Variation in root biomass for clonal eucalypts as a function of regime and site quality

by

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Declaration

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Summary

The South African forestry industry may reduce imposed carbon taxation by accounting for the industry's carbon sequestration. This study investigates the potential of *Eucalyptus grandis x urophylla* root systems to fix carbon and the factors that influence the growth of these roots. A two-way factorial design was used to compare the relative and upscaled belowground biomass of stands under planted regimes and coppiced regimes, as well as high and low site qualities (based on site index). Allometric models were developed to predict the bulk belowground biomass for both management regimes combined and for each management regime (planted or coppiced) separately, as well as root size class models (coarse, medium and fine) for each of the treatments, based on above ground variables. This study shows that the absolute belowground biomass is greater for high quality stands, while low quality stands have greater relative belowground biomasses. This study also shows that both the relative and absolute belowground biomass of coppiced stands are greater than that of planted stands. A novel finding of this study is that there may be a net belowground biomass and carbon accumulation over multiple rotations for planted stands, and this accumulation can be increased by implementing a regime consisting of a planted crop followed by a single coppice rotation.

Opsomming

Die Suid Afrikaanse bosbedryf mag koolstof belasting verminder deur rekening te hou van koolstof wat deur die bedryf gesekwestreer word. Hierdie studie ondersoek die potensiaal van *Eucalyptus grandis x urophylla* wortelstelsels om koolstof te sekwestreer, asook die faktore wat die groei van hierdie wortels beïnvloed. ʼn Tweerigting-faktoriaal ontwerp is gebruik om die relatiewe asook opgeskaalde ondergrondse biomassa van opstande wat slegs geplant is, met opstande wat stomploot-verjonging ondergaan het te vergelyk asook die relatiewe en opsgeskaalde ondergrondse biomassa van opstande op hoë en lae groeiplek bonniteite. Allometriese modelle is ontwikkel om totale ondergrondse biomassa te voorspel vir hierdie twee bestuurspraktyke (gesamentlik en afsonderlik). Allometriese modelle is ook ontwikkel om die biomassa van die gegewe wortel grootteklasse (grof, medium en fyn) vir elk van die behandelings te voorspel. Hierdie studie wys dat die absolute ondergrondse biomassa van hoë-bonniteit opstande groter is as die van lae-bonniteit opstande, maar dat die relatiewe ondergrondse biomassa groter is vir lae-bonniteit opstande. Hierdie studie wys ook dat beide die relatiewe en absolute ondergrondse biomassa van opstande wat stomploot-verjonging ondergaan het groter is as vir opstande wat bloot aangeplant is. ʼn Noemenswaardige bevinding van hierdie studie is dat daar ʼn akkumulasie van ondergrondse biomassa na veelvoudige rotasies mag wees vir geplante opstande, en dat hierdie akkumulasie verder vermeerder kan word deur ʼn regime te implementeer waar ʼn geplante rotasie gevolg word deur ʼn enkele stomploot-verjongingsrotasie.

This thesis is dedicated to
my family and friends
who have continuously supported me throughout my studies

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List of commonly used abbreviations

ANOVA – analysis of variance

AGB – above ground biomass

BGB – belowground biomass

dbh – diameter at breast height

Dq – quadratic mean diameter

H – top height of tree

Hd – dominant height of stand

HSIC – high site index coppiced

HSIP – high site index planted

LSIC – low site index coppiced

LSIP – low site index planted

SI – site index

1 Introduction

1.1 Anthropogenic Climate Change – a need for change

The world is currently experiencing climate change, with continuously rising temperatures, changes in precipitation patterns and a higher frequency of drought and heat waves (Jackson, 2018). This widespread climate change, due to anthropogenic activities, such as deforestation and the burning of fossil fuels, is occurring sooner than had initially been predicted (Li, *et al*., 2018). Anthropogenic heat emissions have increased by approximately 2% per year from 1965 to 2013, with more than 90% of these emissions credited to fossil fuels (Lu, *et al*., 2017). Aside from the modern-day climate change, it has also been suggested that there is historical evidence for negative feedback between civilization and environmental impact, the earliest recorded example being the onset of the Greek 'Dark Ages' (Rothacker, *et al*., 2018).

Rapid climate change, coupled with increasing international pressure and awareness, has resulted in several initiatives such as the International Carbon Action Partnership; the Kyoto Protocol; and the United Nations Framework Convention on Climate Change (UNFCCC). Members are required to adopt set policies to align themselves in the cause for mitigating climate change (INCAP, 2018, UNFCCC, 2018). To help mitigate climate change, South Africa has committed to address this challenge by aligning and complying with the United Nations Framework Convention on Climate Change; countries Reducing Emissions from Deforestation and Forest Degradation (REDD+), and Intergovernmental Panel on Climate Change (IPCC) initiatives through the South African Department of Environmental Affairs (DEA). In its initial phase, this convention requires industries in South Africa to be taxed, based on their carbon emissions. If there is evidence that a company or industry can reduce their carbon emissions, or even sequester carbon, there may be financial benefits for them.

1.2 Role of commercial forest plantations – a potential combatant to climate change?

There are five major carbon pools on earth: the geologic pool; the oceanic pool; the pedologic pool; the atmospheric pool (a fluctuation in which causes climate change), and the biotic pool. Wood is the major contributor to the biotic carbon pool and is estimated to store 400-500×10^{15} g carbon globally (Lal, 2008).

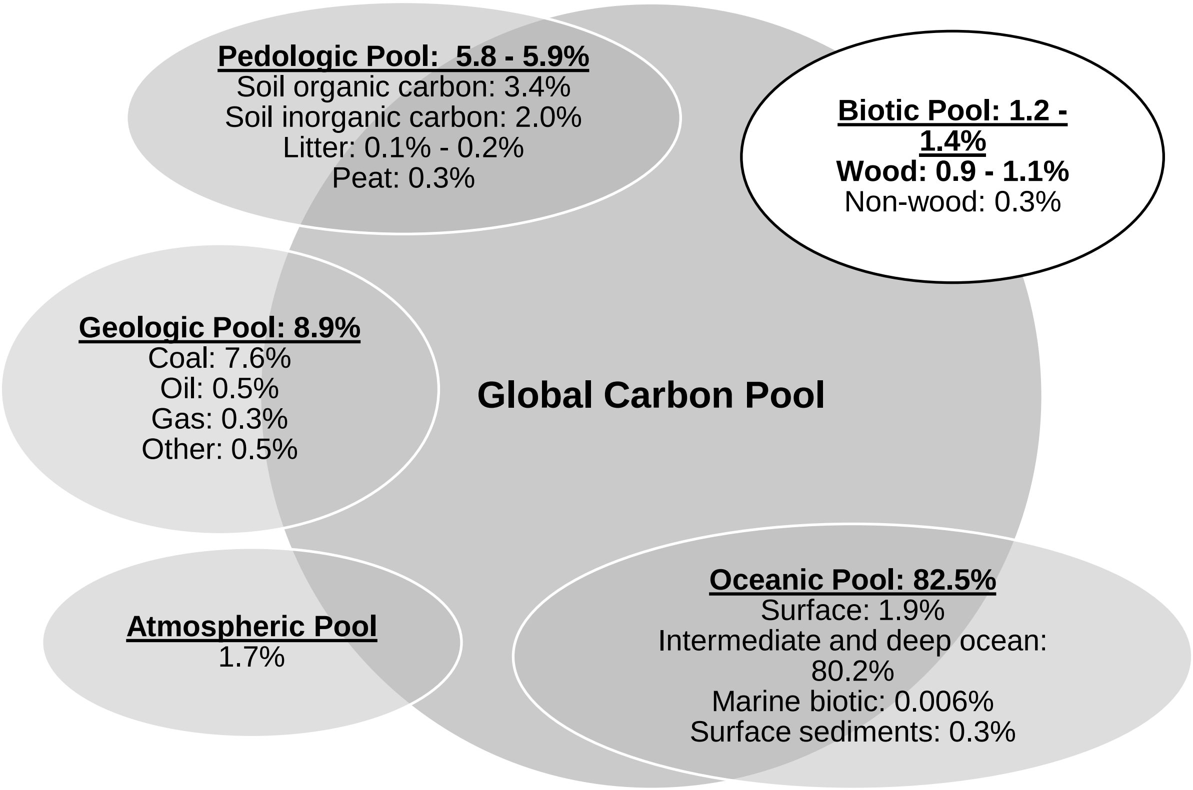

Figure 1.1: The estimated contribution of individual carbon storage pools to global carbon pools (Lal, 2008)

Given the size of the wood-based carbon pool relative to the atmospheric carbon pool, it has been suggested that a global reforestation project could mitigate the CO_2 problem in addition to bringing many other ecological benefits (Breuer, 1979). Condit (2008) confirms that natural forests store a large quantity of carbon, effectively removing this greenhouse gas from the atmosphere and thereby providing a means of addressing global warming. By managing forests as sustainable plantations, a significant increase in ecosystem carbon can be achieved (Wei & Blanco, 2014) which allows them to play an important role in mitigating the build-up of atmospheric CO_2 (Van Minnen, *et al*., 2008).

To better understand the role that terrestrial forests play in carbon storage, it is important to understand the various biomass pools within these forests. Typically, a terrestrial forest is subdivided into the following pools for biomass studies: the trees (consisting of foliage, live crown branches, dead branches, stem, bark, and roots) and non-tree biomass (consisting of decaying litter and undergrowth) (Mohart, *et al*., 2016; Muyambo, 2017).

1.3 The case for South Africa – root biomass in commercially managed eucalypt plantations

South Africa has approximately 1.27 million ha of land managed under commercial plantations (Edwards, 2012), of which 42.7% consists of eucalypt plantations (Godsmark, 2016). Eucalypts in South Africa are either managed as planted or coppiced establishments, over a range of site qualities. These plantations are typically managed to secure a biomass feedstock for wood processing plants, almost exclusively making use of the above ground stems. The roots are typically left in field as they present several technical difficulties in extraction and processing, such as costly harvesting and impurities trapped amongst the roots, and therefore not economically feasible.

Increased pressure on companies to mitigate carbon emissions has brought new interest to the below ground biomass left in field. Roots make up a substantial biomass pool and have the potential to sequester large amounts of carbon for prolonged periods of time. This will benefit the forestry industry financially by reducing proposed environmental taxes. To benefit from this, the forestry industry needs to accurately predict the amount of biomass and carbon trapped in roots. Since physically measuring enough roots to get an adequate representation is very costly, a more efficient approach is to model the belowground biomass based on aboveground characteristics. This requires the understanding of how belowground biomass relates to above ground biomass, as well as the factors that influence this relationship.

1.4 Aims

This study aims to quantify the biomass and carbon allocation in roots for *Eucalyptus grandis x urophylla*, a widely planted and highly productive hybrid planted in South Africa and internationally, for high and low site qualities, for both planted and coppiced stands. The following research questions are addressed:

1. Does site quality have an influence on the relative belowground biomass?
2. Does the management regime have an influence on the relative belowground biomass?
3. Can belowground biomass be modelled as a function of above ground tree size, site quality and management regime type?

4. Is there a net increase in the belowground biomass and carbon pools for planted versus coppiced (once) regimes over a prolonged period for both high and low site qualities?

From these questions, the following hypothesis are tested:

$H0_1$: Site quality has no influence on the relative belowground biomass for *Eucalyptus grandis x urophylla* (*E. gxu*).

Ha_1: Site quality has an influence on the relative belowground biomass for *E. gxu*.

$H0_2$: Establishment type has no influence on the relative belowground biomass for *E. gxu*.

Ha_2: Establishment type has an influence on the relative belowground biomass for *E. gxu*.

$H0_3$: Belowground biomass cannot be modelled as a function of above ground tree size, site quality and establishment type

Ha_3: Belowground biomass can be modelled as a function above ground tree size, site quality and establishment type.

$H0_4$: There is no increase in the belowground biomass and carbon pools over a prolonged period for either of the management regimes on both high and low site qualities.

Ha_4: There is an increase in the belowground biomass and carbon pools over a prolonged period for at least one of the management regimes on one of the site qualities.

2 Literature Review

2.1. Factors influencing root size

In South Africa, there is a general lack of data, as well as limited research, on which factors drive the root mass developement of commercially managed eucalypts, specifically *Eucalyptus grandis* and its hybrids (Du Toit & Dovey, 2005, Campion, *et al*., 2006, Du Toit, 2008). To quantify root- or belowground biomass, it is important to understand what factors drive their growth. Schenk and Jackson (2002a) suggest that a large proportion of the variation in root system sizes can be predicted from above-ground plant size, growth form and climatic variables. There are existing hypotheses and experimental evidence that suggest that root size relative to shoot size becomes lower as moisture availability increases (Mokany, *et al*., 2006; Schenk & Jackson, 2002a). Schenk and Jackson (2002a) found that maximum rooting depths showed strong, positive relationships with mean annual precipitation (MAP), which is in apparent contradiction with the conventional assumption that plants tend to be more deeply rooted in more arid environments. This is substantiated by Campion, *et al* (2006), who found that irrigation caused an increase in both above and below ground biomass in a *Eucalyptus grandis* stand in South Africa. It is therefore important to note that the relative size of roots may be bigger in drier regions, although the absolute rooting depth and total belowground biomass, as with the overall growth of the plant, increases with an increase in MAP. Although maximum rooting depth may be greater in areas with greater MAP, the depth at which plants have 50% to 95% of their total root biomass are significantly deeper in drier environments than in humid environments (Schenk & Jackson, 2002b). The fact that relative belowground biomass is less in higher rainfall regions is further substantiated by the fact that, although water usage increases in higher rainfall regions, the water-use efficiency is also higher (Stape, *et al*., 2004) meaning that the roots are more efficient in absorbing water.

Since above-ground plant size has a strong influence on below-ground biomass (Schenk & Jackson, 2002a), a method to relate roots ranging from larger tree sizes to smaller tree sizes is needed. An absolute ratio which allows this method of estimation is the root: shoot ratio and is commonly used in below-ground carbon allocation studies as well as general allometric studies (Ledo, *et al*., 2018; Liepins, *et al*., 2018; Schenk & Jackson, 2002a; Leyton, 1952).

2.1. Root: shoot partitioning in eucalypts

Coppicing is a form of vegetative reproduction which occurs in eucalypts, with two types of regeneration (Penfold & Willis, 1961). These are stump shoots, which grow from either dormant or adventitious buds, and root sprouts, which grow from sprouts produced by roots, shoots arising from root buds or adventitious roots resulting from a wound in the root (Lust & Mohammady, 1973). The new shoot growth develops from epicormic buds and (or) lignotubers, found in the live bark and cambium at the base and upper root systems of the trees (Penfold & Willis, 1961) It has long been standard practice in commercially managed plantations in South Africa to take advantage of this reproduction to extend the crop for additional rotations (Roberts, *et al*., 2018). Based on data from literature, there is strong evidence to suggest that there is a significant difference between the root: shoot ratios of planted and coppiced trees (Table 2.1), with the root biomass proportion of coppiced trees being roughly double that of planted trees at rotation age (6 – 9 years). This is to be expected, because while the above ground biomass must regrow after harvesting, the roots from the initial planted rotation remain, with additional growth taking place.

It is evident from the data in Table 2.1 that tree age plays a role in the root: shoot ratio for coppiced trees. Below ground biomass ranges from as low as 31% of total biomass at a tree age of nine years (Herrero, *et al*., 2014) to as much as 83% of total biomass at a tree age of 3 years (Razakamanarivo, *et al*., 2012). This suggests that it is important to account for age when comparing the root: shoot ratio of planted and coppiced trees.

The data in Table 2.1 suggest a significant increase in biomass partitioning towards roots when subjected to coppicing, however there is no clear trend regarding further increases in belowground biomass when subjected to multiple coppice rotations. Recent studies have also shown that a two cycle rotation (i.e. one planted rotation followed by one coppiced rotation) is more profitable than extended coppiced rotations, where productivity and biomass production may decrease due to mortality (Pereira de Rezende, *et al*., 2005), while new a new crop with improved genetic material can be planted in its place. It has also become common practice in South Africa to manage plantations in this manner, as described by Little and Du Toit (2013). Roberts, *et al* (2018) have done a similar study into the cost-effectiveness of different cut-stump control management options. Due to the inherent variability in the amount of biomass in coppiced root systems (personal observation) it is expected that intensive sampling is required to make conclusions regarding trends increasing root biomass with repeatedly coppiced rotations. This is substantiated by the increase in heterogeneity of tree roots as they age, and the consequent increase in sampling uncertainty (Sochacki, *et al*., 2017).

Among the commercially important species reviewed in Table 2.1 (*E. grandis*, Eucalyptus hybrids, and *E. grandis x urophylla*), the effect of genotype seems to have an insignificant influence on the root: shoot ratio, although there may be large variances in biomass partitioning for other species of this genus. There is, however, limited literature focusing on below ground biomass partitioning for the commercially grown eucalypts in South Africa. To understand the dynamics of belowground biomass partitioning under local conditions requires further research and intensive sampling. In particular, a system of planting followed by a single coppice rotation should be investigated as this system is commonly used in South African eucalypt plantation forests.

Table 2.1: Summary of total biomass and root: shoot partitioning in eucalypts from existing literature.

Study	**Species**	**Study Location**	**Climate/ Rainfall**	**Age of stems (years)**	**Coppiced/ Planted**	**Total Biomass (t ha^{-1})**	**Above Ground Biomass**	**Below Ground Biomass**	**Root: Shoot Ratio**
Du Toit, *et al.*, 2000	*Eucalyptus grandis*	Karkloof, South Africa	950 mm	7	Coppiced (4 rotations)	206.0	59.9%	40.1%	1:1.49
Laclau, *et al.*, 2000	*Eucalyptus* hybrids*	Pointe Noir, Congo	1200 mm (Levillain, *et al.*, 2011)	6	Planted	138.5	83.4%	16.6%	1:5.02
Levillain, *et al.*, 2011	*Eucalyptus grandis x urophylla*	Pointe Noir, Congo	1200 mm	6	Planted	71.4	77%	23%	1:3.35
Keith, *et al.*, 1997	*Eucalyptus pauciflora*	Piccadilly Circus, Canberra, Australia	1205 mm	58	Natural Regeneration (from seed) – unfertilised	137.9 (C only)	80.3%	19.7%	1:4.08
					Natural Regeneration (from seed) – P-fertilized	131.7 (C only)	80.6%	19.4%	1:4.15
Chen, *et al.*, 2003	Eucalypt open-forest savannah (dominated by *E. tetrodonata* and *E. miniata*	Darwin, Australia	>1200 mm		Natural open-forest savannah	50.0 (carbon only)	61.4%	38.6%	1:1.59
Herrero, *et al.*, 2014	*Eucalyptus globulus*	Cantabria, Northern Spain	1146 mm	9	Planted	76.5	82.7%	17.3%	1:4.78
				9	Coppiced (4 rotations)	195.0	69.0%	31%	1:2.23
Razakamanarivo, *et al.*, 2012	*Eucalyptus robusta*	Malagasy Highlands, Madagascar	1600 mm	3	Coppiced (root age 47 – 87 years)	110.91	17.0%	83%	1:0.20
				5	Coppiced (root age 47 – 87 years)	125.24	22.7%	77.3%	1:0.29

* *The hybrid in this experiment crosses between* Eucalyptus alba *(female parent) and the result of crosses between* Eucalyptus *hybrids from Brazil, thought to be* Eucalyptus grandis, Eucalyptus robusta, Eucalyptus urophylla *and* Eucalyptus botryoides.

2.2. Sampling methods

Common methodologies used to determine belowground tree biomass are listed in Table 2.2. Sampling methods are classified into two groups, i.e. non-destructive sampling and destructive sampling. Examples and characteristics of these two groups were assessed, highlighting the advantages and disadvantages of each sampling method, as well its applicability.

Table 2.2: Comparison of methods for estimating below ground biomass (Addo-Danso, *et al*., 2016, Fahey, *et al*., 2017)

Method	**Type**	**Principle**	**Cost**	**Labor/ Time**	**Accuracy**
GPR Scanning	Non-destructive	Remote sensing by means of radar	High	Low	Low
Allometric Equations	Non-destructive	Mathematic relationship between above- and belowground biomass	Low	Low	Not specific to species or environment
Core Sampling	Non-destructive or semi-destructive	Roots in a soil-column is up-scaled to represent a section around the tree	High	High	Dependent on sampling-intensity
Bulk Excavation	Destructive	All roots, along with soil are dug up and then sieved	High	High	High
Root Excavation	Destructive	Roots are unearthed and then measured	High	High	High
Trench Profile	Semi-destructive	Roots are counted in a trench dug next to tree	Lower	Lower	Low

2.2.1. Non-destructive sampling

1. Ground penetrating radar scanning (GPR) is a remote-sensing device which uses radar to obtain images of roots within the ground (Webb, 2017, Butnor, *et al*., 2001, Butnor, *et al*., 2003, Butnor, *et al*., 2016, Addo-Danso, *et al*., 2016). Butnor *et al*. (2001, 2003, 2016) and Lorenzo *et al*. (2010) discuss the components, operational principles and theoretic background of the GPR in depth. Advantages of the GPR

system are that it is portable (Butnor, *et al*., 2001) and can also be used to repeatedly monitor and characterize roots since it is not destructive. A problem, however, is that this method tends to underestimate the below ground biomass since, especially near the stump, the scanner is obstructed from picking up roots that are below others (Butnor, *et al*., 2016).

2. Allometric equations estimate the volume or mass of different sections of a tree based on its relationship to other sections of that tree (Keith, *et al*., 2000). These equations can be derived by carefully measuring various characteristics of many trees (Bredenkamp, 2012). Allometric relationships are influenced by factors such as stem diameter (dbh), tree height (H) and crown volume (Sochacki, *et al*., 2007b). There are studies where suitable allometric equations have been developed to predict the relationship between above- and below-ground biomass (Sochacki, *et al*., 2007b, Keith, *et al*., 1997, Johnson & Risser, 1974, Liepins, *et al*., 2018), and in these cases R^2 values greater than 0.9 were typically achieved. There are, however, few studies on the allometric relationship between above and belowground biomass specifically for *Eucalyptus grandis* X *urophylla* grown in a plantation environment in the summer rainfall regions of South Africa. Table 2.3 below provides examples of studies where allometric models have been used to predict belowground biomass or carbon flux.

Table 2.3: Examples of allometric models used in existing studies to model belowground biomass.

Author/s	**Species**	**Region**	**Goal**	**Usage**	**Model/Estimation quality**
(Stape, *et al*., 2008)	*E. grandis* × *urophylla*	Brazil	Total below ground carbon allocation/Soil CO_2 efflux	$TBCA = F_S - F_A + \Delta[C_S + C_R + C_L + C_T]^*$	
(Giardiana & Ryan, 2002)	*E. saligna*	Hawaii			
(Clutter, *et al*., 1983)	General		Predicting stem volume	$B_t = b_0 + b_1 d^{b2} H^{b3} + \varepsilon^{**}$	
(Sochacki, *et al*., 2007b)	*Eucalyptus globulus,* *Eucalyptus occidentalis,* *Pinus radiata,* *Allocasuarina huegeliana* *and Acacia celastrifolia*	Australia	Predicting whole tree and root biomass	$lnB_t = b_0 + b_1 \ln(d) + b_2 \ln(H) + \ln \varepsilon$	
				$B_r = b_0 e^{b_1} d_{10}^{b_2} H$	$R^2 = 0.77 - 0.88$, C = 23 - 27 %

* $TBCA$ = total belowground carbon allocation, F_S = soil respiration, F_A = litterfall, C_S = carbon content (CC) of mineral soil, C_R = CC of coarse roots, C_L = CC of litter layer, C_T = CC of stumps

**B_t = total tree biomass, d = stem diameter, H = tree height, ε = error, B_r = total root biomass

3. Core Sampling. The time-consuming nature of root sampling has led to the development of an inexpensive and compact soil-coring device, with the additional benefit that roots can be characterized at depths of up to 6 m (Sochacki, *et al*., 2007a). Sochacki, *et al* (2017) studied the accuracy of various belowground biomass sampling methods, and found that with 25 core samples for a 7-year-old eucalypt would result in an uncertainty level of 81%. When combined with other sampling methods, however, sampling uncertainty can be reduced to as low as 8% with 25 core samples. Sochacki, *et al* (2007a) present an in-depth discussion on the working of a soil-coring device. Fahey, *et al* (2017) suggest that the most efficient method to sample fine roots in rocky soils to a depth of 30 cm is through manual coring. Coring bits tend to compress the soil, which results in an overestimation of belowground biomass (Park, *et al*., 2007).

2.2.2. Destructive sampling

1. Bulk excavation entails digging up the soil within a designated radius or plot around the sample tree along with the roots, whether it be manual or by use of a machine (e.g. back-actor), and then sieving the soil to retain the roots (Fahey, *et al*., 2017, Sochacki, *et al*., 2017, Brassard, *et al*., 2011). Sochacki *et al* (2017) suggest that bulk excavation is the simplest and also potentially the most efficient method to attain a sampling uncertainty of lower than 10%. The main disadvantage with the bulk excavation method is that it can be expensive and laborious (Danjon & Reubens, 2008).

2. Root excavation (as defined here) is the unearthing of the roots by means of hand tools and aims to unearth the root system as intact as possible. The major benefit of this method is the ability to obtain the 3-dimensional architecture of the roots (Danjon & Reubens, 2008). This process is the most labour-intensive and time consuming method (Reubens, *et al*., 2007) as cited by (Danjon & Reubens, 2008) but can be sped up by using water under low pressure (Danjon & Reubens, 2008, Pavlychenko, 1937). This has the added benefit of reducing the breakage of fine roots and is especially useful in sandy soils (Stoeckeler & Kluender, 1938). Besides being time consuming, this method also requires a large amount of water (Pavlychenko, 1937).

3. Trench profiling. A trench profile can be dug to reveal a below ground face from which the lateral distribution of the roots can be studied, (Laclau, *et al*., 2013) while the excavated soil can also be sieved to estimate root biomass (Levillain, *et al*., 2011).

Different layouts can be used for the pits depending on site conditions (i.e. soil depth) (Chidumayo, 2014, Costa, *et al*., 2014). Sampling uncertainty may be reduced if the trench is positioned nearer to the sample tree where a greater portion of the roots are located, as is the case with soil coring (Sochacki, *et al*., 2017). Fahey, *et al* (2017) suggest that, from a labour cost perspective, the trench method is the most efficient, however this method assumes that roots are uniformly distributed, which may be questionable for older stands since the heterogeneity of the roots increase with age (Park, *et al*., 2007, Sochacki, *et al*., 2017). Park, *et al* (2007) also argue that, due to the number of repetitions required to obtain a suitable level of uncertainty, combined with the laborious nature of digging trenches, this method is less efficient than coring.

It is evident from the literature reviewed that each method has its merits. If repeated measurements are required without damaging the root system, the GPR is recommended, given that a correction factor exists to correct for the underestimation of roots. Allometric equations are the easiest way to estimate belowground biomass but are dependent on suitable parameters obtained from careful measurements above- and belowground. If high accuracy is required, either bulk excavation or root excavation is recommended, depending on whether the root system needs to be intact and if water is available to assist this method.

3 Methodology

The aim of this study is to quantify the below ground carbon allocation in *Eucalyptus grandis* x *urophylla*, enabling the comparison between different site qualities, classified by site index (SI), as well as establishment type at site level (i.e. mass per unit area). This methodology is designed to meet this.

3.1 Study sites

The study was carried out in *E. grandis* x *urophylla* plantations established at KwaMbonambi, north of Richards Bay, KwaZulu-Natal (35º36'S, 48º6'E). Four study sites were selected to cover the scope of the study: Low Site Index Planted (LSIP), Low SI Coppiced (LSIC), High SI Planted (HSIP) and High SI Coppiced (HSIC) (Figure 3.1).

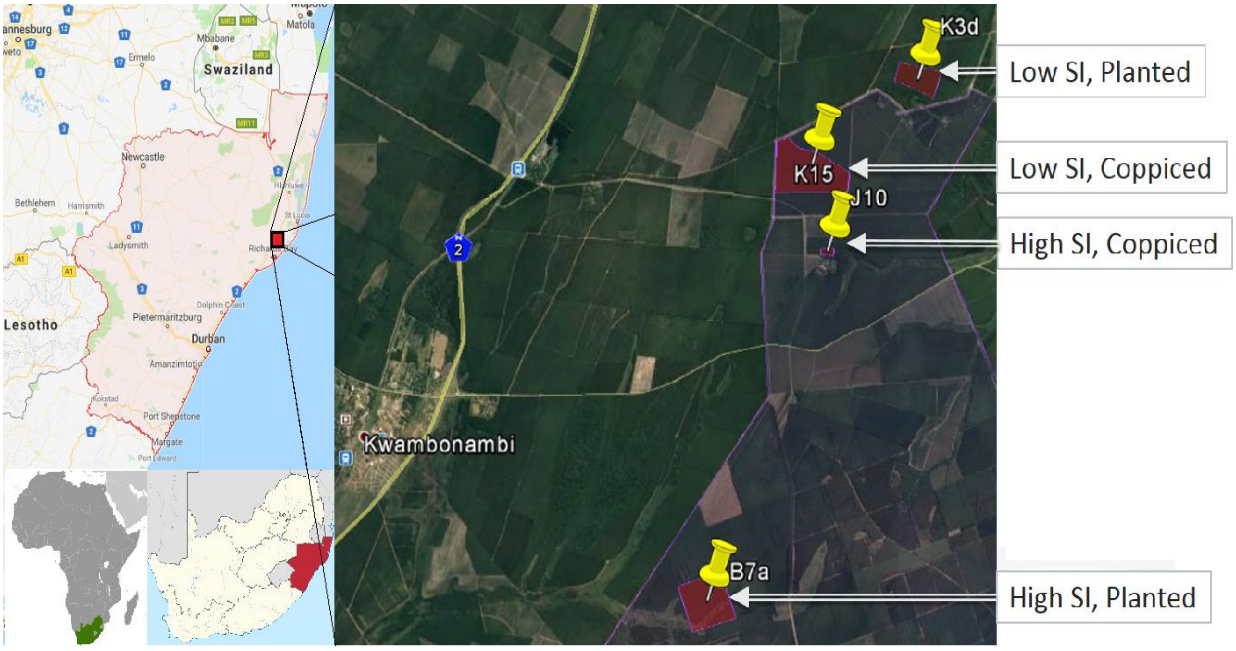

Figure 3.1: Location of study sites on a map of KwaMbonambi, South Africa

The climate of the area is characterized by warm, humid, wet summers and temperate, drier winters, with a mean maximum temperature of 27 °C, a mean minimum temperature of 15.8 °C and an overall mean of 21.4 °C. Mean annual rainfall in the region for the period 2016 to 2018 was 1297 mm (Mondi, 2016-2018). The elevation is 35 m above sea level with a predominantly flat topography and sandy soils. The four treatments selected for this study are shown in Table 3.1 and Figure 3.2 shows the area distribution vs site index of *E. gxu* planted by Sappi's in KwaZulu–Natal

(Sappi Database, 2017). The SI's of the selected stands are representative of the middle two quartiles of the area distribution.

Table 3.1: Main characteristics of selected sites

Establishment type	Site index[6]	Current tree age
Planted	22.6	6.8
Planted	17.7	5.8
Coppiced	24.0	6.5
Coppiced	17.7	6.2

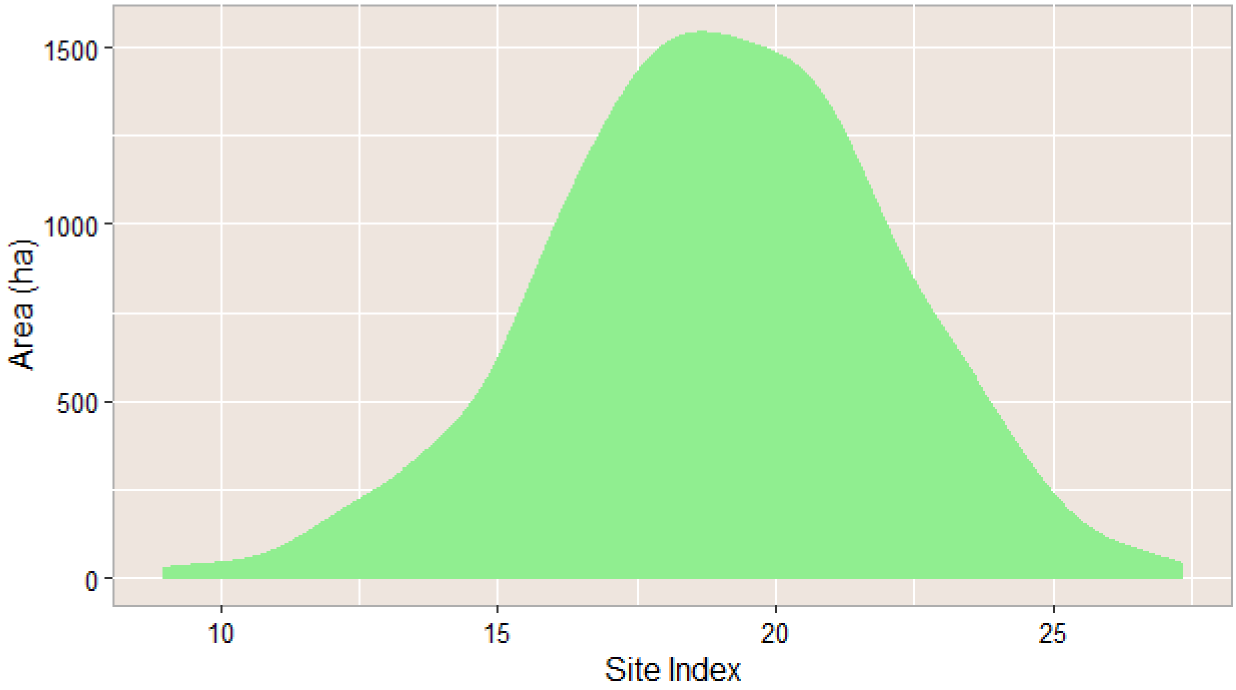

Figure 3.2: Distribution of the total plantation area (y) for a given SI (x) for *Eucalyptus grandis x urophylla* in KwaZulu-Natal (Sappi Database, 2017)

3.2 Field enumerations

Field enumerations were performed to upscale the sample plots to a per hectare value. This consisted of measuring 30 dbh-height pairs (Addendum A) and enumerating one representative field plot per treatment with tree diameters (Addendum B). Tree heights were measured using a Haglof Vertex Laser VL5 and their respective dbh's were measured using a dbh tape. To avoid edge effects (Wise, *et al*., 2013; Cadenasso, *et al*., 1997), all enumerations were taken deeper than three rows from the edge of the compartment.

Dbh distribution for each site was determined by establishing representative circular field plots using a Haglof Vertex Laser VL5 to demarcate the plot outline in field, and dbh’s were measured for all trees falling inside the plot using a dbh tape. The plot radius was predetermined as 12.62 m yielding a plots size of 500 m^2 for the high SI planted site as well as for the low SI planted and coppiced sites. A plot radius of 8.9 m was used for the high SI planted site, yielding a plot size of 250 m^2. This was done since the compartment size was too small to accommodate a 500 m^2 plot.

3.3 Sample trees

Six trees were selected in each site based on a representation of the tree size distribution in the respective compartments (Addendum C).

3.3.1 Aboveground biomass sampling

Selected trees were felled, and the following measurements taken:

- Tree height
- Tree height to minimum utilizable diameter (3.0 cm)

The tree was then debranched, and the canopy and the stem for each tree was weighed individually using a hang-scale (fresh mass). One canopy sample and one stem disc was taken from each site for moisture content determination.

3.3.2 Belowground biomass sampling

3.3.2.1 Root bole excavation

The root bole excavation technique, as described in the literature, was chosen for root sampling in this study. The midpoints between the sampled tree and the four diagonally adjacent trees were used as the corners of the area to be excavated (Figure 3.3).

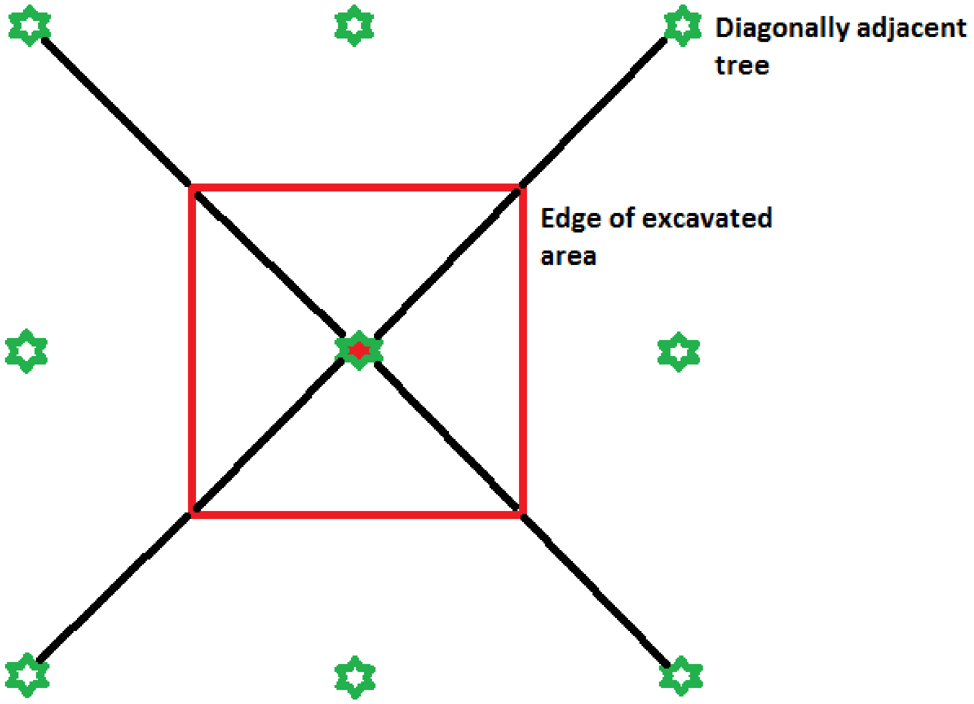

Figure 3.3: Layout of excavation area

A back-actor was used to excavate the bulk of the root bole and the resulting hole further excavated by hand to ensure a rectangular excavation with vertical sides to soil depth of 1 m (Figure 3.4). Roots extending past the boundary of the hole were cut off at the boundary and added to the sample roots. It was assumed that, although roots from neighbouring trees would extend past the boundaries of the excavation area, they would in fact be mirrored by roots from the sample tree. The bottoms of the holes were inspected for remaining roots, which were added to the sample roots.

Figure 3.4: The bulk of the root bole was excavated using a back-actor, after which the hole was further excavated by hand for more precise digging.

The soil was then passed through a purpose-built sieving table with a 13 mm aperture mesh (Figure 3.5). Although a large proportion of the roots were finer than the mesh, they were still retained due to their orientation towards the sieve which prevented them from passing through (Figure 3.6). Soil that had passed through the sieve was placed back in the hole.

Figure 3.5: Purpose built sieving table sieve

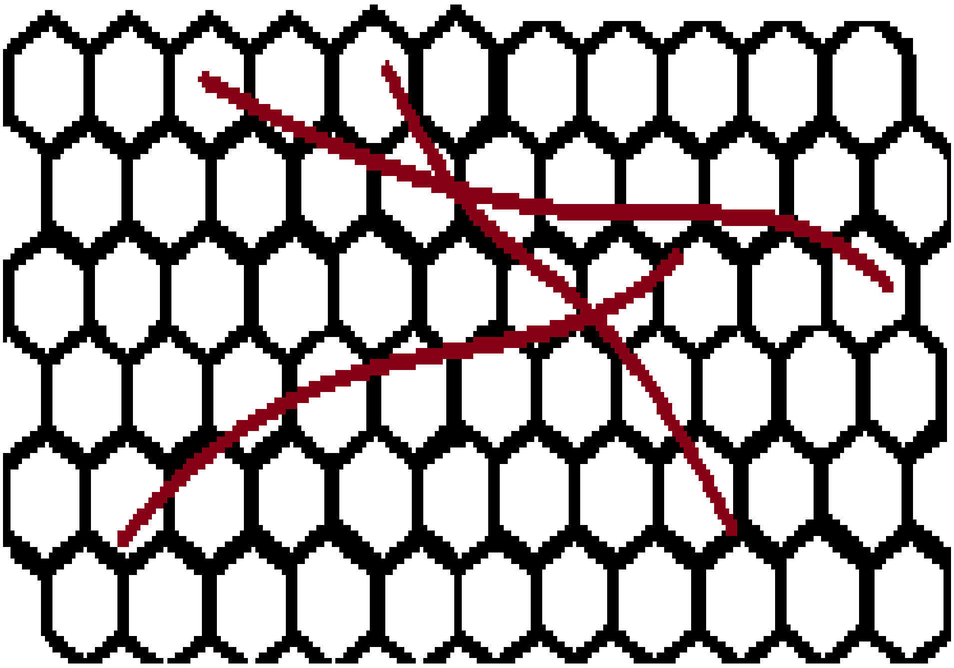

Figure 3.6: Schematic of fine roots retained by sieve.

After excavation, roots were divided into three size classes based on diameter: coarse (larger than 5.0 cm); medium (1.0 cm to 5.0 cm) and fine (less than 1.0 cm). Coarse and medium roots were cleaned in field using brushes. These were then weighed in field using a hanging scale. Fine roots were collected and cleaned of any soil. Soil from the high SI planted site was slightly adhesive, and in this case fine roots were rinsed in water. For the other three sites, the soils were non-adhesive, and easily cleaned with a brush. The fresh mass of the fine root samples was then determined using a battery-operated scale in field.

Sub-samples from each root size class from each tree were taken for further analysis.

3.3.2.2 Stumps

For planted sites, the diameters of 30 trees were measured at four heights, i.e. breast height, stump height, half of stump height and ground level. Stump height was determined as the mean height of the stumps for the six sampled trees, respectively. This was done to perform a regression which would enable the modelling of the volume of the stumps on an area basis.

For coppiced trees, the stump height varied much more than that of the planted trees, largely due to varying size of the root bole above the ground (Figure 3.7). Stumps of the six sampled trees for each of the coppiced sites were therefore measured at three heights (Top, Middle and Base), as well as the stump height, so that the volumes of these could be calculated (refer to 3.5.2 & 3.5.3).

Figure 3.7: Root boles above ground of coppiced trees varied much more than that of planted trees

3.3.2.3 Coring

Two soil core samples (0 - 1.0 m and 1.0 - 2.0 m), using a coring bit with an inner diameter of 97 mm and outer diameter of 102 mm, were taken after root bole excavation was completed and the holes had been backfilled with the excavated soil. This was done to determine whether a significant number of roots had remained in the excavated soil up to one-meter depth and to determine if significant quantities of roots occur in the soil horizons spanning from 1.0 - 2.0 m depth.

The layout for these holes were based on a circular, or Nelder Wheel (Nelder, 1962), pattern (Figure 3.8). Since the soil in the hole had effectively been homogenised with the sieving, it was not necessary to account for the root mass diminishing with lateral distance from tree location (Sochacki, *et al*., 2017). The locations of the holes were randomly assigned for each tree, with a 1-4 (North, East, South, West) for the direction from the centre, and a 1-8 for the distance in decimetres from the centre. Samples from the soil cores were wet-sieved by rinsing the samples in water, using a wire mesh with a one mm aperture to retain the roots. These samples were then oven-dried to constant mass at 105 °C.

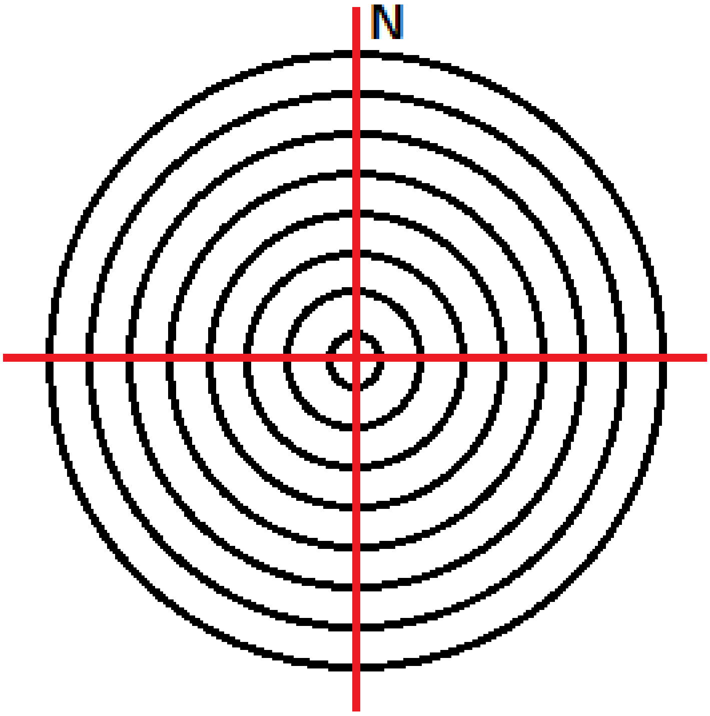

Figure 3.8: Coring layout with 10 cm concentric lines, oriented according to North.

3.4 Moisture content determination

Moisture content (MC) was determined for each root system, stem and tree canopy for each site to determine the absolute dry mass of the biomass (Addendum C). This was done using the manual for building tree volume and biomass allometric equations by Picard, *et al*. (2012). Stem discs and roots were dried at 105ºC to constant mass, and canopy samples were dried at 70ºC until constant mass in convection ovens. Oven temperatures were confirmed using a thermometer. One sample from each size class for each of the four sites were used to control moisture content daily until a constant weight was reached.

MC, expressed as a percentage, was calculated on wet basis, with a maximum MC value of 100% (Equation 1). This is in accordance with what is commonly used in the forestry and pulp and paper industry (Meincken & Tyhoda, 2014).

Equation 1

$$MC = \frac{m - m_0}{m}$$

Where:

m = mass of wet wood; m_0 = mass of dry wood

This can then be transcribed to make the dry mass of the gross sample the subject of the equation:

If

$$\frac{m - m_0}{m} = \frac{M - M_0}{M}$$

Then

$$M_0 = M - \left(\frac{m - m_0}{m}\right) \times M$$

Where:

m = subsample mass of wet wood; m_0 = subsample mass of dry wood
M =gross sample mass of wet wood; M_0 = gross sample mass of dry wood

3.5 Volume and density determination

3.5.1 Volume and density of roots

The Archimedes principle of water displacement was used to determine volume and density of roots (Picard, *et al*., 2012) (Addendum C). After the samples were dried to constant mass, one sub-sample from each root size class from each tree was selected and soaked until fully saturated. A beaker filled with water was placed on a balance scale and the scale was zeroed. The samples were then individually dunked in the water in a manner that it was fully submersed and still fully suspended in the water by using a needle. The reading on the scale was then recorded as it is numerically equivalent to the volume of the sample.

3.5.2 Volume and density of coppiced stumps

Initially, stumps would have been modelled with roots as belowground biomass. After some preliminary data analysis, however, it became evident that there was much larger variance in coppiced belowground biomass than in planted belowground biomass. To account for this variance, an attempt was made to model stumps separately from the roots. Eight months had elapsed between the initial measurements of the belowground biomass and the consequent remeasurement of the stumps, and the markings on the sampled planted root systems had faded. Fortunately, this was not the case with the coppiced root systems, and therefore the same root systems that had been initially sampled could be remeasured for stump volumes. Three diameters measurements for each of these sampled tree stumps were taken (Top, Middle and Base), along with the height of these stumps. This was used to calculate the volumes of these stumps using Newton’s Formula (Bredenkamp, 2012) (Equation 2). The stump masses were then calculated by using their representative stem densities of trees on each of these sites (Equation 3).

Equation 2

$$v = \frac{g_u + 4g_m + g_l}{6} \times l$$

Where:

v = volume of stump
g_m = cross-sectional area at midpoint of stump
g_l, g_u = cross-sectional area at the lower and upper end of stump
l = length of stump

Equation 3

$$M = \rho \times V$$

Where:
M = Mass
ρ = density
V = Volume

3.5.3 Volume and density of planted stumps

The stumps of the sampled trees for planted sites could not be remeasured. To resolve this, the diameters of 30 trees (ranging from small to large) located near the sampled trees were measured at four heights, i.e. breast height, stump height, half of stump height and ground level, along with the heights of the trees, for both low and high SI treatments. Stump height was determined as the mean height of the stumps for the six sampled trees at each of the two sites.

The Max and Burkhart function (Equation 4) was used to model the stump diameters based on the dbh and height of the enumerated trees using parameters specific to *Eucalyptus grandis x urophylla* published by Morley (2008). These stump diameters were then compared with the measured diameters, and an additional linear regression (Equation 5) was applied to the modelled stumps to reduce the error. The parameters for this regression were selected in a Stepwise Algorithm based on the Akaike Information Criterion (AIC) (Venables & Ripley, 2002).

Equation 4

$$d_u^2 = dbh^2 \left[b_0\left({}^{h}/_{H} - 1\right) + b_1\left(\left({}^{h}/_{H}\right)^2 - 1\right) + b_2\left(\alpha_1 - {}^{h}/_{H}\right)^2 I_1 + b_3\left(\alpha_2 - {}^{h}/_{H}\right)^2 I_2\right]$$

Where:

d_u = predicted diameter at given height
dbh = diameter at breast height
h = height of d_u
H = top height of tree
α_i = join points, expressed as ${}^{h}/_{H}$ (relative height)
$I_i = 1\ if\ {}^{h}/_{H} \leq \alpha_i, 0\ if\ {}^{h}/_{H} > \alpha_i$ (*i* = 1, 2)

And:

Equation 5

$$D = b_4 + b_5 D_{MnB} + b_6 h$$

Where:

D_{MnB} = Diameter as calculated with the Max and Burkhart function
h = Height at which diameter is calculated

The stump mass for the planted trees were then also calculated using their representative stem densities.

3.6 Carbon content determination

For carbon content, samples from each section of root (coarse, medium and fine) were bulked for the sample sites, i.e. three size classes for the four sample sites, with the six replications in each site being bulked (Table 3.2). This was done to save costs, and to retain enough biomass for other procedures. Carbon content for the coarse roots were used for stumps as well. Total Carbon content of the plant material was determined on a 150 to 200 mg dried and milled subsample (<0.400 mm) through total combustion using a Leco Truspec® CN analyser.

Table 3.2: Samples bulked for carbon content determination

High Site Index, Planted			**Low Site Index, Planted**		
Coarse roots X 6 samples, bulked	Medium roots X 6 samples, bulked	Fine roots X 6 samples, bulked	Coarse roots X 6 samples, bulked	Medium roots X 6 samples, bulked	Fine roots X 6 samples, bulked
High Site Index, Coppiced			**Low Site Index, Coppiced**		
Coarse roots X 6 samples, bulked	Medium roots X 6 samples, bulked	Fine roots X 6 samples, bulked	Coarse roots X 6 samples, bulked	Medium roots X 6 samples, bulked	Fine roots X 6 samples, bulked

3.7 Modelling aboveground biomass

3.7.1 Dbh-height regression

Dbh-height regressions (Equation 6) were derived for each of the sites based on 30 enumerated trees for each site, covering a range of small to large trees. Dbh was transformed to the inverse of dbh, and tree height was transformed to the natural logarithm of tree height. The data had some severe outliers, as evidenced by their Studentized Residual. This was likely due to inexperience in measuring tree heights, as well as gusts of wind. A robust modelling technique, which implements Huber's M-estimator, was used to fit the models (Venables & Ripley, 2002):

Equation 6

$$\ln H = b_{12} + b_{13} \frac{1}{dbh}$$

3.7.2 Mean tree method

The mean tree's aboveground volume was modelled based on the quadratic mean diameter (D_q) and the corresponding mean height (regressed height based on D_q) (Burkhart & Tomé, 2012; Van Laar & Akça, 2007). The aboveground volumes of planted trees were calculated using a volume function developed numerically for the species from Equation 3 (Equation 7) (Pienaar & Kotze, 2001). Coefficients for *Eucalyptus grandis x urophylla* were obtained from Morley (2008).

Equation 7

$$V_t = \left(\frac{\pi}{40\ 000}\right) \times k \times dbh^2 \times H$$

Where:

V_t = stem volume
$k = \left(\frac{b_1}{3}\right) + \left(\frac{b_0}{2}\right) - (b_0 + b_1) + \left(\frac{b_2}{3}\right) a_1^3 + \left(\frac{b_3}{3}\right) a_2^3$

The aboveground volumes of coppiced trees were calculated by using an equation developed for coppiced *E. grandis x urophylla* by Schwegman, *et al*. (2018) (Equation 8):

Equation 8

$$V_t = 10^{b_{12} + b_{13} \log_{10} dbh} + b_{14} \log_{10} H$$

The stem mass was then calculated by multiplying the stem volumes by their respective stem densities (based on a disc sampled from each site). From this, the up-scaled aboveground biomass (t/ha) was calculated by multiplying the mean tree mass with the stem count (Equation 9).

Equation 9

$$AGB = (m_{TA} \times n_{ha}) \div 1000$$

Where:

AGB = Aboveground Biomass (t/ha)
m_{TA} = mass (kg) of the mean tree's stem
n_{ha} = stem count (per hectare)

3.7.3 Diameter distribution frequency method

Sampled trees were grouped into diameter classes of 2 cm increments, covering the range of diameters found in the enumerated plots. The heights for these groups were calculated using their respective dbh-height regression functions, based on the middle diameter of each group. Tree volumes were calculated using Equation 8, which were then multiplied with their respective stem densities to determine stem mass. These modelled stem masses were then multiplied by their stem count (per hectare) to obtain the up-scaled aboveground biomass (Equation 10).

Equation 10

$$AGB = (m_{BA} \times n_B) \div 1000$$

Where:

AGB = Aboveground biomass (t/ha)
m_{BA} = mass (kg) of the representative tree's stem for a given diameter class
n_B = number of trees in given diameter class (per hectare)

3.8 Modelling belowground biomass

Three regression models were derived for bulk belowground biomass: one model representing all four treatments (HSIP, LSIP, HSIC and LSIC) (Equation 11), one model for Planted Sites (both High and Low Site Index), and one model for Coppiced Sites (both High and Low Site Index) (Equation 12). These models were based on the 24 sample trees.

The preferred model used dbh, height, and Site Index as input parameters. A natural logarithmic transformation was applied to all variables, as has been done by other studies (Table 2.3). The model representing both planted and coppiced sites included the dummy variable for "planted" or "coppiced" in the model as "0" or "1. A stepwise selection based on the Akaike Information Criterion as well as a scatterplot with all the measured variables were used to indicate if a significant improvement in the models could be obtained by including other variables than mentioned above. The models were tested for normality using the Shapiro-Wilk test, and for homoscedasticity by reviewing the spread of the residuals.

The bulk model, for all four sites is:

Equation 11

$$\ln(BGB) = b_7 + b_8 \ln(dbh) + b_9 \ln(H) + b_{10} \ln(Hd) + b_{11} E$$

The planted and coppiced models are:

Equation 12

$$\ln(BGB) = b_7 + b_8 \ln(dbh) + b_9 \ln(H) + b_{10} \ln(Hd)$$

Where:

BGB = Belowground biomass
Hd = Dominant height of stand
E = Type of establishment (planted = 0, coppiced = 1)

In addition to the bulk models, models for each root class were also created. These models had the same structure as the bulk model, but separate models were created for planted and coppiced sites for each of the root classes (coarse, medium, and fine). A natural logarithmic transformation was once again imposed on the parameters. These models were also tested for normality with the Shapiro-Wilk test and homoscedasticity by reviewing the spread of the residuals.

As with the up-scaling of the aboveground biomass, the belowground biomass was also calculated using two methods, i.e. "Mean tree method" and "Diameter distribution frequency method" (Equations 13 & 14, respectively). This was done for bulk root biomass as well as for classed root biomass.

Equation 13

$$BGB_u = (m_{TB} \times n_{ha}) \div 1000$$

Where:

BGB_u = upscaled belowground biomass
m_{TB} = mass (kg) of the mean tree's roots
n_{ha} = stem count (per hectare)

Equation 14

$$BGB_u = (m_{BB} \times n_B) \div 1000$$

Where:

m_{BB} = mass (kg) of the representative tree's roots for a given diameter class
n_B = number of trees in given diameter class (per hectare)

3.9 Relating belowground biomass to aboveground biomass

Literature review has suggested that both root: shoot ratio (Equation 15) and belowground biomass as a percentage of total biomass (Equation 16) can be used to compare the biomass allocation of various sites:

Equation 15

$$RSR = BGB: AGB$$

Where:

RSR = root: shoot ratio

Equation 16

$$BGB_{\%} = \frac{BGB}{BGB + AGB}$$

Where:

$BGB_{\%}$ = Belowground biomass as a percentage of the total biomass

3.10 Accumulation of belowground biomass

To determine if there would be a net accumulation of belowground biomass for either a planted only regime or a planted + coppice regime over a prolonged period, as well as how these would compare, the belowground biomass was added over a number of rotations and offset by a decomposition rate presented by Stephan (2018). The resulting equation (Equation 17) thus has two components: the belowgound biomass of the latest rotation, plus the sum of the decomposed remnants of previous rotations.

Equation 17

$$BGB_A = BGB_n + \sum_{i=1}^{m} BGB_i \times e^{-kt}$$

Where:

BGB_A = Accumulated biomass to current rotation; BGB_n = Belowground biomass of latest rotation
n = number of rotations
m = $n - 1$ if current rotation is planted; $n - 2$ if current rotation is once coppiced
t = time lapse between harvesting of BGB_i and latest rotation

4 Results

4.1 Tree growth on selected sites

Basic descriptive measurements of the stands used to represent the four treatments are shown in Table 4.1, confirming that the differences in productivity in Hd classes, Dq, height and volume were all significantly different ($p < 0.001$ in all cases, except for SI, where the Hd was used for comparison of means instead). When the selected site indices (centring around 18 and 23 m) are compared with this distribution (Table 4.1), it can be noted that they fall within the two middle quartiles. This illustrates that this study is representative of the majority of *E. grandis x urophylla* stands in the province.

Table 4.1: Summary of above ground biomass recorded at age 7 years for each of the four treatments

Treatment	Dbh range (cm)	Quadratic mean diameter (Dq, cm)	Mean height (m)	Dominant height (m)	Standing volume (m^3)	Site index (10, m)
High Site Index, Planted	8.3 - 17.8	15.1	21.5	22.6	250.0	22.3
Low Site Index, Planted	2.9 - 15.3	12.2	16.9	17.7	104.0	16.5
High Site Index, Coppiced	9.2 - 22.2	16.5	22.2	24.0	183.4	23.4
Low Site Index, Coppiced	7.6 - 14.7	12.2	17.1	17.7	117.8	16.7

4.2 Sampled trees

Figure 4.1 shows the distribution of total biomass for sampled trees. These were insignificantly higher for coppiced sites than for planted sites of similar quality ($p = 0.06$ for high SI, $p = 0.44$ for low SI). Figure 4.2 shows the total biomass for each of the sampled trees, coloured by tree section and grouped by treatment, and illustrates that the six trees which were sampled for each treatment covered the range in tree size of the stand that they represented. Figure 4.3 shows boxplots of the root: shoot ratios of each of the treatments, with coefficient of variance of 0.16, 0.49, 0.10 and 1.11 for High SI Planted, HSIC, LSIP and LSIC, respectively, and illustrates that there is greater variability in the relationship between above- and belowground biomass for coppiced trees than for planted trees.

Analysis of variance (ANOVA)revealed that there is a significant difference between the means of the root: shoot ratios of HSIP and HSIC ($p = 0.03677$), as well as between

HSIP and LSIP (p = 0.01795) (Table 4.2). In comparing the LSIP and LSIC, one point was found to be a severe outlier (2nd tree for LSIC, Figure 4.2), and upon further inspection, it was recognised that this specific tree may have coppiced late, and therefore had a younger stem than the other trees. When this data point was removed for the comparison of means, a significant difference was also found (p = 0.02745). The HSIC stand had a lower relative root biomass than the LSIC stand, but this difference was not significant. (p = 0.6526) (Figure 4.3, Table 4.2).

Table 4.2: Analysis of Variance (ANOVA) of the belowground biomass for the different treatments

	Sum of Squares	**Degrees of Freedom**	**F-Value**	**P (>F)**
High SI (Planted vs Coppiced)	0.12770	1	5.801	0.03677
Residuals (High SI)	0.22013	10		
Low SI (Planted vs Coppiced)	0.03189	1	6.906	0.02745
Residuals (Low SI)	0.04156	9		
Planted (High SI vs Low SI)	0.00781	1	7.991	0.01795
Residuals (Planted)	0.00977	10		
Coppiced (High SI vs Low SI)	0.00607	1	0.217	0.6526
Residuals (Coppiced)	0.25192	9		

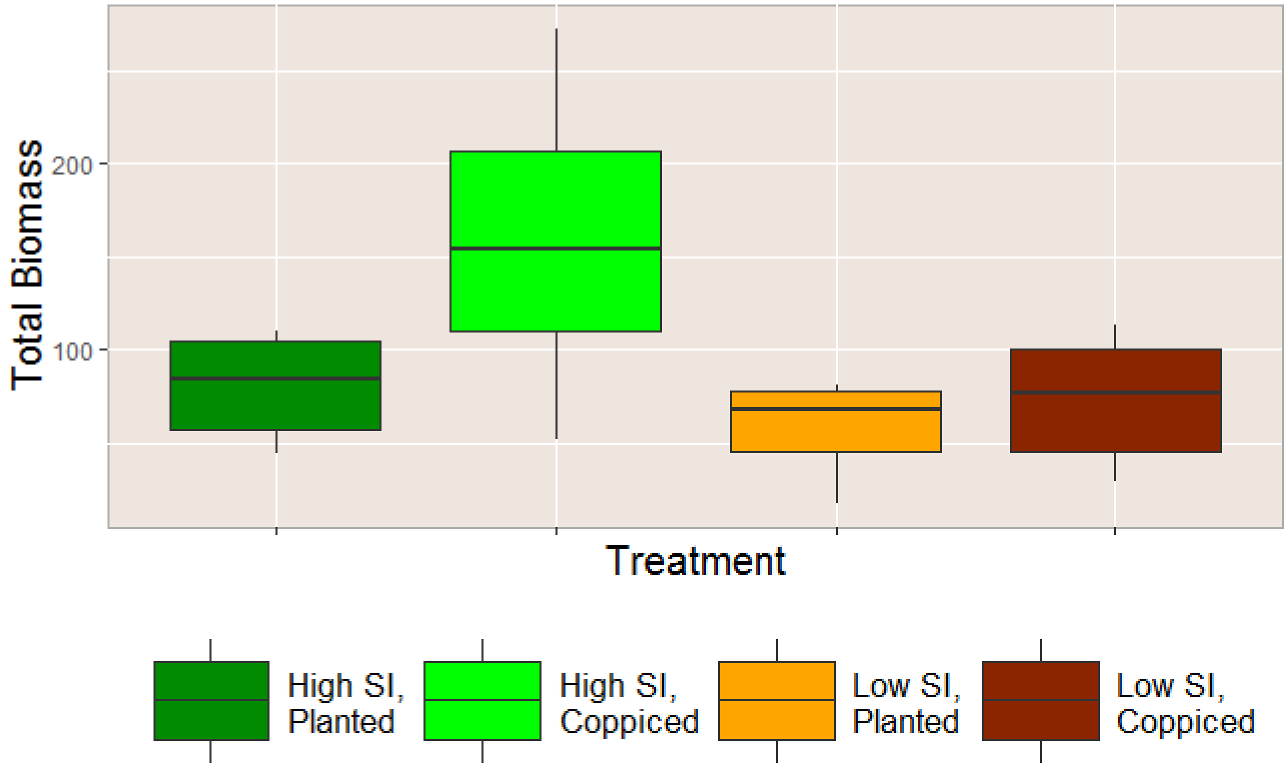

Figure 4.1:Boxplot representing the total biomass of the 6 sampled trees in each treatment. The coloured section represents the interquartile range, while the bars represent the minimum and maximum values.

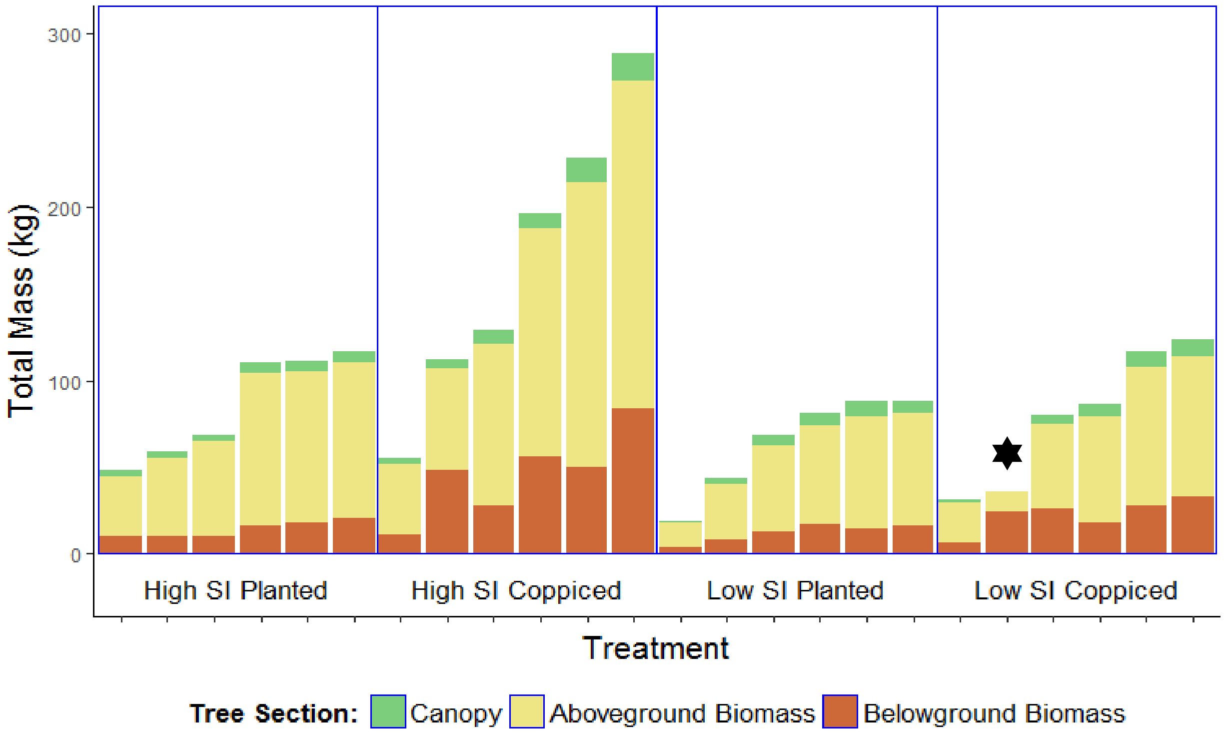

Figure 4.2: Total biomass for each sampled tree in each of the four treatments, ranked from small to large and grouped by treatment. ✡: Outlier tree.

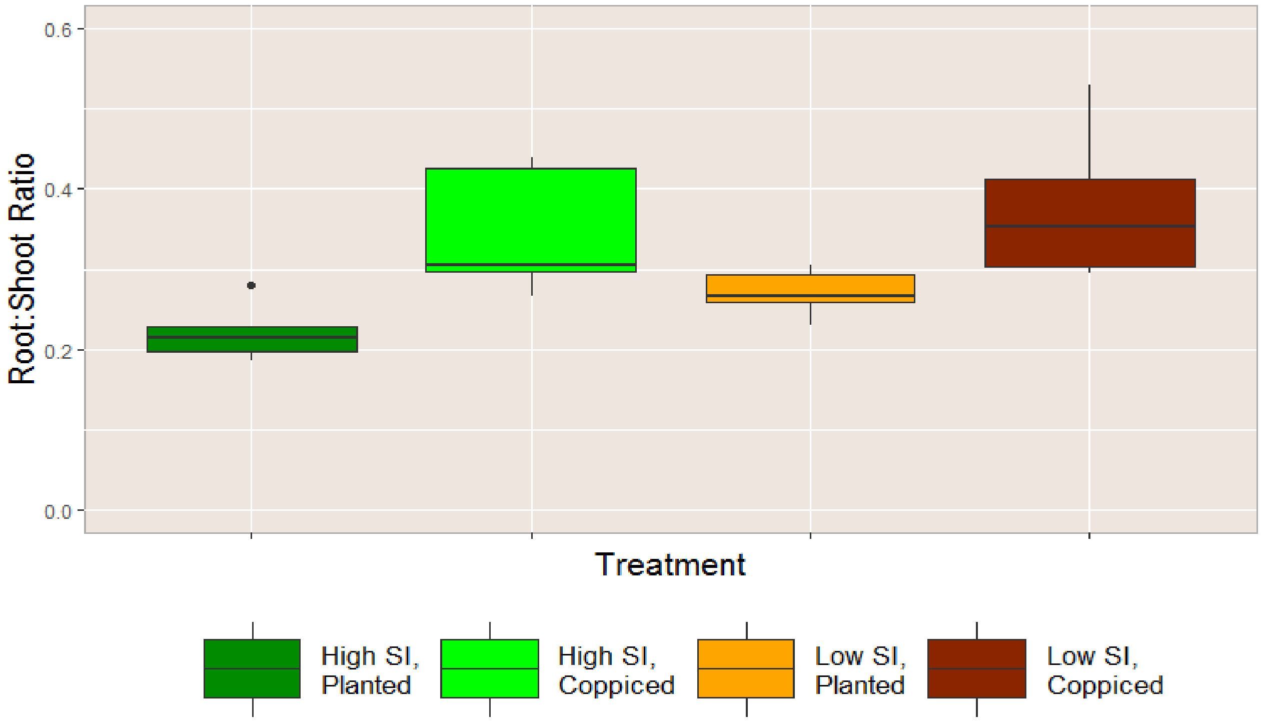

Figure 4.3: Boxplot representing the relative root biomass of the 6 sampled trees in each treatment. The coloured section represents the interquartile range, while the bars represent the minimum and maximum values. Outliers are shown as dots. Note: there are two points with relative root biomass outside the plot range, viz. 0.82 (High SI, Coppiced) and 2.2 (Low SI Coppiced).

4.3 Allometric equations

The developed allometric equations predicting root biomass, along with their respective p-values and adjusted R-square values are shown in Table 4.3. Nine allometric equations were developed to estimate various biomass components in the stand. The modelled dry root classes, i.e. coarse roots, medium roots and fine roots, as well as the stumps, which were modelled using the Max and Burkhart taper function, are discussed separately under Section 4.4. The total root biomass correlated more strongly with aboveground variables (dbh, H and Hd) for planted trees than for coppiced trees, with adjusted R-squared values of 0.97 and 0.67 respectively.

Figure 4.4 shows the predicted vs observed values of the below ground biomass for the Planted, Coppiced and Combined models. It is evident that the confidence interval for the planted model is narrower than that of the coppiced model, as is the confidence interval of the combined model. There is also a slight overprediction of small root systems and a slight underprediction for large roots with all models. In all cases the regressions were highly significant ($p < 0.01$). Also, the models overpredict the biomass for small trees and under-predict for large trees, although this is more apparent with the coppiced model. Despite this, a 95% confidence interval of the slopes of the predicted vs observed models suggest that a slope of 1 is plausible for all the models. Additionally, linear models of predicted vs. observed with an offset of 1 suggest that the slopes are not significantly different from 1 ($p > 0.05$).

Table 4.3: Summary of allometric root models derived from sampled trees for different root-sections in each treatment, showing the p-values and adjusted R-squares.

Model	**Equation**	**P-value**	**Adj. r-square**
Planted and coppiced, all belowground biomass	$\ln RM = -3.15 + 0.27\ln DBH - 2.16 \ln H + 1.12 \ln DH + 1.00E$	<0.001	0.8209
Planted, all belowground biomass	$\ln RM = 0.192 + 1.658\ln DBH + 1.311\ln H - 1.885 \ln DH$	<0.001	0.9657
Coppiced, all belowground biomass	$\ln RM = -2.78 + 3.65\ln DBH - 2.84 \ln H + 1.66 \ln DH$	<0.01	0.6663
Planted coarse roots	$\ln RM = -0.044 + 2.392\ln DBH + 0.599 \ln H - 1.928 \ln DH$	<0.001	0.9518
Planted medium roots	$\ln RM = -1.699 + 0.355 n DBH + 3.055 \ln H - 2.202 \ln DH$	<0.01	0.7908
Planted fine roots	$\ln RM = -3.633 + 2.054\ln DBH - 1.323 \ln H + 0.741 \ln DH$	<0.001	0.8325
Coppiced coarse roots	$\ln RM = -3.08 + 3.68\ln DBH - 2.78 \ln H + 1.60 \ln DH$	<0.001	0.6175
Coppiced medium roots	$\ln RM = -5.05 + 4.17\ln DBH - 3.77 \ln H + 2.20 \ln DH$	<0.01	0.7818
Coppiced fine roots	$\ln RM = -4.87 + 2.61\ln DBH - 2.19 \ln H + 1.65 \ln DH$	<0.01	0.7122

Where:

RM = root mass (kg)

dbh = diameter at breast height (cm)

H = tree height (m)

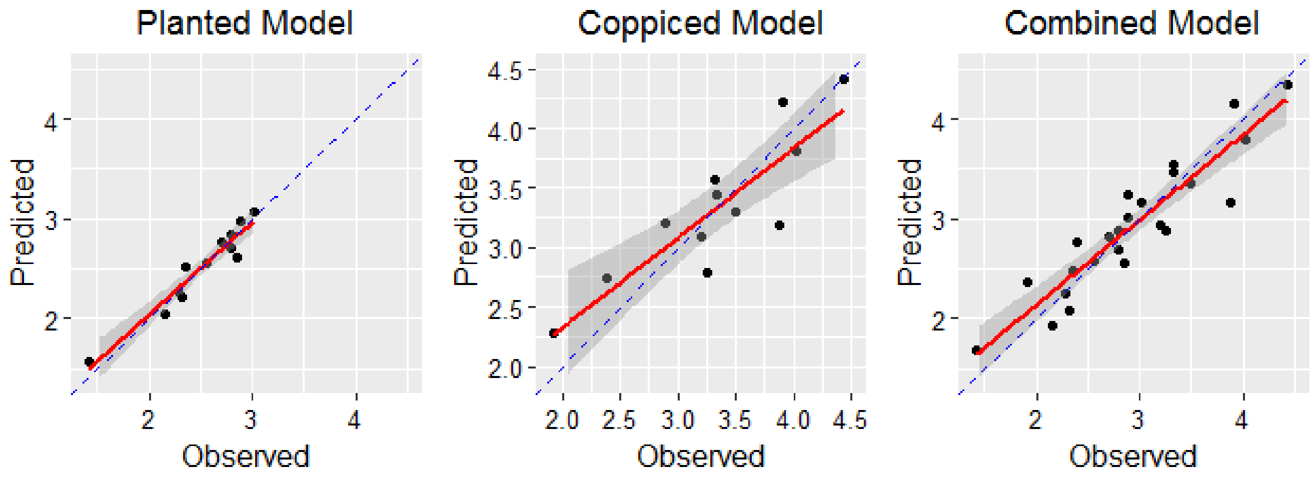

Figure 4.4: Predicted vs Observed plots for the Planted, Coppiced and Combined models. The dashed line indicates the y = x line, and the grey coloured area represents the 95% confidence interval.

4.4 Up-scaled biomass

The densities of stem wood disc samples (taken at 1.3 m height) are presented in Table 4.4. Although it was not the main aim of the study to investigate the stem density of *E. gxu*, these densities serve to compare the studied trees with other published studies. The observed wood densities per treatment are comparable with published *E. gxu* densities (Sharma, *et al*., 2015, Gomino, *et al*. 2001, Wei & Borralho, 1997).

Table 4.4: Stem densities for each treatment based on a sample disc for each site. Published densities from du Toit, *et al*. (2016), Sharma, *et al*., 2015, Gomino, *et al*. 2001, Wei & Borralho, 1997

Rotation	**Site Quality**		**Published**
	High Site Index	Low Site Index	
Planted	427.4 kg.m^{-3}	468.1 kg.m^{-3}	420 - 571 kg.m^{-3}
Coppiced	574.2 kg.m^{-3}	559.1 kg.m^{-3}	420 - 571 kg.m^{-3}

The total above ground, belowground and stump biomass of the four treatments are shown in Figures 4.5 (absolute biomass) and 4.6 (relative biomass). The upscaled root biomass for bulk roots as well as individual root classes were calculated using the allometric root models shown in Table 4.3 and the densities shown in Table 4.4. These results show that the absolute above- and belowground biomass for high SI treatments are higher than for low SI treatments, but the relative root biomass (as a percentage of the total biomass) for low SI treatments are in fact slightly higher (Figure 4.5 & 4.6).

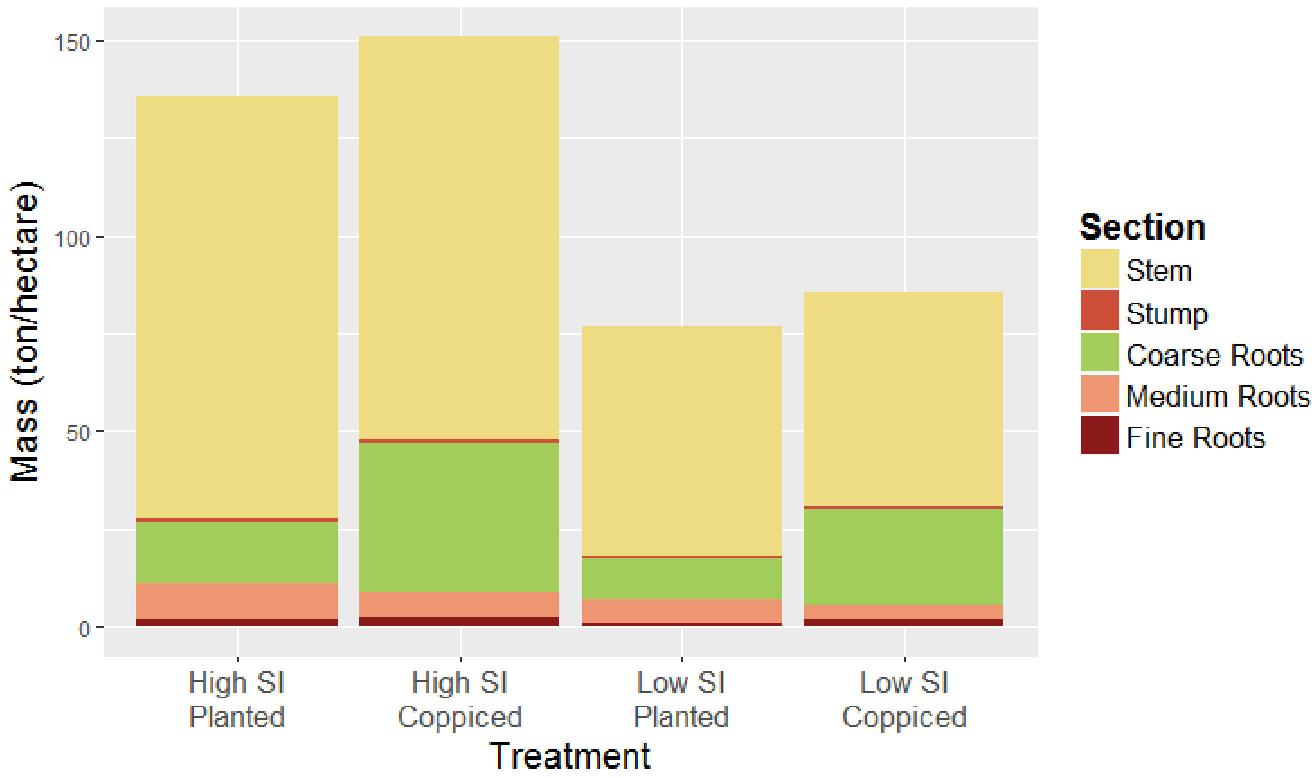

Figure 4.5: Up-scaled, modelled mass per unit area of biomass components for each of the tested treatments based on enumerated field plots.

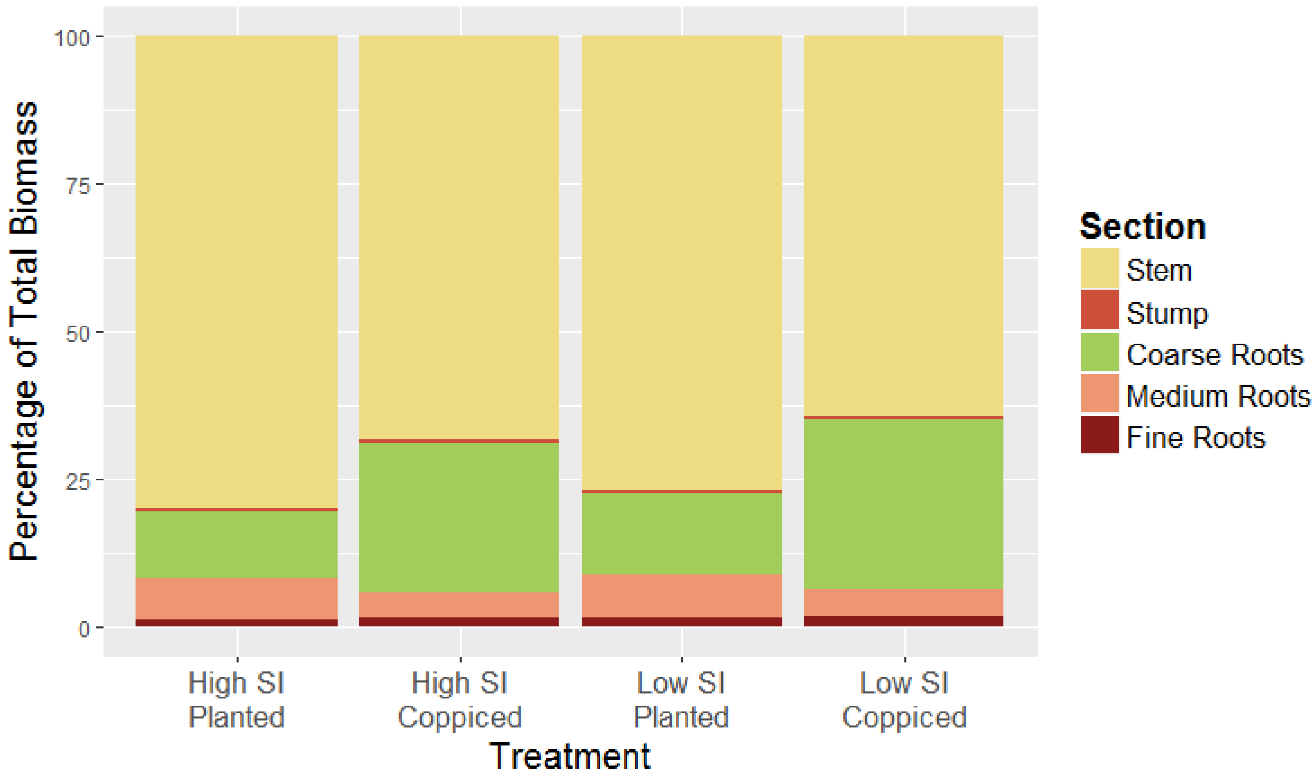

Figure 4.6: Up-scaled, relative mass of tree sections for each of the tested treatments based on enumerated field plots.

4.5 Carbon content

Table 4.5 shows the carbon content for each of the root-size classes for each of the treatments as a percentage as well as units per hectare. Though there are slight differences in carbon content between root classes and treatments, there is no obvious trend. This suggests that the bulk root mass may be used to predict the carbon stored, rather than using separate models for each root class.

Table 4.5: Carbon mass for tested treatments, grouped by root class, as percentage as well as units per hectare.

Treatment	**Root Class**						**Average**	
	Coarse		**Medium**		**Fine**			
	%	**Ton/ha**	**%**	**Ton/ha**	**%**	**Ton/ha**	**%**	**Ton/ha**
High SI Planted	44.1	7.7	48.2	4.4	49.3	1.0	47.2	12.8
Low SI Planted	48.2	5.1	47.9	2.7	46.0	0.5	47.4	8.5
High SI Coppiced	48.3	18.5	48.6	3.2	48.5	1.1	48.5	22.9
Low SI Coppiced	46.4	11.4	48.0	1.9	47.3	2.6	47.2	14.4
Average	46.8	10.4	48.2	3.0	47.8	0.8	47.6	14.7

4.6 Carbon accumulation

Table 4.6 shows the carbon accumulation after two rotations for planting only and for planting plus one coppiced rotation. Here it can be observed that two planted rotations fix more carbon than a planted rotation plus one coppiced rotation for both high and low SI's. Figure 4.7 shows the accumulation of carbon over 10 rotations, as calculated in Section 3.10. Here it can be seen that for both high and low SI's, there is a greater accumulation of biomass if the management regime allows for planted plus one coppice than if it consists of planting only. Another observation that can be made is that the asymptote of equilibrium between biomass accumulation and decay is reached later for planted plus one coppice regimes than for planted only regimes.

Table 4.6: Net carbon accumulation over two rotations: Plant + Replant vs. Plant + Coppice. *Decomposition rate estimated to have a half-life of one rotation.

Regime	Accumulated carbon (first rotation, ton/ha)	Decomposition	Accumulated carbon (second rotation, ton/ha)	Total accumulated carbon after two rotations (ton/ha)
Plant, High SI	12.8	50 %	12.8	19.2
Plant + 1 Coppice, High SI	12.8	NA	10.1	22.9
Plant, Low SI	8.5	50 %	8.5	12.8
Plant + 1 Coppice, Low SI	8.5	NA	5.9	14.4

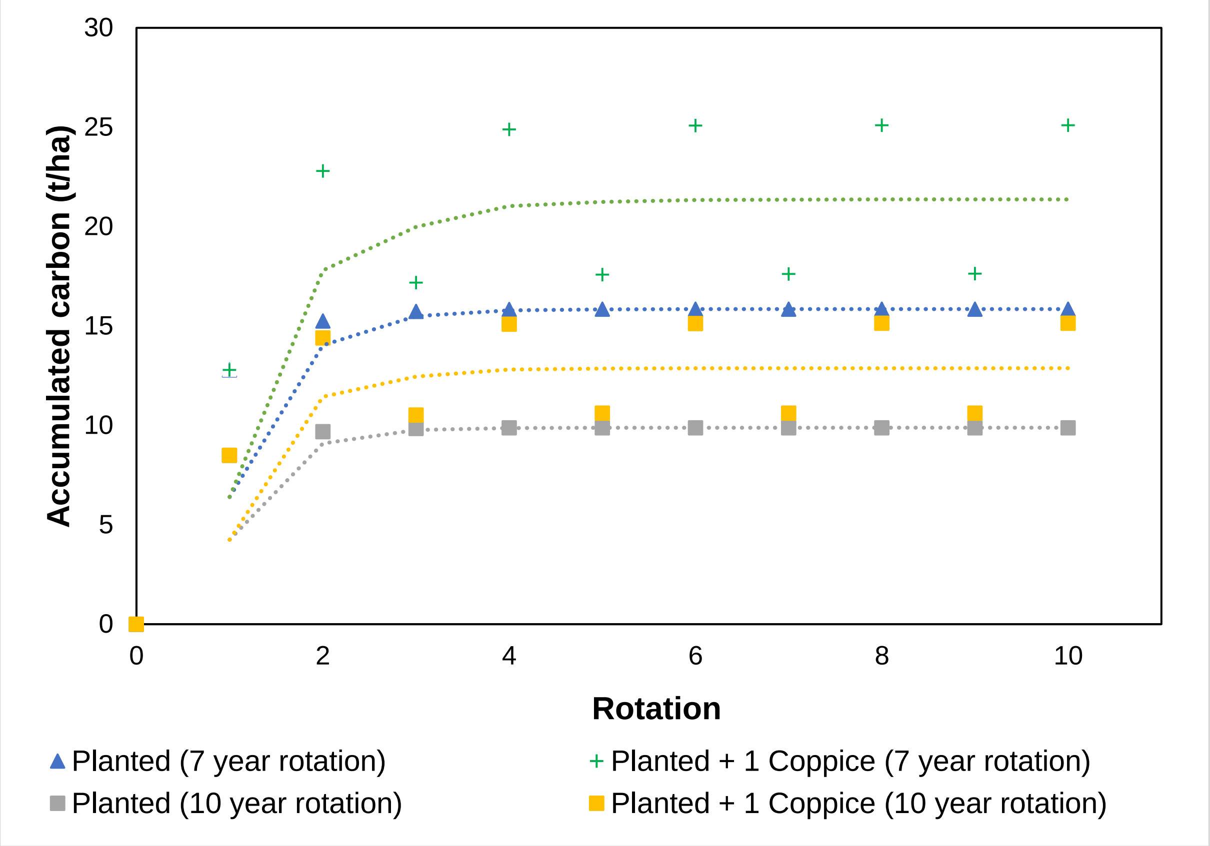

Figure 4.7: Carbon accumulation over ten rotations for the selected treatments with weighted average lines, as calculated in 3.10 Accumulation of belowground biomass

5 Discussion

5.1 Importance of tree age and relative biomass

The relative root biomass presented by Razakamanarivo *et al* (2012) (Table 2.1) is much higher than that of any of the other articles reviewed. This highlights the fact that relative root biomass can be misleading if not interpreted in context. The absolute root biomasses given in Razakamanarivo’s (2012) article are in fact very similar to the root biomass of commercially grown once coppiced eucalypts at rotation age. It is therefore important to consider the age or maturity of the above ground part of the tree, as a young (small) trees growing from a coppiced root system would have a small relative biomass. Although relative biomass is a very useful technique to estimate below ground biomass, this is only useful if compared to trees with similar above ground characteristics. This is further highlighted by the fact that the relative root biomass for the five-year-old trees presented in this article are already noticeably lower than that of the three-year-old trees. The absolute root biomass presented by Razakamanarivo (2012) is therefore useful to understand the increase of absolute belowground biomass repeatedly coppiced stands, but not the relationship between above and below ground biomass for trees at rotation age. This illustrates the importance of presenting the belowground biomass in a standardised format.

5.2 Sampled trees

The sampled trees for this study were selected to cover the range of the aboveground trees of the stands, i.e. small dbh to large dbh. This was done to improve the predictive capabilities of the models, since the smallest and largest trees have greater leverage when performing a regression. This increases the reliability of the models when estimating belowground biomass at stand level.

The range of the root: shoot ratios for planted trees are relatively small when compared to coppiced trees. This is assumed to be because a large amount of the belowground biomass for coppiced trees (regardless of aboveground size) is the result of the previous (planted) rotation’s growth, while only a part of the belowground biomass growth can be attributed to the current (coppiced) rotation’s growth. While the roots for planted trees start growing when the shoots start growing, and then increase as the aboveground biomass increases, the roots of coppiced trees are already large when the new shoot begins to grow. Thus, although the shoot for a selected tree may be suppressed, and not become very large, the roots for that tree may already be large. This may contribute to widen the range in root: shoot ratios for coppiced stands relative to planted stands.

5.3 Model investigation

The results show that models can be derived to predict the amount of belowground biomass at a stand level from dbh and height. The predictive capabilities of the belowground biomass model for planted stands is much better than that for coppiced stands. This is evident from the difference in the adjusted r-square values from the models, as well as the predicted vs. observed plots (Figure 4.4) This is expected, as the range for the relative belowground biomass in coppiced trees is much higher than for planted trees (Results: Figures 4.2 & 4.3). It is assumed that the larger variation in relative root mass for coppiced trees is due to the inherently irregular growth of coppiced root systems. This irregular growth may be due to several factors, such as the total amount of coppiced shoots that emerge after clear-felling, the time delay before and the way coppice reduction is applied, as well as environmental factors. Another reason for this may be that the aboveground tree may have been a dominant tree in the first rotation, resulting in a large root system, but then experienced a delayed early growth in the coppiced rotation and became suppressed. It is, however, expected that a greater sampling intensity focusing on coppiced root systems will be a more efficient approach to reducing uncertainty and improving predictive capabilities than would including more variables in the model.

5.4 Root physiology

When comparing the root class models, it is evident that the largest difference in adjusted r-square values between planted and coppiced models are found for the coarse roots (0.9518 vs. 0.6175, Table 4.3). Most of the additional growth following coppicing appears to occur in the coarse root section which, as a proportion, increases from 12.7% of the biomass for planted treatments to 27.0% of the biomass for coppiced treatments, while the difference in biomass for the other root sections between planted and coppiced treatments at 7 years are much less (7.0% vs. 4.4% for medium roots and 1.5% vs. 1.7% for fine roots, respectively) (Figures 4.5 & 4.6). This may suggest that the additional root growth occurs mostly in the coarse root class.

Fine roots also turn over at a relatively rapid rate when compared to medium and coarse roots, with a production rate of up to 2.8 t/ha/a (Matamala, *et al*., 2003, Du Toit, 2008, Jourdan, *et al*., 2008), although it must be kept in mind that this mass is in an equilibrium, and not constantly accumulating throughout the rotation like coarse and medium roots.

5.5 Site index influence

For this study, it was decided to compare high SI and low SI stands of similar ages in the investigation of belowground biomass, and how it relates to above ground biomass. This is a fair comparison to make if the assumption holds that the relative belowground biomass stays constant throughout the life-cycle of the tree. If, however, a tree should invest more in belowground growth in the earlier stages of development, this comparison would require the biological age of the trees to correspond to the actual age in years. It is clear from the results of this study that the absolute belowground biomass, as well as overall biomass, for the high SI stands are higher than that of the low SI stands, and, in contrast, that the relative belowground biomass for the low SI stands are higher than that of the high SI stands. This is in line with what literature suggests (Section 2.1). The high SI stands, however, are felled at 7-8 years, whereas the low SI stands are felled at 10 years, and this highlights an interesting predicament for this study. The low SI stands in this study were sampled at 6-7 years, the same age as the high SI stands, however, such a stand would typically have an additional 3-4 years of growth under typical management regimes. Should the relative growth of the belowground biomass not be linearly correlated to the growth of the above ground biomass, the comparison between relative belowground biomass of high SI stands and low SI stands may be biased. The importance of this is further emphasized when comparing the relative belowground biomass of coppiced trees. Although the age of the shoots is the same, the age of the roots are 14-16 years for the high SI stands and 17-18 years for the low SI stands. Should the comparison be made between trees at rotation age, the age of the roots for high SI stands would still be 14-16 years, but the age of the roots for the low SI stands would be 20-22 years if the currently implemented regime were followed. To account for this would require studying the relative belowground biomass of both high and low SI stands throughout the entire rotation to get an understanding of the influence of age on relative belowground biomass.

Based on the underlying assumption that the relative belowground biomass remains constant throughout the life cycle of the trees, and that the difference in relative belowground biomass between high and low SI stands are due to site quality factors, inferences can be made as to what the driving factors are behind the biomass partitioning, and why this differs for high and low SI stands. The absolute belowground biomass is higher for high SI stands than for low SI stands, while the relative belowground biomass is higher for low SI stands than for high SI stands. The same is true for suppressed trees inside one treatment, where, although the absolute belowground biomass for that tree is less than for larger trees, the relative belowground biomass is higher. This suggests that trees that are under stress tend to invest more in belowground growth than above ground growth or are simply unable to drive above ground growth to keep up with their fast-growing counterparts. This also illustrates how that, once a tree has become dominant, it can more efficiently manage its resource allocation and drive above ground growth more effectively.

The mechanism that drives the belowground growth may well differ between low SI stands and suppressed trees in general. Suppressed trees need to adapt to become more shade tolerant, and they therefore need to adjust their leaf morphology and branching patterns to maximise photosynthetic activity. This changes the nutrient and water requirements of the trees, putting a higher demand on the acquisition of these resources (Poorter & Van der Werf, 1998; Coomes & Grubb, 2000), which drives root growth. For trees growing in low quality sites, the resource and water availability is lower, and, based on the assumption that the trees would allocate more resources to the organ that acquires the most limiting resource, the trees therefore need to invest more in colonizing the soil to obtain enough resources for aboveground growth (Reynolds & Thornley, 1982; Johnson & Thornley, 1987; Ledo, *et al*., 2017). This investment in belowground growth has the subsequent effect of retarding aboveground growth.

5.6 Upscaled biomass

The up-scaled relative root biomass from this study, which is based on the allometric models presented, is comparable to what has been found by other studies (Table 2.1). These confirm that the relative biomass of the roots in coppiced establishments are larger than that of planted establishments. Contrastingly, it seems apparent from Table 4.5 that the gross accumulated belowground biomass at rotation age for two planted establishments would be more than the belowground biomass of a coppiced establishment (plant +1) at rotation age. It is therefore important to bear in mind that, unless the planted crop is coppiced, decomposition will effectively start shortly after harvesting. On the other hand, when a tree is harvested, but allowed to coppice, the bulk of the coarse and medium sized roots will not decompose for yet another rotation, in addition to the subsequent growth of the roots.

5.7 Carbon content and long-term carbon pool

The carbon contents found in this study are similar to what has been published by Gifford (2000) at 47.9 %, 46.1 % and 43.5 % for root diameters > 10 mm, 4-10 mm and < 2 mm respectively. The carbon contents of the individual root classes assessed in this study are also similar to each other (Table 4.5), which suggests that these can be bulked together when predicting carbon content of belowground biomass. Although this study did not investigate the types and quantities of different carbon bonds found inside the roots, such as cellulose, hemicellulose, and lignin, it is expected that this may influence the long-term carbon pool, as lignin has been found to decompose at a slower rate than cellulose and hemicellulose (Kahl, *et al*., 2017, Fravolini, *et al*., 2018). An improvement on this study would thus be to quantify the relative amounts of lignin, cellulose and hemicellulose, with their respective carbon contents, for each of the root classes, as well as for planted and coppiced root systems, to determine if root size and type would have an influence on the long term carbon pool. If this can be done, it is expected that it may reflect a difference in the long term carbon pools of planted only management regimes and planted plus one coppice management regimes, since the root system from a planted plus one coppice regime consists of more coarse roots than that of a planted only regime. This highlights the importance of understanding what the driving factors of root decay is.

There is a net increase in the long term belowground carbon pool until a point where the belowground biomass growth and decay rates reach equilibrium. Based on the assumption that the decay rates of roots in both management regimes are the same, there would be a greater increase in the long-term belowground biomass pool of the planted plus one coppice regime. This is because the roots are not undergoing decay until the stand is replanted, whereas a planted only regime experiences decay after each rotation. For the treatments in this study the growth rate of the belowground biomass during a coppiced rotation is greater than the decay rate. There is thus a greater and more prolonged increase in belowground biomass and carbon over multiple rotations for once coppiced regimes than for planted only regimes. Regimes making use of one coppiced rotation would therefore make a greater contribution to carbon sequestration and subsequent mitigation of climate change. This would promote the industry's compliance to climate change policies and increase financial benefits through reduced carbon taxes.

Should the growth rate of belowground biomass during a coppiced rotation be less than the decay rate of the belowground biomass, the accumulated biomass over a prolonged period will be less. This may be the case for regimes that make use of multiple coppiced establishments as the rate of additional root growth is expected to slow down after being coppiced multiple times (Table 2.1). This will also be reflected in sites where belowground growth is slow due to climatic variables and soil productivity, and decay is more rapid. It is therefore very important to understand what the rate of belowground biomass decay is for a given stand, as well as the growth rate of the belowground biomass, as this will determine whether an additional coppiced establishment will result in a net biomass and carbon pool increase or decrease.

6 Conclusions

The root biomass pool in commercially managed plantations has the potential to make a significant contribution in offsetting carbon emissions. A concise understanding of the relationship between above and belowground biomass, as well as the factors driving this relationship, are required to estimate the amount of belowground biomass and sequestered carbon of a given stand. While studies have been done to estimate the belowground biomass pools of forests around the world, there is still limited knowledge on the specific root allocation in *Eucalyptus grandis x urophylla* under South African management regimes and climatic conditions. This study set out to test the following:

1. Does site quality have an influence on belowground biomass allocation?
2. Does regime, i.e. planting or coppicing, have an influence on belowground biomass allocation?
3. Can the belowground biomass be modelled based on aboveground metrics?
4. Is there a net increase in the belowground biomass pool for planted and planted plus on coppice regimes over a prolonged period for both high and low site qualities?

Both site quality (high and low, based on SI) and regime (planted vs. coppiced) affect the relative belowground biomass allocation, although the regime has a greater influence on relative belowground biomass allocation. The study confirmed that although the total belowground biomass is greater in high SI stands than in low SI stands, the relative belowground biomass is greater in low SI stands. Similarly, the study also shows that although total belowground biomass of a tree in a given stand is greater for large trees, the relative belowground biomass is greater for smaller trees. Coppicing resulted in the relative belowground biomass of the trees to be greater than planting only, as well as a larger belowground biomass pool at strand level. Three allometric models were presented to model total belowground biomass, as well as an additional six allometric models that predict the biomass of the individual root classes (coarse, medium and fine) for both planted and coppiced stands. A novel finding of this study is that there is a net increase in the belowground biomass and carbon pools over a prolonged period for the planted regimes on both high and low site qualities, and that this can be further increased by managing the stands with one coppice regime.

The root biomass from commercially managed eucalypts can mitigate climate change by sequestering carbon. Based on results from this study, carbon sequestration can be increased by implementing one coppiced rotation after clear-fell, promoting the industry’s compliance to climate change policies and increasing financial benefits.

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8 Addenda

8.1 Addendum A: Above ground regression data

Treatment	Tree Height	DBH	Stump Height	UD	MD	LD	Treatment	DBH	Height
High SI Planted	22,5	17,5	11	22,6	24,2	27,7	High SI Coppiced	13.6	21.4
High SI Planted	19,9	12,5	11	15,4	16	17,2	High SI Coppiced	9.2	15.7
High SI Planted	23,5	18,7	11	22,5	23,5	25,1	High SI Coppiced	12.5	23
High SI Planted	22,6	16,8	11	20	21,8	23,4	High SI Coppiced	19.7	23
High SI Planted	17,9	12,1	11	14,2	14,5	15,5	High SI Coppiced	15.5	21
High SI Planted	20,5	14,6	11	16,6	17,8	19,5	High SI Coppiced	19.9	23.2
High SI Planted	21,7	16,4	11	19,5	20,2	21,3	High SI Coppiced	11.4	20.6
High SI Planted	22,0	15	11	17,6	18,9	20,1	High SI Coppiced	19.9	24.8
High SI Planted	20,3	11,9	11	14,2	14,4	15	High SI Coppiced	15.2	23.6
High SI Planted	20,6	14,6	11	17,2	18,2	19,1	High SI Coppiced	13.6	21.4
High SI Planted	19,1	11,3	11	13,2	13,5	15,8	High SI Coppiced	15.4	22
High SI Planted	21,6	16,3	11	20,2	20,6	22,1	High SI Coppiced	14.7	19.6
High SI Planted	22,6	15,6	11	18,5	19,4	20,3	High SI Coppiced	15.2	20.4
High SI Planted	22,2	16,2	11	19,8	21	23,8	High SI Coppiced	16.3	21.3
High SI Planted	22,4	16,5	11	19,8	21	25,6	High SI Coppiced	13	20.9
High SI Planted	22,5	18,6	11	23,7	24,8	28,8	High SI Coppiced	15.8	23.6
High SI Planted	20,8	14,5	11	17,4	17,8	19,4	High SI Coppiced	15.6	21.9
High SI Planted	22,0	17,3	11	20,3	21,2	23	High SI Coppiced	19.1	22.9
High SI Planted	21,2	16	11	19,9	20,8	22,5	High SI Coppiced	11.8	17.7
High SI Planted	20,2	14,7	11	19,2	20,5	21,5	High SI Coppiced	21.9	24.1
High SI Planted	21,1	15,8	11	19,9	21,2	25	High SI Coppiced	21.6	24.1
High SI Planted	22,2	18,4	11	22,6	23,5	25,5	High SI Coppiced	18	22.2
High SI Planted	21,6	14,4	11	17,8	18,9	19,5	High SI Coppiced	22.2	26.1
High SI Planted	22,6	15,2	11	18,1	18,7	20,1	High SI Coppiced	14.5	23.6
High SI Planted	20,7	13	11	15,9	15,9	17	High SI Coppiced	16.2	22
High SI Planted	23,1	17,1	11	21,4	22,6	23,6	High SI Coppiced	18.7	23.7
High SI Planted	22,4	14,1	11	16,5	17,1	18,2	High SI Coppiced	18	22.2
High SI Planted	18,2	10,1	11	12,6	13	15	High SI Coppiced	20.6	22.6
High SI Planted	21,0	15,2	11	17,5	18,2	20,6	High SI Coppiced	20.2	19
High SI Planted	21,3	13,8	11	16,7	17,2	18,9	High SI Coppiced	11.1	11.7
Low SI Planted	18,6	13,4	10,5	17,1	17,6	20,6	Low SI Coppiced	13.2	18.1
Low SI Planted	18,7	14,2	10,5	18,3	18,4	19,5	Low SI Coppiced	12.6	18.2
Low SI Planted	16,1	9,8	10,5	12,2	12,4	12,8	Low SI Coppiced	14.2	18.5
Low SI Planted	17,2	14,1	10,5	17,8	18,5	19,5	Low SI Coppiced	10.4	18.2
Low SI Planted	17,8	14,1	10,5	17,8	18,1	19,4	Low SI Coppiced	13.1	17.3
Low SI Planted	17,0	12,4	10,5	15,7	15,6	16,9	Low SI Coppiced	12.2	17
Low SI Planted	17,1	12,9	10,5	16,2	17,1	17,8	Low SI Coppiced	11.2	17.3
Low SI Planted	17,2	12,8	10,5	15,6	16,2	17,6	Low SI Coppiced	12.2	17.5
Low SI Planted	16,1	11,1	10,5	13,7	14	14,5	Low SI Coppiced	11.1	18.4

Low SI Planted	16,7	13,1	10,5	16	16,6	17,1	Low SI Coppiced	11	17.1
Low SI Planted	17,7	13,8	10,5	16,9	17,3	18,8	Low SI Coppiced	11.5	16.3
Low SI Planted	17,8	12,9	10,5	16,5	16,7	17	Low SI Coppiced	11.6	16.7
Low SI Planted	17,7	14,6	10,5	17,2	17,6	18,8	Low SI Coppiced	12.9	15.1
Low SI Planted	17,9	14,8	10,5	19,9	19,6	20,3	Low SI Coppiced	13.2	16.7
Low SI Planted	15,0	9,9	10,5	14,3	14,4	15,2	Low SI Coppiced	10.6	16.4
Low SI Planted	17,3	14	10,5	18,3	19	20,8	Low SI Coppiced	11.5	17.2
Low SI Planted	17,8	16,8	10,5	24,4	24,9	28	Low SI Coppiced	13.7	17.3
Low SI Planted	16,9	12,5	10,5	16,1	16,8	18,4	Low SI Coppiced	10	15.3
Low SI Planted	17,2	13	10,5	17,5	17,5	18,5	Low SI Coppiced	12.6	16.5
Low SI Planted	17,3	13,6	10,5	17,6	19,2	23	Low SI Coppiced	11.7	17.6
Low SI Planted	17,7	14,4	10,5	18,2	18,4	19,7	Low SI Coppiced	13	16.7
Low SI Planted	12,6	14,9	10,5	19,5	19,8	20,4	Low SI Coppiced	9.6	16.1
Low SI Planted	17,7	14,8	10,5	18,9	20,7	21,8	Low SI Coppiced	13.8	18.5
Low SI Planted	16,6	10,7	10,5	13,2	13,3	13,7	Low SI Coppiced	13.6	17.9
Low SI Planted	17,1	14,7	10,5	19,4	19,9	21,8	Low SI Coppiced	10.6	14.9
Low SI Planted	16,8	13,2	10,5	16,4	16,8	17,7	Low SI Coppiced	12.1	17.3
Low SI Planted	17,4	16	10,5	20,9	21,1	22,1	Low SI Coppiced	12.9	16.7
Low SI Planted	15,8	9,3	10,5	12,1	12,1	12,1	Low SI Coppiced	8.6	14.8
Low SI Planted	17,1	12,3	10,5	15,5	15,7	15,9	Low SI Coppiced	7.7	13.9
Low SI Planted	16,9	13,3	10,5	16,6	16,7	17,1	Low SI Coppiced	9.5	15.9

8.2 Addendum B: Above ground enumerations data

Treatment	Tree No	DBH (cm)	Treatment	Tree No	DBH (cm)
High SI Planted	1	13	High SI Coppiced	1	13.6
High SI Planted	2	15	High SI Coppiced	2	9.2
High SI Planted	3	13.1	High SI Coppiced	3	12.5
High SI Planted	4	13.5	High SI Coppiced	4	19.7
High SI Planted	5	11.9	High SI Coppiced	5	15.5
High SI Planted	6	17.5	High SI Coppiced	6	19.9
High SI Planted	7	13.8	High SI Coppiced	7	11.4
High SI Planted	8	15	High SI Coppiced	8	19.9
High SI Planted	9	16.7	High SI Coppiced	9	15.2
High SI Planted	10	16.5	High SI Coppiced	10	13.6
High SI Planted	11	14	High SI Coppiced	11	15.4
High SI Planted	12	16.5	High SI Coppiced	12	14.7
High SI Planted	13	15.5	High SI Coppiced	13	15.2
High SI Planted	14	15.2	High SI Coppiced	14	16.3
High SI Planted	15	16.6	High SI Coppiced	15	13
High SI Planted	16	14.8	High SI Coppiced	16	15.8
High SI Planted	17	16	High SI Coppiced	17	15.6
High SI Planted	18	15.3	High SI Coppiced	18	19.1
High SI Planted	19	15.9	High SI Coppiced	19	11.8
High SI Planted	20	17	High SI Coppiced	20	21.9
High SI Planted	21	16.2	High SI Coppiced	21	21.6
High SI Planted	22	14.1	High SI Coppiced	22	18
High SI Planted	23	10.5	High SI Coppiced	23	22.2
High SI Planted	24	11.3	Low SI Coppiced	1	13.6
High SI Planted	25	16.8	Low SI Coppiced	2	8
High SI Planted	26	13.3	Low SI Coppiced	3	11.5
High SI Planted	27	14	Low SI Coppiced	4	10.8
High SI Planted	28	16.8	Low SI Coppiced	5	13.5
High SI Planted	29	15.1	Low SI Coppiced	6	12.6
High SI Planted	30	16.6	Low SI Coppiced	7	8.6
High SI Planted	31	15.6	Low SI Coppiced	8	13.5
High SI Planted	32	15.2	Low SI Coppiced	9	13.5
High SI Planted	33	15.2	Low SI Coppiced	10	12.1
High SI Planted	34	15.6	Low SI Coppiced	11	13.5
High SI Planted	35	17.2	Low SI Coppiced	12	12.9
High SI Planted	36	15.5	Low SI Coppiced	13	14.3
High SI Planted	37	14.6	Low SI Coppiced	14	13.7
High SI Planted	38	15.2	Low SI Coppiced	15	12.8
High SI Planted	39	13.9	Low SI Coppiced	16	11.8
High SI Planted	40	12.2	Low SI Coppiced	17	13.8
High SI Planted	41	17.2	Low SI Coppiced	18	11.5
High SI Planted	42	16.2	Low SI Coppiced	19	11.9
High SI Planted	43	9.2	Low SI Coppiced	20	7.6
High SI Planted	44	15.7	Low SI Coppiced	21	10.8
High SI Planted	45	16.8	Low SI Coppiced	22	13.9
High SI Planted	46	16.1	Low SI Coppiced	23	10.6
High SI Planted	47	14.5	Low SI Coppiced	24	13.3
High SI Planted	48	16.7	Low SI Coppiced	25	13.3
High SI Planted	49	15.5	Low SI Coppiced	26	11.85
High SI Planted	50	14.8	Low SI Coppiced	27	12.2
High SI Planted	51	8.3	Low SI Coppiced	28	9.3
High SI Planted	52	14.8	Low SI Coppiced	29	11.5
High SI Planted	53	13.8	Low SI Coppiced	30	13.3
High SI Planted	54	15.3	Low SI Coppiced	31	11.55
High SI Planted	55	10	Low SI Coppiced	32	12.6
High SI Planted	56	15.3	Low SI Coppiced	33	13

High SI Planted	57	17.6	Low SI Coppiced	34	12.2
High SI Planted	58	15.7	Low SI Coppiced	35	10.6
High SI Planted	59	15.3	Low SI Coppiced	36	14.7
High SI Planted	60	17.4	Low SI Coppiced	37	13
High SI Planted	61	14.3	Low SI Coppiced	38	12.7
High SI Planted	62	14.2	Low SI Coppiced	39	13.7
High SI Planted	63	17.1	Low SI Coppiced	40	9.65
High SI Planted	64	16.1	Low SI Coppiced	41	12.3
High SI Planted	65	16.8	Low SI Coppiced	42	11.7
High SI Planted	66	12.8	Low SI Coppiced	43	13.1
High SI Planted	67	10.7	Low SI Coppiced	44	9.7
High SI Planted	68	16	Low SI Coppiced	45	13.9
High SI Planted	69	15.8	Low SI Coppiced	46	13.7
High SI Planted	70	17.2	Low SI Coppiced	47	11.9
High SI Planted	71	14.8	Low SI Coppiced	48	12.9
High SI Planted	72	17.2	Low SI Coppiced	49	10.8
High SI Planted	73	14	Low SI Coppiced	50	12.7
High SI Planted	74	15.5	Low SI Coppiced	51	11.5
High SI Planted	75	16.7	Low SI Coppiced	52	13.1
High SI Planted	76	17.8	Low SI Coppiced	53	12.8
High SI Planted	77	15.2	Low SI Coppiced	54	11.6
High SI Planted	78	14	Low SI Coppiced	55	12.2
High SI Planted	79	12.1	Low SI Coppiced	56	12
Low SI Planted	1	11.9	Low SI Coppiced	57	12.9
Low SI Planted	2	12.3	Low SI Coppiced	58	7.8
Low SI Planted	3	14.1	Low SI Coppiced	59	11.5
Low SI Planted	4	11.3	Low SI Coppiced	60	13.4
Low SI Planted	5	12.8	Low SI Coppiced	61	11.8
Low SI Planted	6	15.3	Low SI Coppiced	62	12.1
Low SI Planted	7	15.3	Low SI Coppiced	63	11.9
Low SI Planted	8	10.8	Low SI Coppiced	64	12.9
Low SI Planted	9	14.7	Low SI Coppiced	65	11.8
Low SI Planted	10	12.5	Low SI Coppiced	66	12.3
Low SI Planted	11	9.6	Low SI Coppiced	67	13.3
Low SI Planted	12	12.4	Low SI Coppiced	68	9.8
Low SI Planted	13	12.4	Low SI Coppiced	69	11.9
Low SI Planted	14	12.6	Low SI Coppiced	70	12.4
Low SI Planted	15	10.8	Low SI Coppiced	71	12
Low SI Planted	16	12.6	Low SI Coppiced	72	11.9
Low SI Planted	17	12.9	Low SI Coppiced	73	12.4
Low SI Planted	18	8.9			
Low SI Planted	19	13.6			
Low SI Planted	20	13.5			
Low SI Planted	21	11.5			
Low SI Planted	22	13.5			
Low SI Planted	23	13.4			
Low SI Planted	24	12			
Low SI Planted	25	14.1			
Low SI Planted	26	13.1			
Low SI Planted	27	11.8			
Low SI Planted	28	14.6			
Low SI Planted	29	11.6			
Low SI Planted	30	2.9			
Low SI Planted	31	6.5			
Low SI Planted	32	11.7			
Low SI Planted	33	13.2			
Low SI Planted	34	8.5			
Low SI Planted	35	13.5			
Low SI Planted	36	12.8			

Low SI Planted	37	10.3			
Low SI Planted	38	14.7			
Low SI Planted	39	8.1			
Low SI Planted	40	13.1			
Low SI Planted	41	10.6			
Low SI Planted	42	10.3			
Low SI Planted	43	13			
Low SI Planted	44	13.3			
Low SI Planted	45	12			
Low SI Planted	46	13.9			
Low SI Planted	47	7.8			
Low SI Planted	48	12.7			
Low SI Planted	49	11.1			
Low SI Planted	50	11.5			
Low SI Planted	51	10.9			
Low SI Planted	52	11.4			
Low SI Planted	53	10.1			
Low SI Planted	54	13.5			
Low SI Planted	55	10.8			
Low SI Planted	56	11.45			
Low SI Planted	57	9.8			
Low SI Planted	58	13.3			
Low SI Planted	59	14.9			
Low SI Planted	60	14.2			
Low SI Planted	61	11.4			
Low SI Planted	62	14.1			
Low SI Planted	63	12.5			
Low SI Planted	64	12.4			

8.3 Addendum C: Sampled tree data

Tree ID	Compartment	Tree number	DBH	Total Height	Utilizable Height	Stump Height	Stem Mass W	Live Canopy Mass W
1	High SI Planted	1	12	19,2	17,1	10	97	9,2
2	High SI Planted	2	16,6	20,2	18,7	10	186,5	18,5
3	High SI Planted	3	13,6	19,2	17,7	13	116	10,7
4	High SI Planted	4	17,2	20	18,5	10	192,5	18,2
5	High SI Planted	5	15,6	19,7	17,3	15	188	18
6	High SI Planted	6	12	17,6	15,5	8	74	8,7
7	High SI Coppiced	1	12,5	20,1	17,9	22	107	13,2
8	High SI Coppiced	2	10,7	19,2	16,3	16	75	9,2
9	High SI Coppiced	3	17	24	22,2	20	246	22,2
10	High SI Coppiced	4	18,7	23,4	21,2	19	299,8	37
11	High SI Coppiced	5	14,9	22	20,5	20	171,5	20,2
12	High SI Coppiced	6	20,1	24	21,7	20	346,5	42,2
13	Low SI Planted	1	13,6	16,3	13,6	12	109,5	15,8
14	Low SI Planted	2	8,1	11,2	10,1	10	27	3,3
15	Low SI Planted	3	10,4	14,5	13,1	10	62	7,7
16	Low SI Planted	4	13	15,1	13,7	11	95	14,4
17	Low SI Planted	5	14	16	14,7	10	125,5	16,7
18	Low SI Planted	6	14,2	15,4	14,1	10	124,8	18,2
19	Low SI Coppiced	1	8,2	10,1	7,6	27	21,5	1,3
20	Low SI Coppiced	2	11,8	18	16,4	25	92	9,9
21	Low SI Coppiced	3	14	18,7	16,8	20	147,9	19,5
22	Low SI Coppiced	4	14,4	18,5	17,2	32	148,5	17
23	Low SI Coppiced	5	9	15,2	12,5	18	42,5	4,5
24	Low SI Coppiced	6	13	17,6	16,1	22	113	14,2

Tree ID	Above Ground Wet	Coarse Roots W	Medium Roots W	Fine Roots W	Below Ground Wet	Stem Sub-sample wet	Canopy Sub-sample wet	Coarse Roots sub-sample W
1	106,2	13,3	10,9	1,6	25,8	338,59	333,43	136,91
2	205	30	10,5	2,5	43	338,59	333,43	474,01
3	126,7	17,5	7	2,3	26,8	338,59	333,43	489,21
4	210,7	31,5	13,2	3,7	48,4	338,59	333,43	172,61
5	206	24	13	2,5	39,5	338,59	333,43	445,81
6	82,7	13,5	8,2	2,9	24,6	338,59	333,43	221,61
7	120,2	75	11,5	2,9	89,4	526,85	294,83	789,31
8	84,2	19,8	3,5	2,8	26,1	526,85	294,83	240,01
9	268,2	91,5	15,2	4,1	110,8	526,85	294,83	479,51
10	336,8	90,5	13,2	4,3	108	526,85	294,83	209,01
11	191,7	48	8,2	3,4	59,6	526,85	294,83	187,31
12	388,7	130,8	27,9	5,4	164,1	526,85	294,83	198,41
13	125,3	26	8,7	2,5	37,2	705,54	285,19	275,61
14	30,3	6	2,7	1,2	9,9	705,54	285,19	258,61
15	69,7	11,5	7,7	1,6	20,8	705,54	285,19	215,24
16	109,4	19,5	8,2	1,9	29,6	705,54	285,19	298,54
17	142,2	27	7,9	1,9	36,8	705,54	285,19	243,44
18	143	23	10,2	3,1	36,3	705,54	285,19	452,14
19	22,8	41,8	8,7	2,2	52,7	642,89	242,71	155,44
20	101,9	45,8	5,2	1,6	52,6	642,89	242,71	222,44
21	167,4	59,5	9,2	2,4	71,1	642,89	242,71	171,44
22	165,5	47	7,9	3,5	58,4	642,89	242,71	270,84
23	47	10,3	2,2	1,8	14,3	642,89	242,71	203,14
24	127,2	30	4,7	3	37,7	642,89	242,71	209,94

Tree ID	Medium Roots sub-sample W	Fine Roots sub-sample W	Stem Sub-sample dry	Canopy Sub-sample dry	Coarse Roots sub-sample D	Medium Roots sub-sample D	Fine Roots sub-sample D
1	66,09	31,17	147,41	111,71	50,5	27,51	15,42
2	281,29	31,42	147,41	111,71	189,87	120,63	16,6
3	71,99	32,53	147,41	111,71	186,83	28,17	15,05
4	130,09	37,11	147,41	111,71	70,48	56,48	19,35
5	200,79	30,97	147,41	111,71	179,88	78,08	19,78
6	99,29	36,17	147,41	111,71	90,36	38,23	14,85
7	132,07	28,17	263,2	113,08	437,4	57,26	15,39
8	99,12	32,36	263,2	113,08	101,92	39,99	12,62
9	238,96	29,57	263,2	113,08	237,02	125,69	19,69
10	246,81	31,37	263,2	113,08	95,57	121,6	14,79
11	216,62	34,16	263,2	113,08	85,3	103,09	20,4
12	145,26	23,92	263,2	113,08	100,65	69,01	16,3
13	77,35	31,88	319,18	128,82	128,82	34,14	16,01
14	53,55	32,37	319,18	128,82	105,74	20,5	16,73
15	48	29,58	319,18	128,82	86,93	19,19	15,89
16	122,8	25,32	319,18	128,82	132,86	45,63	16,28
17	87,8	28,76	319,18	128,82	107,08	38,26	18,24
18	74,4	32,44	319,18	128,82	178,65	32,27	14,14
19	150,84	30,67	306,08	124,47	71,17	70,65	18,31
20	80,84	31,16	306,08	124,47	110,43	38,24	14,27
21	90,54	29,88	306,08	124,47	79,76	44,36	12,87
22	72,84	29,66	306,08	124,47	131,16	27,63	19,23
23	78,34	35,13	306,08	124,47	100,8	36,63	13,51
24	81,98	28,58	306,08	124,47	95,27	46,74	16,37

Tree ID	Mass for Density Coarse	Mass for Density Medium	Mass for Density Fine	Volume Coarse	Volume Medium	Volume Fine
1	29,97	12,09	6,17	76,03	26,73	14,77
2	55,09	43,3	6,52	129,51	85,73	14,2
3	53,22	4,14	7,73	127,32	10,68	20,38
4	36,66	26,41	6,45	82,54	56,35	15,21
5	53,09	18,13	8,93	118,44	44,81	19,86
6	42,21	16,81	6,04	98,2	39,91	14,2
7	72,73	15,2	7,61	112,01	28,82	17,06
8	39,66	12,17	5,65	81,99	25,1	11,06
9	39,53	48,76	6,05	121,52	75,98	12,25
10	48,63	13,98	9,56	91,77	26,25	20,54
11	42,45	51,83	8,75	79,62	90	19,03
12	48,75	12,84	7,85	79,7	22,69	14,76
13	62,54	6,44	8,03	120,71	11,85	16,35
14	40,19	6,19	4,73	94,36	13,37	11,78
15	34,01	10,6	6,78	79,11	25,34	15,59
16	38,51	17,11	4,26	74,92	41,73	9,65
17	47,06	26,83	5,63	92,32	57,62	13,55
18	47	15,77	7,32	98,42	33,52	17,76
19	39,26	34,45	6,83	77,51	64,88	14,85
20	57,83	18,33	5,35	108,38	33,81	12,74
21	39,7	21,68	5,5	75,37	37,33	12,47
22	71,9	9,04	6,31	127,69	20,75	13,82
23	29,39	13,07	5,19	66,25	21,89	12,16
24	56,62	17,22	5,63	115,49	30,86	12,6