0.07	14.29
	3	1.18	0.08	14.50
	4	1.17	0.08	13.88
	Mean	1.12	0.08	13.88
250-300	1	1.09	0.08	13.79
	2	1.03	0.08	13.44
	3	1.11	0.09	13.02
	4	1.04	0.07	13.94
	Mean	1.07	0.08	13.55
300-400	1	0.96	0.07	13.20
	2	0.88	0.06	14.37
	3	1.02	0.07	15.17
	4	0.93	0.07	13.98
	Mean	0.94	0.07	14.18
400-500	1	0.77	0.07	11.79
	2	0.77	0.06	12.43
	3	0.78	0.07	11.68
	4	0.77	0.05	15.03
	Mean	0.77	0.06	12.73
500-600	1	0.68	0.06	11.70
	2	0.69	0.06	11.35
	3	0.70	0.05	12.94
	4	0.68	0.05	12.66
	Mean	0.69	0.06	12.16
600-700	1	0.54	0.05	11.18
	2	0.58	0.05	10.82
	3	0.53	0.05	11.91
	4	0.57	0.05	10.67
	Mean	0.56	0.05	11.15
700-800	1	0.39	0.04	9.54
	2	0.45	0.04	10.81
	3	0.40	0.04	9.65
	4	0.43	0.04	11.03
	Mean	0.42	0.04	10.26
800-900	1	0.31	0.03	9.18
	2	0.34	0.04	8.62
	3	0.30	0.04	8.27
	4	0.33	0.04	8.64
	Mean	0.32	0.04	8.68
900-1000	1	0.24	0.03	7.13
	2	0.27	0.03	7.78
	3	0.22	0.03	6.56
	4	0.26	0.04	7.03
	Mean	0.24	0.03	7.12
1000-1100	1	0.20	0.03	7.11
	2	0.25	0.04	6.50
	3	0.18	0.03	6.87
	4	0.23	0.03	6.99
	Mean	0.22	0.03	6.87
1100-1200	1	0.17	0.03	5.23
	2	0.21	0.03	6.08
	3	0.17	0.03	4.89
	4	0.19	0.03	5.84
	Mean	0.18	0.03	5.51

Profile/Site 241

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.30	0.07	18.51
	2	1.34	0.09	14.93
	3	1.23	0.08	16.09
	4	1.43	0.09	15.59
	Mean	1.32	0.08	16.28
50-100	1	0.97	0.08	12.14
	2	0.98	0.08	13.03
	3	0.96	0.07	12.92
	4	1.16	0.08	14.87
	Mean	1.02	0.08	13.24
100-150	1	0.80	0.06	12.79
	2	0.96	0.06	16.10
	3	0.86	0.07	12.67
	4	0.93	0.07	13.39
	Mean	0.89	0.06	13.74
150-200	1	0.76	0.06	13.06
	2	0.79	0.06	14.07
	3	0.82	0.06	12.71
	4	0.88	0.06	13.64
	Mean	0.81	0.06	13.37
200-250	1	0.72	0.06	12.16
	2	0.82	0.05	16.65
	3	0.84	0.05	15.58
	4	0.97	0.07	14.60
	Mean	0.84	0.06	14.75
250-300	1	0.69	0.05	12.57
	2	0.59	0.04	13.94
	3	0.72	0.04	17.16
	4	0.76	0.07	11.59
	Mean	0.69	0.05	13.82
300-400	1	0.56	0.05	12.43
	2	0.53	0.04	12.08
	3	0.51	0.04	11.66
	4	0.61	0.05	11.36
	Mean	0.55	0.05	11.88
400-500	1	0.47	0.04	13.00
	2	0.46	0.04	11.13
	3	0.51	0.04	11.90
	4	0.55	0.04	13.61
	Mean	0.50	0.04	12.41
500-600	1	0.41	0.03	12.15
	2	0.35	0.03	11.20
	3	0.47	0.03	17.63
	4	0.46	0.04	10.94
	Mean	0.42	0.03	12.98
600-700	1	0.43	0.05	8.76
	2	0.31	0.05	6.46
	3	0.50	0.05	9.54
	4	0.53	0.05	9.86
	Mean	0.44	0.05	8.66
700-800	1	0.59	0.05	12.36
	2	0.34	0.05	6.48
	3	0.53	0.06	9.35
	4	0.53	0.04	12.31
	Mean	0.50	0.05	10.12
800-900	1	0.35	0.04	8.93
	2	0.30	0.05	6.41
	3	0.39	0.05	8.42
	4	0.32	0.04	8.28
	Mean	0.34	0.04	8.01
900-1000	1	0.23	0.04	6.09
	2	0.29	0.04	6.64
	3	0.39	0.04	9.15
	4	0.23	0.03	6.85
	Mean	0.28	0.04	7.18
1000-1100	1	0.17	0.03	6.04
	2	0.22	0.05	4.83
	3	0.26	0.05	5.46
	4	0.20	0.03	6.04
	Mean	0.21	0.04	5.59
1100-1200	1	0.20	0.02	9.69
	2	0.21	0.04	5.19
	3	0.25	0.05	5.32
	4	0.26	0.03	9.99
	Mean	0.23	0.03	7.55

Profile/Site 242

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.03	0.08	13.70
	2	1.31	0.09	14.81
	3	1.49	0.11	13.53
	4	1.27	0.08	15.59
	Mean	1.28	0.09	14.41
50-100	1	1.06	0.06	17.66
	2	0.98	0.07	14.84
	3	1.08	0.07	15.90
	4	1.02	0.06	16.28
	Mean	1.04	0.06	16.17
100-150	1	0.96	0.06	16.91
	2	1.09	0.06	16.99
	3	0.97	0.06	16.88
	4	1.02	0.06	17.69
	Mean	1.01	0.06	17.12
150-200	1	0.98	0.05	19.80
	2	0.93	0.06	16.19
	3	1.14	0.05	21.38
	4	0.78	0.06	13.62
	Mean	0.96	0.05	17.75
200-250	1	1.05	0.05	21.58
	2	0.78	0.05	14.81
	3	0.66	0.05	12.64
	4	0.91	0.06	15.62
	Mean	0.85	0.05	16.16
250-300	1	0.59	0.05	12.74
	2	0.57	0.04	13.80
	3	0.75	0.05	13.89
	4	0.66	0.05	14.01
	Mean	0.64	0.05	13.61
300-400	**1**	0.58	0.05	11.15
	2	0.57	0.04	14.66
	3	0.55	0.05	12.10
	4	0.54	0.04	12.29
	Mean	0.56	0.05	12.55
400-500	**1**	0.55	0.04	12.96
	2	0.48	0.04	13.08
	3	0.59	0.04	15.12
	4	0.46	0.04	11.30
	Mean	0.52	0.04	13.11
500-600	**1**	0.51	0.04	12.10
	2	0.33	0.04	9.26
	3	0.49	0.04	12.49
	4	0.71	0.03	25.85
	Mean	0.51	0.04	14.93
600-700	**1**	0.60	0.04	17.34
	2	0.48	0.03	14.30
	3	0.53	0.04	14.64
	4	0.42	0.03	12.89
	Mean	0.51	0.03	14.80
700-800	**1**	0.31	0.03	9.60
	2	0.24	0.03	7.51
	3	0.23	0.03	7.34
	4	0.24	0.03	8.73
	Mean	0.26	0.03	8.29
800-900	**1**	0.15	0.03	5.06
	2	0.21	0.03	6.50
	3	0.17	0.03	6.50
	4	0.18	0.03	6.62
	Mean	0.18	0.03	6.17
900-1000	**1**	0.32	0.03	11.25
	2	0.37	0.03	13.90
	3	0.15	0.02	6.82
	4	0.32	0.03	12.16
	Mean	0.29	0.03	11.03
1000-1100	**1**			
	2	0.20	0.02	9.64
	3	0.09	0.02	5.09
	4	0.14	0.02	6.29
	Mean	0.14	0.02	7.00
1100-1200	**1**			
	2	0.11	0.02	5.83
	3	0.28	0.02	13.47
	4	0.16	0.02	8.45
	Mean	0.18	0.02	9.25

Profile/Site 243

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.48	0.11	13.49
	2	1.34	0.09	14.84
	3	1.49	0.10	14.44
	4	1.49	0.10	14.76
	Mean	1.45	0.10	14.38
50-100	1	1.25	0.09	13.71
	2	1.04	0.09	11.99
	3	1.29	0.11	12.26
	4	1.30	0.10	13.48
	Mean	1.22	0.09	12.86
100-150	1	1.10	0.08	14.56
	2	1.05	0.08	12.45
	3	1.12	0.08	13.25
	4	1.07	0.10	11.08
	Mean	1.08	0.09	12.83
150-200	1	1.07	0.08	13.37
	2	0.93	0.08	11.16
	3	1.03	0.07	14.04
	4	0.99	0.07	13.69
	Mean	1.01	0.08	13.07
200-250	1	0.86	0.07	12.93
	2	0.90	0.08	10.65
	3	0.98	0.08	12.39
	4	0.93	0.08	12.07
	Mean	0.92	0.08	12.01
250-300	1	0.77	0.06	13.85
	2	0.87	0.07	12.11
	3	0.86	0.07	12.07
	4	0.79	0.06	12.99
	Mean	0.82	0.06	12.76
300-400	1	0.66	0.06	10.59
	2	0.63	0.06	10.80
	3	0.70	0.06	11.01
	4	0.62	0.06	10.61
	Mean	0.66	0.06	10.75
400-500	1	0.55	0.05	10.82
	2	0.58	0.05	11.26
	3	0.61	0.05	11.89
	4	0.53	0.05	11.54
	Mean	0.57	0.05	11.38
500-600	1	0.45	0.05	9.87
	2	0.46	0.05	10.05
	3	0.52	0.04	12.00
	4	0.44	0.05	9.80
	Mean	0.47	0.05	10.43
600-700	1	0.30	0.04	8.31
	2	0.28	0.03	8.35
	3	0.34	0.04	9.01
	4	0.30	0.03	9.52
	Mean	0.30	0.03	8.80
700-800	1	0.23	0.03	8.00
	2	0.21	0.03	7.53
	3	0.23	0.03	7.54
	4	0.21	0.03	6.70
	Mean	0.22	0.03	7.44
800-900	1	0.17	0.02	7.91
	2	0.14	0.02	5.83
	3	0.19	0.03	6.98
	4	0.14	0.02	6.24
	Mean	0.16	0.02	6.74
900-1000	1	0.16	0.02	8.65
	2	0.14	0.02	7.45
	3	0.13	0.02	5.73
	4	0.12	0.02	5.95
	Mean	0.14	0.02	6.94
1000-1100	1	0.16	0.02	7.78
	2	0.09	0.01	6.75
	3	0.13	0.02	7.32
	4	0.09	0.02	4.00
	Mean	0.12	0.02	6.46
1100-1200	1	0.17	0.02	9.64
	2	0.08	0.01	8.79
	3	0.10	0.01	7.62
	4	0.12	0.01	8.71
	Mean	0.12	0.01	8.69

Profile/Site 244

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.31	0.08	16.48
	2	1.32	0.09	15.48
	3	1.44	0.08	18.46
	4	1.43	0.09	15.49
	Mean	1.37	0.08	16.48
50-100	1	0.98	0.07	14.05
	2	1.01	0.07	14.37
	3	1.06	0.07	15.11
	4	0.90	0.07	13.77
	Mean	0.99	0.07	14.32
100-150	1	0.80	0.06	12.62
	2	0.92	0.06	15.31
	3	0.97	0.06	16.84
	4	0.80	0.06	14.44
	Mean	0.87	0.06	14.80
150-200	1	0.84	0.06	14.81
	2	0.78	0.06	13.78
	3	0.83	0.06	14.15
	4	0.79	0.06	14.06
	Mean	0.81	0.06	14.20
200-250	1	0.74	0.06	12.70
	2	0.62	0.05	12.04
	3	0.72	0.05	13.70
	4	0.65	0.05	12.72
	Mean	0.68	0.05	12.79
250-300	1	0.64	0.05	12.65
	2	0.61	0.05	13.21
	3	0.67	0.05	13.58
	4	0.63	0.05	13.69
	Mean	0.64	0.05	13.28
300-400	1	0.55	0.05	12.21
	2	0.50	0.04	12.05
	3	0.54	0.04	12.91
	4	0.51	0.04	12.48
	Mean	0.52	0.04	12.41
400-500	1	0.50	0.04	11.82
	2	0.41	0.03	12.41
	3	0.44	0.04	11.38
	4	0.42	0.04	11.84
	Mean	0.44	0.04	11.86
500-600	1	0.40	0.04	11.39
	2	0.29	0.03	10.50
	3	0.28	0.03	10.51
	4	0.29	0.03	11.41
	Mean	0.31	0.03	10.96
600-700	1	0.29	0.03	11.12
	2	0.21	0.02	9.63
	3	0.25	0.03	10.10
	4	0.19	0.02	9.20
	Mean	0.24	0.02	10.01
700-800	1	0.22	0.03	8.66
	2	0.21	0.02	8.85
	3	0.20	0.03	7.93
	4	0.23	0.02	9.78
	Mean	0.22	0.02	8.81
800-900	1	0.21	0.03	7.70
	2	0.20	0.03	7.85
	3	0.23	0.02	9.32
	4	0.21	0.03	8.40
	Mean	0.22	0.03	8.32
900-1000	1	0.15	0.02	7.56
	2	0.14	0.02	6.92
	3	0.13	0.02	6.66
	4	0.17	0.02	7.66
	Mean	0.15	0.02	7.20
1000-1100	1	0.11	0.02	6.40
	2	0.09	0.02	5.12
	3	0.08	0.02	4.39
	4	0.10	0.02	6.31
	Mean	0.09	0.02	5.55
1100-1200	1	0.10	0.02	5.71
	2	0.08	0.02	5.69
	3	0.05	0.02	3.53
	4	0.08	0.01	6.16
	Mean	0.08	0.01	5.27

Profile/Site 245

Depth (mm)	**Replication**	**C (%)**	**N (%)**	**C:N**
0-50	1	1.09	0.15	7.43
	2	1.27	0.14	9.18
	3	1.29	0.15	8.45
	4	1.24	0.15	8.19
	Mean	1.22	0.15	8.31
50-100	1	0.94	0.13	7.33
	2	1.19	0.13	9.21
	3	0.99	0.13	7.74
	4	1.02	0.13	7.89
	Mean	1.03	0.13	8.04
100-150	1	0.92	0.12	7.61
	2	0.93	0.11	8.41
	3	0.81	0.12	7.01
	4	0.88	0.12	7.54
	Mean	0.89	0.12	7.64
150-200	1	0.85	0.11	7.54
	2	0.84	0.11	7.84
	3	0.89	0.11	7.99
	4	0.87	0.11	7.99
	Mean	0.86	0.11	7.84
200-250	1	0.87	0.10	8.99
	2	0.81	0.10	8.19
	3	0.82	0.10	8.49
	4	0.81	0.10	8.12
	Mean	0.83	0.10	8.45
250-300	1	0.77	0.10	7.73
	2	0.73	0.09	7.67
	3	0.79	0.09	8.42
	4	0.71	0.09	7.47
	Mean	0.75	0.10	7.82
300-400	1	0.65	0.10	6.79
	2	0.66	0.09	7.15
	3	0.61	0.10	6.40
	4	0.59	0.09	6.53
	Mean	0.62	0.09	6.72
400-500	1	0.55	0.08	6.61
	2	0.57	0.08	6.72
	3	0.49	0.09	5.74
	4	0.46	0.08	5.46
	Mean	0.51	0.08	6.13
500-600	1	0.41	0.06	6.48
	2	0.44	0.06	6.90
	3	0.37	0.05	7.34
	4	0.32	0.05	6.29
	Mean	0.39	0.06	6.75
600-700	1	0.30	0.05	5.86
	2	0.25	0.05	5.36
	3	0.23	0.05	4.63
	4	0.22	0.05	4.80
	Mean	0.25	0.05	5.16
700-800	1	0.20	0.04	5.03
	2	0.18	0.04	4.83
	3	0.18	0.03	5.48
	4	0.17	0.04	4.40
	Mean	0.18	0.04	4.93
800-900	1	0.14	0.03	5.48
	2	0.18	0.03	5.41
	3	0.14	0.03	5.07
	4	0.11	0.03	4.00
	Mean	0.14	0.03	4.99
900-1000	1	0.16	0.03	5.69
	2	0.16	0.03	4.99
	3	0.13	0.03	5.68
	4	0.09	0.02	4.03
	Mean	0.13	0.03	5.10
1000-1100	1	0.12	0.03	4.25
	2	0.12	0.03	4.69
	3	0.11	0.02	5.96
	4	0.08	0.02	3.71
	Mean	0.11	0.02	4.65
1100-1200	1	0.10	0.02	4.48
	2	0.11	0.02	4.87
	3	0.10	0.02	4.42
	4	0.09	0.02	3.87
	Mean	0.10	0.02	4.41

Profile/Site 246

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.31	0.09	15.19
	2	1.16	0.08	14.12
	3	1.04	0.08	12.98
	4	1.15	0.08	15.13
	Mean	1.17	0.08	14.35
50-100	1	0.88	0.07	13.50
	2	1.01	0.07	14.66
	3	0.93	0.06	15.09
	4	0.79	0.06	13.23
	Mean	0.90	0.06	14.12
100-150	1	1.00	0.07	14.05
	2	0.90	0.07	13.38
	3	0.87	0.06	13.60
	4	0.75	0.05	14.19
	Mean	0.88	0.06	13.80
150-200	1	0.87	0.06	14.03
	2	0.85	0.06	13.59
	3	0.83	0.07	12.82
	4	0.77	0.05	14.25
	Mean	0.83	0.06	13.67
200-250	1	0.81	0.06	13.09
	2	0.81	0.06	13.69
	3	0.74	0.06	13.40
	4	0.70	0.05	12.82
	Mean	0.71	0.06	13.25
250-300	1	0.73	0.06	13.02
	2	0.68	0.06	11.55
	3	0.74	0.06	12.95
	4	0.71	0.05	13.14
	Mean	0.71	0.06	12.66
300-400	1	0.60	0.05	12.06
	2	0.55	0.05	11.23
	3	0.62	0.05	11.99
	4	0.58	0.05	11.86
	Mean	0.59	0.05	11.79
400-500	1	0.56	0.05	11.94
	2	0.43	0.04	11.05
	3	0.33	0.05	6.76
	4	0.54	0.04	12.65
	Mean	0.46	0.04	10.60
500-600	1	0.42	0.04	11.52
	2	0.36	0.04	10.01
	3	0.46	0.04	11.29
	4	0.38	0.04	10.26
	Mean	0.40	0.04	10.77
600-700	1	0.32	0.03	9.52
	2	0.25	0.03	8.31
	3	0.32	0.04	8.99
	4	0.23	0.03	7.14
	Mean	0.28	0.03	8.49
700-800	1	0.18	0.02	7.84
	2	0.17	0.03	6.78
	3	0.24	0.03	8.16
	4	0.18	0.03	6.95
	Mean	0.19	0.03	7.43
800-900	1	0.16	0.02	6.70
	2	0.17	0.02	6.91
	3	0.19	0.03	7.34
	4	0.16	0.02	6.92
	Mean	0.17	0.02	6.97
900-1000	1	0.12	0.02	6.26
	2	0.15	0.02	6.77
	3	0.17	0.02	7.04
	4	0.14	0.02	6.44
	Mean	0.14	0.02	6.63
1000-1100	1	0.14	0.02	7.05
	2	0.12	0.02	6.54
	3	0.10	0.02	5.34
	4	0.10	0.02	5.75
	Mean	0.11	0.02	6.17
1100-1200	1	0.10	0.02	5.52
	2	0.12	0.02	6.53
	3	0.14	0.02	6.54
	4	0.12	0.02	6.20
	Mean	0.12	0.02	6.20

Profile/Site 247

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.06	0.07	15.76
	2	1.13	0.07	16.98
	3	1.18	0.07	17.81
	4	0.96	0.05	18.72
	Mean	1.08	0.06	17.32
50-100	1	0.78	0.05	16.41
	2	0.79	0.04	17.88
	3	0.94	0.05	17.74
	4	0.90	0.05	16.83
	Mean	0.85	0.05	17.21
100-150	1	0.86	0.05	16.53
	2	0.88	0.04	20.08
	3	0.84	0.05	16.24
	4	0.77	0.05	15.34
	Mean	0.84	0.05	17.04
150-200	1	0.71	0.05	14.65
	2	0.72	0.04	16.11
	3	0.75	0.06	13.27
	4	0.77	0.05	15.00
	Mean	0.74	0.05	14.76
200-250	1	0.81	0.05	15.37
	2	0.81	0.05	15.91
	3	0.78	0.05	14.30
	4	0.74	0.05	14.55
	Mean	0.78	0.05	15.03
250-300	1	0.70	0.05	14.27
	2	0.78	0.05	15.46
	3	0.85	0.06	15.06
	4	0.70	0.05	14.44
	Mean	0.76	0.05	14.81
300-400	1	0.64	0.05	13.67
	2	0.66	0.05	13.22
	3	0.63	0.05	13.64
	4	0.60	0.04	13.56
	Mean	0.63	0.05	13.52
400-500	1	0.61	0.05	13.95
	2	0.60	0.05	12.68
	3	0.60	0.04	13.68
	4	0.51	0.04	13.40
	Mean	0.58	0.04	13.43
500-600	1	0.52	0.04	12.62
	2	0.52	0.04	12.17
	3	0.48	0.04	12.55
	4	0.46	0.04	12.62
	Mean	0.50	0.04	12.49
600-700	1	0.41	0.03	12.12
	2	0.44	0.04	12.76
	3	0.43	0.032	13.46
	4	0.41	0.03	14.02
	Mean	0.42	0.03	13.09
700-800	1	0.25	0.03	8.92
	2	0.30	0.03	10.51
	3	0.31	0.03	11.11
	4	0.28	0.03	10.19
	Mean	0.28	0.03	10.18
800-900	1	0.18	0.02	7.94
	2	0.22	0.02	10.54
	3	0.24	0.02	9.61
	4	0.22	0.02	9.22
	Mean	0.21	0.02	9.33
900-1000	1	0.15	0.02	8.50
	2	0.17	0.02	8.75
	3	0.16	0.02	8.02
	4	0.16	0.02	7.96
	Mean	0.16	0.02	8.31
1000-1100	1	0.11	0.02	6.41
	2	0.14	0.02	8.09
	3	0.15	0.02	8.79
	4	0.14	0.02	7.57
	Mean	0.13	0.02	7.72
1100-1200	1	0.14	0.02	8.12
	2	0.12	0.02	8.01
	3	0.14	0.02	9.00
	4	0.10	0.01	7.74
	Mean	0.13	0.02	8.22

Profile/Site 248

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.32	0.08	17.56
	2	0.99	0.07	14.72
	3	1.11	0.08	14.60
	4	0.72	0.05	13.52
	Mean	1.04	0.07	15.10
50-100	1	0.91	0.07	13.17
	2	0.70	0.05	14.06
	3	0.84	0.06	14.78
	4	0.87	0.06	15.74
	Mean	0.83	0.06	14.44
100-150	1	0.94	0.06	15.47
	2	0.75	0.05	15.14
	3	0.81	0.06	13.68
	4	0.79	0.06	13.87
	Mean	0.82	0.06	14.54
150-200	1	0.87	0.06	14.34
	2	0.83	0.06	14.56
	3	0.77	0.06	13.87
	4	0.78	0.05	14.24
	Mean	0.81	0.06	14.25
200-250	1	0.74	0.06	11.92
	2	0.74	0.06	12.17
	3	0.74	0.06	12.53
	4	0.71	0.06	12.40
	Mean	0.73	0.06	12.26
250-300	1	0.73	0.05	13.83
	2	0.82	0.05	16.02
	3	0.69	0.05	13.40
	4	0.73	0.06	13.07
	Mean	0.74	0.05	14.08
300-400	1	0.59	0.05	12.48
	2	0.57	0.05	12.36
	3	0.58	0.05	12.39
	4	0.56	0.05	10.93
	Mean	0.57	0.05	12.04
400-500	1	0.55	0.04	12.29
	2	0.52	0.04	12.01
	3	0.51	0.04	12.75
	4	0.52	0.05	11.49
	Mean	0.52	0.04	12.13
500-600	1	0.47	0.04	11.72
	2	0.53	0.04	12.18
	3	0.47	0.04	12.14
	4	0.48	0.04	11.61
	Mean	0.49	0.04	11.91
600-700	1	0.41	0.04	11.45
	2	0.40	0.04	11.25
	3	0.37	0.03	11.13
	4	0.40	0.03	12.00
	Mean	0.39	0.03	11.46
700-800	1	0.31	0.03	9.81
	2	0.30	0.03	11.74
	3	0.28	0.03	9.85
	4	0.30	0.03	10.58
	Mean	0.30	0.03	10.50
800-900	1	0.28	0.03	10.21
	2	0.24	0.03	9.59
	3	0.27	0.03	9.52
	4	0.19	0.02	8.09
	Mean	0.24	0.03	9.35
900-1000	1	0.22	0.03	8.72
	2	0.20	0.02	8.96
	3	0.16	0.02	7.63
	4	0.16	0.02	7.90
	Mean	0.19	0.02	8.30
1000-1100	1	0.20	0.02	9.06
	2	0.13	0.02	7.11
	3	0.15	0.02	7.38
	4	0.14	0.02	8.04
	Mean	0.15	0.02	7.90
1100-1200	1	0.13	0.02	6.97
	2	0.13	0.02	7.14
	3	0.12	0.02	6.33
	4	0.11	0.02	6.66
	Mean	0.12	0.02	6.78

Profile/Site 249

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.41	0.10	14.47
	2	1.50	0.11	14.22
	3	1.46	0.10	15.25
	4	1.50	0.11	13.08
	Mean	1.47	0.10	14.25
50-100	1	1.31	0.09	15.16
	2	1.37	0.10	14.29
	3	1.44	0.10	13.96
	4	1.49	0.11	13.88
	Mean	1.40	0.10	14.32
100-150	1	1.26	0.09	14.22
	2	1.24	0.09	14.35
	3	1.47	0.10	14.60
	4	1.39	0.11	12.70
	Mean	1.34	0.10	13.97
150-200	1	1.17	0.09	13.14
	2	1.17	0.09	13.31
	3	1.32	0.09	14.34
	4	1.39	0.11	12.76
	Mean	1.26	0.09	13.39
200-250	1	1.14	0.09	12.13
	2	1.29	0.09	14.79
	3	1.14	0.08	13.59
	4	1.30	0.10	13.28
	Mean	1.11	0.08	13.16
250-300	1	1.12	0.09	13.11
	2	1.05	0.08	12.45
	3	1.15	0.08	14.66
	4	1.10	0.09	12.42
	Mean	1.11	0.08	13.16
300-400	1	0.75	0.08	9.25
	2	0.75	0.08	9.73
	3	0.75	0.08	9.29
	4	0.75	0.09	8.42
	Mean	0.75	0.08	9.17
400-500	1	0.74	0.08	9.86
	2	0.75	0.07	10.36
	3	0.72	0.07	10.46
	4	0.73	0.08	9.31
	Mean	0.74	0.07	10.00
500-600	1	0.75	0.08	9.52
	2	0.66	0.06	10.58
	3	0.66	0.06	10.44
	4	0.73	0.07	10.30
	Mean	0.70	0.07	10.21
600-700	1	0.68	0.07	9.88
	2	0.56	0.05	11.98
	3	0.64	0.05	11.81
	4	0.49	0.05	9.11
	Mean	0.59	0.06	10.69
700-800	1	0.57	0.05	10.99
	2	0.38	0.04	9.90
	3	0.47	0.04	11.56
	4	0.41	0.04	9.72
	Mean	0.46	0.04	10.55
800-900	1	0.56	0.05	11.61
	2	0.27	0.03	8.57
	3	0.38	0.03	11.98
	4	0.32	0.03	10.36
	Mean	0.38	0.04	10.63
900-1000	1	0.42	0.04	11.11
	2	0.20	0.02	8.98
	3	0.26	0.03	10.67
	4	0.23	0.02	9.35
	Mean	0.28	0.03	10.03
1000-1100	1	0.33	0.03	10.55
	2	0.15	0.02	10.12
	3	0.21	0.02	10.79
	4	0.16	0.01	11.09
	Mean	0.21	0.02	10.64
1100-1200	1	0.23	0.02	10.75
	2	0.11	0.01	9.78
	3	0.19	0.02	12.82
	4	0.16	0.02	10.71
	Mean	0.17	0.02	11.02

Profile/Site 250

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.48	0.06	23.32
	2	1.49	0.07	20.59
	3	1.31	0.05	24.21
	4	1.08	0.06	17.75
	Mean	1.34	0.06	21.47
50-100	1	1.03	0.06	16.63
	2	1.22	0.07	18.67
	3	1.15	0.06	18.12
	4	0.98	0.05	17.89
	Mean	1.10	0.06	17.83
100-150	1	0.95	0.05	19.24
	2	0.93	0.06	16.06
	3	1.00	0.06	17.15
	4	0.99	0.06	16.99
	Mean	0.97	0.06	17.36
150-200	1	0.90	0.05	17.99
	2	0.86	0.05	16.46
	3	0.91	0.05	19.93
	4	0.94	0.05	19.41
	Mean	0.90	0.05	18.45
200-250	1	0.82	0.05	17.01
	2	0.85	0.05	17.54
	3	0.91	0.05	18.74
	4	1.03	0.05	20.47
	Mean	0.90	0.05	18.44
250-300	1	0.77	0.04	18.63
	2	0.78	0.04	20.38
	3	0.80	0.04	18.38
	4	0.67	0.04	15.24
	Mean	0.76	0.04	18.16
300-400	1	0.66	0.04	15.76
	2	0.65	0.04	16.08
	3	0.67	0.04	16.21
	4	0.65	0.04	16.67
	Mean	0.66	0.04	16.18
400-500	1	0.52	0.04	13.35
	2	0.52	0.03	15.60
	3	0.59	0.04	15.09
	4	0.55	0.03	17.23
	Mean	0.54	0.04	15.32
500-600	1	0.44	0.03	15.73
	2	0.45	0.03	16.07
	3	0.40	0.03	15.02
	4	0.39	0.03	14.36
	Mean	0.42	0.03	15.29
600-700	1	0.37	0.02	16.39
	2	0.35	0.03	14.32
	3	0.26	0.02	13.73
	4	0.24	0.02	12.89
	Mean	0.31	0.02	14.33
700-800	1	0.27	0.02	14.42
	2	0.27	0.02	13.65
	3	0.22	0.02	11.95
	4	0.24	0.02	12.93
	Mean	0.25	0.02	13.24
800-900	1	0.22	0.02	11.98
	2	0.21	0.02	11.75
	3	0.22	0.02	11.18
	4	0.26	0.02	12.97
	Mean	0.23	0.02	11.97
900-1000	1	0.19	0.02	11.54
	2	0.21	0.02	8.42
	3	0.21	0.02	11.19
	4	0.20	0.02	10.02
	Mean	0.20	0.02	10.29
1000-1100	1	0.17	0.02	9.37
	2	0.21	0.02	10.47
	3	0.18	0.02	10.15
	4	0.18	0.02	9.94
	Mean	0.19	0.02	9.98
1100-1200	1	0.17	0.02	10.00
	2	0.19	0.02	9.46
	3	0.18	0.02	9.93
	4	0.17	0.02	9.84
	Mean	0.18	0.02	9.81

Profile/Site 251

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.27	0.08	15.57
	2	1.48	0.10	14.20
	3	1.47	0.09	15.79
	4	1.06	0.07	14.23
	Mean	1.32	0.09	14.95
50-100	1	1.48	0.09	15.68
	2	1.34	0.08	16.25
	3	1.30	0.09	13.91
	4	1.48	0.07	20.74
	Mean	1.40	0.09	16.64
100-150	1	1.04	0.09	11.31
	2	1.27	0.07	18.31
	3	1.04	0.08	13.88
	4	0.89	0.07	13.30
	Mean	1.06	0.08	14.20
150-200	1	0.87	0.07	12.52
	2	1.14	0.08	13.78
	3	0.99	0.07	14.30
	4	0.85	0.07	12.84
	Mean	0.96	0.07	13.36
200-250	1	0.85	0.07	12.29
	2	0.97	0.07	14.20
	3	0.86	0.06	14.36
	4	0.78	0.05	14.29
	Mean	0.86	0.06	13.79
250-300	1	0.77	0.07	10.82
	2	0.79	0.07	11.89
	3	0.84	0.05	16.05
	4	0.67	0.06	12.01
	Mean	0.77	0.06	12.69
300-400	1	0.62	0.07	9.32
	2	0.70	0.06	12.04
	3	0.69	0.05	14.08
	4	0.62	0.05	12.11
	Mean	0.66	0.06	11.89
400-500	1	0.59	0.06	9.54
	2	0.63	0.05	11.66
	3	0.64	0.06	11.64
	4	0.55	0.05	11.57
	Mean	0.60	0.05	11.10
500-600	1	0.54	0.04	12.48
	2	0.59	0.05	10.96
	3	0.54	0.05	10.29
	4	0.43	0.04	10.74
	Mean	0.52	0.05	11.11
600-700	1	0.46	0.04	12.03
	2	0.53	0.06	9.44
	3	0.46	0.05	9.88
	4	0.43	0.04	10.63
	Mean	0.47	0.05	10.50
700-800	1	0.38	0.04	9.58
	2	0.44	0.05	9.14
	3	0.47	0.05	10.17
	4	0.38	0.04	9.46
	Mean	0.42	0.04	9.59
800-900	1	0.38	0.04	10.49
	2	0.40	0.05	8.94
	3	0.43	0.05	9.32
	4	0.39	0.04	9.82
	Mean	0.40	0.04	9.64
900-1000	1	0.33	0.04	8.30
	2	0.31	0.04	8.09
	3			
	4	0.35	0.04	9.84
	Mean	0.33	0.04	8.74
1000-1100	1	0.35	0.04	9.18
	2	0.25	0.04	6.87
	3			
	4	0.31	0.04	8.77
	Mean	0.30	0.04	8.27
1100-1200	1	0.31	0.04	8.66
	2	0.22	0.03	6.74
	3			
	4	0.29	0.03	8.43
	Mean	0.27	0.03	7.94

Profile/Site 252

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.32	0.11	12.40
	2	1.38	0.12	11.67
	3	1.39	0.09	14.62
	4	1.24	0.10	12.80
	Mean	1.33	0.10	12.87
50-100	1	1.02	0.10	10.61
	2	1.09	0.09	12.27
	3	1.13	0.10	11.73
	4	0.99	0.09	11.23
	Mean	1.06	0.09	11.46
100-150	1	0.84	0.08	10.12
	2	0.95	0.09	10.82
	3	0.89	0.08	10.93
	4	0.71	0.08	9.31
	Mean	0.85	0.08	10.29
150-200	1	0.68	0.07	9.56
	2	0.74	0.08	9.59
	3	0.77	0.08	9.91
	4	0.77	0.07	10.33
	Mean	0.74	0.08	9.85
200-250	1	0.60	0.06	9.28
	2	0.70	0.08	8.98
	3	0.71	0.08	9.00
	4	0.75	0.07	10.69
	Mean	0.69	0.07	9.49
250-300	1	0.54	0.07	7.76
	2	0.61	0.07	8.95
	3	0.63	0.07	8.40
	4	0.61	0.07	8.35
	Mean	0.59	0.07	8.36
300-400	1	0.50	0.06	8.11
	2	0.45	0.06	7.35
	3	0.54	0.07	7.61
	4	0.49	0.06	8.26
	Mean	0.49	0.06	7.83
400-500	1	0.35	0.06	5.67
	2	0.39	0.05	7.28
	3	0.46	0.06	7.86
	4	0.47	0.06	7.28
	Mean	0.41	0.06	7.02
500-600	1	0.43	0.06	7.46
	2	0.36	0.05	7.07
	3	0.44	0.06	7.05
	4	0.51	0.06	7.97
	Mean	0.43	0.06	7.39
600-700	1	0.53	0.08	7.08
	2	0.39	0.06	7.04
	3	0.44	0.07	6.75
	4	0.52	0.07	7.18
	Mean	0.47	0.07	7.01
700-800	1	0.53	0.08	6.60
	2	0.45	0.07	6.20
	3	0.49	0.08	6.43
	4	0.55	0.07	8.24
	Mean	0.51	0.07	6.87
800-900	1	0.54	0.08	6.93
	2	0.48	0.08	6.41
	3	0.48	0.06	7.88
	4	0.54	0.07	7.36
	Mean	0.51	0.07	7.14
900-1000	1	0.52	0.07	7.31
	2	0.44	0.07	6.58
	3	0.50	0.08	6.59
	4	0.53	0.07	7.68
	Mean	0.50	0.07	7.04
1000-1100	1	0.42	0.07	6.46
	2	0.39	0.06	6.41
	3	0.48	0.07	6.70
	4	0.53	0.06	9.41
	Mean	0.45	0.06	7.25
1100-1200	1	0.44	0.07	6.32
	2	0.43	0.06	7.19
	3	0.46	0.07	6.53
	4	0.50	0.07	7.01
	Mean	0.46	0.07	6.76

Profile/Site 253

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	1.45	0.10	14.86
	2	1.50	0.12	12.32
	3	1.43	0.11	13.05
	4	1.44	0.10	15.01
	Mean	1.45	0.11	13.81
50-100	1	1.03	0.08	12.74
	2	1.42	0.11	12.99
	3	1.26	0.09	13.37
	4	1.22	0.10	12.79
	Mean	1.23	0.09	12.97
100-150	1	0.95	0.08	12.06
	2	1.38	0.11	12.80
	3	1.20	0.10	12.28
	4	1.11	0.09	12.57
	Mean	1.16	0.09	12.43
150-200	1	0.93	0.08	11.80
	2	1.22	0.10	12.08
	3	1.07	0.09	11.52
	4	1.02	0.08	13.15
	Mean	1.06	0.09	12.14
200-250	1	0.90	0.08	11.17
	2	1.06	0.09	11.23
	3	0.95	0.09	10.99
	4	0.93	0.08	11.56
	Mean	0.96	0.09	11.24
250-300	1	0.85	0.07	12.37
	2	0.96	0.09	11.20
	3	0.91	0.08	11.20
	4	0.90	0.08	11.67
	Mean	0.91	0.08	11.61
300-400	1	0.74	0.08	9.45
	2	0.72	0.08	9.15
	3	0.73	0.07	9.92
	4	0.75	0.08	9.57
	Mean	0.73	0.08	9.52
400-500	1	0.66	0.07	9.15
	2	0.69	0.08	9.22
	3	0.66	0.07	9.82
	4	0.70	0.08	9.09
	Mean	0.68	0.07	9.32
500-600	1	0.61	0.06	9.46
	2	0.66	0.07	10.04
	3	0.61	0.06	10.04
	4	0.60	0.07	8.66
	Mean	0.62	0.07	9.55
600-700	1	0.53	0.06	9.08
	2	0.59	0.07	8.99
	3	0.47	0.05	8.95
	4	0.44	0.06	7.73
	Mean	0.51	0.06	8.69
700-800	1	0.41	0.05	8.02
	2	0.54	0.05	10.62
	3	0.38	0.05	7.51
	4	0.36	0.05	7.58
	Mean	0.42	0.05	8.43
800-900	1	0.34	0.05	7.47
	2	0.48	0.06	8.54
	3	0.26	0.04	7.01
	4	0.35	0.05	7.58
	Mean	0.36	0.05	7.65
900-1000	1	0.30	0.04	7.67
	2	0.42	0.05	7.98
	3	0.19	0.03	6.07
	4	0.29	0.04	7.74
	Mean	0.30	0.04	7.36
1000-1100	1	0.26	0.03	7.71
	2	0.34	0.04	7.91
	3	0.15	0.03	6.00
	4	0.25	0.04	7.13
	Mean	0.25	0.03	7.19
1100-1200	1	0.23	0.03	7.21
	2	0.29	0.04	7.57
	3	0.15	0.02	6.51
	4	0.21	0.03	6.35
	Mean	0.22	0.03	6.91

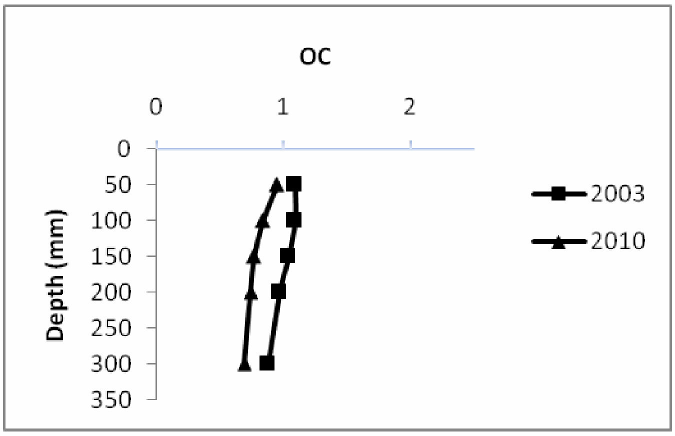
Profile/Site 254

Depth (mm)	Replication	C (%)	N (%)	C:N
0-50	1	2.73	0.16	17.16
	2	2.26	0.14	16.04
	3	2.24	0.13	17.20
	4	1.95	0.13	15.58
	Mean	2.30	0.14	16.50
50-100	1	1.76	0.12	14.86
	2	2.32	0.12	18.94
	3	1.59	0.11	14.11
	4	1.89	0.12	16.14
	Mean	1.89	0.12	16.01
100-150	1	1.37	0.11	12.44
	2	1.47	0.11	13.15
	3	1.37	0.11	12.76
	4	1.39	0.11	13.22
	Mean	1.40	0.11	12.89
150-200	1	1.21	0.10	12.66
	2	1.33	0.10	13.96
	3	1.29	0.10	12.85
	4	1.25	0.09	13.55
	Mean	1.27	0.10	13.25
200-250	1	1.17	0.09	13.78
	2	1.19	0.09	13.33
	3	1.18	0.09	12.97
	4	1.13	0.09	13.24
	Mean	1.17	0.09	13.33
250-300	1	1.06	0.08	13.03
	2	1.27	0.09	14.08
	3	1.09	0.08	14.19
	4	1.07	0.08	13.62
	Mean	1.13	0.08	13.73
300-400	1	0.92	0.08	11.73
	2	0.88	0.07	12.55
	3	0.86	0.07	12.52
	4	0.89	0.07	12.50
	Mean	0.89	0.07	12.33
400-500	1	0.90	0.07	12.60
	2	0.74	0.07	11.38
	3	0.78	0.06	13.07
	4	0.79	0.07	11.11
	Mean	0.80	0.07	12.22
500-600	1	0.74	0.07	11.40
	2	0.65	0.06	10.92
	3	0.57	0.05	11.84
	4	0.68	0.06	11.11
	Mean	0.66	0.06	11.32
600-700	1	0.54	0.05	11.14
	2	0.52	0.05	11.38
	3	0.49	0.05	10.33
	4	0.57	0.05	10.74
	Mean	0.53	0.05	10.90
700-800	1	0.34	0.04	9.62
	2	0.35	0.04	8.39
	3	0.33	0.04	8.70
	4	0.41	0.04	9.70
	Mean	0.36	0.04	9.10
800-900	1	0.25	0.03	7.96
	2	0.27	0.04	7.85
	3	0.26	0.03	8.20
	4	0.29	0.04	8.05
	Mean	0.27	0.03	8.02
900-1000	1	0.21	0.03	6.75
	2	0.25	0.04	6.83
	3	0.23	0.03	7.26
	4	0.24	0.03	7.19
	Mean	0.23	0.03	7.01
1000-1100	1	0.19	0.03	7.54
	2	0.27	0.04	6.84
	3	0.23	0.03	7.64
	4	0.19	0.03	5.98
	Mean	0.22	0.03	7.00
1100-1200	1	0.17	0.03	5.51
	2	0.25	0.04	5.78
	3	0.18	0.03	6.00
	4	0.17	0.03	5.48
	Mean	0.19	0.03	5.69

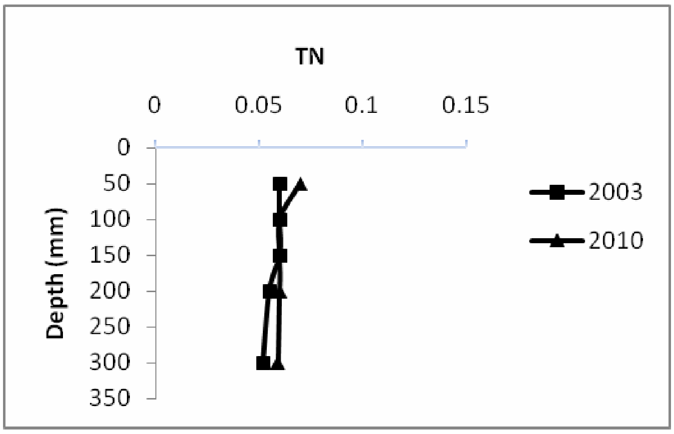
APPENDIX B

Organic C (%) and total N (%) in the first 300 mm soil depth for the each of 27 sampled sites in the Weatherley catchment before and after afforestation, 2003 and 2010, respectively.

Profile/Site201

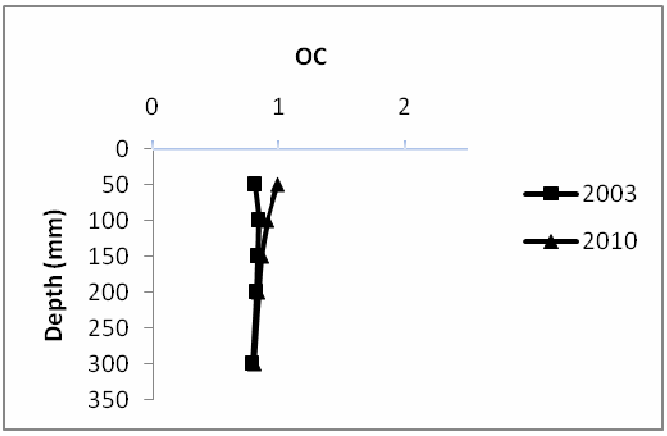


Organic C (%)



Total N (%)

Profile/Site 202



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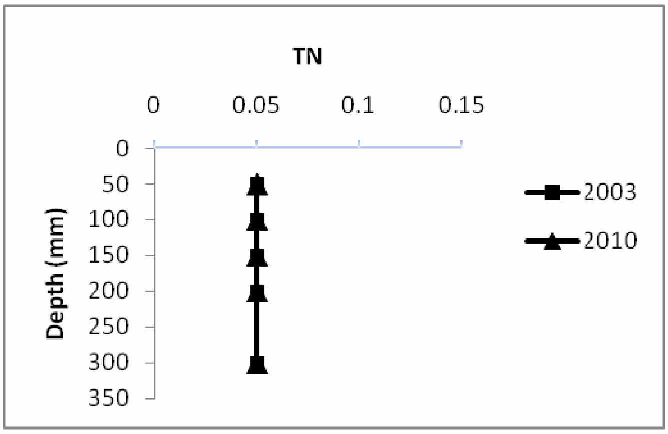
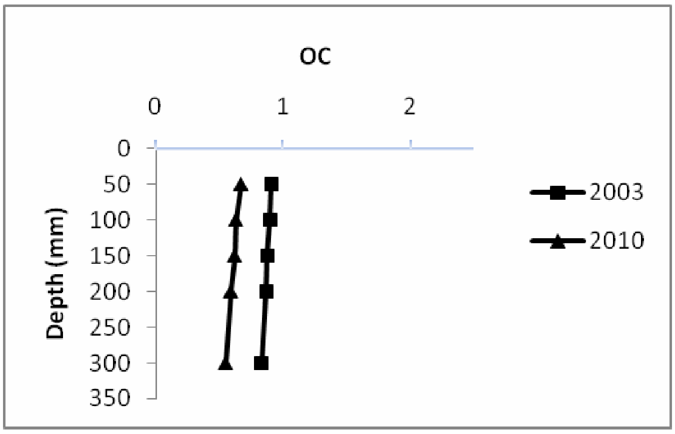


Total N (%)

Profile/Site 203



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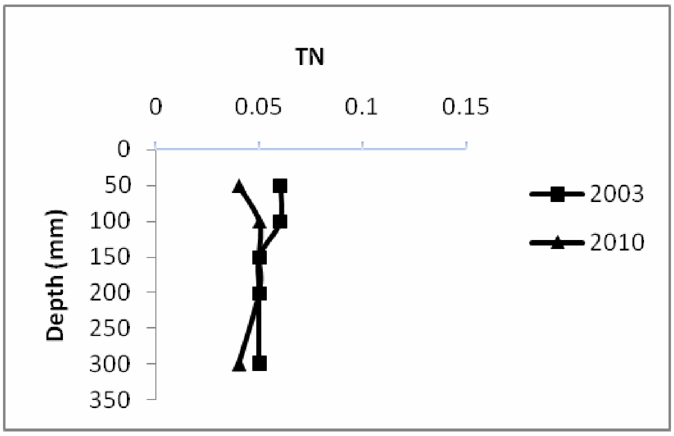

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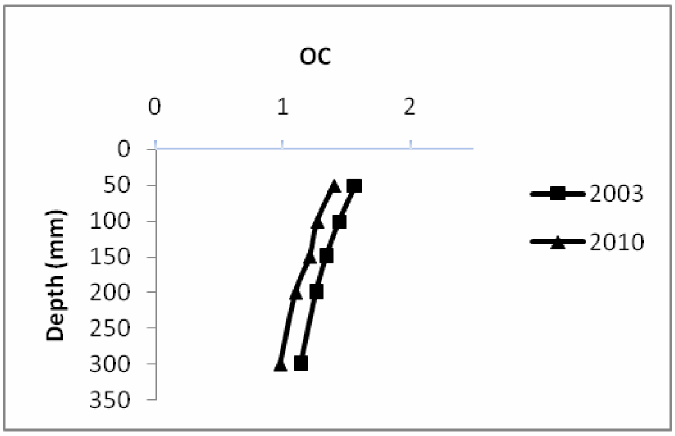
Profile/Site209



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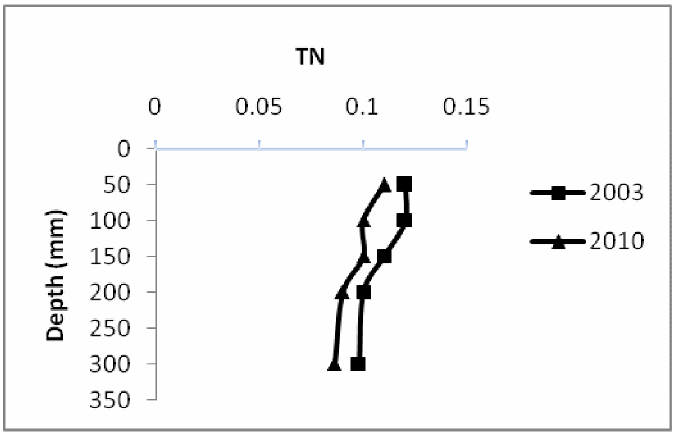
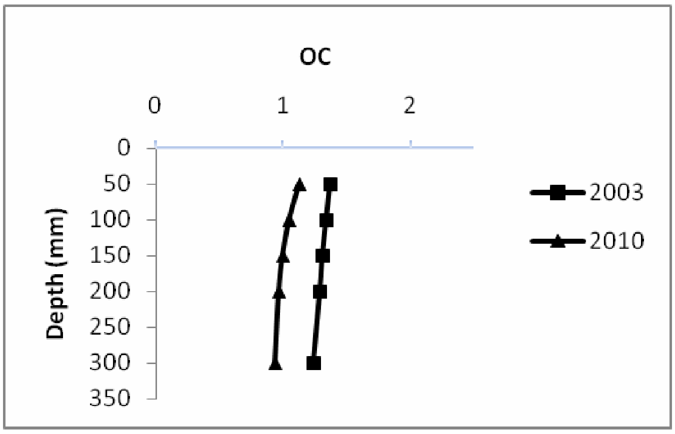


Total N (%)

Profile/Site 210



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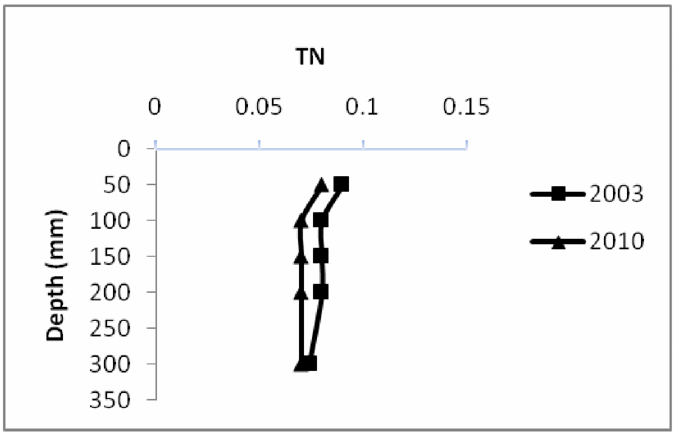

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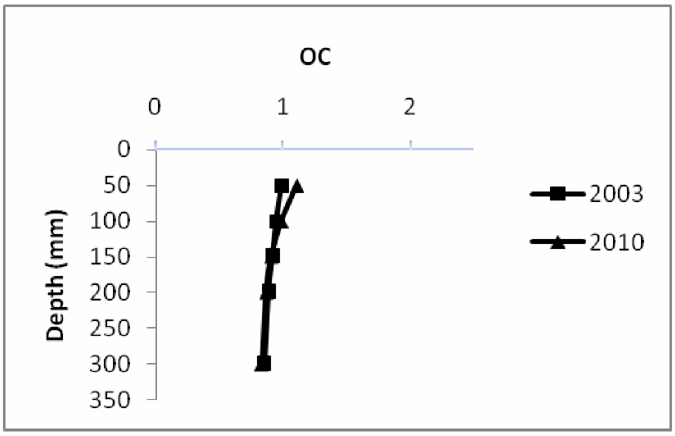
Profile/Site 212



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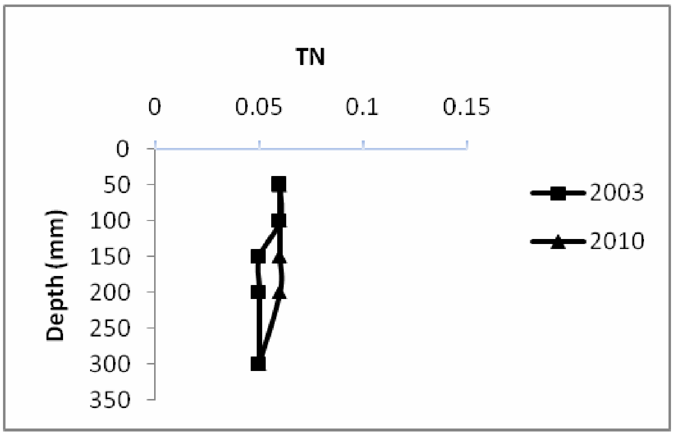

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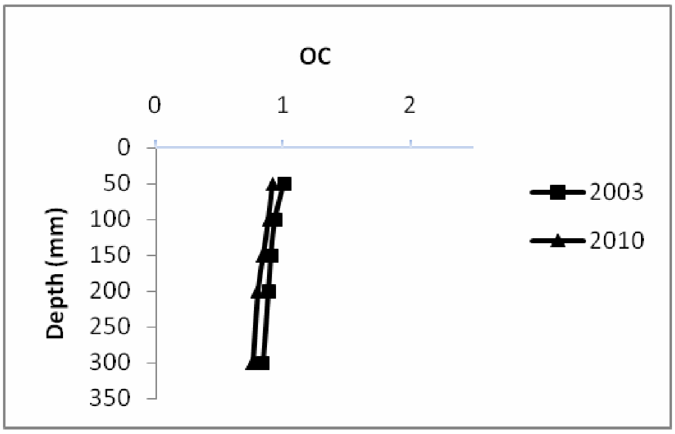
Profile/Site220



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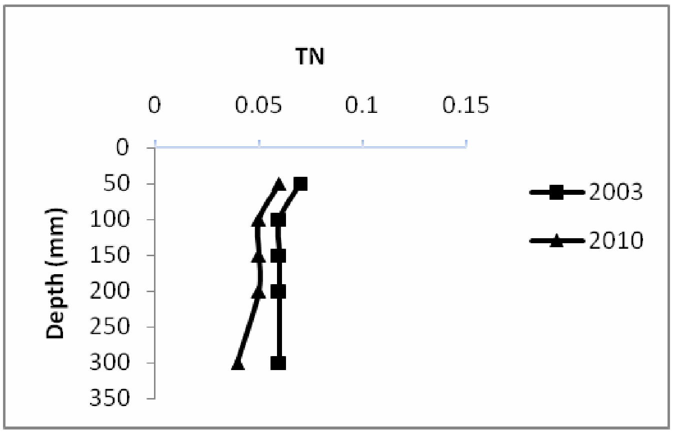
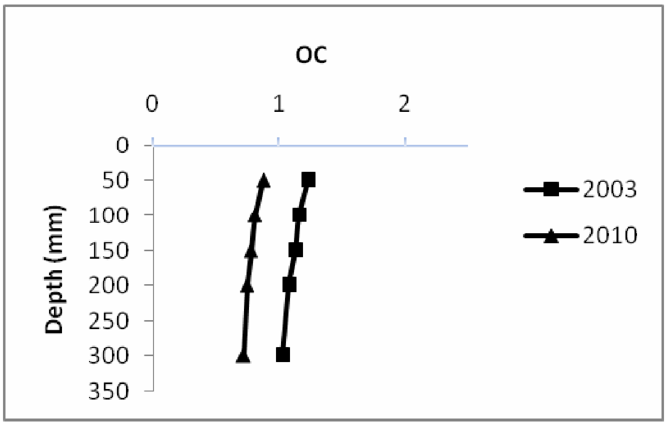


Total N (%)

Profile/Site 221



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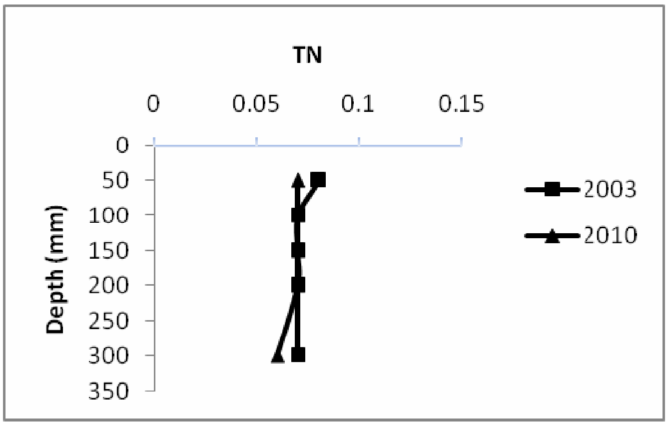
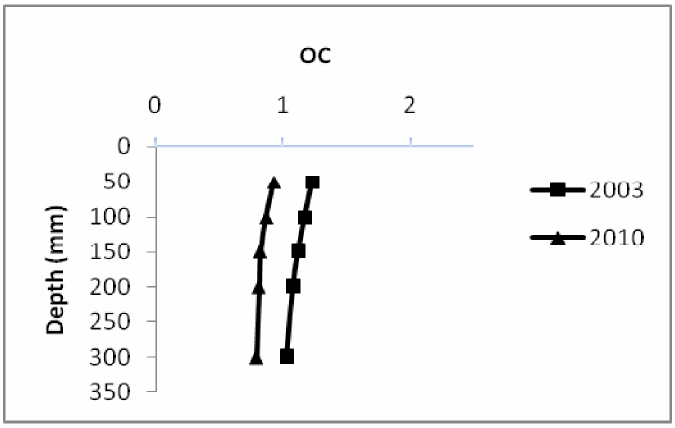


Total N (%)

Profile/Site 222



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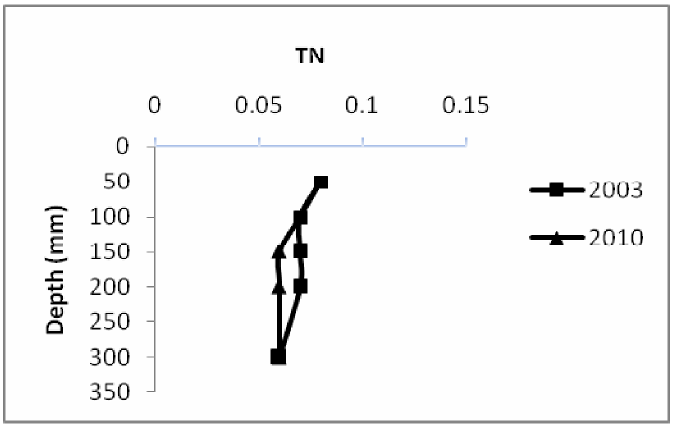

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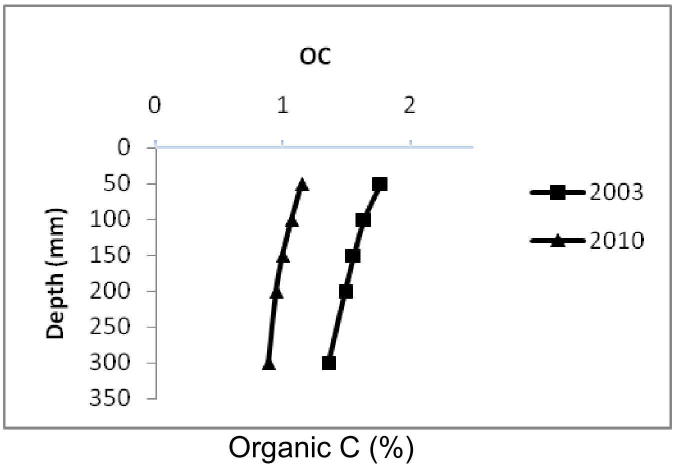
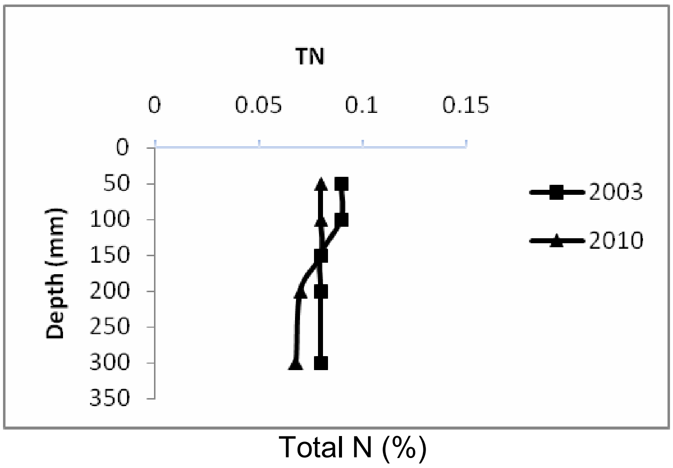
Profile/Site 232





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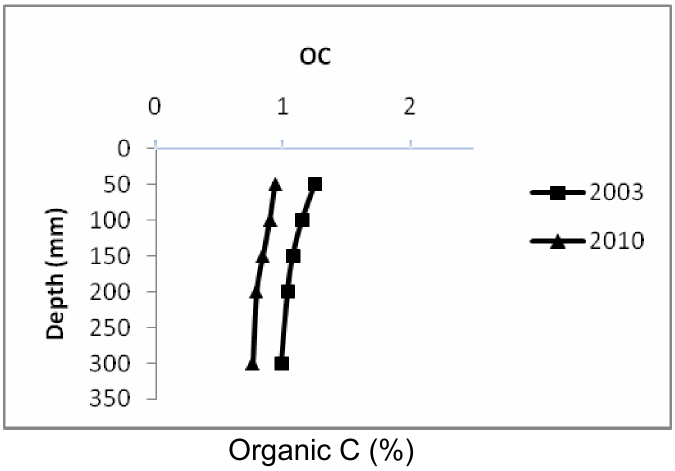

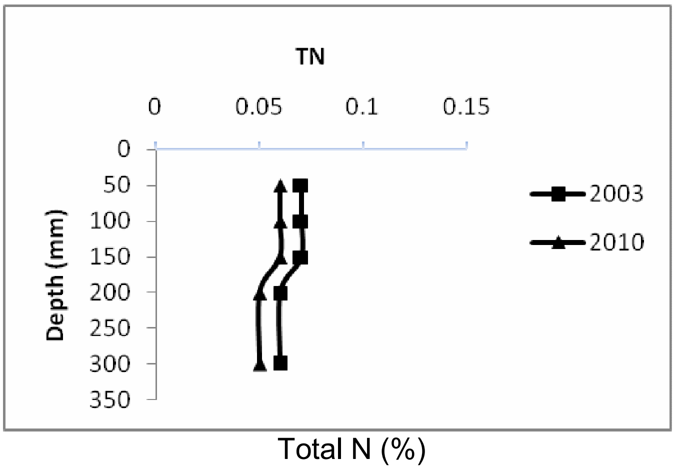

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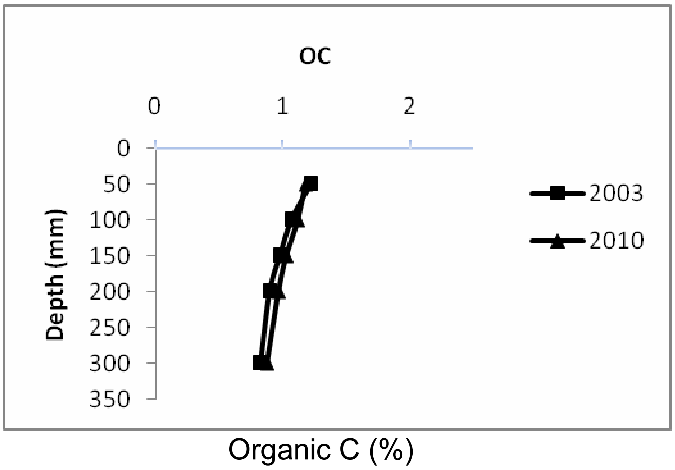
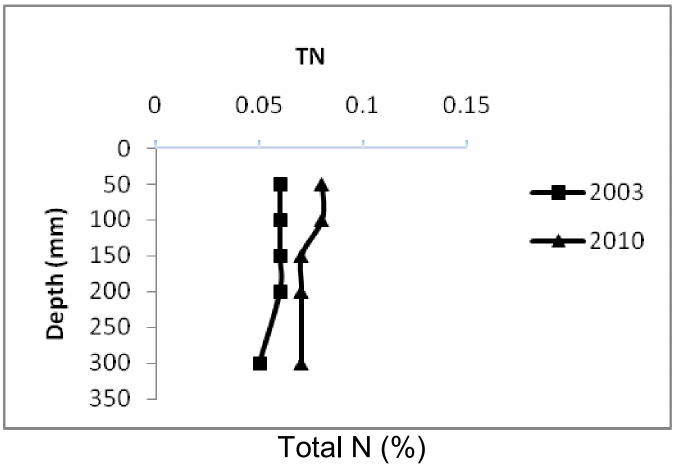
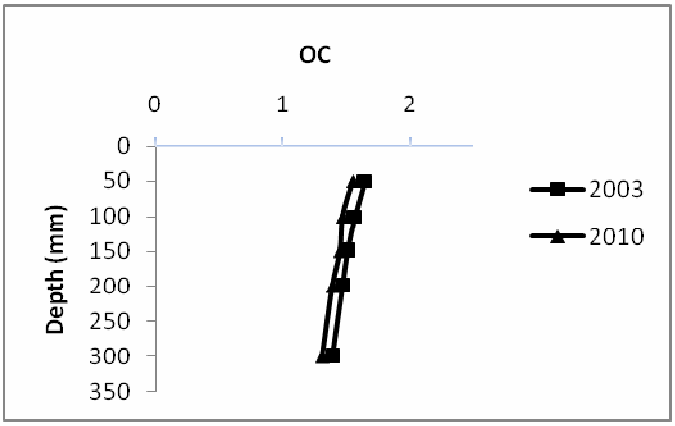




Profile/Site 240



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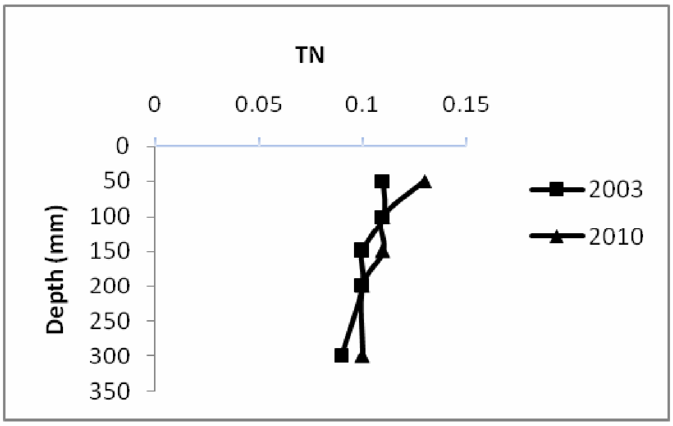

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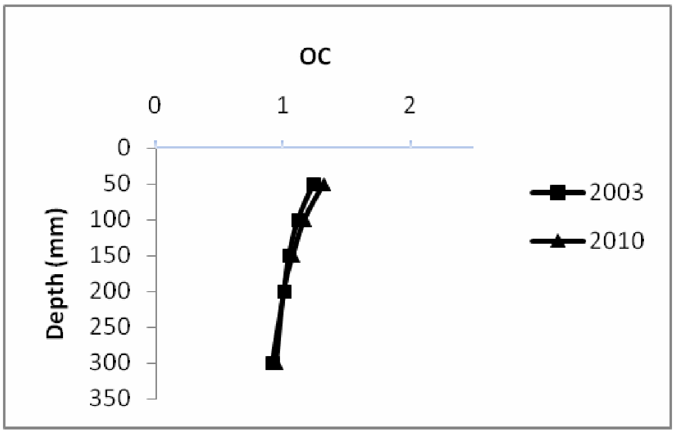
Profile/Site 241



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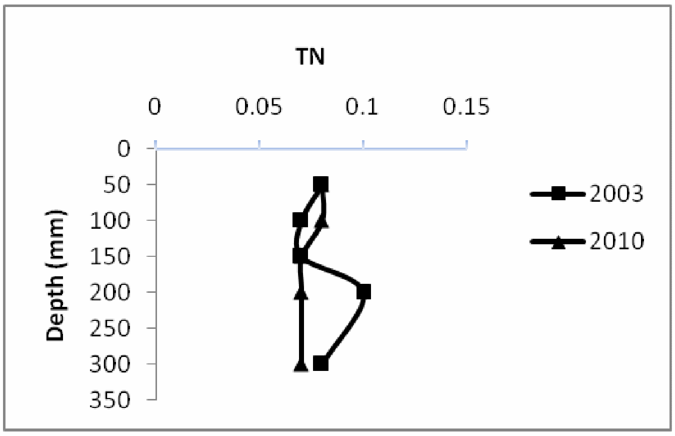

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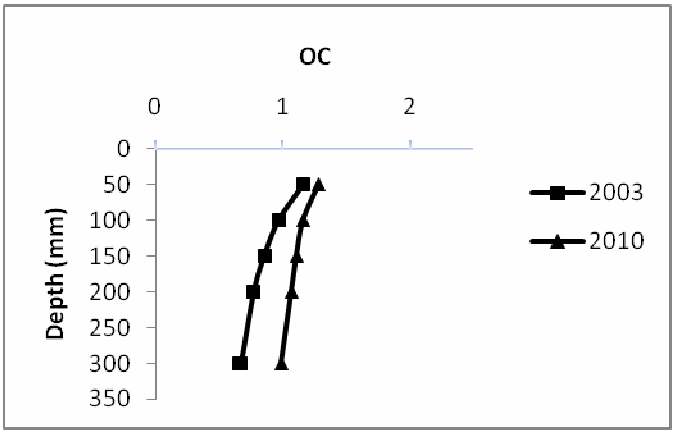
Profile/Site 242



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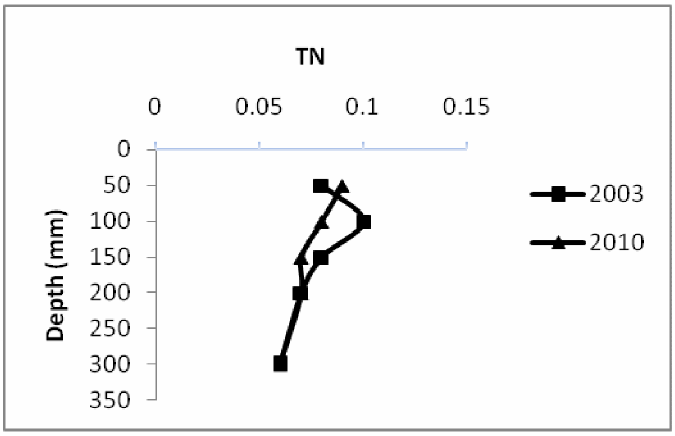

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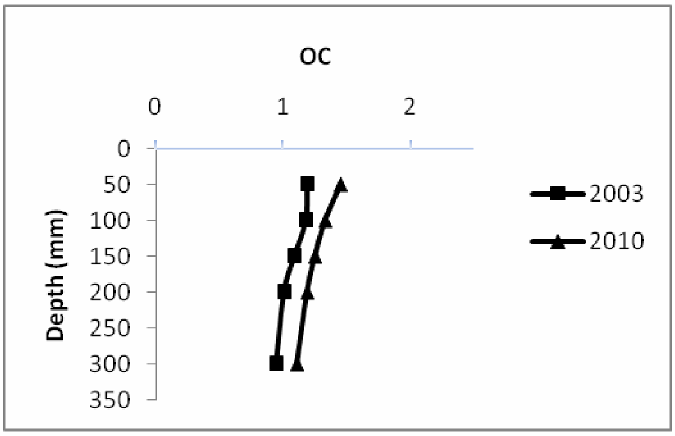
Profile/Site 243



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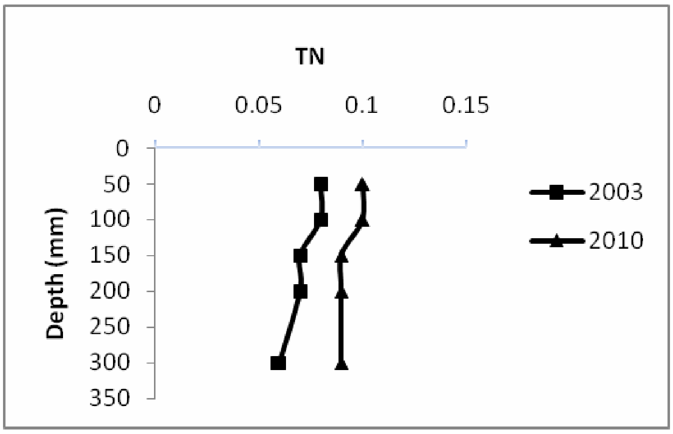

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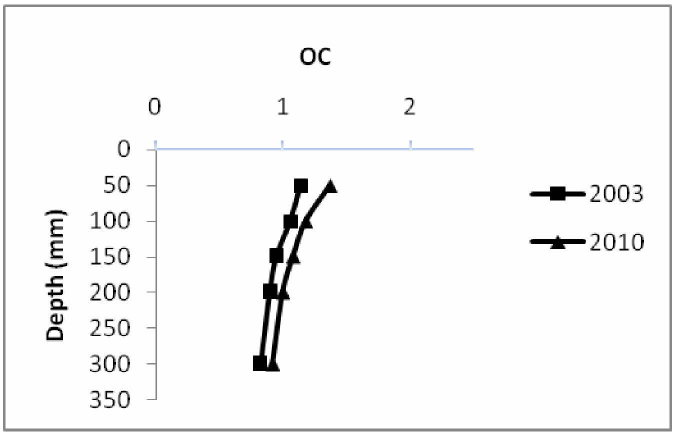
Profile/Site 244



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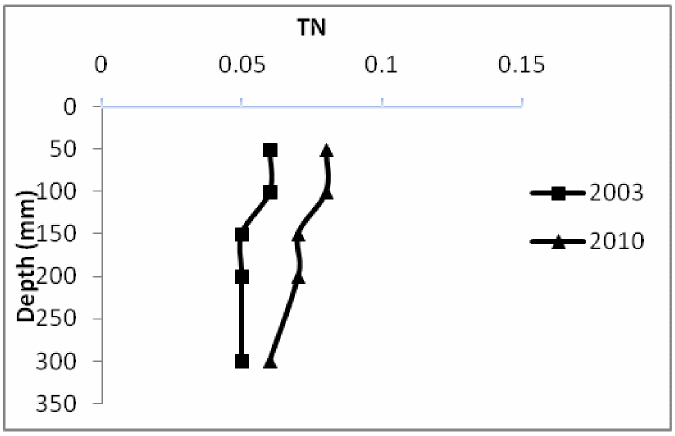

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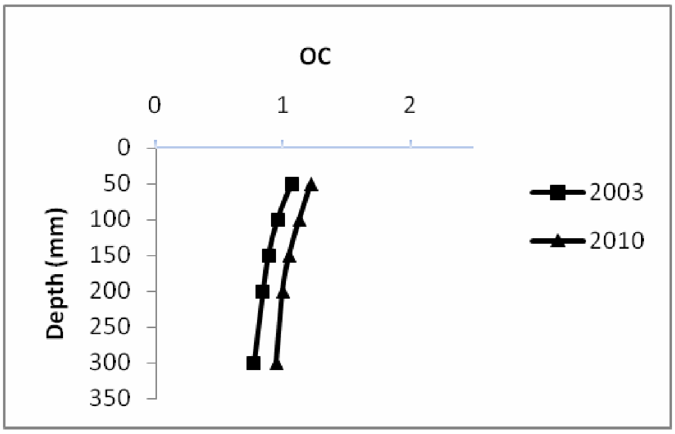
Profile/Site 245



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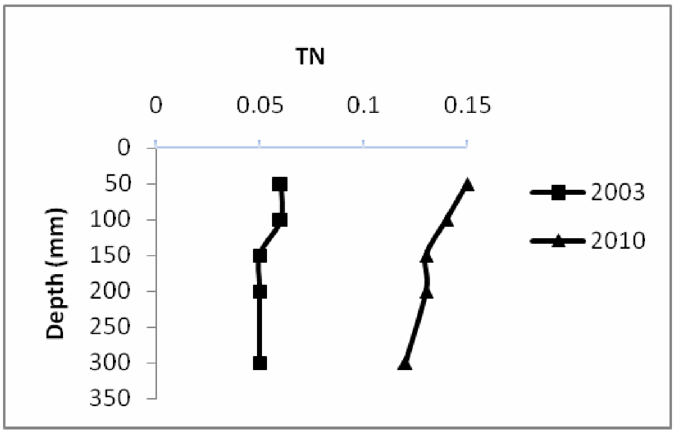

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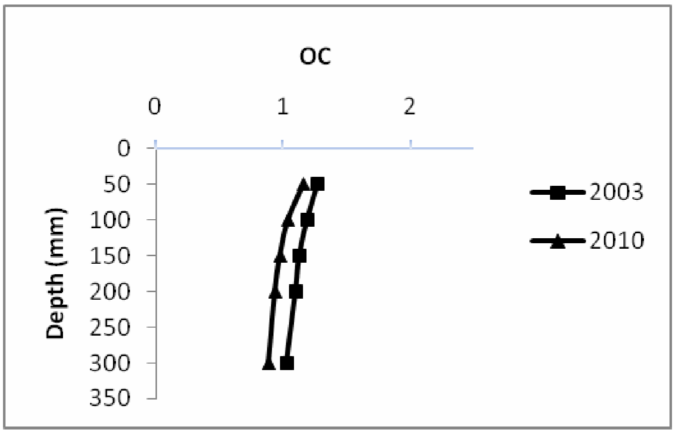
Profile/Site 246



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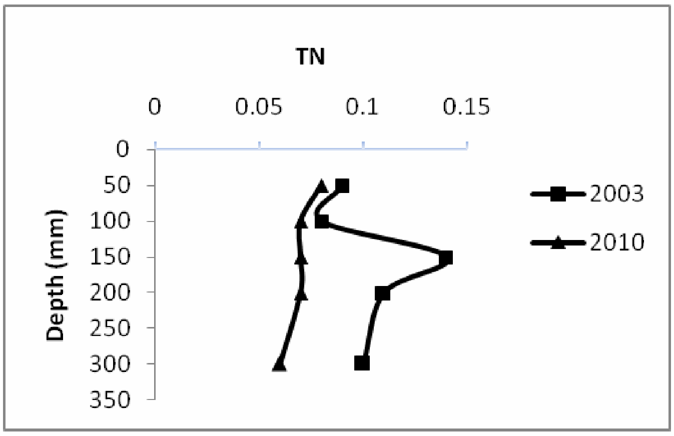
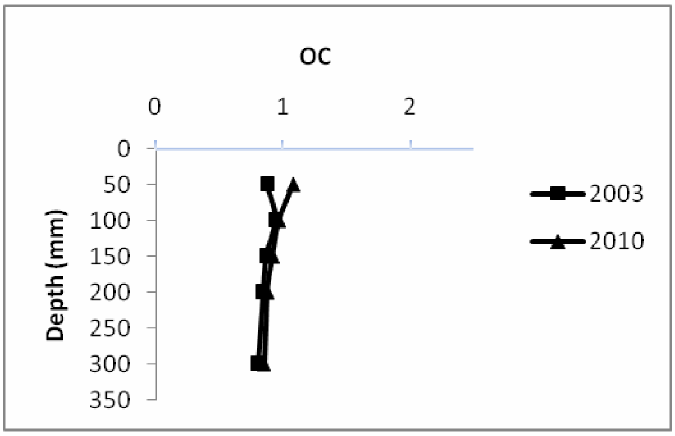


Total N (%)

Profile/Site 247



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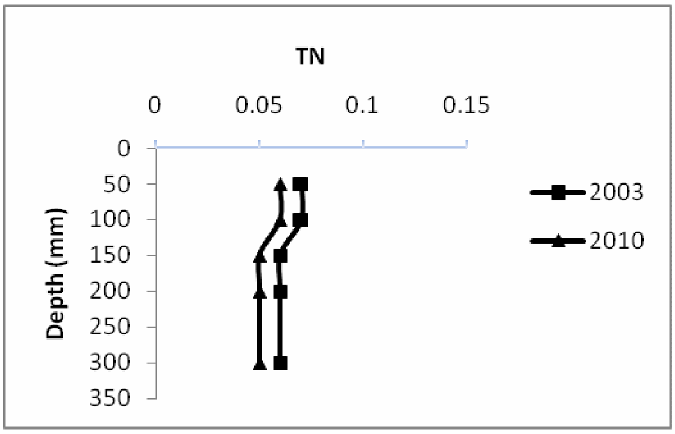

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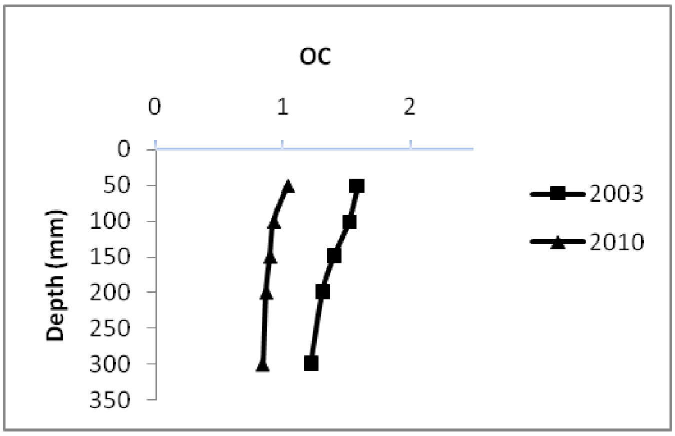
Profile/Site 248



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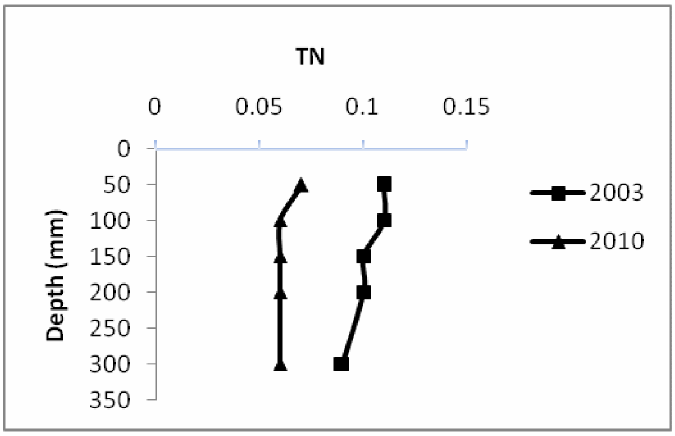

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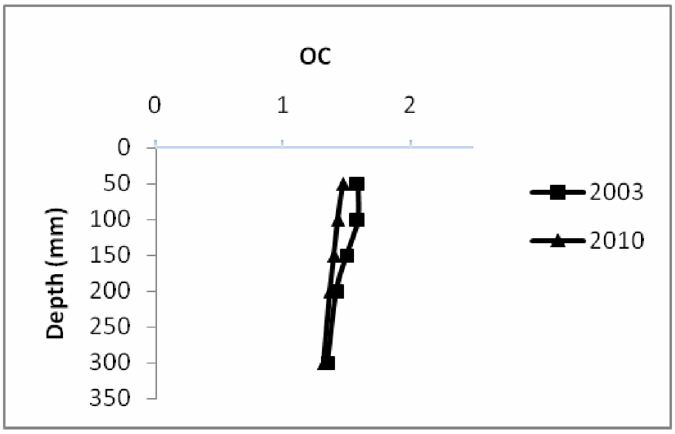
Profile/Site 249



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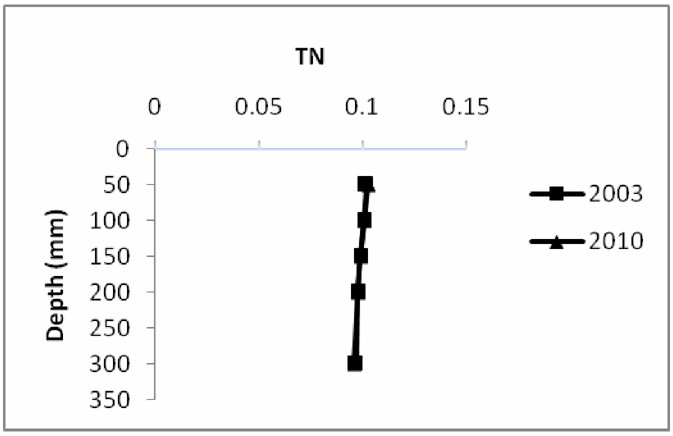
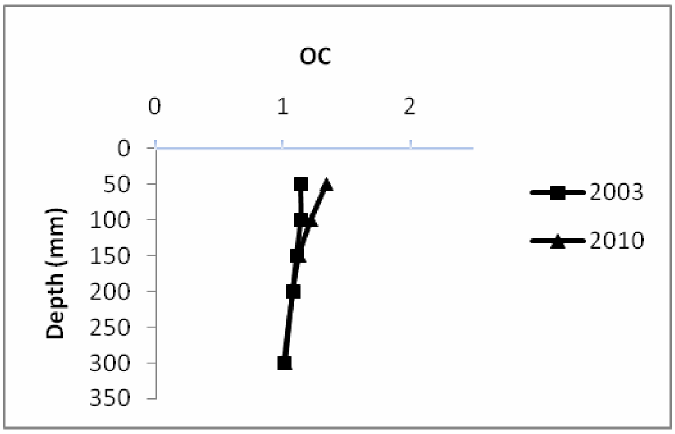


Total N (%)

Profile/Site 250



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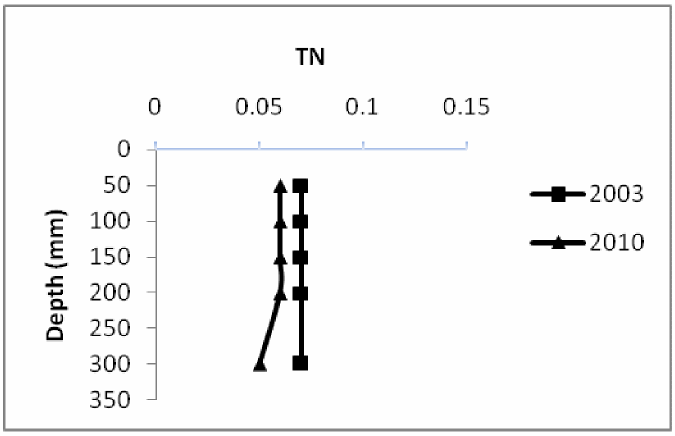
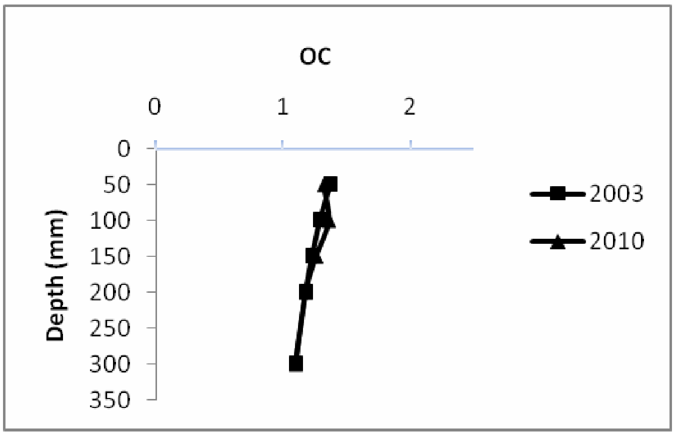


Total N (%)

Profile/Site 251



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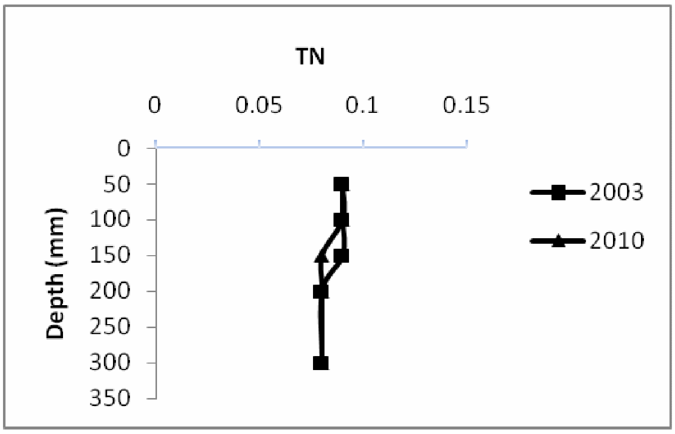
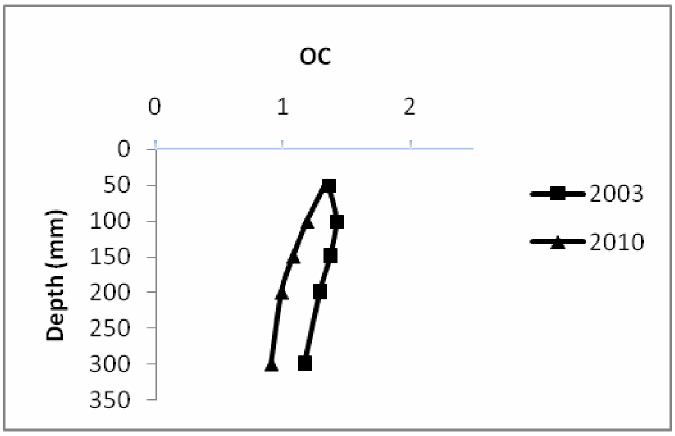


Total N (%)

Profile/Site 252



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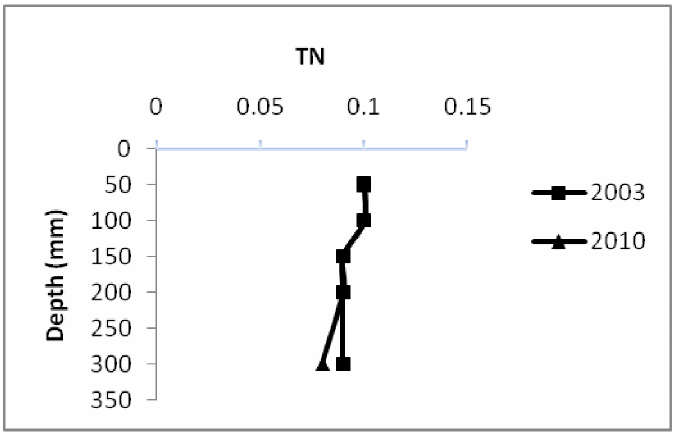
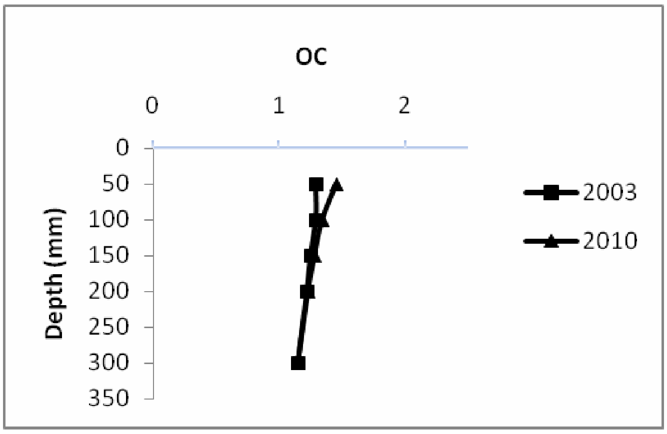


Total N (%)

Profile/Site 253



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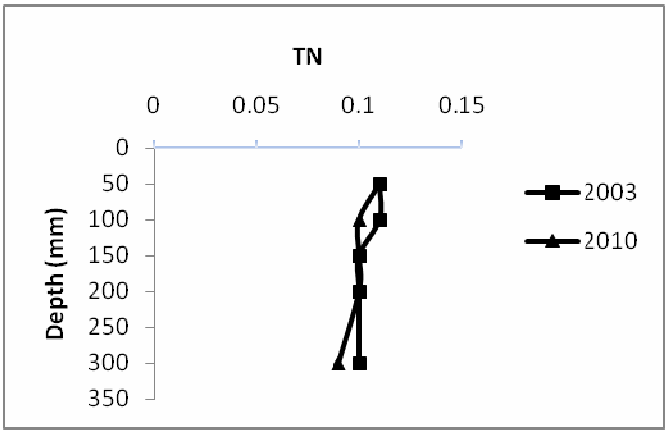
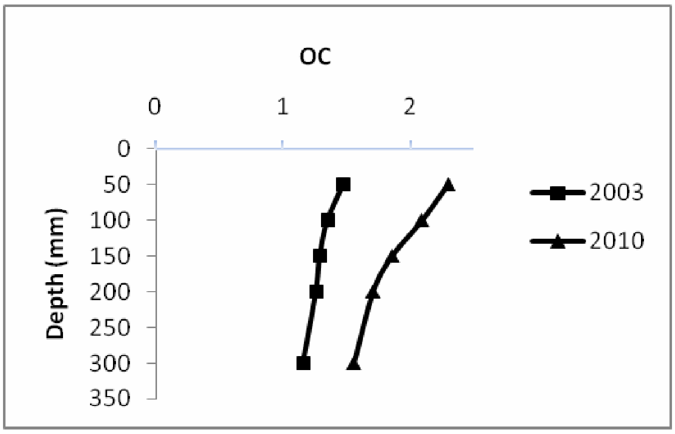


Total N (%)

Profile/Site 254



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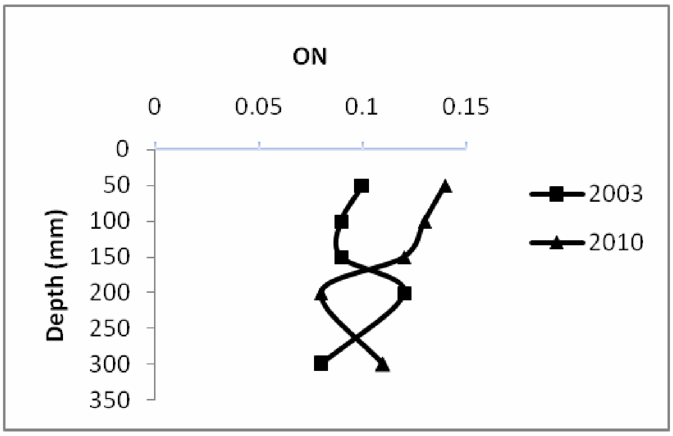

Total N (%)

APPENDIX C

Litter mass (kg m^{-2}), C (%), N (%), and C:N ratios of the replicated samples and their means for the 27 sampled sites in the Weatherley catchment eight years after afforestation in 2010.

Site	Replication	Litter mass (kg m^{-2})	C (%)	N (%)	C:N
201	1	1.60	39.0	0.76	51.7
	2	1.50	40.3	0.77	52.1
	3	1.35	35.8	0.90	39.6
	4	1.66	40.5	0.67	60.6
	Mean	1.53	38.9	0.78	51.0
202	1	1.03	39.4	0.62	63.3
	2	0.97	40.2	0.59	68.7
	3	0.89	42.1	0.57	73.4
	4	1.61	42.5	0.57	74.9
	Mean	1.13	41.1	0.59	70.1
203	1	1.02	41.6	0.55	75.5
	2	0.91	43.1	0.52	83.1
	3	1.10	44.8	0.64	70.2
	4	0.91	42.7	0.61	69.8
	Mean	0.99	43.1	0.58	74.7
209	1	0.98	40.6	0.43	95.2
	2	0.70	40.2	0.36	112.5
	3	0.98	41.8	0.41	102.5
	4	0.96	41.6	0.35	119.1
	Mean	0.91	41.1	0.39	107.3
210	1	2.49	44.3	0.61	72.2
	2	1.86	39.7	0.67	59.3
	3	1.81	44.0	0.65	67.5
	4	2.13	42.8	0.63	68.2
	Mean	2.07	42.7	0.64	66.8
212	1	2.08	40.6	0.98	41.4
	2	1.91	38.7	0.95	40.6
	3	2.19	42.0	0.92	45.9
	4	2.42	41.7	0.85	49.0
	Mean	2.15	40.8	0.93	44.2
220	1	1.66	46.4	0.77	60.2
	2	2.09	43.1	0.86	50.4
	3	2.12	46.9	0.84	55.7
	4	2.72	40.7	0.85	48.1
	Mean	2.15	44.3	0.83	53.6
221	1	1.80	43.1	0.75	57.6
	2	2.09	46.4	0.76	60.9
	3	1.88	44.4	0.75	59.5
	4	2.14	37.7	0.82	45.7
	Mean	1.98	42.9	0.77	55.9
222	1	1.11	40.0	0.98	41.0
	2	1.33	37.7	0.75	50.1
	3	1.32	40.3	0.95	42.5
	4	1.39	43.8	0.99	44.3
	Mean	1.29	40.5	0.92	44.5

Site	Replication	Litter mass (kg m^{-2})	C (%)	N (%)	C:N
232	1	2.53	34.8	0.59	58.6
	2	2.16	38.8	0.66	59.0
	3	1.58	35.9	0.58	61.5
	4	2.40	36.2	0.54	66.8
	Mean	2.17	36.4	0.59	61.5
233	1	1.99	34.7	0.70	49.3
	2	1.74	39.0	0.63	62.2
	3	1.31	40.2	0.64	62.5
	4	1.61	39.2	0.66	59.8
	Mean	1.66	38.3	0.66	58.5
235	1	2.05	33.6	0.60	56.3
	2	1.74	36.7	0.52	70.9
	3	1.03	37.7	0.50	74.9
	4	1.63	37.2	0.58	64.3
	Mean	1.61	36.3	0.55	66.6
240	1	2.58	36.9	1.00	37.0
	2	4.65	31.4	0.89	35.2
	3	4.36	25.8	0.68	37.7
	4	3.12	34.8	0.96	36.1
	Mean	3.68	32.2	0.88	36.5
241	1	2.85	39.1	0.75	52.0
	2	1.70	39.2	0.82	47.8
	3	2.34	39.6	0.86	45.9
	4	1.92	37.9	0.76	49.7
	Mean	2.20	39.0	0.80	48.9
242	1	1.66	96.8	1.94	50.0
	2	2.23	39.4	0.94	41.7
	3	2.31	38.1	0.97	39.3
	4	2.27	39.3	0.83	47.2
	Mean	2.12	53.4	1.17	44.6
243	1	2.83	31.9	0.72	44.5
	2	3.37	33.6	0.80	41.8
	3	2.21	36.3	0.99	36.7
	4	3.44	38.1	0.81	46.8
	Mean	2.96	35.0	0.83	42.5
244	1	3.21	30.6	0.74	41.6
	2	2.34	37.0	0.76	48.9
	3	2.76	38.4	0.97	39.5
	4	2.60	40.5	0.75	54.09
	Mean	2.73	36.6	0.81	32.5
245	1	1.87	34.2	1.01	34.0
	2	2.20	42.6	0.87	49.2
	3	2.37	39.7	0.99	40.2
	4	2.10	38.1	0.99	38.5
	Mean	2.14	38.7	0.97	40.5

Site	Replication	Litter mass (kg m^{-2})	C (%)	N (%)	C:N
246	1	1.96	43.9	0.81	53.9
	2	2.97	41.1	0.67	61.3
	3	2.77	41.7	0.82	50.7
	4	2.31	43.9	0.73	60.3
	Mean	2.50	42.7	0.76	56.6
247	1	1.65	45.4	0.80	56.7
	2	2.23	44.9	0.76	59.0
	3	2.08	43.2	0.67	64.8
	4	2.28	44.6	0.71	63.0
	Mean	2.06	44.5	0.74	60.9
248	1	2.08	43.0	0.79	54.1
	2	1.42	43.6	0.67	65.3
	3	1.27	42.3	0.88	48.3
	4	1.99	43.5	0.79	55.4
	Mean	1.69	43.1	0.78	55.8
249	1	2.17	37.5	0.68	55.0
	2	1.78	39.6	0.73	53.9
	3	1.98	32.8	0.65	50.5
	4	1.79	34.1	0.64	53.0
	Mean	1.93	36.0	0.68	53.1
250	1	1.98	37.3	0.73	51.2
	2	1.61	39.7	0.76	52.5
	3	1.28	36.0	0.67	53.9
	4	2.63	31.8	0.61	52.0
	Mean	1.88	36.2	0.69	52.4
251	1	1.86	37.3	0.63	59.5
	2	2.20	34.8	0.57	61.0
	3	1.21	39.0	0.70	55.6
	4	1.41	42.4	0.68	62.0
	Mean	1.67	38.4	0.65	59.5
252	1	1.57	36.5	0.70	52.3
	2	1.23	39.1	0.63	62.0
	3	1.73	38.9	0.64	60.8
	4	2.57	37.9	0.75	50.7
	Mean	1.78	38.1	0.68	56.5
253	1	1.49	41.7	0.65	64.0
	2	1.55	37.8	0.74	51.0
	3	1.63	39.3	0.75	52.6
	4	1.13	38.2	0.79	48.2
	Mean	1.45	39.3	0.73	54.0
254	1	1.53	40.2	0.90	44.5
	2	2.77	42.0	1.07	39.4
	3	2.80	40.9	0.77	52.9
	4	3.47	37.1	0.88	42.1
	Mean	2.64	40.1	0.91	44.7

APPENDIX D

Tree C stocks (Mg ha^{-1}) for the 12 replicated trees and their averages for the 25 sampled sites in the Weatherley catchment eight years after afforestation in 2010.

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
201	31.3		
201	50.2		
201	0.0	27.2	
201	39.4		
201	30.7		
201	36.9	35.7	
201	25.1		
201	34.2		
201	15.5	24.9	
201	37.8		
201	26.0		
201	20.3	28.1	29.0
202	40.2		
202	17.4		
202	33.0	30.2	
202	30.8		
202	47.1		
202	30.7	36.2	
202	33.6		
202	36.6		
202	32.0	34.1	
202	27.6		
202	45.1		
202	39.7	37.5	34.5
203	27.1		
203	29.5		
203	36.5	31.1	
203	33.3		
203	45.7		
203	41.4	40.2	
203	39.1		
203	35.7		
203	50.6	41.8	
203	30.3		
203	55.0		
203	51.3	45.5	39.6

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
210	12.8		
210	95.3		
210	43.2	50.4	
210	90.4		
210	128.7		
210	330.1	183.1	
210	50.5		
210	88.7		
210	0.0	46.4	
210	110.0		
210	12.0		
210	185.5	102.5	95.6
212	88.5		
212	55.0		
212	1.7	48.4	
212	86.1		
212	77.7		
212	69.7	77.9	
212	89.6		
212	54.3		
212	92.0	78.6	
212	52.7		
212	59.7		
212	0.0	37.5	60.6
220	15.4		
220	25.9		
220	184.5	75.2	
220	139.8		
220	118.4		
220	27.7	95.3	
220	0.0		
220	0.0		
220	205.7	68.6	
220	63.4		
220	5.4		
220	0.0	23.0	65.5

Site	Total tree C mass ($Mg\ C\ ha^{-1}$)	Replicate Average ($Mg\ C\ ha^{-1}$)	Site Average ($Mg\ C\ ha^{-1}$)
221	39.4		
221	0.0		
221	0.0	13.1	
221	0.0		
221	182.9		
221	7.1	63.3	
221	218.7		
221	200.3		
221	106.2	175.1	
221	46.6		
221	177.0		
221	9.2	77.6	82.3
222	119.1		
222	0.0		
222	202.3	107.2	
222	183.6		
222	220.9		
222	45.1	149.8	
222	0.0		
222	26.5		
222	0.0	8.8	
222	59.1		
222	0.0		
222	58.8	39.3	76.3
232	25.6		
232	33.0		
232	38.7	32.5	
232	46.5		
232	28.5		
232	38.6	37.9	
232	40.1		
232	41.5		
232	32.0	37.9	
232	33.5		
232	42.1		
232	36.4	37.3	36.4

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
233	42.0		
233	38.4		
233	68.9	49.8	
233	43.1		
233	66.1		
233	83.8	64.3	
233	27.6		
233	43.6		
233	42.8	38.0	
233	29.0		
233	42.0		
233	61.1	44.0	49.0
240	28.6		
240	0.0		
240	121.6	50.1	
240	69.4		
240	116.5		
240	0.0	62.0	
240	91.0		
240	0.0		
240	95.9	62.3	
240	88.3		
240	81.0		
240	121.3	96.9	67.8
241	46.5		
241	49.9		
241	24.1	40.2	
241	36.0		
241	0.0		
241	43.9	26.6	
241	0.0		
241	67.0		
241	69.1	45.4	
241	58.1		
241	57.9		
241	93.7	69.9	45.5

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
242	64.7		
242	65.7		
242	45.1	58.5	
242	40.2		
242	0.0		
242	53.2	31.1	
242	20.1		
242	82.7		
242	72.6	58.5	
242	93.4		
242	77.0		
242	0.0	56.8	51.2
243	123.3		
243	103.7		
243	85.8	104.2	
243	97.0		
243	0.0		
243	46.9	48.0	
243	5.3		
243	0.0		
243	0.0	1.8	
243	137.9		
243	0.0		
243	0.0	46.0	50.0
244	76.4		
244	0.0		
244	41.1	39.2	
244	13.3		
244	80.7		
244	85.8	59.9	
244	40.7		
244	0.0		
244	119.0	53.3	
244	61.9		
244	75.8		
244	89.3	75.7	57.0

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
245	8.2		
245	62.7		
245	45.0	38.6	
245	51.3		
245	95.9		
245	86.9	78.0	
245	86.6		
245	0.0		
245	83.6	56.7	
245	0.0		
245	90.0		
245	71.7	53.9	56.8
246	237.7		
246	26.2		
246	28.0	97.3	
246	239.4		
246	69.4		
246	177.4	162.1	
246	279.5		
246	151.0		
246	375.8	268.8	
246	15.0		
246	254.8		
246	24.0	98.0	156.5
247	176.7		
247	179.5		
247	15.1	123.8	
247	448.1		
247	0.0		
247	151.2	199.8	
247	125.1		
247	73.4		
247	57.7	85.4	
247	173.0		
247	369.1		
247	0.0	180.7	147.4

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
248	271.3		
248	197.4		
248	55.0	174.6	
248	0.0		
248	51.4		
248	227.3	92.9	
248	50.4		
248	29.4		
248	85.2	55.0	
248	43.7		
248	0.0		
248	308.6	117.4	110.0
249	38.1		
249	41.7		
249	49.7	43.2	
249	34.0		
249	38.2		
249	42.8	38.4	
249	52.4		
249	43.9		
249	34.8	43.7	
249	0.0		
249	14.0		
249	38.9	17.6	35.7
250	34.9		
250	0.0		
250	46.2	27.0	
250	32.9		
250	45.5		
250	59.5	46.0	
250	39.1		
250	41.4		
250	49.2	43.2	
250	30.2		
250	47.5		
250	5.4	27.7	36.0

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
251	44.1		
251	23.4		
251	41.2	36.3	
251	0.0		
251	27.1		
251	51.4	26.2	
251	21.3		
251	27.0		
251	49.2	32.5	
251	56.0		
251	35.7		
251	13.0	34.9	32.5
252	28.4		
252	17.4		
252	24.7	23.5	
252	12.6		
252	29.3		
252	31.6	24.5	
252	26.6		
252	19.9		
252	30.2	25.6	
252	40.3		
252	17.6		
252	23.5	27.1	25.2
253	30.8		
253	39.0		
253	32.6	34.1	
253	30.9		
253	39.4		
253	0.0	23.5	
253	28.0		
253	41.7		
253	35.5	35.1	
253	39.2		
253	44.8		
253	36.2	40.1	33.2

Site	Total tree C mass (Mg C ha^{-1})	Replicate Average (Mg C ha^{-1})	Site Average (Mg C ha^{-1})
254	92.3		
254	0.0		
254	91.8	61.4	
254	83.9		
254	32.8		
254	0.0	38.9	
254	106.2		
254	89.1		
254	82.3	92.5	
254	86.0		
254	83.1		
254	102.9	90.7	70.9