The effects of compaction and residue management on soil properties and growth of *Eucalyptus grandis* at two sites in KwaZulu-Natal, South Africa.

by

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Submitted in fulfillment of the academic requirements for the degree of

Doctor of Philosophy

in the Discipline of Soil Science
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March 2010

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Abstract

Concerns have been raised over the long-term site productivity (LTSP) of short rotation plantation forests, such as those of *Eucalyptus*, in South Africa. This is because diminished productivity of long rotation plantations overseas has been found to be generally due to decreases in soil porosity and organic matter. Since soil porosity and organic matter in plantations are mainly affected by soil compaction by harvesting machinery and residue management, the more frequent harvesting of short rotation plantations are of particular concern. Therefore the effects of soil compaction and residue management on soil properties at two sites, one a low organic carbon, sandy soil (Rattray), the other a high organic carbon, clay soil (Shafton) were investigated. The potential of early *E. grandis* productivity as an indicator of changes in soil properties at these sites was also evaluated.

Three different levels of compaction (low, moderate and high) were applied to the sites by three methods of timber extraction, i.e. manual, logger and forwarder loaded by a logger, respectively. Three types of residue management, i.e. broadcast, windrow and residue removal were also applied. A factorial treatment design was used to ensure a resource-efficient study that allowed separation of main and interaction effects.

Various soil physical and chemical properties were measured at intervals from before treatment implementation, until approximately 44, and 38 months after treatment implementation at Rattray and Shafton, respectively. Trees were planted at a commercial espacement at both trials, and their growth monitored over the same time period. In addition, to accelerate early growth, negate silvicultural variation, and determine changes in stand productivity with treatments, a portion of the treatment plots were planted at a very high density and harvested when these trees reached canopy closure at about six months of age.

Moderate and high compaction treatments at both sites resulted in significant increases in penetrometer soil strength, and often in bulk density. Increasing residue retention decreased the compaction effects of machinery and, generally,

increased the total quantity of nutrients contained in residues and soil. Changes in soil bulk density and organic matter as a result of the treatments in turn affected soil water characteristics, generally decreasing plant available water capacity with increasing compaction intensity and residue removal. Tree growth measurements showed that at both sites, tree productivity was negatively affected at some point by increasing compaction. In contrast, residue management only significantly affected tree growth at Shafton, initially increasing and later decreasing growth with residue removal. These variations in tree growth over time in response to treatments are most likely a result of changes in tree characteristics that occurred with age. In addition, trees did not always reflect changes in soil properties that may affect LTSP, most likely because these soil properties had not yet reached levels that would affect tree growth.

It was therefore concluded that early tree growth is not always a good indicator of changes in LTSP, and that soil properties are a more reliable indicator. Plantation management practices that lead to soil compaction and residue removals will negatively impact LTSP in South Africa. However, variable responses of the two soils indicate that soils vary in their sensitivity to compaction and residue management. This therefore needs to be quantified across a range of major soil types in the South African forestry industry.

Preface

The experimental work described in this thesis was carried out in the School of Environmental Sciences, University of Kwa-Zulu Natal, Pietermaritzburg, from January 2004 to March 2010, under the supervision of Professor Jeffrey C. Hughes and Dr Colin W. Smith.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

DECLARATION - PLAGIARISM

I, Diana Nicolle Rietz declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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Acknowledgements

So many people and organisations were involved in the completion of this thesis. However, some stand out, whose contribution must be acknowledged.

First and foremost, I would like to thank the director of the Institute for Commercial Forestry Research, Prof Colin Dyer, for giving me the means to perform this study. It would not have been possible otherwise.

My supervisor Prof Jeff Hughes, supported me with his vast knowledge, saint-like patience and dry humour, gave me good advice and direction, all the while giving me room to work in my own way.

My co-supervisor, Dr Colin Smith has encouraged me, helped me to learn in leaps and bounds, and has done his utmost to turn me into a scientist who can not only do the science, but can communicate it to others.

All three examiners were extremely thorough and added considerable value to this thesis.

SAPPI Forests (Pty) Ltd and Mondi Ltd for permission to use their land and for supplying the means to implement the trials.

The field work for this study was extensive, physically demanding and often in adverse weather conditions. However, several people made the experience as pleasant as possible, and I have many good memories, and count them all my friends. They are Messers Gregory Fuller, Denis Oscroft, Michael Buthelezi, Musa Mkhwanazi, the late Bheki Ndawonde and Ms Chané Nel.

After the field work, came the laboratory portion of the study, and Mr Tad Dorasamy and the late Mr Essack Abib of the University of KwaZulu-Natal created the space for me to work, and assisted me in many areas. I will always be grateful to Mrs Mary Galbraith and Mr Michael Buthelezi, who performed many of the routine analyses. Thanks also go to Mr Michael Chetty who compiled the results and provided laboratory support.

Dr Principle Ndlovu and Dr Keith Little helped with the statistical analyses, thereby increasing the value of the data.

The tedious tasks of proof reading, formatting and printing this thesis were kindly carried out by Ms Patricia Stannard, Ms Chloe Boshoff, and Mrs Sally Upfold.

Many friends have done more for me than I can ever repay or express, but in particular, Mr Gert van den Berg, Ms Patricia Stannard, Mr Sean Best, Dr Louis Titshall, Ms Cathy Ford, Dr Carol Rolando, Dr Keith Little and Ms Justine Tempest.

My parents, Jennifer Rietz, Kenneth Winch and Peter Rietz, have taught me more than I will ever be able to consciously fathom.

Lastly, my dear animals, Kayla, Your Man, Zeta, Cara and Axe brought sanity and happiness to me, even in the darkest days of this thesis, and of my life.

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Glossary of Terms

Allometry: The study of the proportional allocation of resources to different plant parts (Medhurst *et al.*, 1999). It is often inferred from the differences between a particular component and total mass, or differences in relative growth rate between components (Cromer and Jarvis, 1990)

Forest floor: The layer of organic material between the mineral soil and the top of the litter layer. It includes leaves and branches fallen through the rotation of the stand, as well as the decomposing layer of these leaves and branches above the mineral soil.

Gross primary productivity (GPP): The total photosynthesis or total amount of organic matter assimilated, at a site.

Harvest residue: After the felling of a eucalypt stand, branches and tree tops with unutilisable stemwood are cut from the stems of trees. These stems are then stripped of bark and removed from the stand. Harvest residue refers to the bark, branches, associated foliage and tree tops left on a site.

Long-term: At least 50 years, possibly more. The number of future rotations must not be limited by decline in soil productivity.

Mass water content ($\ominus_m$): The mass of water held per unit mass of oven dry soil, and is also known as gravimetric soil water content (Or and Wraith, 2000).

Matric potential: The potential energy of water in a soil arising from the combination of capillary and adsorptive forces within the soil matrix (Or and Wraith, 2000).

Net primary productivity (NPP): The total amount of organic matter produced by a site, i.e. GPP minus the organic matter lost to respiration.

Net primary productivity minus root turnover (NPP$_{-RT}$): Net primary productivity minus the organic matter lost to fine root turnover.

Nitrogen mineralization: The conversion of organic N (in the soil) into inorganic (plant available) N, usually ammonium or nitrate, that is the major source of N to growing plants (Norton, 2000).

Ontogeny: The development, or series of changes undergone by an individual throughout its life, i.e. the course of genesis, growth, maturation, and decline (Fitting *et al.*, 1921; Larcher, 2003). It is dependent on individual genetics, chronological age and growth environment. Therefore, two individuals identical in genetics and chronological age may be at different ontogenetic stages (i.e. one has juvenile foliage, while the other has only mature foliage) due to differences in the growth environment. The resultant allometric relationships of these two individuals will therefore be different as the former is at a younger stage physiologically.

Root:Shoot Ratio: Fine root biomass/foliage biomass (Gonçalves and Mello, 2004).

Site productivity: The plantation forestry productivity of a given site. It is affected by all factors that will influence growth of the trees particular to that site, such as soil depth, nutritional status and water retention characteristics, as well as climate. It is not affected by management factors such as spacing (i.e. stems ha^{-1}), weeding or coppice reduction/control. It is often measured by gross or net primary production (GPP or NPP), often at canopy closure.

Soil bulk density: Calculated as the mass of oven dry soil/volume of soil (Skopp, 2000).

Soil productivity: The concept that soil factors affect plantation growth.

Soil quality: In this instance maximum soil quality would be regarded as the maximum **plantation** productive potential of a site's soil, such that every site has the potential to attain maximum soil quality, even if soil productivity is not very high. For example, a site may have a shallow soil and inherently poor nutrient status and therefore, a low soil productivity. However, if that soil has as high a nutrient status as is possible for that soil, and the rooting depth has not been compromised, then the soil has a high soil quality. Soil quality declines if management of that soil is not optimal for plantation forestry.

Stand productivity: The (economic) productivity of a stand as measured by tree volume or mass (or measures that can derive volume, such as tree height, basal area etc.). Stand productivity is dependent on factors such as site, climate, species, silviculture and pest/disease occurrence.

Sustainability:

Broad-sense sustainability: The United Nations Conference on Environment and Development (1992) definition (as follows) has been utilised in this study:

"*The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems*" (Lawes *et al.*, 1999).

Narrow-sense sustainability: The economic yield (i.e. wood volume), over future rotations (Evans, 1999).

Type II growth response: A growth response as a result of a "real" change in site productivity, as opposed to a Type I growth response which is as a result of inducing an earlier stage of stand growth (e.g. weeding results in a Type I growth response, because non-weeded stands still reach canopy closure, although later than weeded stands). Decreases in stand productivity as a result of depletion of site nutrients, would be regarded as a Type II growth response (Snowdon and Waring, 1984)

Volumetric water content (θ_v*):* The volume of water held per unit volume of soil (Or and Wraith, 2000).

List of Symbols and Abbreviations

Productivity:

GPP   Gross primary productivity.

NPP   Net primary productivity.

NPP_{-RT} Net primary productivity less fine root turnover.

LTSP   Long-term site productivity.

Climate:

MAP   Mean annual precipitation.

MAT   Mean annual temperature.

Treatments:

C_L Low compaction; timber extracted manually.

C_M Moderate compaction; timber extracted with a 3 wheel logger.

C_H High compaction; timber extracted with a 3 wheel logger and forwarder.

B   Broadcast residue management.

W   Windrow residue management.

R   Residues removed.

Plot positions:

IR   Interrow; areas either side of the stumpline.

SL   Stumpline; line of stumps from the previous rotation.

Time:

T0   Time at which treatments were implemented.

TP   Time of planting.

TH   Time of harvesting of sub-plot trees.

TF   Time of final soil measurement.

Soil:

Sa   Sand.

Si   Silt.

Cl   Clay.

LOI   Loss on ignition.

WB   Walkley-Black.

ρ_b Bulk density (Mg m^{-3}).

$T\rho_b$ Troxler bulk density (Mg m^{-3}).

MBD	Maximum bulk density ($Mg\ m^{-3}$).
C_{Index}	Compression index.
CSI	Compaction sensitivity index.
PSS	Penetrometer soil strength.
PSS_0	Penetrometer soil strength prior to treatment implementation.
PSS_1	Penetrometer soil strength after treatment implementation.
AWC	Available water capacity.
RAW	Readily available water.
LLWR	Least limiting water range.
θ_m	Mass soil water content ($kg\ kg^{-1}$).
θ_v	Volumetric soil water content ($m^3\ m^{-3}$).

Tree:

DAP	Days after planting.
GLD	Ground-line diameter (of stem).
DBH	Diameter (of stem) at breast height.
BI	Biomass index.
LAI	Leaf area index.
SLA	Specific leaf area.

Statistics:

ANOVA	Analysis of variance.
LSD	Least significant difference.
r^2	Percentage variance accounted for, an adjusted form of R^2.
NS	Not significant.
*	$0.01 < p < 0.05$
**	$0.001 < p < 0.01$
***	$p < 0.001$

Chapter 1
Introduction

There are currently 1.28 million ha of plantations in South Africa, of which 478 000 ha are planted to eucalypts, accounting for 55% of the total area planted for industrial pulpwood. Of the eucalypts, *Eucalyptus grandis* is by far the dominant planted species (DWAF, 2006). Although pulpwood plantations do not represent a large portion of South Africa's total land area (around 0.5%), the pulp and paper industry contributes significantly to South Africa's GDP and employs many people (ZAR 6 billion or 0.5% with 13 200 people employed directly in 2003; Chamberlain *et al.*, 2005). As a result of several (governmental) Acts, increases in the area of land under plantation forestry in the future are unlikely (Aitken, 2004; Scotcher, 2004).

Unlike the forestry industry, the agricultural sector has considerable, well-established evidence that certain agricultural practices have a negative impact on the long-term productivity of agricultural land, despite the improvement of genotypes (Kelting *et al.*, 1999; Turner *et al.*, 1999; Vance, 2000). In addition to this, there is a common view that the restoration of productivity is substantially more difficult and costly than the maintenance or improvement of it (Gessel, 1981). These and other factors have led to concerns about the long-term productivity of plantation forests (Johnson, 1994; Burger and Kelting, 1998; Kelting *et al.*, 1999).

Plantations by their very nature alter the ecological functioning of a site. However, it is still not known whether these alterations as well as the effects of management operations, are detrimental, neutral or beneficial to plantation productivity. Although all forest plantation practices impact a site and its ecosystem, some practices are more detrimental than others (Worrell and Hampson, 1997). In cases where plantation productivity has conclusively declined as a result of management practices, these declines have been due to a decrease in soil porosity (particularly macroporosity), soil organic matter or site nutrients (i.e. soil plus residues) (Powers *et al.*, 1995; Kelting *et al.*, 1999; Binkley and Stape, 2004; Deleporte *et al.*,

2008). Of the practices most likely to decrease porosity, harvesting and site preparation practices that involve machinery result in significant soil compaction (Hatchell *et al.*, 1970, McColl and Powers, 1984; Powers *et al.*, 1995; Misra and Gibbons, 1996; Ares *et al.*, 2005). Residue management and the movement of machinery over the residues are most likely to affect the soil organic matter and nutrient content (McColl and Powers, 1984; Dyck and Cole, 1994; Powers *et al.*, 1995; Jurgensen *et al.*, 1997; Laiho *et al.*, 2003).

Approximately 80 000 ha of eucalypt plantations are harvested in South Africa each year (Smith, 2006). To ensure the marketability of products and to maintain site productivity, many South African plantations are voluntarily certified, mainly through the International Organisation for Standardisation (ISO) and the Forest Stewardship Council (FSC; Lamoral, 1998). In addition, several organisations have published guidelines for plantation operations (e.g. Forest Engineering Working Group of South Africa, 1994; Forestry Industry Environmental Committee, 1995). Although the process of certification or adherence to guidelines increases the potential to maintain productivity, it does not supply the necessary tools with which to measure potential changes, particularly on a site-specific basis. Site-specific changes in long-term site productivity (LTSP) can only be assessed through the development of criteria and indicators of LTSP. These criteria and indicators are identified, and values can be developed, from studies that investigate the resultant changes in soil properties from plantation management across a range of sites, and the effects of these changes on successive rotations (Lawes *et al.*, 1999).

In many studies, stand productivity responses to harvesting and residue management practices have been found to vary across sites (e.g. Greacen and Sands, 1980; Warkotsch *et al.*, 1994; Kelting *et al.*, 2000; Powers *et al.*, 2005; Smith, 2006). These varying responses may have been caused by one or several of the following:

- Stand productivity responses to similar practices vary substantially with site and soil type.

- Productivity was measured using stand productivity rather than site productivity (i.e. tree volume rather than net primary productivity; NPP). This may result in incorrect conclusions as some practices may result in less tree volume, but similar total quantities of biomass (e.g. at high stocking rates) or *vice versa*.

- Non-treatment effects confound results. Variation in silviculture, stocking or pest and disease infestations between treatments, e.g. particular treatments may result in lower levels of competing vegetation which then influences growth.

- Stand productivity was usually assessed at rotation end when forest stands may not be fully utilising the site, particularly with respect to nutrients. At this time, nutrients are mainly obtained either via internal nutrient cycling or from the litter layer of that stand. At canopy closure in contrast, leaf and fine root development often reaches a maximum and there is substantially less reliance on processes such as internal nutrient cycling. This results in the maximum requirement for soil resources by the stand occurring at this time (Miller, 1995). Canopy closure, therefore, may be the best time to determine changes in productivity.

- The quantity and extent of root systems from previous rotations may allow subsequent rotations to overcome the effects of harvesting and residue management practices. New roots grow into the old root channels that provide microsites with good soil physical and nutritional properties (Powers *et al.*, 1990; Nambiar and Sands, 1992; Morris and Miller, 1994; Kelting, 1999; Smith, 2000).

1.1 Aim and outline of the study

The aim of this study was to evaluate the effect of different levels of soil compaction (implemented through harvesting practices) and residue management on soil properties, and on the growth of *Eucalyptus grandis*, at two contrasting sites. In particular, the use of the productivity of young, fast-growing *Eucalyptus* stands as indicators of the changes in soil properties as a result of the treatments were evaluated.

Chapter 2 explores the concepts of sustainability and long-term site productivity, the relationship between them, and principles behind the measurement of long-term site productivity. **Chapter 3** details the selected trial sites, the manner in which treatments were applied, and measurements taken. The subsequent three chapters assess the effects of treatments on soil chemical and physical (**Chapters 4 - 6**) properties. **Chapter 7** analyses the relationships between changes in soil properties on tree growth, productivity and allometry. The final chapter (**Chapter 8**) gives the overall conclusions of the study.

Chapter 2

Concepts of Sustainability

This study focuses on the impact of certain forest plantation operations on soil properties that can influence the sustainability of future forest plantations. Therefore concepts surrounding sustainability, and the relationship between sustainability and LTSP were reviewed. More detailed discussions of the effects of specific changes in soil characteristics and the effect of these on LTSP are contained in each of the following chapters.

2.1   Introduction

Sustainability is essentially the ability to maintain something over time (Prabhu *et al.*, 2001). Although it is a commonly utilised term and many have proposed definitions, a clear, concise definition of forest sustainability has not yet been developed (Vance, 2000; Innes and Karnosky, 2001; Prabhu *et al.*, 2001). This is because sustainability has different meanings to different groups, as it is assessed relative to an "ideal state", and it is the assessment of that "ideal state" that varies (Burger and Kelting, 1998; Vance, 2000; Innes and Karnosky, 2001; Prabhu *et al.*, 2001). For example, a production forester would consider sustainability to be the maintenance or improvement of timber yields over time. However, an ecologist may view sustainability in the light of species biodiversity and the occurrence and functioning of all expected ecological processes. Conversely, a politician would include social and economic processes in the definition. These contrasting ideas of sustainability lead one to the realisation that sustainability may be best defined in relation to the expected role of a particular forest, and that these expectations may change over time. These goals must be met almost simultaneously, while meeting present needs and providing options for the future (Innes and Karnosky, 2001; McCool and Stankey, 2001; Prabhu *et al.*, 2001; Rametsteiner, 2001). Even from a scientific point of view, what constitutes sustainability varies considerably and the "ideal state" has been variously defined as:

- The natural state that has not suffered human effects.

- A pre-existing state.
- The state of the system under low intensity management.
- The maximum potential of a particular system to meet human needs without affecting the future productivity (of the crop in question) of that system (Doran and Parkin, 1996; Vance, 2000).

It is therefore not possible to provide a definition that is acceptable to all groups and situations. Although the final definition of the "ideal state" (and sustainability) is often considered to be an external, anthropocentric concept, it often contains characteristics important for environmental sustainability (Doran and Parkin, 1996; Vance, 2000). During UNCED (1992) the following definition of "broad-sense" sustainability was formed (Lawes *et al.*, 1999):

"*The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems*".

Most other definitions (see Burger and Kelting, 1998 and Prabhu *et al.*, 2001 for examples of these) describe broad-sense sustainability in a similar manner. These reflect a world-view, stating that forest management must simultaneously meet the needs of the present without negatively affecting future yields by practicing ethical land stewardship that is ecologically viable (environmentally sound by conserving soil, air and water quality; and wildlife and fish habitat), economically feasible (affordable), and socially desirable (Burger and Kelting, 1998; McCool and Stankey, 2001; Prabhu *et al.*, 2001; Rametsteiner, 2001). Attaining a balance between these three "needs" presents an enormous challenge to those in pursuit of sustainable production (Doran and Parkin, 1996). In contrast, "narrow-sense" sustainability purely relates to the change in economic yield (i.e. wood volume) over rotations (Evans, 1999).

In this study, sustainability will be evaluated in more detail than that understood by narrow-sense, but not as in-depth as broad-sense sustainability would indicate (aspects such as social sustainability will not be included). As a result of this, and other implications of the term sustainability, the term "long-term site productivity" is considered more appropriate for this study. This refers to the maintenance of ecosystem processes necessary for the sustained production of timber over future rotations.

2.2 Criteria for LTSP studies of forest plantations

Several studies (e.g. Powers *et al.*, 1990; Tiarks *et al.*, 1992; Morris and Miller, 1994; Powers *et al.*, 1996; Miller *et al.*, 2004) have reviewed LTSP literature of plantation forestry. These reviews determined a common set of criteria that were used to assess the results and validity of conclusions (concerning LTSP) of previous studies. Previous studies had to contain all three of the following criteria (determined by Powers *et al.*, 1990; Morris and Miller, 1994) to yield valid information on LTSP:

1. Growth measurements must have been made for a sufficient period of time, so that the influence of temporary differences in initial site conditions has been reduced and the ability of the site to support tree growth is fully utilised.
2. Differences in tree growth must be as a result of differences in the soil environment, rather than as a result of differences in resource allocation due to weed competition, stocking or pests and diseases.
3. A true experimental control must exist, i.e. a control reference against which the effect of the treatment can be assessed. This control must not be confounded in any way by extrinsic variation.

In addition, results from the studies needed to be interpreted correctly. Snowdon and Waring (1984) investigated tree response to fertiliser application and weed control and found that there were two basic patterns of response (Type I and II). Type I growth responses occur when a treatment does not alter site productivity,

but rather stand productivity. It is identified by parallel growth responses between the treatment and control with time. Eventually (if the stand is allowed to grow for a lengthy time period), the control and treatment growth response curves will meet, as site resources become limiting (**Figure 1.1a**). An example would be early weed control that improves the early growth of a stand, but does not alter site productivity. In contrast, Type II responses are identified by divergent growth responses that increase with time as a result of changes in site productivity (**Figure 1.1b**). A third type of response has also been documented (Miller *et al.*, 2004; **Figure 1.1c**). This type of response cannot be attributed to either changes in site or stand productivity, as yield differences remain as a result of initial differences in growth. If in the following rotation, growth differences are maintained, despite identical silviculture, it can be assumed that a change in site productivity has taken place.

As a result of these conditions, very few of the review studies could definitively confirm that LTSP had declined. Most studies have either poor data, or the data are anecdotal and often retrospective in nature, making separation of cause from effect difficult (Powers *et al.*, 1990; Morris and Miller, 1994; Powers *et al.*, 1996; Worrell and Hampson, 1997; Richardson *et al.*, 1999; Miller *et al.*, 2004). As a solution, Geppart *et al.* (1984, cited by Miller *et al.*, 2004) suggested that to determine if a management practice affects LTSP the following questions must be answered:

1. What properties or processes are changed by the practice?
2. What is the relative magnitude and direction of change?
3. What is the duration of the effect?
4. What interactions with other changes are likely?
5. Are the forest practices occurring on a spatial or time scale likely to cause an impact on the site (i.e. is natural amelioration of effects likely to occur within constraints of time and space of current management practices)?
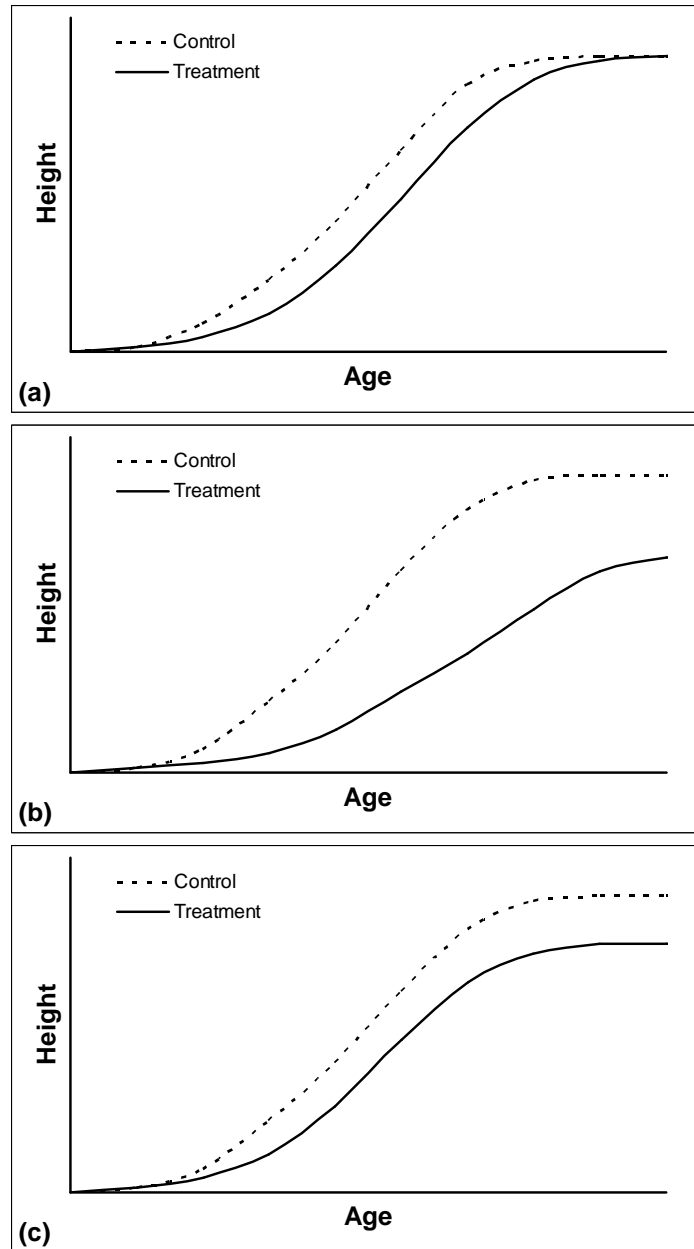
Figure 2.1: Hypothetical growth response (demonstrated by tree height) as a result of a treatment relative to the control: (a) temporary decrease followed by recovery of stand productivity (no impact on site productivity, or Type I response); (b) decrease in site productivity (Type II response); and (c) initial decrease in stand productivity that does not recover during that rotation (possible decline in site productivity). Adapted from Snowdon and Waring (1984) and Miller *et al.* (2004).

The complexity, even of plantation ecosystems, means that it is neither possible nor necessary to evaluate every single process and component of an ecosystem to monitor its productivity and predict with reasonable surety the consequences of forest management. In addition, the importance of processes and components in an ecosystem will vary from site to site. It is therefore desirable to identify the key processes, which will, with quantification, allow acceptably accurate predictions concerning long-term productivity for that plantation (Kimmins, 1994; Burger and Kelting, 1998). Turner *et al.* (1999) suggested that in order to adequately monitor changes in plantation sustainability, sustainability and performance indicators are required. These indicators must provide information on the actual characteristics of plantation forests and how they are changed by management. Ideally parameters that indicate processes within the system need to be identified such as:

- Actual productivity measures (i.e. net primary production).
- Yield of harvested products (i.e. stemwood).
- Changes in soil properties (including changes over rotations).
- Genetic improvements.
- Impacts of pests and diseases.
- Environmental changes (for example, in water quality).

2.3   LTSP of South African *Eucalyptus* plantations

Concerns have been expressed regarding the LTSP of South African eucalypt plantation forestry as a result of the following:

- Rotation lengths are short, typically only between 6 and 11 years in pulpwood crops, so that harvesting and silvicultural impacts are more frequent, resulting in shorter recovery periods combined with greater quantities of biomass removal over time (Tiarks *et al.*, 1990; Smith and Norris, 1995).
- Increases in mechanisation and heavy machinery use in plantations as a result of the increasing demand for forest products, local labour shortages and improvements in technology (Grey and Jacobs, 1987; Reisinger *et al.*, 1988; Smith, 2000; Brink, 2001). Loss of soil productivity is generally

related to the cumulative quantity and mass of equipment that enters a stand (Tiarks *et al.*, 1990).

- Year-round harvesting results in sites being harvested when soils are most susceptible to damage (e.g. wet soils are more prone to topsoil disturbance and compaction than dry soils; Grey and Jacobs, 1987).

- Soils in South Africa do not undergo freeze-thaw cycles as a result of the warm temperate and sub-tropical climates of this area. In addition, clay minerals present in soils planted to forestry in the summer rainfall area are generally kaolinitic resulting in low shrink-swell properties. The lack of either freeze-thaw or shrink-swell processes prevents the self amelioration by soils of compaction (Warkotsch *et al.*, 1994; Smith, 1995; 2003).

- Since residues contain substantial quantities of nutrients their management (e.g. burning, windrowing or broadcasting) is of major importance. In addition, subsequent movement of harvesting equipment may remove, break-up or mix residues with the topsoil, all of which have implications for soil organic matter levels, which, in turn, affect nutrient dynamics and soil physical properties (Norris, 1995; Ballard, 2000).

2.4   Measurement of management effects on LTSP

Many authors have highlighted the necessity for well-designed long-term field experiments to test the extent to which plantation management affects LTSP (Dyck and Cole, 1990; Lousier; 1990; Morris and Miller, 1994; Richardson *et al.*, 1999). Recommendations for these trials are that:

- They are spread over a wide range of sites.
- They are run over several successive rotations with employment of very similar management and tree genetics.
- The climate is monitored during the rotations.

This will allow changes in productivity to be correctly attributed to changes in LTSP. Such trials, however, may become empirical in nature if no attempt is made to understand the mechanisms altering site productivity (Richardson *et al.*, 1999). All experiments are conducted under a specific set of conditions and therefore an

understanding of the changes in soil processes that occur over time is essential to be able to extrapolate to other sites and conditions. Also, the time frames of forest production are so large (six years at the minimum), that comparisons of management practices are not timely enough (Morris *et al.*, 1997; Burger and Kelting, 1998; Amateis *et al.*, 2003a). In addition, factors (such as stemwood volume) are erroneously often considered measures of LTSP, or are incomplete without measurement of another variable (Powers *et al.*, 1996; Burger and Kelting, 1998; Miller *et al.*, 2004). These problems can be overcome by measurement of both the soil properties and processes, and the plantation using approaches that ensure measurement of LTSP.

2.4.1 Soil measures

Soil is regarded as the least renewable structural component of a terrestrial ecosystem, and declines in site productivity are often linked to a decrease (or loss) of soil function (Kimmins, 1996; Burger and Kelting, 1998; Powers *et al.*, 1998). This has particularly been found to be the case in several crops that are grown as monocultures (such as wheat, maize and cotton) which in some countries, despite improved genotypes and intensive management have shown declining productivity (and sustainability) as a result of deteriorating soil productivity (Lal and Pierce, 1991; Mitchell, *et al.,* 1991; Hulugalle and Scott, 2008). In addition, the direct link between soil environment and plant growth results in the use of soil properties or changes in indicators of soil productivity as measures of long-term forest productivity (Burger and Kelting, 1998).

The concept of soil quality (or soil health) was introduced as one component of sustainable agriculture in the early 1990's (Fenton *et al.*, 1999). Mismanagement of soil has historically been shown to result in malnutrition (in the case of soils under food crops), poverty and economic disaster; indicating a strong link between soil health and plant, animal, and ultimately, human health (Bezdicek *et al.*, 1996). This concept has therefore been investigated and developed in the agricultural sector (e.g. Lal, 1993; Doran and Parkin, 1994; Schipper and Sparling, 2000) and, less frequently, in the forestry sector (e.g. Gale *et al.*, 1991; Burger and Kelting,

1999; Kelting *et al.*, 1999). Soil quality has been defined as "*the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health*" (Doran and Parkin, 1994). Ideally, of course, a soil quality index or model would include parameters that quantify the soil's ability to perform productive, environmental, and health functions (Bezdicek *et al.*, 1996; Burger and Kelting, 1998). The quantification of all soil functions is at present an impossible task and so our incomplete understanding of ecosystem functioning must be used to make the best scientifically based evaluation possible (Morris *et al.*, 1997).

The role of soils in forest productivity is mainly one of air, water and nutrient supply in response to demands made by forests as a result of climatic characteristics and physiological age of the stand (Burger and Kelting, 1998), as well as providing structural support to the trees. The ability of the soil to fulfill these roles is dependent on a combination of soil physical, chemical and biological characteristics and processes. However, the effects of various key soil factors (or processes) on tree growth are not fully understood. If this was the case, then long-term responses could be estimated from the effects of various practices on these factors or processes (Morris and Lowery, 1988; Richardson *et al.*, 1999). Currently, relationships between soil factors and productivity are assumed, and have generally not been determined, especially against NPP (Powers *et al.*, 1990). Key processes (i.e. those that give enough understanding of a system to make certain desired predictions) will vary with forest/ecosystem type and scientific/management objectives. Quantitative measurement of key processes may allow the estimation of other processes in the ecosystem, thereby decreasing the need to measure each distinct process (Comerford *et al.*, 1994). As a result of our incomplete understanding of the effects of the soil system on forest productivity, the measurement of effects of key soil properties and processes on forest productivity (over time) is currently the best available method to assess soil-based criteria of LTSP (Burger and Kelting, 1998).

Historically, only the nutrient-supply function of soils was studied in the context of plantation sustainability (Rennie, 1955; Pritchett 1979; Dyck and Cole, 1994; Johnson, 1994). South African research in this area has found some evidence of potential declines in productivity as a result of intensive silviculture through theoretical nutrient budget studies, particularly in regard to nitrogen (du Toit and Scholes, 2002; du Toit, 2003). While this information is useful, it provides information only on one aspect of the role of soil in plantation productivity, which can be relatively easily ameliorated by fertiliser application, unless related to organic matter decline.

Only a handful of studies have been undertaken to assess changes in soil physical, chemical and microbial properties and plantation forest NPP. Many studies have concentrated solely on the effects of soil physical properties (e.g. Froehlich, 1979; Gale *et al.*, 1991; Costantini and Doley, 2001), soil chemical properties (e.g. Burger and Pritchett, 1988; Gale *et al.*, 1991; Arocena, 2000), or microbial properties (e.g. Perry *et al.*, 1982) on tree growth. Studies relating individual soil properties to NPP have been collated and reviewed extensively by Nambiar (1996); Jurgensen *et al.* (1997), Powers *et al.* (1998), Powers (1999), Fox (2000) and Schoenholtz *et al.* (2000).

In cases where plantation productivity has conclusively declined as a result of changes in soil properties it has generally been found to be as a result of a decrease in soil porosity (particularly macroporosity) and/or soil organic matter (Dyck and Cole, 1994; Powers *et al.*, 1995; Kelting *et al.*, 1999; Binkley and Stape, 2004; Ares *et al.*, 2005). Powers *et al.* (2005) reviewed the first decade of results from 26 North American trials investigating the effects of soil compaction and organic matter removal (through residue management) on LTSP over a range of sites and forest types. Their study showed that soil compaction effects varied with initial soil bulk density, texture and the degree of understory competition. Organic matter removal had no effect on forest growth at the time of measurement, despite consistent declines in soil carbon concentrations and nitrogen availability. Although these trials were ten years old, only the most productive sites were approaching canopy closure as a result of the long rotation length. The trials were

therefore regarded by the authors as being in infancy and warned that trends and conclusions from the studies may change in the future. Miller *et al.* (2004) reviewed studies investigating the effects of machinery use in plantations on LTSP in North America (including the work of Powers and co-authors). They found that soil compaction (with the exception of sandy soils) reduced, and that soil disturbance (such as puddling or displacement) had variable, site-specific effects on LTSP. The effects of residue management on LTSP in the tropics have been investigated in a number of studies through a network funded by the Centre for International Forestry Research (CIFOR). Sites with nutrient-poor soils generally showed reductions in eucalypt growth with residue removal (e.g. Gonçalves *et al.*, 2004a in Brazil; Nzila *et al.*, 2004 in the Republic of Congo or Congo-Brazzaville (hereafter termed the Congo); Xu *et al.*, 2004 in China; O'Connell *et al.*, 2004a in Australia). Growth responses to residue management on more fertile sites varied, although significant changes in soil nutrient levels and fluxes were found (e.g. du Toit *et al.*, 2004; O'Connell *et al.*, 2004a).

Several studies have quantified the effects of harvesting, in particular, and several residue management practices on soils and tree growth in South Africa. Warkotsch *et al.* (1994) found that *E. grandis* growth (at six months old) was lower in areas of high penetrometer soil strength (PSS) in a sandy soil in Zululand. However, not only was the study of a preliminary nature and not statistically replicated; but extraction routes (and distance from routes), rather than plots, were utilised as treatments. Therefore plot sizes were not large enough to prevent tree root growth into uncompacted areas. Smith (2003) investigated the effect of soil compaction on harvesting extraction roads on the growth of *E. grandis* and two clonal hybrids of *E. grandis* at three sites in Zululand. At one site with a slightly finer soil texture (4 to 11% clay content), soil compaction resulted in significantly lower tree growth for all species/clonal hybrids (8 to 26% decrease) after eight years on the extraction road. However, there was no significant effect on growth at either of the other sites (five- and eight-year-old stands) where the soils had a coarser texture. Similarly, working on other sandy soils in the Zululand region, Smith and du Toit (2005) showed that, despite increases in bulk density, PSS and decreases in soil aeration, tree growth (measured by wood volume) was not

significantly affected. This was attributed to an increase in plant available water as a result of soil compaction on the sandy soils. More recently, Smith (2006) studied the effect of various harvesting practices on soil compaction and growth over a full rotation (12 years) of *E. grandis* at two contrasting sites in the KwaZulu-Natal (KZN) Midlands. At both sites, growth declines were evident for all harvesting treatments when compared to no compaction (where timber was manually removed). Moreover, the growth curves (basal area and volume) appeared to be diverging and indicative of a Type II growth response (Snowdon and Waring, 1984) suggesting that the treatments are affecting LTSP (Smith, 2006).

These variable tree responses to compaction can be attributed to:

- A variation in soil response to compaction as a result of mainly soil textural, structural and depth differences.
- In some studies, it is possible that the soil was not compacted sufficiently to impact tree growth.
- The nature of machinery movement in plantations results in variable levels of compaction within soil, both horizontally and vertically.
- Small plot sizes.
- Similar effects on soil properties may be advantageous at different sites (i.e. moist vs dry sites).
- Tree species vary in their requirements of optimal soil conditions, and respond differently to similar soil changes.
- Previous rotation root systems that may alleviate the effects of compaction on trees (Greacen and Sands, 1980; Grey and Jacobs, 1987; Nambiar and Sands, 1992; Nambiar, 1996; Smith, 1998; van Lear *et al.*, 2000; Costantini and Doley, 2001; Sanderson *et al.*, 2006).

Dalgleish (1999) investigated carbon dynamics in a young, irrigated and fertilised *E. grandis* plantation, but did not assess the effect of these carbon dynamics on tree growth. Du Toit *et al.* (1999; 2004) and du Toit and Scholes (2002) reported on the effects of residue management on *E. grandis* early tree growth and biomass on a clay soil in the KZN Midlands. They concluded that increased nutrient availability in the burnt, fertilised and slash-retained treatments plus

mixing by a three-wheel logger, positively affected early tree growth. They also found that only the burning of harvest slash residue resulted in a major loss of nutrients. It was therefore concluded that the site was reasonably well buffered with regards to nutrients against all other commercial harvest residue treatments.

The variation in site factors (such as soil texture and organic matter content), intensity of harvesting and/or site preparation operations, and the site conditions at the time of the operation influence the extent to which site productivity will be degraded and the soil's ability to either resist or recover from damage (Dyck and Cole, 1994; Powers, 1999; Kelting *et al.*, 2000; Xu *et al.*, 2000). All of these factors impact the growth of the next forest rotation through alteration of the rooting environment. It is recognised that if, after a disturbance at a specific site, the site is given enough time to recover to its pre-disturbance conditions, that the ecological sustainability of a site will be maintained. This period is termed its "ecological rotation" (Kimmins, 1974).

2.4.2 Plantation measures

Plantation productivity is a component of, and is often used as an indicator of, LTSP (Richardson *et al.*, 1999; Morris and Smith, 2002). The productivity of any ecosystem is dependent on "*the efficiency with which matter and energy enter, move through, and are stored at the various trophic levels*" (Morris *et al.*, 1997). **Actual** productivity is dependent on the physical, chemical and climatic factors of a site and their interaction within a specific biological framework. It is therefore dependent on both the inherent features of a site (e.g. climate, geology, topography), and those that can be manipulated by management (generally associated with the soil, such as porosity, organic matter, nutrients and tree species) (Powers *et al.*, 1990; van Miegroet *et al.*, 1994; Kimmins, 1996; Kelting, 1999). It is therefore productivity under a certain set of conditions or limitations. **Potential** productivity, however, is the productivity of a site without any limitations (with respect to management) but is still dependent on the physical, chemical and climatic factors of a site. Potential productivity can either be estimated theoretically or physically.

2.4.2.1   Theoretical determination of productivity

Process-based models such as CABALA and 3-PG can be used to determine the potential productivity of plantations (Landsberg and Waring, 1997; Dewar, 2001; Battaglia *et al.*, 2004). In South Africa, only, 3-PG has been parameterised for *E. grandis* (Esprey and Sands, 2004). However when the performance of this model was tested, researchers involved warned that it is not infallible and under certain conditions gave inaccurate estimates of productivity (Esprey and Smith, 2002; Dye *et al*; 2004; Campion *et al.*, 2005). In addition, this model has not been thoroughly tested in South African plantations of very young *E. grandis* trees. Under such circumstances, physical determination of productivity is most accurate.

2.4.2.2   Physical determination of productivity

Changes in potential site productivity can be quantified by measuring actual site productivity (Powers *et al.*, 1996). Many international studies reviewed (by Powers *et al.*, 1990; Morris and Miller, 1994; Powers *et al.*, 1996; Worrell and Hampson, 1997; Richardson *et al.*, 1999; Miller *et al.*, 2004) utilised stemwood measures (i.e. stemwood height, diameter and/or volume) coupled with survival as the only measures of actual site productivity. In Southern African *Pinus* plantations, comparisons of stemwood production over successive rotations were also performed to assess changes in long-term productivity (e.g. Evans, 1975; 1978; 1996; 1999; Morris, 1986). In the few South African *Eucalyptus* long-term productivity studies, stemwood volume was also used as the indicator variable (e.g. Smith and du Toit, 2005; Smith, 2006).

The use of stemwood volume to assess actual site productivity is regarded by some as insufficient, as it only captures a small portion of site productivity with the rest being held in roots, foliage, reproductive parts and litter (Dyck and Cole, 1994; Laiho *et al.*, 2003). In addition, treatments that decrease the short-term allocation of carbon to tree stemwood may not necessarily degrade the long-term productivity of a site, as in the case of inadequate weed control (Powers, 1999).

The measurement of productivity solely by stemwood volume/mass may therefore lead to uncertain and misleading conclusions. However, it is an easily measured and economically important variable (Morris and Smith, 2002). In commercial plantations, site index (the average dominant stand height at a specific stand age; von Gadow and Bredenkamp, 1992) is often used as a measure of site productivity (Morris and Smith, 2002). This is because this measure is generally thought to not be affected by factors that alter the partitioning of NPP into stemwood. However, there is evidence to the contrary, and this has been discussed in detail by Morris and Smith (2002).

Plantation productivity is limited by the ability of a site to supply the resources for plant growth, and by the capacity of the plantation to convert these into organic matter (Battaglia *et al.*, 1998). The result is termed gross primary production (GPP) and is mainly dependent on the capture and utilisation of light, and hence on leaf area (Battaglia *et al.*, 1998; Powers, 1999). Gross primary production, however, also includes a portion of productivity that is lost through respiration or allocation to symbiotic organisms such as mycorrhizal fungi. Since GPP can be difficult to accurately quantify, actual site productivity is most easily and comprehensively quantified by dry matter production, i.e. GPP minus respiration, or NPP (Powers *et al.*, 1990). However, NPP includes biomass lost through fine root turnover. This portion of NPP is particularly difficult to determine, and thus NPP minus fine root turnover (NPP_{-RT}) is often measured.

Thus, it has been hypothesised that an estimate of a site's potential productivity can be made if leaf area is measured when it peaks, which usually occurs around the same time as canopy closure. At this stage, tree growth and nutrient uptake rates are so high that the stand fully utilises the site for water and nutrients, i.e. when production is maximised trees fully exploit a site (Miller, 1995; Powers *et al.*, 1996; Powers *et al.*, 1998; Powers, 1999). If potential productivity is determined at this stage, stocking has no influence on it, as potential productivity relates to the potential growth on a site, when constrained by climate, soil and genetics of the plant material (Powers *et al.*, 1996). In South African *E. grandis*, plantations nutrient accretion and leaf area index have been found to peak at or just after canopy closure (Dovey *et al.*, 2007). When similar effects have been seen in other

plantation eucalypts, this has been attributed to an increase in carbon allocation to stemwood at the expense of foliage due to rapid changes in the light conditions experienced by tree crowns (Cromer *et al.*, 1993; Medhurst *et al.*, 1999).

It is therefore important that changes in LTSP resulting from changes in the soil environment only be assessed while factors that can influence NPP at canopy closure such as climate, tree genetics, silviculture, pest and disease incidence, are held constant. If these factors, and their interaction, are not held constant, meaningful comparisons of productivity at any age are not possible (van Miegroet *et al.*, 1994; Powers *et al.*, 1995; Kelting *et al.*, 1999; Miller *et al.*, 2004). A change in one of these factors may intensify or counteract changes in other factors. For example, changes in soil properties may be either masked or enhanced with improvements or changes in tree genotype (Vance, 2000; Miller *et al.*, 2004). Additionally, practices such as burning can lead to higher productivity initially, but may reduce site productivity in the long-term (Rab, 1996; 1999; Ballard, 2000). A site may not be highly productive, but may be managed sustainably, and *vice versa*. Therefore a site's productive potential may not be achieved as a result of management objectives and natural disturbances (Kimmins, 1996; Powers *et al.*, 1996).

As a result of plantation forestry rotation lengths of at least six years, the use of plantation measures to determine changes in LTSP is often not timely enough for comparisons of management practices (Morris *et al.*, 1997; Burger and Kelting, 1998; Amateis *et al.*, 2003a). A solution may be an approach that determines productivity at canopy closure in highly stocked stands (Adlard *et al.*, 1984). Micro- and mesocosms are commonly used in experimental ecology as small-scale replications of actual ecological systems (e.g. Lawton, 1995; Fraser and Keddy, 1997). In addition, productivity determined at canopy closure is not dependent on stocking, but rather maximum leaf area when the stand is fully exploiting a site (Powers *et al.*, 1996; Powers *et al.*, 1998).

This theory has led some (e.g. Kelting, 1999; Amateis *et al.*, 2003a; 2003b; Watt *et al.*, 2005) to plant trees at a close espacement, as maximum leaf area will be attained at an earlier stage than in trees planted at a commercial espacement.

This leads to an early high demand for site resources as competition sets in faster than in commercial stands, thereby allowing early diagnosis of limiting soil resources. This method would also allow the early shading out of weeds, so that growth is not influenced by differences in weed control. The small plot sizes also decrease the likelihood of microsite variation within plots affecting results, as may occur in larger, commercially spaced plots (Amateis *et al.*, 2003a). It has been proposed that responses to soil properties at canopy closure in densely spaced trees will be very similar to those obtained in commercially spaced trees (Kelting, 1999; Kelting *et al.*, 2000).

If this approach is used purely to quantify the effects of soil changes on NPP at canopy closure, the scaling up of NPP responses of trees in the densely planted plots to those of commercially spaced plots is not necessary. If, however, growth responses (such as bole diameter and height) are measured, it will be necessary to quantitatively link the growth of trees in the densely planted plots with those of the commercially spaced plots (Amateis *et al.*, 2003a). If this is required, Amateis *et al.* (2003a; 2003b) identified three difficulties associated with this scaling up of tree growth responses as follows:

1. Allometric relationships change with physiological age. This may mean that although similar models for treatment responses may be developed for both densely planted and commercially spaced trees, the parameters in the models will be different.
2. Relating tree growth through different chronological time scales is highly problematic, as trees would have experienced different growing conditions during the different measurement periods.
3. If competition has set in (leading to self thinning), stand dynamics vary. This final difficulty can be avoided if trees are harvested at canopy closure allowing the assumption that competition will not have set in substantially enough for this to become problematic.

To date, three studies (Amateis *et al.*, 2003a; 2003b; Sharma *et al.*, 2003) quantitatively linked the growth of trees in densely planted plots to that of trees in commercially spaced plots. However, all of these studies utilised the same set of data.

Only two studies have utilised densely planted trees to quantify changes in productivity as a result of soil compaction and/or residue management. Kelting (1999) investigated changes in several soil properties (including the development of a soil quality index) and NPP_{-RT} of densely planted *Pinus taeda* (loblolly pine) seedlings. Results suggested that operations which affected plant available soil water, soil aeration and net nitrogen mineralisation, such as compaction and residue retention, had the greatest effect on seedling growth. In New Zealand, *Pinus radiata* and *Cupressus lusitanica* seedlings were densely planted in separate plots across a range of sites with two main treatments (fertiliser vs no fertiliser application and compaction vs no compaction) applied to each species at each site (Watt *et al.*, 2005). Site most strongly affected growth, followed by fertilisation, and then compaction (which had a negative effect). Removal of the climatic effects of temperature and rainfall found that the soil properties which most affected growth were C:N ratio, total soil nitrogen and phosphorus and depth of the A horizon.

Due to the scarcity of such investigations, the present study aims to investigate further the effects of soil compaction and residue management and their interaction on site productivity and the use of growth and NPP measures of densely stocked plots as indicators of the LTSP of South African *Eucalyptus* plantations. This will then enable the assessment of many management practices that lead to soil compaction and affect residues, resulting in improved future management of forest plantations.

Chapter 3

Materials and Methods

3.1 Description of sites, trial layout and treatment implementation

3.1.1 Description of trial sites

In South Africa, approximately 13 and 30% of *Eucalyptus* grown for pulpwood is found in Zululand and the Midlands areas of KZN, respectively (DWAF, 2006). Therefore a study site was located in each of these areas, Rattray in Zululand; Shafton in the Midlands. Although both of these sites are situated in the summer rainfall region of South Africa, they differ considerably with respect to climate, geology and soil properties (**Tables 3.1** and **3.2**). The lithologies that the sites were located on represent approximately 5 and 14% of all plantation areas in the country. Within Zululand, 90% of pulpwood plantations (*Eucalyptus*, *Pinus* and *Acacia sp.*), are growth on recent aeolian sand, while in the Midlands, 30% are growth on dolerite/shale (Smith *et al.*, 2005; C.W. Smith, 2010, pers. comm.[1]). Rainfall was monitored during the growth period (**Appendix 3.1**). Soil samples were taken prior to implementation of the trials to assess their texture, nutrient status and carbon content (**Tables 3.3** - **3.5**).

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[1] Dr C.W. Smith, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Table 3.1: Site and climatic information for the two study sites.

Property	Rattray	Shafton
Coordinates:	28°37' 25" S	29°27' 30" S
	32°04' 15" E	30°12' 36" E
Climatic Zone[a]	Sub-tropical	Warm temperate
Altitude (m.a.s.l.)	50	1190
Aspect	East facing	East facing
Weather station climatic data		
Name:	Mposa	Cedara
Coordinates:	28°36' 59" S	29°31' 44" S
	32°01' 48" E	30°16' 48" E
Mean annual precipitation[b] (MAP; mm)	1046	841
MAP from 2004 - 2007 (mm)	956	849
Mean annual temperature (°C)	21.8	16.8
Average temperature range (°C)	17.1 – 26.9	9.9 – 22 .5
Absolute temperature range[b] (°C)	5.4 – 42.3	-5.0 – 37.3

[a] From: RDASA (1994).
[b] From: Schulze (2008).

Table 3.2: Geological, topographical and soil information for the two study sites.

Property		Rattray	Shafton
Geology		Recent aeolian sand	Dolerite/Ecca shale
Topography		Coastal plain	Undulating upland plateau
Slope angle		0.6 °	3.8 °
Soil Classification	SA[a]: Form	Fernwood	Kranskop
	Family	Hopefield (1210)	Fordoun (1100)
	USDA[b]	Typic Ustipsamment	Haplic Haplustox
	WRB[c]	Hyperalbic arenosol	Acric humic xanthirhodic ferralsol
Soil depth		1.2 m +	1.0 m
A horizon	Depth	0-0.2 m	0-0.2 m
	Colour (dry)	10 YR 7/3; very pale brown	7.5 YR 3/2; dark brown
	Structure	Single grain	Fine sub-angular blocky
	Boundary[d]	Diffuse	Sharp
E/B1 horizon	Depth	0.2 m +	0.2-0.45 m
	Colour (dry)	7.5 YR 7/4; pink	7.5 YR 4/6; strong brown
	Structure	Single grain	Apedal
	Boundary	-	Diffuse
	Notes	Signs of wetness/mottling increase with depth	
B2 horizon	Depth		0.45 – 1.0 m
	Colour (dry)		10 R 3/6; dark red
	Structure		Apedal

[a] South Africa (Soil Classification Working Group, 1991).
[b] United States Department of Agriculture (Soil Survey Staff, 2006).
[c] World Reference Base for Soil Resoirces (FAO, 2001).
[d] boundary with next horizon.

Table 3.3: Selected soil properties at Rattray. Average (n = 8) values are given with standard deviations in parentheses.

Property	Soil Depth (m)		
	0-0.3	**0.3-0.6**	**0.6-0.9**
Clay (%)	3.7 (0.5)	4.3 (1.1)	4.9 (1.1)
Fine silt (%)	1.4 (0.7)	1.3 (0.8)	1.4 (0.8)
Coarse silt (%)	1.8 (1.1)	2.0 (1.5)	2.0 (1.8)
Very fine sand (%)	4.7 (0.6)	4.5 (0.8)	4.4 (1.2)
Fine sand (%)	54.3 (1.2)	54.5 (0.9)	53.9 (1.6)
Medium sand (%)	30.6 (1.2)	30.1 (0.9)	30.0 (1.5)
Coarse sand (%)	3.4 (0.5)	3.2 (0.7)	3.3 (0.5)
Soil texture	Sand	Sand	Sand
pH (KCl)	4.82 (0.472)	4.28 (0.13)	4.33 (0.09)
Total N (g kg^{-1})	0.21 (0.09)	0.20 (0.01)	0.18 (0.06)
P (mg kg^{-1})	1.69 (0.35)	1.52 (1.58)	1.41 (0.16)
K (cmol$_c$ kg^{-1})	0.17 (0.01)	0.14 (0.01)	0.13 (0.01)
Ca (cmol$_c$ kg^{-1})	0.33 (0.08)	0.18 (0.08)	0.09 (0.08)
Mg (cmol$_c$ kg^{-1})	0.17 (0.03)	0.14 (0.04)	0.13 (0.05)
Na (cmol$_c$ kg^{-1})	0.04 (0.01)	0.05 (0.01)	0.05 (0.02)
Exch. acidity (cmol$_c$ kg^{-1})	0.14 (0.03)	0.32 (0.10)	0.36 (0.09)
ECEC (cmol$_c$ kg^{-1})	0.73	0.72	0.67
Acid saturation (%)	18.80	44.12	54.13

Table 3.4: Selected soil properties at Shafton. Average (n = 8) values are given with standard deviations in parentheses.

Property	Soil Depth (m)		
	0-0.3	**0.3-0.6**	**0.6-0.9**
Clay (%)	69.0 (4.5)	66.0 (4.6)	65.5 (8.8)
Fine silt (%)	6.8 (3.5)	10.7 (4.8)	11.8 (6.4)
Coarse silt (%)	7.1 (4.1)	8.2 (5.2)	8.4 (6.2)
Very fine sand (%)	8.7 (3.6)	8.0 (6.1)	7.7 (4.0)
Fine sand (%)	2.9 (4.7)	1.6 (7.0)	1.5 (6.8)
Medium sand (%)	2.3 (4.9)	1.3 (5.5)	2.1 (6.1)
Coarse sand (%)	3.2 (4.6)	4.1 (4.9)	3.0 (8.0)
Soil texture	Clay	Clay	Clay
pH (KCl)	4.31 (0.07)	4.94 (0.40)	5.50 (0.29)
Total N (g kg^{-1})	2.36 (0.38)	1.31 (0.23)	0.70 (0.17)
P (mg kg^{-1})	0.05 (0.02)	0.00 (0.00)	0.00 (0.00)
K (cmol$_c$ kg^{-1})	0.09 (0.02)	0.05 (0.02)	0.03 (0.01)
Ca (cmol$_c$ kg^{-1})	0.36 (0.13)	0.21 (0.19)	0.21 (0.15)
Mg (cmol$_c$ kg^{-1})	0.60 (0.07)	0.47 (0.15)	0.29 (0.07)
Na (cmol$_c$ kg^{-1})	0.07 (0.01)	0.07 (0.02)	0.05 (0.01)
Exch. acidity (cmol$_c$ kg^{-1})	1.11 (0.20)	0.23 (0.14)	0.09 (0.04)
ECEC (cmol$_c$ kg^{-1})	2.22	1.02	0.68
Acid saturation (%)	50.08	22.26	13.84

Table 3.5: Soil organic carbon content (as determined by Walkley-Black) at Rattray and Shafton. Average (n = 27) values are given, with standard deviations in parentheses.

| Depth (m) | Soil organic carbon content (%) | |
	Rattray	Shafton
0 – 0.05	0.96 (0.26)	15.94 (5.64)
0.05 – 0.15	0.47 (0.14)	7.16 (0.90)
0.15 – 0.3	0.45 (0.05)	5.62 (0.70)
0.45 – 0.6	0.43 (0.07)	3.16 (0.50)

3.1.2   Site history

The Rattray site has had at least six rotations, while the Shafton trial site is currently in its fifth rotation (C.W. Smith, 2007, pers. comm.[2]; P. Viero, 2007, pers. comm.[3]). In the most recent rotation, these sites were established as harvesting impact trials, discussed in detail by Smith and du Toit (2005) and Smith (2006). The objective of these trials was to evaluate the cumulative effect of harvesting operations on soil compaction from one rotation to the next.

3.1.2.1   Rattray

The previous trial at Rattray consisted of four harvesting treatments (replicated four times in a randomised block design) that resulted in three levels of compaction and two residue management treatments. These were motor-manual felling and extraction of timber (control), mechanised felling and extraction with a tracked harvester, and motor-manual felling and 3-wheel logger extraction of timber. Residues in the manually extracted timber plots were either broadcast or windrowed. The timber was extracted every fifth or sixth row by a forwarder (an area termed the "extraction route"). Penetrometer measurements across the trial indicated that there was very little increase in soil strength as a result of the tracked harvester operation, but a substantial increase in soil strength with the 3-wheel logger. Penetrometer soil strength was also measured in the extraction route and was found to be considerably higher than that measured in the 3-wheel logger

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[3] Mr P. Viero, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

treatments. The effect of residue management treatments on soil properties was considered to be negligible at the end of the rotation due to the rapid decomposition of residues as a result of the climate (high humidity and temperature), even prior to planting of the previous trial (Smith and du Toit, 2005). This was confirmed by soil organic carbon results of samples taken across the trial (**Table 3.5**). Just before felling the previous trial, the trees (*E. grandis* x *E. camaldulensis*) were measured, and it was found that they had an average diameter at breast height (DBH) and height of 156 mm and 24.1 m, respectively.

3.1.2.2   Shafton

The previous trial at Shafton consisted of considerably more timber extraction treatments than at Rattray. Felling was performed motor-manually and residues across the entire trial site were windrowed. Seven extraction treatments were replicated four times in a randomised block design. These extraction treatments were:

- Manual (control).
- 3-wheel logger.
- Tractor/trailer combination.
- Forwarder (1, 5 and 10 passes).
- Extraction route (similar to that of the Rattray trial).

Soil strength did not significantly increase (relative to the control) with the tractor/trailer combination. Two of the forwarder treatments (5 and 10 passes) gave very similar soil strength results, while the 3-wheel logger yielded a unique (relative to the other treatments) soil strength pattern with depth (Smith, 2006). Prior to felling, *E. grandis* trees at this site had an average DBH of 149 mm, and a height of 22.8 m.

The nature of the soil strength results at both trials (and organic carbon results at Rattray), indicated that many of the original treatments at the trials were either not severe enough to cause a substantial effect on the soil relative to the control, or were similar to other treatments imposed. The trials therefore had the potential to be altered slightly to meet the objectives of the current study, while addressing their original long-term objective.

3.1.3 Trial layout

The emphasis in this study, compared to the original designs was to have a more structured approach to evaluating the effect of harvesting through creating gradients of impacts for soil compaction and residue management. A minimum of three (of both) compaction and residue management treatments are necessary to create a regression. Therefore minimum, maximum and intermediate levels of both compaction and residue management treatments had to be implemented. Factorial designs allow a resource-efficient (in this case, land area and cost) analysis of both main and interaction effects (e.g. the effect of compaction alone, and the resultant effect of compaction under different residue management levels; McConway *et al.*, 1999). As a result, the three levels of compaction were combined with the three levels of residue management, giving a total of nine treatments (**Table 3.6**), each of which were replicated three times.

Table 3.6: Combination of treatments used for the trials.

Compaction → Residue management ↓	Low (C_L)	Moderate (C_M)	High (C_H)
Broadcast (B)	$C_L B$	$C_M B$	$C_H B$
Windrow (W)	$C_L W$	$C_M W$	$C_H W$
Removed (R)	$C_L R$	$C_M R$	$C_H R$

The previous trial layouts were adapted to allow the incorporation and implementation of new treatments without destroying the integrity of the original trials. For example, plots without any compaction in the previous trial were maintained as such in the new trial, and highly compacted plots were re-compacted by heavy machinery. Plots that were moderately compacted in the previous rotation, as determined by penetrometer soil strength results (Smith and du Toit, 2005; Smith, 2006) were then re-implemented with the moderate compaction treatment. As a result, some of the moderately compacted treatment plots had undergone different treatments in the previous rotation, e.g. at Shafton, similar levels of compaction had resulted from the tractor-trailer and 1 pass of the forwarder treatments (average profile PSS of 3657 and 3600 kPa, respectively). Since the original trials contained a different treatment structure, some plots were not utilised in the new trial layouts (**Figure 3.1**). In addition, the current treatments could not be arranged into randomised blocks due to the previous trial design.
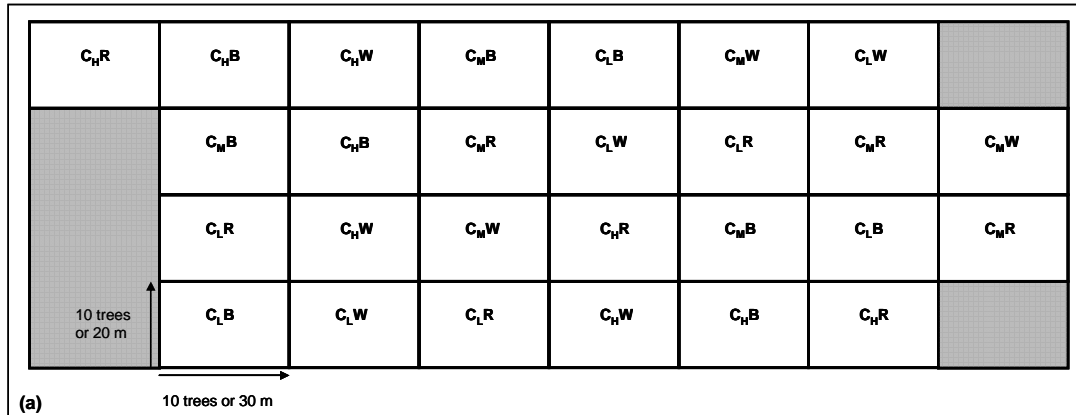
Figure 3.1: Trial layout of (a) Rattray and (b) Shafton trials. Treatments: low (C_L), moderate (C_M) and high (C_H) compaction; broadcast (B), windrowed (W) and removed (R) residue management. Grey areas indicate areas from the previous trial that could not be incorporated into the current trial. Figures are not to scale.

3.1.4   Treatment implementation

The experimental treatments applied were not designed to mimic operational practices, but rather to create extremes that may occur as a result of current or future practices.

Prior to any treatment implementation, main plot (i.e. plots of 20 x 30 m and 19.2 x 24 m at Rattray and Shafton, respectively) positions were demarcated in the standing crop (the rotation prior to that of this study) at both trials. Trees were felled motor-manually and the branches and tops cut from the utilisable stemwood. Trees were then cross-cut into lengths, manually de-barked and stacked in-field. Wood stacks were placed at the edges of each main plot. Residue management treatments were then imposed in each of the main plots as follows:

- **Broadcast residue** (**B**): the forest floor was left intact and all harvest residue (consisting of bark, branches and tops) spread evenly.
- **Windrowed residue** (**W**): the forest floor was left intact and the harvest residue windrowed (i.e. bark and small branches were left on the plot, while large branches and tops were piled in windrows. Although not indicated in **Figure 3.1**, narrow lengths of land between plots running along the "top" and "bottom" of plots were included in the trial design for windrows, i.e. for piles of surplus residues. These windrows did not form part of the measurement plots.
- **Residue removed** (**R**): both harvest residue and the majority of the forest floor was removed from the plot and placed in the windrows using fire rakes, leaving only very fine decomposing organic matter and topsoil intact.

An example of these residue treatments is shown in **Plate 3.1**.

Plate 3.1: An example of residue management treatments (at Shafton).

After the residue management treatments were implemented, main plots were then clearly demarcated by danger tape tied to pegs at the four corners of each main plot to limit machinery movement to the appropriate main plots. Harvesting treatments were then applied in the following manner (full details of vehicle specifications can be found in **Appendix 3.2**):

- **Low compaction** (C_L): timber was carried off the main plot manually.
- **Moderate compaction** (C_M): a 3-wheel logger (weighing 5.2 tonnes loaded) extracted the timber. To ensure even coverage of these main plots, the logger was forced to travel in particular routes around the main plots. As a result of the manoeuvrability of the 3-wheel logger, areas within the stumpline and interrow were traversed (**Figure 3.2** and **Plate 3.2**). This

machinery disturbed the topsoil in the residue removed treatment, and broke up and mixed residue with topsoil in the other residue treatments.

- **High compaction** (C_H): a 3-wheel logger extracted the timber, and loaded a forwarder until a full load was obtained (the forwarder weighed about 33.2 tonnes fully loaded). The forwarder then moved up and down the interrows of the main plots for a total of ten passes (**Figure 3.2** and **Plate 3.2**).
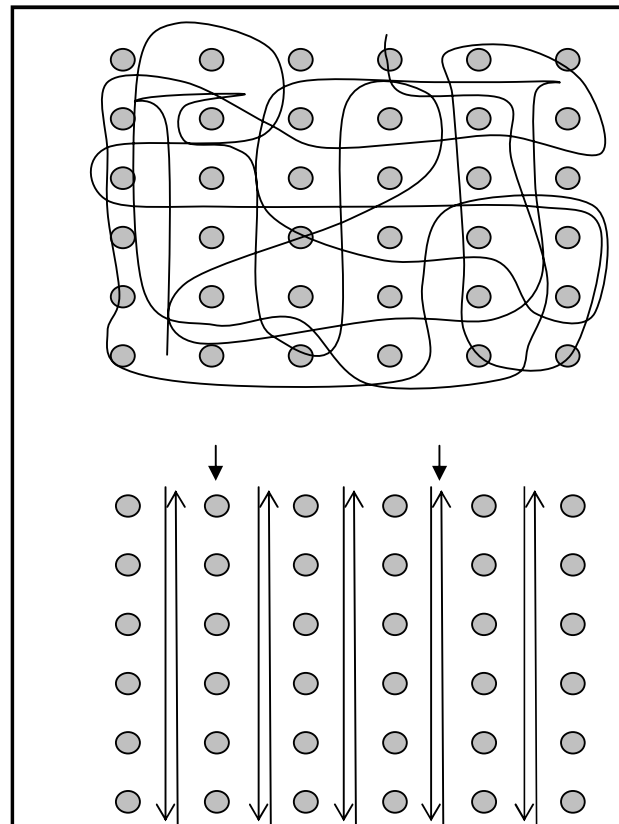
Figure 3.2: Representation of the movement of machinery over main plots (⬭ represents a stump from the previous rotation). (a) An example of the route of the 3-wheel logger. The route is erratic and crosses the stumpline and interrow frequently (the positions of which are indicated in (b)); (b) the forwarder moved up and down the interrow only.

Plate 3.2:   Machinery used to create the different compaction treatments; (a) a 3-wheel logger moving in a windrowed residue plot at Rattray (i.e. C_M treatment); (b) a 3-wheel logger loading the forwarder at Shafton in a residue removed plot (i.e. C_H treatment); and (c) a fully loaded forwarder moving up and down a broadcast residue plot at Rattray (i.e. C_H treatment).

3.1.5   Pre-planting operations

Three operations were carried out prior to planting:
1.   Within each main plot a randomly chosen area (to allow later statistical analysis) was demarcated for the planting of 9 x 9 seedlings at a dense espacement hereafter termed 'sub-plots'.
2.   With the exception of the sub-plots, pits were prepared throughout the trials at 2 x 3 m and 2.4 x 2.4 m apart at Rattray and Shafton, respectively, to match the previous stand density. This was performed manually using hoes and marked planting cables to ensure uniform spacing.
3.   A pre-plant spray (broad-spectrum herbicide containing glyphosate; Roundup®) was then applied to the site to control any competing vegetation (**Appendix 3.3**).

3.1.6   Genetic material

As a result of successful tree breeding, the growth of plantation eucalypts in South Africa has improved (Verryn, 2002), and use of improved material may mask any changes in site productivity between rotations (Vance, 2000; Miller *et al.*, 2004). However, to allow comparisons between studies and as a result of the prevalence of *E. grandis* pulpwood plantations in South Africa, *E. grandis* was planted at both trials. In the case of Shafton, material that was as similar as possible to that planted in the previous rotation was also obtained.

The specific clonal hybrid (*E. grandis* x *E. camaldulensis*) used in the previous trial at Rattray was therefore replaced with a *E. grandis* clone (TAG 14) in this study as unimproved *E. grandis* is highly susceptible to disease in Zululand. This material was obtained from the Mondi nursery in Zululand. The trial at Shafton was planted with similar genetic material to the previous rotation, i.e. unimproved *E. grandis* (EG 62372, Grade 1) obtained from Sappi Shaw Research Centre, Howick, KZN.

The trials were planted from 20-22 September 2004 (Rattray) and from 23-24 November 2004 (Shafton), using two planting strategies:

1. For the long-term growth studies (the main plots), seedlings were planted in the created pits, each with 1 litre of water to promote seedling survival (**Table 3.7**).

2. In the sub-plots, notches were created (i.e. a small trowel was used to make a hole just slightly bigger than the root plug of the seedling) and a seedling immediately planted, with 1 litre of water. Notch planting minimised disturbance to the soil and ensured that seedling roots felt the full effects of the soil environment due to the treatments as soon as possible. In addition, the seedlings were planted in rows matching that of the surrounding main plot seedlings (**Table 3.7**, **Figure 3.3**). To avoid bias, these sub-plots were randomly located within each of the main plots.

Table 3.7:   Details of planting operations at Rattray and Shafton.

	Rattray	Shafton
Main plots		
Spacing between trees (m)	2 x 3	2.4 x 2.4
Stocking (stems ha^{-1})	1 667	1 736
No. of trees per plot	100 (10 x 10)	80 (8 x 10)
Guard rows per plot	2	2
No. of inner measured trees	36 (6 x 6)	24 (4 x 6)
Sub-plots		
Spacing between trees (m)	1 x 1	0.8 x 0.8
Stocking (stems ha^{-1})	10 000	15 625

No fertiliser was applied at planting. Blanking operations (i.e. replacement of dead seedlings with live ones) were carried out to obtain the best possible survival. At Rattray, this operation was carried out three times within two months of planting. The weather at Rattray was extremely dry and hot the first six weeks after planting. This resulted in a number of seedlings dying, and very limited growth of the remaining live seedlings. Over the entire trial 334 seedlings were replaced (out of an original 4482 seedlings planted). At Shafton, extremely wet and cold weather

accompanied by hail just after planting destroyed many seedlings particularly prior to the first blanking operation. In the two blanking operations carried out within a month after planting a total of 597 seedlings were replaced out of the original 4104 seedlings planted.
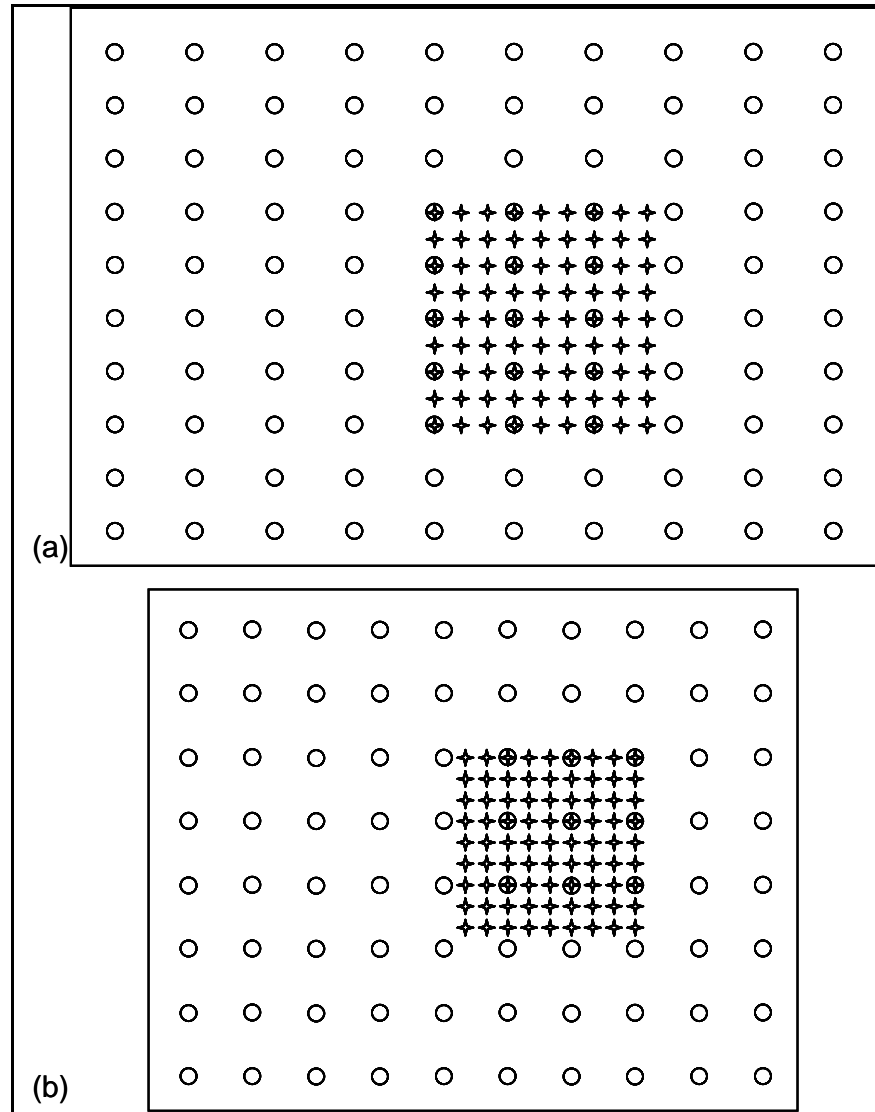
Figure 3.3: Diagram of a main treatment plot at (a) Rattray; and (b) Shafton. Trees in the main plots are represented by ○; trees in the sub-plots by ✛; trees that remained after the sub-plot trees were thinned to maintain the stocking of the stand are represented by ⊕.

Competing vegetation was controlled until canopy closure of the main plot trees at each trial. Prevalent competing vegetation at Rattray necessitated a combination of chemical and hand weeding (on five occasions in total) in which grasses were sprayed with a fluaziprop-butyl–containing herbicide (Fusillade®) and broad-leaf weeds immediately adjacent to trees were hand weeded. At Shafton, competing vegetation was dominated by broad-leaf weeds and was not as vigorous as that at Rattray, resulting in only two chemical weeding operations using Roundup®. Unfortunately, the first weeding operation was partially performed by labour weeding the area surrounding the trial who strayed into the trial, resulting in some sub-plot trees being erroneously sprayed. The remainder of the area was sprayed under supervision shortly thereafter. The second operation was performed without incident.

Coppice from the previous tree crop was initially controlled with Roundup® prior to planting, and thereafter manually controlled (using axes and cane knives). This operation was performed four times at Rattray and three times at Shafton.

All operations and the order in which they were performed are outlined in the respective trial diaries (**Appendix 3.3**).

3.2   Site measurements

Measurements and sampling were performed on the day prior to treatment implementation (T0), in the two days prior to planting (TP), at sub-plot tree harvest (TH), and when trees at Rattray and Shafton were 42 and 39 months old, respectively, (TF). Therefore sampling was carried out at different times after treatment implementation (**Table 3.8**). In addition, some monitoring was carried out between TP and TF.

Table 3.8: Time after treatment implementation (months) at which soil and residue samples were taken at Rattray and Shafton.

Sampling time	Rattray	Shafton
T0	0	0
TP	1.3	8.3
TH	7.0	15.3
TF	43.5	47.3

3.2.1   Soil sampling

At both T0 and TP, soil samples were taken by auger from the approximate centre of each main plot. These samples were used for the following purposes:

1. To check for soil uniformity across the trial (for soil depth and any changes in morphology of horizons) prior to treatment implementation.

2. Samples were taken from 0 to 0.3 m, 0.3 to 0.6 m and 0.6 to 0.9 m for chemical and physical analyses to be used as background information for the trials at T0. These samples were bulked into eight samples representing eight areas (i.e. 3 - 4 neighbouring plots) within each trial for laboratory analysis.

3. To measure gravimetric water content using the same samples as in 2. for PSS measurements taken at T0 and TP.

At TH and TF, soil samples were taken to evaluate the nutritional and organic matter status of the topsoil and subsoil of each treatment plot. Four sample points were randomly selected in each plot, two in the interrow, and two in the stumpline. Soil was taken from the 0 – 0.05 m, 0.05 – 0.15 m and 0.15 – 0.60 m depths. Samples from the interrows were bulked within their plots and depths, resulting in six soil samples from each plot, three representing the interrow, and the remainder representing the stumpline soils. For determination of organic carbon content, interrow and stumpline samples were bulked to give an average for each plot at each depth.

3.2.2   Soil bulk density

3.2.2.1   Troxler

Soil bulk density was measured with a Troxler 3440 series surface moisture density gauge (Troxler Electronic Laboratories, NC, USA), referred to here as a Troxler, and its bulk density values as Troxler bulk density (**Plate 3.3**). Measurements were taken at TP, at four randomly chosen points (two in the stumpline, two in the interrow) around the sub-plots at Rattray and Shafton, resulting in a total of 108 sample points per trial. Measurements were taken at each point between 0 to 0.1 m, 0 to 0.2 m and 0 to 0.3 m. At one of these points per plot, a PSS measurement was taken to determine the correlation between PSS and bulk density at the time of measurement.

Plate 3.3:   The Troxler 3440 series surface moisture density gauge.

3.2.2.2   *Undisturbed soil cores*

Undisturbed soil cores (0.075 m diameter, 0.05 m high) were taken at both sites at TP at 0.03 to 0.08 m (or 0.11 to 0.16 m) and 0.41 to 0.46 m. A total of 56 cores were taken at each trial, i.e. at 28 points over a range of bulk densities and organic carbon contents. At the Rattray trial, 20 of these sample points corresponded to a point at which a Troxler measurement had been taken. Since the Shafton trial was sampled later, the sampling strategy was improved so that all 28 sample points corresponded to a Troxler measurement point. The 0.03 – 0.08 and 0.11 – 0.16 m cores corresponded to Troxler measurements taken between 0 and 0.1 m, and 0.1 to 0.2 m, respectively, while the 0.41 – 0.46 m cores were used to characterise bulk density between 0.4 and 0.5 m. From this point forward the cores are referred to as having originated from the 0 – 0.1; 0.1 -0.2, or 0.4 – 0.5 m depths. Stratified random sampling of the Troxler readings was used to select these sample points. The undisturbed soil cores were used to determine:

a) Soil bulk density, both in the topsoil and subsoil as the Troxler only determined bulk density to 0.3 m.

b) A calibration between the bulk density values obtained by the Troxler and actual soil bulk density. Topsoil cores either 0.03 to 0.08 m (16 cores) or 0.11 to 0.16 m (14 cores) were taken in order to:

  – Ensure the effect of organic matter on Troxler readings (i.e. in the 0.02 to 0.09 m layer) was quantified.

  – Obtain a core from a central position in the 0 to 0.3 m soil layer, the maximum depth layer in which a Troxler reading was taken.

c) The effect of bulk density and organic matter on water retention analyses. This could then be extrapolated to the effect of treatments on water retention.

As a result of the effect of soil organic matter on Troxler values and water retention, loss on ignition (**Section 3.3.7.2**) was determined on the soil trimmed from the undisturbed soil cores.

3.2.3   Penetrometer soil strength

Penetrometer soil strength was measured at T0 and TP at a total of eight randomly selected measurement points per main plot at both trials. To enable quantification of the variation in machinery movement between the two harvesting treatments after implementation, PSS was measured both in the interrow and stumpline (four measurements in each). This was performed using a semi-automatic cone penetrometer (Geotron Hand Penetrometer Model P5, Geotron, P.O. Box 2656, Potchefstroom, 2520, South Africa) that measures PSS at 0.01 m increments down the soil profile to a depth of 0.8 m (cone diameter 12.8 mm, cone length 50 mm, cone apex angle 30°; basal area 130 m m^2) and measures up to a maximum PSS of 5000 kPa (**Plate 3.4**). At Shafton, at TP however, soil strength below 0.5 m exceeded the measuring capabilities of the penetrometer at several sample points, and therefore no values below this depth were obtained at these points.

Plate 3.4:   (a) Geotron Hand Penetrometer, Model P5; (b) close up of penetrometer data-logger.

3.2.4   <u>Soil water</u>

To monitor changes in surface soil water content (0 – 0.05 m) under the different treatments, measurements were taken at both trials between TP and TH using a thetaprobe (Delta-T Devices Ltd, UK; **Plate 3.5**). A total of 12 measurements were taken in each main plot on each occasion. Six measurement points were randomly selected in the interrow, the other six in the stumpline.

At Rattray, this was performed on three separate occasions, at 85, 132 and 166 days after planting (DAP). However, at Shafton, although several attempts were made, the thetaprobe could only be used at 70 DAP. This was because, during drier periods, the soil at the site became so hard that the thetaprobe prongs would bend, not only damaging the equipment but also giving unreliable values.

Plate 3.5:   Delta-T Thetaprobe and HH2 Moisture Meter.

3.2.5   <u>Residue sampling</u>

At both TP and TH, a 1 m^2 quadrat was randomly thrown into each plot containing residues (i.e., broadcast and windrow residue plots). A cane knife was used to cut the residues outside the quadrat from those inside the quadrat. The residues were collected from inside the quadrat down to the mineral soil. In the case of the windrow plots, measurements were only made on the inter-windrow area as this is where tree measurement plots were located. Residues were thereafter taken to the laboratory for analysis (**Section 3.3.2**).

At TF in Rattray, residues had decomposed into a thin layer on the soil surface, therefore at two sample points in each plot, a 0.2 x 0.2 m area of the decomposed residues were collected. At Shafton, the fire had burnt much of this layer, as well as litter that had fallen from the new stand. Therefore, where possible, both burnt residues and litter were sampled in the same manner as at Rattray. This led to samples being taken, even for the R plots. These samples were then taken to the laboratory for analysis (**Section 3.3.2**).

3.2.6　Tree measurements

3.2.6.1　Sub-plot tree measurement and harvesting

At both trials, measurements of ground-line diameter (GLD), height and crown width of sub-plot trees were made until they attained canopy closure. At Rattray, this was performed at 69, 132, 166 and 209 DAP, while at Shafton it was at 70, 120 and 211 DAP.

At canopy closure of trees in the sub-plots (i.e. 209 and 211 DAP at Rattray and Shafton, respectively, or TH), five trees within each sub-plot were selected (by stratified random sampling) for biomass harvesting. In all cases aboveground biomass was separated into foliage and stem plus branch components, and weighed. These components were then separately bulked for each plot (e.g. the foliage from five trees in a plot) and a sub-sample taken of approximately 0.3 and 0.4 kg for the foliage, and stem plus branch components, respectively. The foliar sub-samples were first placed in cold boxes and then both sets of sub-samples were taken back to the laboratory for analysis.

Of the five trees selected for aboveground biomass harvesting, one (the median size tree) was sampled belowground for coarse (>2 mm diameter) and fine (<2 mm diameter) root biomass. To enable regressions between belowground and aboveground components, six additional trees (the three smallest and the three largest harvested) throughout the trial were selected for belowground biomass

harvesting. The precise estimation of belowground biomass requires much time and effort. Therefore, in an attempt to attain an estimate of belowground biomass within a suitable time frame, the following methodology was utilised. Fine roots were sampled by placing a 0.2 x 0.2 m quadrat over the cut stem of the tree. A cane knife was used to cut vertically into the soil to a depth of 0.05 m around the quadrant. The soil was then excavated (excluding the stem and any coarse roots attached to it) and removed to the laboratory. A fork was then used to lift as much as was possible of the belowground stem and coarse roots (**Plate 3.6**) which were then also taken to the laboratory.

Plate 3.6: The excavated pit around a tree stem. The stem and coarse roots are about to be lifted from the soil.

3.2.6.2 Tree thinning and main plot tree measurements

At canopy closure (after biomass harvesting), the sub-plot trees were thinned to the planting density of the main plot trees. Although not investigated removal of trees for below-ground measurements is unlikely to have had a measurable effect on compaction as only one or at most two trees were removed per plot. Ground-line diameter or diameter at breast height (DBH; once this could be measured on all the trees) was measured on the inner measured trees (**Table 3.7**) in the main plots between 6 months of age, and 31 and 43 months of age at Shafton and

Rattray, respectively. Tree height was also measured, but after tree height averaged approximately 10 m across the trials (after 24 and 38 months of age at Rattray and Shafton, respectively) height was only measured on selected trees. This is because trees became too large to easily measure. A standardised relationship (**Equation 3.1**; Bredenkamp, 1993) was used to determine the coefficients of linear regression developed between the DBH and height of the selected trees (**Appendix 3.4**). These regressions were then used to predict tree heights.

ln height (m) = b_0 + b_1/DBH (cm) **Equation 3.1**

3.3 Laboratory procedures and calculations

3.3.1 Soil sample processing and analysis

Soil samples were air-dried and sieved to <2 mm before being analysed.

3.3.1.1 *Particle size analysis*

Particle size analysis was determined by the pipette method (Gee and Bauder, 1986). The only modification to the method was the treatment of the soil plus sodium hexametaphosphate and sodium carbonate (Calgon) with ultrasound at 300W for 3 minutes to ensure dispersion. Sand fractions were determined separately using a dry sieving technique after silt and clay fractions were removed (Gee and Bauder, 1986).

3.3.1.2 *Soil water retention (undisturbed soil cores)*

Undisturbed soil cores were initially saturated with water for a few days. A tension table was then used for the determination of water content at high matric potentials (-1.0, -2.0, -3.0, -4.0, -5.0, -6.5, -8.0, -10.0 kPa). This table was

composed of a layer of coarse sand overlain by diatomaceous earth (Smith and Thomasson, 1974; Klute, 1986). The cores were equilibrated at each matric potential for a minimum of 48 hours and were weighed prior to alteration of the matric potential of the table. The soil cores were then subjected to matric potentials of -30, -60 and -100 kPa on ceramic plates in pressure chambers. The cores were assumed to have equilibrated to the matric potential in the pressure chamber when no further water was released from the cores over 48 hours. Cores were also weighed between each of these potentials to determine soil water content. Disturbed soil samples obtained during trimming of the soil cores were used to determine soil water content at a matric potential of -1500 kPa using a pressure membrane extractor (Richards, 1941; Klute, 1986).

From the resultant data, soil porosity, air-filled porosity and pore-size distribution could be calculated (**Appendix 3.5**). In addition, soil water content was expressed both on a mass and volume basis, as the expression of water content on a mass basis indicates changes in pore geometry without volume effects, while volumetric water content is useful for practical and modelling applications (Smith *et al.*, 2001; **Appendix 3.5**).

3.3.1.3   Calculation of Troxler bulk density

Since the Troxler measured soil bulk density between 0 and 0.1, 0.2 or 0.3 m ($T\rho_{b(0-0.1)}$, $T\rho_{b(0-0.2)}$ and $T\rho_{b(0-0.3)}$, respectively), it was necessary to calculate the bulk density of the soil between 0.1 and 0.2 m ($T\rho_{b(0.1-0.2)}$, **Equation 3.2**), and between 0.2 and 0.3 m ($T\rho_{b(0.2-0.3)}$, **Equation 3.3**).

$$T\rho_{b(0.1-0.2)} = 2T\rho_{b(0-0.2)} - T\rho_{b(0-0.1)}$$ **Equation 3.2**

$$T\rho_{b(0.2-0.3)} = 3T\rho_{b(0-0.3)} - T\rho_{b(0-0.1)} - T\rho_{b(0.1-0.2)}$$ **Equation 3.3**

3.3.1.4 Bulk density (undisturbed soil cores)

After the cores had been used to measure water retention, they were oven dried at 105°C, and bulk density calculated as the mass of o ven dry soil per unit volume of the core (Blake and Hartge, 1986). These bulk density values were used to calibrate the Troxler (**Appendix 3.6**).

a) Maximum bulk density, compression index and compaction sensitivity index

The susceptibility of soils to compaction is determined partially by their compactability and compressability (Bradford and Gupta, 1986). This has been thoroughly quantified in South African forestry soils (Smith. 1995). Compactability refers to the maximum bulk density (MBD) a soil can achieve. Compressibility is measured by a compression index (C_{Index}), and refers to the ability of a soil to resist a decrease in volume when a pressure is applied. Smith (1995) developed equations to predict the MBD and C_{Index} of South African forestry soils, which are utilised in this study.

Smith (1995) found that MBD (Mg m^{-3}) for various soils was well related to clay + silt (Cl+Si (%); r = 0.792; **Equation 3.4**). This equation was used to determine maximum bulk density of the soils at the trials.

$$MBD = 1.756984 + 0.005195*(Cl+Si) - 0.000107*(Cl+Si)^2 \qquad \textbf{Equation 3.4}$$

The C_{Index} was also found to be related to clay + silt (r = 0.809; **Equation 3.5**).

$$C_{Index} = 0.015756*(Cl+Si) - 0.000121*(Cl+Si)^2 - 0.092662 \qquad \textbf{Equation 3.5}$$

Since the susceptibility of a soil to compaction is dependent on both MBD and C_{Index}, Smith (1995) suggested the use of a compaction sensitivity index (CSI). Maximum bulk density and C_{Index} values are classified into susceptibility classes

(with values between 1 and 5). The CSI of a soil is then its MBD class added to its C_{Index} class. This results in values between 2 and 10, with higher values indicating increased sensitivity to compaction.

b)   Relative bulk density

Relative bulk density (Bennie and Burger, 1988) was determined as follows:

Relative bulk density =   <u>actual bulk density</u>   **Equation 3.6**
                                              MBD

where, MBD is determined from **Equation 3.4**. Note that relative bulk density has no units.

3.3.1.5   pH, total nitrogen, extractable phosphorus (Bray-2) and exchangeable cations

Soil pH was determined in a soil:solution ratio of 10 g:25 mL using 1M potassium chloride solution (Thomas, 1996). The pH of the supernatant was read after the samples had stood overnight using a standard glass electrode (Metrohm Hersiau E396B; http://products.metrohm.com).

Nitrogen determination was performed using the Kjeldahl method (Nelson and Sommers, 1980; Donkin *et al.*, 1993a; Mulvaney, 1996).

Extractable phosphorus (Bray-2) was determined using the methodology of Bray and Kurtz (1945). The filtrate was analysed for extractable phosphate colorimetrically at 880 nm automatically performed by a segmented flow autoanalyser (SAN[plus] SYSTEM; Skalar Analytical, Breda, The Netherlands). The colour was developed using the ascorbic acid method (Murphy and Riley, 1962).

Cations (Ca, Mg, K and Na) were extracted by the procedures outlined by Donkin *et al.* (1993a) and Helmke and Sparks (1996). The resultant filtrates were then

diluted with ionisation suppressant (strontium or caesium) solutions, and the cation concentrations determined by atomic absorption spectrophotometry (AAS; SpectrAA-10, Varian Techtron Pty. Ltd., Mulgrave, Victoria, Australia).

a)   Calculation of soil nutrient quantities

The quantity of nutrients contained in the soil between 0 and 0.05; 0.05 and 0.15 and 0.15 and 0.6 m at TH and TF was calculated on a kg ha^{-1} basis by using nutrient concentration values (kg nutrient kg^{-1} soil) measured by soil analyses (**Chapter 5**) and bulk density data (determined in **Chapter 4**). At TP, soil samples were collected only from the 0 – 0.3, 0.3 - 0.6 and 0.6 – 0.9 m depth layers and these were bulked across the trial. To obtain comparisons between the total quantity of nutrients at TP, TH and TF in the soil between 0 and 0.6 m, the TP soil nutrient data were manipulated. It was assumed that soil nutrient concentration values obtained in the 0 – 0.3 m depth layer were the same as that in the 0 – 0.05 and 0.05 – 0.15 m depth layer. For the 0.15 to 0.60 m depth layer, the following calculation was applied to nutrient concentration values:

$$\{[0 – 0.3] + [0.3 – 0.6] + [0.3 – 0.6]\}/3 \qquad\qquad \textbf{Equation 3.7}$$

where, [0 – 0.3] is the nutrient concentration of the 0 – 0.3 m depth layer, and [0.3 – 0.6] is that of the 0.3 – 0.6 m depth layer.

To calculate nutrient quantities at TP, these nutrient concentration values in conjunction with average bulk density values from C_L plots were used (**Chapter 4**).

3.3.1.6   Organic matter and carbon

Soil organic carbon content was determined both by the Walkley-Black oxidation (WB) and loss on ignition (LOI) methods. As a result of the lower cost of the LOI method (compared to the WB method), this was used as a routine method in this study, and unless stated, carbon discussed in the results was determined by LOI. The relationship between organic carbon (WB) and LOI was determined on 202 soil samples per trial (**Appendix 3.7**).

a)   *Walkley-Black method*

The method outlined in Walkley (1947) was followed.

b)   *Loss on ignition method*

Soil samples were placed in crucibles in a muffle furnace at 450℃ for 16 hours according to the methodology of Ball (1964), Donkin (1991) and Donkin *et al.* (1993a).

3.3.1.7   Least limiting water range (LLWR)

The LLWR was calculated using critical values for crop growth determined by da Silva *et al.* (1994) from the literature. These critical values were field capacity at a matric potential of -10 kPa, wilting point at -1500 kPa, air-filled porosity at 10% and PSS at 2000 kPa. In some instances, PSS at 3000 kPa were also included, as tree root growth has been found to be limited at this level (Sands *et al.*, 1979).

Regression equations developed to determine the effect of bulk density and soil organic carbon content on soil water content were utilised to establish water contents at field capacity and wilting point.

3.3.2   Residue sample processing and analysis

Residue samples, from all sampling times, were weighed, and a representative sub-sample taken and oven dried at 65℃ until a constant mass was obtained.

The oven-dried sub-samples were then bulked within treatments. These samples were ground to pass a 0.5 mm screen. Part of these ground samples was used to determine the soil contamination of the residue samples by loss-on-ignition (as described for soil samples). Another portion of the ground samples was used for analysis of the residues.

3.3.2.1   Carbon and nitrogen

Approximately 50%, by mass, of dry eucalypt components is carbon, and this factor was applied to determine the carbon content of residues (Kaye *et al.*, 2000; Giardina and Ryan, 2002; Corbeels *et al.*, 2003).

Nitrogen determination was performed in a similar manner to soil samples, using the Kjeldahl method (Nelson and Sommers, 1980; Donkin *et al.*, 1993b).

3.3.2.2   Sample preparation

Plant samples were dry ashed, placed in solution and filtered for P, Ca, Mg, K, Na, Cu, Zn, Fe, and Mn analyses using methodology described by Jones and Case (1990) and Donkin *et al.* (1993b).

3.3.2.3   Phosphorus, potassium and sodium

Filtered extracts were run through a segmented flow autoanalyser (SAN[plus] SYSTEM) for the determination of P, in a similar manner to that of soil P analysis. For the determination of K and Na concentrations, 1 mL of filtered extract was added to 10 mL of 10 000 ppm caesium solution and made up to 100 mL with deionised water and concentrations determined by flame emission spectroscopy.

3.3.2.4   Calcium, magnesium, copper, iron, zinc and manganese

Using an AAS, Ca and Mg concentrations in the filtered extract were determined on a 1 mL sample that was combined with 3 mL of 25 000 ppm strontium and 0.5 mL of 0.6 M hydrochloric acid solutions and made up to 50 mL with deionised water (Heffernan, 1985).

Concentrations of Cu, Fe and Zn were determined directly in the filtered extract on the AAS. Manganese concentration was also determined by AAS, after dilution of 5 mL of filtered extract with 15 mL of 0.6 M hydrochloric acid.

a)   Calculation of residue nutrient quantities

Nutrients at TP and TH (kg ha^{-1}) were calculated using nutrient concentration values (kg nutrient kg^{-1} residue) and residue quantities (kg ha^{-1}) (**Chapter 5**).

3.3.3   Tree component processing and analysis

3.3.3.1   Aboveground components

Stem plus branch sub-samples were dried at 65⁰C to a constant mass. Foliar sub-samples were immediately refrigerated and specific leaf area (SLA) measurements performed within two days of harvesting. Specific leaf area was determined on each entire sub-sample (approximately 0.3 kg fresh weight of foliage) on a single sided basis using a Li-Cor 3100 Leaf Area Meter (LI-COR Biosciences, Lincoln, Nebraska, USA). These values were then used to calculate leaf area index (LAI) for each tree harvested (the product of SLA and foliage biomass). Once SLA measurements were completed, the sub-samples were oven dried at 65⁰C to calculate dry mass and were then retained for analysis.

Carbon, nitrogen and sulphur in the foliar samples were determined by a LECO CNS analyser using the Dumas method (Ebeling, 1968; Sweeney, 1989). A sub-sample from each foliar sample was prepared in the same manner as the residue samples (**Section 3.3.2.2**). The quantity of nutrients in the resultant filtered extracts was then measured by inductively coupled plasma optical emission spectrometry (ICP-OES).

3.3.3.2 Belowground components

The Shafton soil samples containing the fine roots were air-dried and placed in a bucket of water containing a dispersant solution of sodium hexametaphosphate plus sodium carbonate (Calgon). The contents of the bucket were frequently stirred ensuring that settled soil was adequately agitated to release any roots. After each stirring any floating organic matter (consisting of fine roots and decomposing biomass) was skimmed off the water surface. This process was repeated until yields of organic matter subsided. Magnesium chloride was then added to the collected organic matter to induce flocculation of any entrapped clay. The contents of this container were also stirred and allowed to settle for at least 1 hour before the organics were skimmed off again. This process was repeated until very little organic matter remained (usually a total of about five times). This is very similar to the methodology of Bauhus and Messier (1999) although they did not use a chemical dispersant. As a result of the low clay content and lack of aggregation in the Rattray soil samples, samples were placed in a bucket of water without any chemical addition, stirred and organic matter skimmed off the surface. All samples were then oven dried at $65^{o}C$ and weighed. Three separate sub-samples of approximately 2 g each were taken from each dried sample. These were weighed, and the fine roots separated from the other organic components using a pair of tweezers, and weighed. This mass was calculated as a percentage of the total sub-sample and averaged across all three sub-samples. This allowed calculation of the total fine root mass obtained in the 0.002 m^3 (equivalent of 2 litres) sample taken from around the tree stem.

The coarse root systems from Shafton were washed with low water pressure into a container in case any roots broke off. This was not necessary with the Rattray root systems as the sandy soil easily dropped off the roots once they were air-dry. Any fine roots found attached to the coarse roots were cut off and both samples were oven dried at $65^{o}C$. The mass of fine roots was added to the total fine root mass in the soil sample. Each coarse root was cut at the point where it joined either another root or the belowground stem (known as the start of the root). The root was then weighed, and in addition to the length of the root, the diameter at

both the start and the end of the root was measured. This allowed calculation of the approximate root volume (**Equation 3.8**) and the development of root volume-mass relationships (**Appendix 3.8**). The rate of taper of roots with an end diameter of 2 mm was also determined (**Equation 3.9**; **Appendix 3.8**) and applied to any coarse roots broken during removal from the ground. The belowground stem was also weighed.

Root volume = [(Radius of start of root + radius of end of root)/2]^2 * pi * length of root
Equation 3.8

Rate of taper = Length of root / diameter at start of root **Equation 3.9**

3.3.4   Biomass index, basal area and stemwood volume calculations

Tree performance was estimated using a biomass index (mm^3), calculated as GLD^2 * height (Eccles *et al.*, 1997). For interest, stand basal area (SBA) and stemwood volumes were also calculated (**Equations 3.10** and **3.11**, respectively; Abed and Stephens, 2003). Tree volumes are generally not determined on such young trees, but rather at rotation end. Therefore tree volume was calculated using a generic equation that assumes that the trees are uniform and cone-shaped, thus assuming a form factor of 3 (Abed and Stephens, 2003).

SBA (m^2 ha^{-1}) = [∑(π * (DBH/2)^2)]/plot area **Equation 3.10**

Stemwood volume (m^3 ha^{-1}) = SBA * Average tree height/3 **Equation 3.11**

3.4   **Statistical analyses**

Statistical analysis was carried out on selected data sets using Genstat Version 11.1 (Payne *et al.*, 2008). Generally simple linear regression or two-way analysis of variance (ANOVA) were performed. Occasionally, split-split plot design analysis was performed as it was more appropriate for the data, as well as to interrogate the data further. If necessary, to ensure error assumptions were met for ANOVA

analyses, transformation of data were performed and carried out according to the principles outlined by Gomez and Gomez (1984). In such instances, or where further details of analyses were required, these are given in the relevant section of each chapter. Results were regarded as significant if a *p* value of less than 0.05 (or 5%) was obtained. Thereafter the differences between treatments was determined using the least significant differences method (treatments with different letters were significantly different). The percentage variance accounted for (r^2) was reported instead of correlation coefficients (R) or the correlation of determination (R^2). This is an adjusted form of R^2 that takes into consideration the number of parameters that have been fitted in the model, unlike R^2, which does not. It is calculated as:

1 – (Residual mean square/total mean square)   **Equation 3.12**

Many regressions were significant ($p<0.001$) but were excluded as a result of low r^2 values ($r^2 < 0.5$).

Chapter 4

Effect of Compaction Treatments and Residue Management on Soil Bulk Density and Strength

4.1. Introduction

Heavy machinery movement is known to increase soil bulk density and to alter pore-size distribution and volume of soils (Reisinger *et al.*, 1988). In South African eucalypt plantations, the mechanisation of operations is increasing, particularly mechanical harvesting (Warkotsch *et al.*, 1994; Brink, 2001; Smith and du Toit, 2005). These eucalypt plantations are often harvested by ground-based machinery that has been found to impact between 10 and 15% of a harvested area (Miller *et al.*, 2004). In some circumstances, harvesting operations and extraction routes are not restricted, especially between rotations, or in instances where the spreading of a lighter impact over an area is desired (Jakobsen and Moore, 1981). In either situation, impacts on the soil of a site could be significant. In addition, machinery is no longer being used purely for timber extraction, but also for felling, debarking, stacking and pitting, and these operations require machinery movement over a much larger area than that of extraction routes. In South Africa, harvesting operations have resulted in increased soil bulk density and PSS (Warkotsch *et al.*, 1994; Smith, 2003; 2006; Smith and du Toit, 2005).

The effect of machinery movement on soil has been found to be affected by the quantity, type and distribution of forest floor or residues left on the site (e.g. Donnelly and Shane, 1986; Smith, 1998; Hutchings *et al.*, 2002; Ampoorter *et al.*, 2007). In South Africa, this effect of plantation residue management on soil responses to machinery movement has not been researched. Elsewhere, the presence of harvest residue was found to reduce soil compaction and disturbance effects by machinery, particularly on moist soils, or if more than one pass was made (King and Haines, 1980; Jakobsen and Moore, 1981; McDonald and Seixas, 1997). Harvest residues are thought to decrease the effective ground pressure and distribute the weight of the machine over a larger area (Wronski and

Humphries, 1994; King and Haines, 1980). In addition, the movement of machinery over residues can also affect their distribution across a site, as well as result in their break-up and/or incorporation with soil (Geist *et al.*, 1989; Rab, 1994; Eisenbies *et al.*, 2005).

Changes in soil bulk density, pore-size distribution and volume, as well as the changes in other soil properties that they induce, often affect plant growth by altering the rooting environment. Several extensive reviews of research investigating the effects of heavy machinery on soil physical properties, and the effect on tree growth in other parts of the world already exist (e.g. Greacen and Sands, 1980; Lousier, 1990; Powers *et al.*, 1996; Ballard, 2000; Miller *et al.*, 2004). However, tree growth responses (in reviewed research) varied widely, and often the actual causes of the responses were not measured, but inferred from the data. In addition, most of this information originated from retrospective studies of areas that lacked true controls or non-compacted areas, where original conditions are unknown, and often with small plot sizes (Powers, 1999).

The extent of compaction effects on the soil are dependent on soil texture, type and quantity of adsorbed cations, organic matter content, moisture content and bulk density at the time of compaction (Wolkowski, 1990; Aust *et al.*, 1995; Smith, 1995; Ball *et al.*, 2000; Prévost, 2004; Ares *et al.*, 2005). Soils with a wide range of particle sizes are more compactable than those with more uniform particle size range (Moolman, 1981; Smith, 1995; Brady and Weil, 1999). Fine textured soils with high organic matter contents are generally more resistant to compaction and have a lower potential maximum bulk density than soils of coarser texture and lower organic carbon content (Greacen and Sands, 1980; Bennie and Burger, 1988; Smith, 1995).

Other factors besides the above soil characteristics and residue cover determine the response of a soil to compaction. These factors influence the type and magnitude of compactive forces applied to the soil. The number of passes, amount and type of pressure, vibration or slip during movement, and speed of the machinery substantially affect soil responses (Soane *et al.*, 1981a; 1981b; Reisinger *et al.*, 1988; Smith, 1998). Axle load determines the degree of subsoil

compaction. Axle loads above 4 t per axle which are common in South African forestry machinery (Smith, 1998) often lead to subsoil compaction (Soane *et al.*, 1981b; 1982; Håkansson *et al.*, 1988).

4.1.1. Effect of compaction, machinery movement and residue management on soil physical properties

Compaction increases bulk density, and changes pore-size distribution and volume, which in turn have an effect on other soil properties. For example, with increases in PSS, changes in soil water retention characteristics and decreases in aeration have been reported (Greacen and Sands, 1980; Smith *et al.*, 1997a; Powers *et al.*, 1998; Ball *et al.*, 2000; Ares *et al.*, 2005). These changes can then in turn affect several chemical and microbial soil properties (Donnelly and Shane, 1986; Lousier, 1990; Miller *et al.*, 2004).

Some of the effects of compaction vary, often as a result of soil textural differences. This is particularly the case with soil water retention characteristics (Smith, 1998; Gomez *et al.*, 2002a; Page-Dumroese *et al.*, 2006). For example, compaction of sandy soils may increase water holding capacity and soil-root contact (Sands *et al.*, 1979; Arvidsson, 1999; Gomez *et al.*, 2002b; Ares *et al.*, 2005). This variability has been considered the cause of variation in tree response to compaction (e.g. Smith, 2003; Smith and du Toit, 2005).

Machinery movement does not only increase soil compaction, but can also mix, rut and displace soil, which affects many of the soil properties discussed above (Rab, 1996; Page-Dumroese *et al.*, 1998; Smith, 1998; Block *et al.*, 2002; Ares *et al.*, 2005). The differentiation between compaction and the other effects of machinery are important when determining the cause of soil and tree responses to ensure that correct inferences are drawn (Miller *et al.*, 2004). In addition, soil organic matter and labile nutrients are usually concentrated in the top few centimetres of soil and decrease rapidly with depth in forest soils (du Toit *et al.*, 2004). Therefore soil displacement can highly impact the soil productivity of an area (Powers *et al.*, 1990; Smith, 1998).

The management of residues, coupled with the effect of machinery movement on those residues also directly affects soil physical properties such as soil temperature and moisture; the former decreasing and the latter increasing with residue retention (Smethurst and Nambiar, 1990b; Jones *et al.*, 1999; Roberts *et al.*, 2005). Indirect effects of residue management occur through changes in soil organic matter levels (Powers *et al.*, 1990). Soil organic matter has many effects on soil physical properties such as aggregation, total porosity, soil water retention characteristics, bulk density, soil strength, infiltration, risk of surface crusting (Smith *et al.*, 1997a; Powers, 1999; Smith, 1998; Prévost, 2004), and if residues are not present, it influences the temperature of the soil (Prescott *et al.*, 2000). The susceptibility of a soil to compaction is reduced with increasing organic matter content, due to increasing soil resistance to deformation and/or elasticity, i.e. the rebounding ability of the soil (Soane, 1990).

Literature relating to the modification of soil compaction caused by machinery by *E. grandis* residues could not be found. However, data were available for residues of other species (natural *E. regnans* and *Acacia*, Jakobsen and Moore, 1981; natural mixed *Quercus sp.*, Donnelly and Shane, 1986; plantation *Pinus taeda*, McDonald and Seixas, 1997; plantation *Picea sitchensis*, Hutchings *et al.*, 2002; natural *Pinus sylvestris*, *Prunus serotina* and *Sorbus ancuparia*, Ampoorter *et al.*, 2007). In all of these studies, the presence of residues reduced soil compaction, but in no instance was compaction completely prevented. Hutchings *et al.* (2002) investigated the differences in clay loam soil responses to compaction with thickness of residues (four treatments with residues ranging between 0.32 and 0.64 m thick). They found no significant differences in PSS between the four residue-retained treatments, although a significant difference in PSS was found between no residue and residue retention to 0.1 m soil depth. McDonald and Seixas (1997) carried out a similar study on a loamy sand, with forwarder movement over different quantities of residues (0, 10 and 20 kg m^{-3}). They found that on a moist soil, increasing residue retention lessened the compactive effects of the forwarder. Under dry soil conditions, however, there was a significantly higher level of compaction in residue removed (0 kg m^{-3}) compared to residue retained (10 and 20 kg m^{-3}) treatments, but no significant difference between the residue retained treatments. Although Ampoorter *et al.* (2007) did not study the

effects of different quantities of residue retention, they found that the retention of a layer of residue over 0.4 m thick reduced PSS to a depth of 0.3 m. They attributed this decrease to the spreading of machine mass over a larger area, thereby reducing the mean soil contact pressure. Increasing thickness of retained residues has caused a concomitant reduction in increases in PSS with compaction (Schäfer and Sohns, 1993, cited by Ampoorter *et al.*, 2007).

While all soil properties are linked, the extent to which each property is affected will vary with soil type and stress applied. The growing environment for roots is determined by the combination of soil properties, and the extent to which each property is affected by the stress applied. For example, soil compaction *per se* has been found not to directly affect root development, rather it is the effect of compaction on other soil properties that affect root growth (Taylor and Brar, 1991). These properties are soil structure, soil strength, total porosity, macropore continuity and quantity, air-filled porosity, gaseous diffusion, volumetric water content and hydraulic conductivity (Letey, 1985; Taylor and Brar, 1991; Smith, 1998; Gomez *et al.*, 2002a).

4.1.2. Soil bulk density and strength

Soil bulk density is often used as a measure by which the effects of compaction can be quantified (e.g. Smith *et al.*, 1997a; Smith *et al.*, 2001; Miller *et al.*, 2004), as well as a predictor variable for estimating soil water retention parameters and total porosity (e.g. Rawls *et al.*, 1991; Smith *et al.*, 2001). This is despite the fact that it neither directly affects root growth nor does it give a measure of soil strength (Grey and Jacobs, 1987; Miller *et al.*, 2004). Bulk density is also used to convert soil properties generally determined on a mass basis into a volume or area basis (Federer *et al.*, 1993; Prévost, 2004). Since bulk density naturally varies with soil texture and organic matter content, there is an inherent variation in bulk density between soil types (King and Haines, 1980; Smith *et al.*, 1997a; Brady and Weil, 1999; Prévost, 2004). To overcome this variation, several studies have quantified the effects of management on relative bulk density (Soane *et al.*, 1981a; Carter, 1990; Smith, 1995).

Soil strength, or the mechanical resistance of a soil to plant root penetration, is well correlated to the resistance of a soil to penetration by a metal probe, measured by a penetrometer (Barley *et al.*, 1965; Sands *et al.*, 1979; Greacen and Sands, 1980; Bengough and Mullins, 1991; Taylor and Brar, 1991). This is despite the fact that the frictional resistance encountered by a probe is between two and eight times greater than that encountered by a plant root (Bengough *et al.*, 1997). In addition, plant roots can bend and follow paths of least resistance (such as macropores or natural failure zones) and often cells are sloughed off from the root cap to create a low-friction sleeve for the root to grow in (Bengough *et al.*, 1997; Miller *et al.*, 2004). Generally, root elongation rate decreases exponentially as soil strength increases until a critical point, after which root penetration ceases (Greacen and Sands, 1980). Tree root-limiting levels of PSS have been found to be as low as 1300 kPa (Zou *et al.*, 2001), but the generally accepted level is 3000 kPa (Sands *et al.*, 1979); while root growth has been found to cease altogether above 4200 kPa (Misra and Gibbons, 1996). As a result of only a few planes of weakness and cracks, compaction of sandy, single grain soils may reach root-limiting levels of PSS at values below 2000 kPa (van Huyssteen, 1989).

Assessment of soil strength in relation to forest productivity is regarded as the simplest and most practical method of quantifying soil physical conditions (Powers *et al.*, 1998). Cone penetrometers are commonly used in agriculture to obtain a quick measure of soil strength to indicate the physical state of a soil, to find traffic compaction and hardpan areas, and to determine the relationship between soil strength and root growth and crop yield (Bradford, 1986). Soil strength is dependent on mainly bulk density, structure, texture, organic matter and water content (Bradford, 1986; Bennie and Burger, 1988; Ekwue, 1990; Smith, 1995; Smith *et al.*, 1997a; 1997b). It therefore often varies a great deal with wetting and drying cycles throughout the year (Spain *et al.*, 1990). However, soil strength in sandy soils is generally dependent on organic matter content, and relatively independent of soil water content (Sands *et al.*, 1979). Penetrometer soil strength also increases with depth as a result of soil hardness, penetrometer probe diameter and overburden pressure (Bradford *et al.*, 1971; Sands *et al.*, 1979; Bennie and Burger, 1988). After a certain depth, PSS either ceases to increase, or decreases with depth, as the failure mechanism changes from shear (at shallow

soil depths) to shear plus compression (at deeper soil depths). This phenomenon is consistent across all soils (unless the probe encounters stones or other resistant material) and the exact mechanisms are reviewed by Bradford (1986).

4.1.3. Persistence of soil compaction

The effects of compaction in forest soils have been recorded to persist up to 23 (Froehlich *et al.*, 1986), 32 (Jakobsen, 1983) and even 50 years (Greacen and Sands, 1980) after initiation of the compaction. In other instances, some sites have been found to recover to pre-disturbance levels in as little as four to five years (Williamson and Neilsen, 2003a; Page-Dumroese *et al.*, 2006). Miller *et al.* (2004) concluded that soil recovery rates after compaction are dependent on compaction severity, soil characteristics (depth, texture, structure, mineralogy, cation exchange capacity, bonding agents, soil solution, organic matter) and climate. When recovery occurs, it is often in the surface soil and is generally as the result of freeze/thaw cycles, shrink/swell cycles and soil macrofaunal and root activity (Greacen and Sands, 1980; Reisinger *et al.*, 1988; Miller *et al.*, 2004). Freeze-thaw and shrink/swell cycles are absent in South African forestry soils and soil recovery from compaction may therefore be extremely slow (Jakobsen 1983; Warkotsch *et al.*, 1994; Smith, 1998; 2003). Earthworm numbers in South African eucalypt soils have been recorded to be relatively low compared to native grass- or woodland (Dlamini, 2002), and amelioration through soil biological activity may be further limited as decreases in soil macrofauna with increasing compaction levels have been recorded (Whalley *et al.*, 1995; Radford *et al.*, 2001). Amelioration by root growth may also not be substantial as it is not only lower under compacted conditions, but the roots also tend to grow along existing soil fractures and old root channels, thus preventing soil loosening. The effectiveness of compaction amelioration by root growth is dependent on the total pore volume, pore size distribution, and continuity remaining after compaction (Miller *et al.*, 2004). Retention of harvesting residue and litter has been found to substantially speed up rates of soil recovery from compaction when compared to their removal (Zabowski *et al.*, 1996). Recovery in subsoils is generally very slow (Reisinger *et al.*, 1988) and this has been found to be the case in some South African forestry soils (van Huyssteen, 1990; Smith, 1998).

4.1.4.   Chapter rationale and objectives

The objectives of this section of the study were to:
- quantify the effect of both compaction treatments and residue management on soil bulk density and penetrometer soil strength;
- evaluate the extent to which the impact of the various compaction treatments on soil compaction is modified by residue management; and
- determine the spatial variability of these soil properties (both vertically and horizontally in the soil) across the treatments.

Measurement of soil surface physical attributes and processes (such as surface crusting and erosion) were excluded from this study. Although these are important to plant growth, only soil properties considered to be most impacted by the treatments at the sites selected were measured. The effects of the treatments on soil water and aeration characteristics are addressed in **Chapter 6**.

4.2.   Materials and methods

Chapter 3 contains the majority of details regarding materials and methods. However, the methodology behind some statistical analyses is presented here.

4.2.1.   Troxler bulk density – statistical analysis

Treatment effects on Troxler bulk density were analysed using a split-split plot ANOVA, with the treatment structure being compaction * residue management * position of the measurement within the plot * soil depth, blocked by replicate. Bulk density values measured prior to treatment implementation were used for calibration of the PSS measurements, but were too few to use as a covariate in the analysis. To supplement these results, a two-way ANOVA was performed on the data within their depth ranges.

4.2.2. Penetrometer soil strength – statistical analysis

Residual effects of harvesting treatments in the previous trials at Rattray and Shafton were quantified by measurement of PSS prior to re-implementation (PSS_0). At Rattray, four treatments were originally applied. These consisted of two levels of compaction (similar to the C_M and C_H treatments), and two controls (or C_L treatments). Residues were windrowed over C_M and C_H and one C_L treatment, and broadcast over the other C_L treatment. As a result of these differences in residue management in the previous trial, and to maintain as similar as possible statistical analysis throughout the data, PSS_0 data from the $C_L B$ plots were excluded. At Shafton, the original trial had seven timber extraction treatments (Smith, 2006), three of which were low compaction (C_L), compaction with a 3-wheel logger (C_M) and compaction with ten passes of a forwarder (C_H). Therefore only PSS results from the plots under these three treatments were analysed for residual treatment effects from the previous trial.

Penetrometer soil strength values for each measurement point were averaged every 0.05 m down the profile. These values were then further averaged within their depth classes with measurements from the same plot, and same plot position of measurement (i.e. interrow or stumpline). Overburden pressure, increasing bulk density and clay content, and decreasing organic matter with depth, often lead to an increase in PSS with depth (Sands *et al.*, 1979; Fritton, 1990). Therefore, soil depth was included in the treatment structure in the statistical analysis of the PSS data. The PSS_0 data were then analysed using a split-split plot ANOVA, with the treatment structure being compaction*position of the measurement within the plot*soil depth, blocked by replicate. Soil water content is known to affect PSS measurements (Smith *et al.*, 1997a), and was therefore measured at the same time as PSS measurements, and was included as a covariate in the analysis of the PSS_0 data. Shafton's data required a square root transformation to prevent violation of error assumptions.

After implementation of the treatments for the current study, PSS measurements were retaken (PSS_1), and the data treated in a similar manner, although the treatment structure now included residue management. At both trials, soil water content and PSS_0 values were found to be related, and therefore both could not be included as covariates. Since PSS_0 had a greater effect, this was chosen as the covariate to be included in the analyses. It was necessary to transform both Rattray and Shafton's data (square root, and log transformations, respectively). At Shafton, soil strength (after treatment implementation) below 0.5 m in some treatments exceeded the measuring capabilities of the penetrometer. In these cases therefore, statistical analyses were not performed on data below this depth.

One of the objectives of this study was to determine the variation in soil properties within the different treatments. Therefore the spread or dispersion of the PSS_1 data set was evaluated by calculation of its standard deviation (standard deviation = $\sqrt{variance}$). Standard deviation values were calculated for PSS_1 data within compaction treatments and soil depth layers.

To further analyse treatment effects on soil strength, the relative changes in PSS_1 (from that of the C_L treatments) were calculated (**Equation 4.1**) within depth layers across the different residue management under the C_M and C_H treatments.

Relative increase in PSS (%) = $PSS_{treatment}/PSS_{CL}$ * 100   **Equation 4.1**

where:
$PSS_{treatment}$ = PSS_1 value (within a depth layer) under the treatment in question.
PSS_{CL} = corresponding PSS_1 value (within the same depth layer) averaged across the C_L treatments.

This data was analysed using a two-way ANOVA (the treatments being residue management and C_M and C_H treatments), with depth as a blocking factor (until the point at which the residue effects were no longer significant). Data from the Shafton trial were transformed (by a square root transformation) to prevent violation of normality assumptions.

4.3. Results and discussion

4.3.1. Maximum bulk density and compression index

Maximum bulk density and C_{Index} values for the soils at the trials were calculated from **Equations 3.1** and **3.2** (**Table 4.1**). These values were then classified according to Smith's (1995) classification, and the CSI determined for each soil (higher values indicating increased sensitivity to compaction).

Although the MBD values determined for Rattray were considerably higher than those of Shafton, the sensitivity of these soils to compaction was fairly similar as a result of Rattray's lower C_{Index} values.

Table 4.1: Maximum bulk density (MBD; Mg m^{-3}), compression index (C_{Index}) and compaction sensitivity index (CSI) for soils at the two trials using the models of Smith (1995).

Trial:	Rattray		Shafton	
Horizon:	**A**	**E**	**A**	**B**
Silt + Clay (%)	7.5	8.1	89.8	81.8
MBD (**Equation 3.1**)	1.790	1.792	1.361	1.466
C_{Index} (**Equation 3.2**)	0.019	0.027	0.346	0.387
CSI	5	5	5	6

4.3.2. Treatment effects on bulk density

4.3.2.1. Rattray

Troxler bulk density (measured between 0-0.1, 0.1-0.2, and 0.2-0.3 m) was significantly ($p<0.05$) affected by the interaction between compaction treatments and residue management, depth of measurement and compaction treatments, and plot position and depth of measurement (**Appendix 4.1A**). The magnitude of the mean square value for the compaction treatments indicates that compaction was the major cause of variation in bulk density, followed by depth, plot position and residue management. The consistent increase in bulk density with increasing depth was expected as this occurs naturally as discussed earlier (**Section 4.2.1**; **Appendix 4.1B** and **C**).

The effect of the compaction treatments on bulk density decreased in the order $C_H > C_M > C_L$ (**Figure 4.1**). Residue retention appears to have reduced the compactive effects of the machinery used, and bulk density decreased within the compaction treatments generally in the order R>W>B. Significant compaction treatment and residue management effects were found on bulk density values measured within each depth (**Appendix 4.1D** and **E**). However, it is clear that the effect of residue retention decreased with depth.

The variability within the plots of the compaction treatments was determined by analysing the bulk density values obtained under the different positions within each compaction plot (**Appendix 4.1A**). The interaction between compaction treatments and plot position was only weakly significant ($p<0.1$). This was due to the manner in which the compaction treatments were implemented. As expected, Troxler bulk density was only significantly ($p<0.1$) higher in the interrows than stumplines in the C_H treatments (**Appendix 4.1F**) since the forwarder moved between the stumplines (**Figure 3.2**).
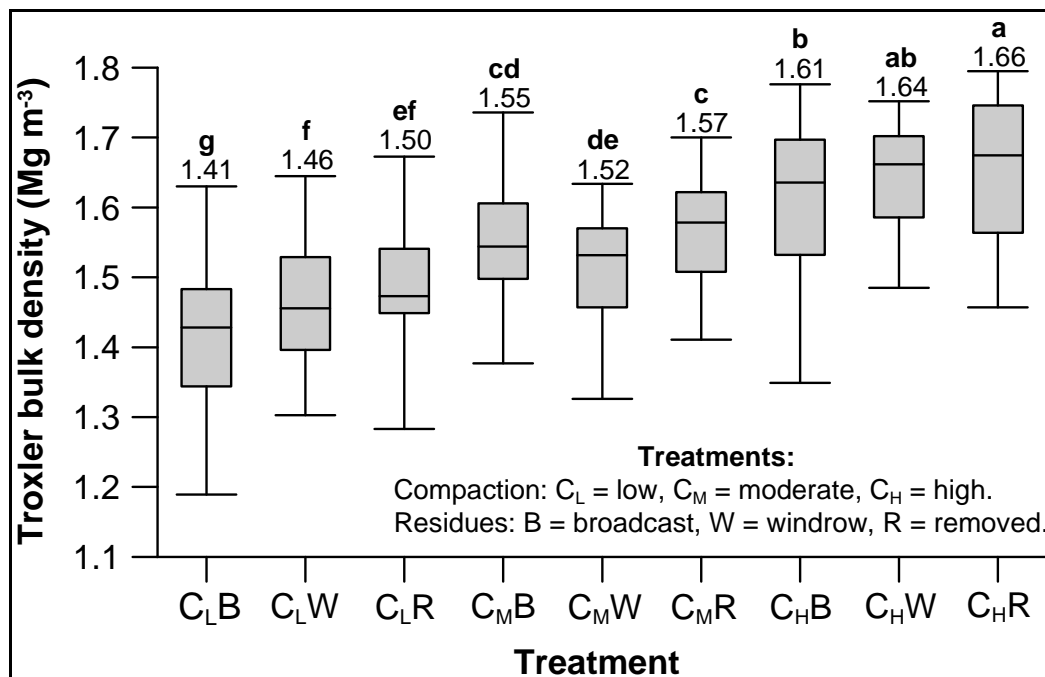
Figure 4.1: Box whisker plot of Troxler bulk density between 0-0.3 m due to compaction treatments and residue management at Rattray. Treatment means are displayed above the box whisker, and treatments with different letters are significantly different ($p<0.001$).

Relative bulk density values (**Table 4.2**) were calculated from soil core bulk density and maximum bulk densities determined from textural analysis (**Section 4.3.1**). The values indicate the effects of the compaction treatments, and in some cases, the C_H treatment compacted the soil almost to its maximum density.

Bulk density (using undisturbed soil cores) was determined at the same site in the previous trial (Sibisi, 1998; Smith, 2003). However, as a result of the objectives of the prior study, the sampling strategy and technique employed were substantially different from those of this study. Therefore the values obtained in the prior study are not comparable to those of this study.

Table 4.2: Range of relative bulk density values (i.e. ratio between soil core bulk density and MBD) at two soil depths under the compaction treatments at Rattray.

Compaction treatment	0 – 0.1 m	0.4 – 0.5 m
Low	0.769 – 0.873	0.839 – 0.917
Moderate	0.845 – 0.906	0.850 – 0.926
High	0.868 – 0.963	0.904 – 0.935

Finally, these results indicate that further compaction of the Rattray soil has occurred with implementation of the current treatments, despite the soil at this time being relatively dry (approximate matric potential of -92 kPa). However, relative bulk density results show that additional compaction of soil in the C_H treatments by machinery in the future cannot be substantial. In addition, the reduction of the effects of compaction by residue retention could have very important management implications.

4.3.2.2. Shafton

Bulk density was measured throughout the trial using a Troxler after implementation of the treatments in 2004 (**Figure 4.2**). Depth had a significant effect but no significant treatment or interrow/stumpline effects were found (**Appendix 4.2**).
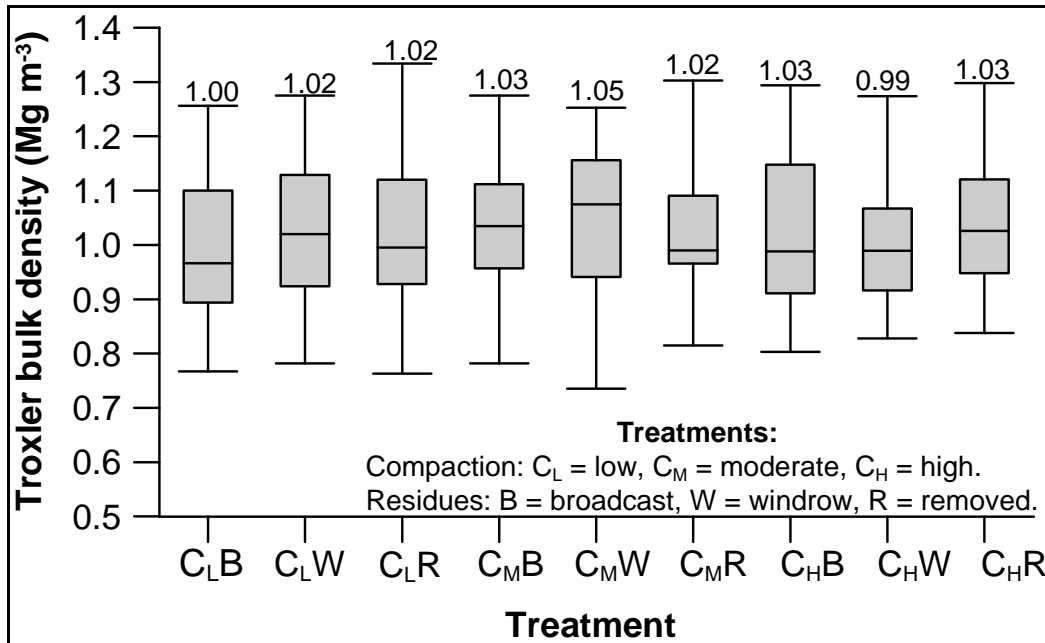
Figure 4.2: Box whisker plot of Troxler bulk density between 0-0.3 m due to compaction treatments and residue management at Shafton. Treatment means are displayed above the box whisker.

Relative bulk density values   show that topsoil compaction did not approach the maximum possible value for this site under either the C_M or C_H treatments (**Table 4.3**), while subsoil values were even less affected by the compaction treatments. However, equations used to determine MBD values were derived from reconstituted cores in the laboratory, and it is unlikely that field soils will ever attain such bulk densities, particularly in heterogeneous soils. The lack of significant treatment effects, coupled with the relative bulk density data, implies that the soil at Shafton is relatively resistant to compaction, due no doubt to its very high organic C content.

Table 4.3: Range of relative bulk density values (i.e. ratio between soil core bulk density and MBD) at two soil depths under the compaction treatments at Shafton.

Compaction treatment	0 – 0.1 m	0.4 – 0.5 m
Low	0.657 – 0.801	0.612 – 0.783
Moderate	0.712 – 0.851	0.670 – 0.780
High	0.694 – 0.858	0.668 – 0.795

Previous studies at this site have only measured bulk density on repacked soil cores (Smith, 1995; 2006), and can therefore not give any information regarding field bulk density as affected by different treatments.

Despite the Shafton soil being quite moist (around a matric potential of -52 kPa) at treatment implementation, bulk density did not significantly increase as a result of compaction treatments. This may be due to an insufficient number of samples having been taken, particularly since Troxler bulk density values at this trial were significantly affected by soil organic carbon (**Appendix 3.6**). This would have increased the variability in measurement and prevented the determination of treatment differences.

4.3.3. <u>Penetrometer soil strength</u>

4.3.3.1. Rattray

a) Residual compaction

Soil water content at the time of PSS_0 measurements ranged across the trial from 0.014 to 0.065 kg kg^{-1} (average = 0.039 kg kg^{-1}).

Residual PSS levels as a result of the previous trial treatments were apparent from the PSS_0 data, and there was a highly significant interaction between depth and compaction treatments and depth and plot position (**Figure 4.3**, **Appendix 4.3**). Significant differences between interrows and stumplines were greatest between 0.25 and 0.40 m, while PSS_0 was significantly greater in C_H than C_M or C_L treatments (**Appendix 4.3**). Although compaction treatment main effects are superseded by interaction effects, these were weakly significant ($p<0.1$) and means decreased in the order $C_H>C_M>C_L$.
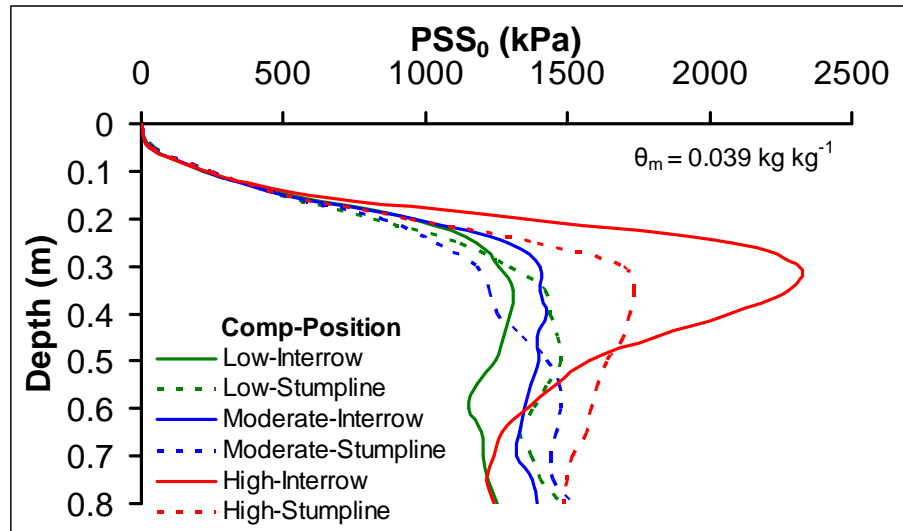
Figure 4.3: Compaction treatment (Comp) and plot position effects on average (28 points per treatment and position) penetrometer soil strength (PSS$_0$) with depth prior to treatment implementation at Rattray.

Penetrometer soil strength was also measured by Smith and du Toit (2005) on the same trial site in the previous rotation. Since soil water contents at the time of that PSS measurement varied between 0.035 and 0.098 m^3 m^{-3} (Smith, 2003), these results are comparable with PSS$_0$ results of this study. The magnitude of PSS obtained by Smith and du Toit (2005) for the 3-wheel logger and zero compaction treatments was similar to that found in this study for the same treatments, despite there being no differentiation between stumpline and interrow in their study. The persistence of treatment effects from the original trial on soil strength measured almost eight years after the original treatments were implemented confirms that natural amelioration of compaction in sandy soils of the Zululand region is very limited (Warkotsch *et al.*, 1994; Smith, 2003).

b)   Effect of compaction treatments on PSS

Soil water content ranged across the trial from 0.021 to 0.055 kg kg^{-1} (averaging 0.038 kg kg^{-1}), at the time of PSS$_1$ measurements.

Residual PSS (i.e. PSS_0) was used as a covariate when analysing treatment effects on PSS_1 (**Appendix 4.4**). Treatment implementation significantly increased PSS under both C_M and C_H treatments, which decreased in the order $C_H > C_M > C_L$ (**Figure 4.4**). However, the interaction between compaction and depth resulted in LSD's being calculated only on this latter data (**Appendix 4.4**). These results showed that below 0.2 m PSS_1 was significantly greater in the C_H treatment than C_M or C_L treatments, while above 0.3 m, PSS_1 was significantly higher in C_M than C_L treatments. Since compaction in this soil type does not easily naturally ameliorate, the effects of machinery movement may accumulate over time, until a maximum bulk density is attained. Interrow PSS was larger than stumpline PSS, however, this was weakly significant ($p<0.1$). There was also a significant interaction between depth and residue management but these effects were complex, and are discussed in detail later.
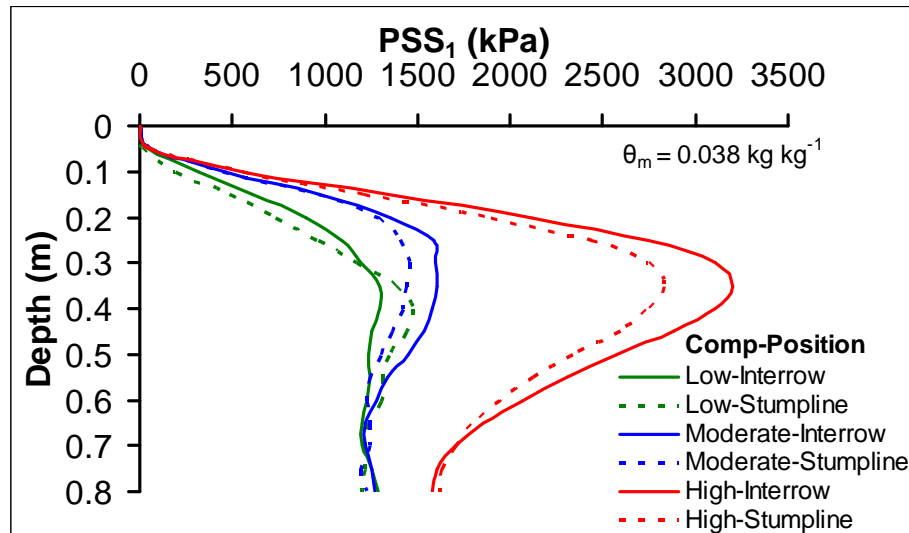
Figure 4.4:   Compaction treatment (Comp) and plot position effects on average (28 points per treatment and position) penetrometer soil strength (PSS_1) with depth at Rattray.

Although root-limiting values of PSS are discussed in more detail in **Chapter 7**, root growth is considered to be severely restricted at PSS above 2000 – 3000 kPa (Sands *et al.*, 1979; da Silva *et al.*, 1994). At Rattray, PSS_1 was found to be above 2000 kPa only in the C_H treatments, between 0.2 and 0.6 m.

c)   *Variation in PSS as a result of compaction treatments*

The calculation of standard deviations in the data within treatments and depth layers (**Figure 4.5**) revealed that the dispersion or variation in PSS_1 was greatest between 0.2 and 0.6 m. In addition, variation in the C_M treatment was considerably lower than either the C_L or C_H treatments.
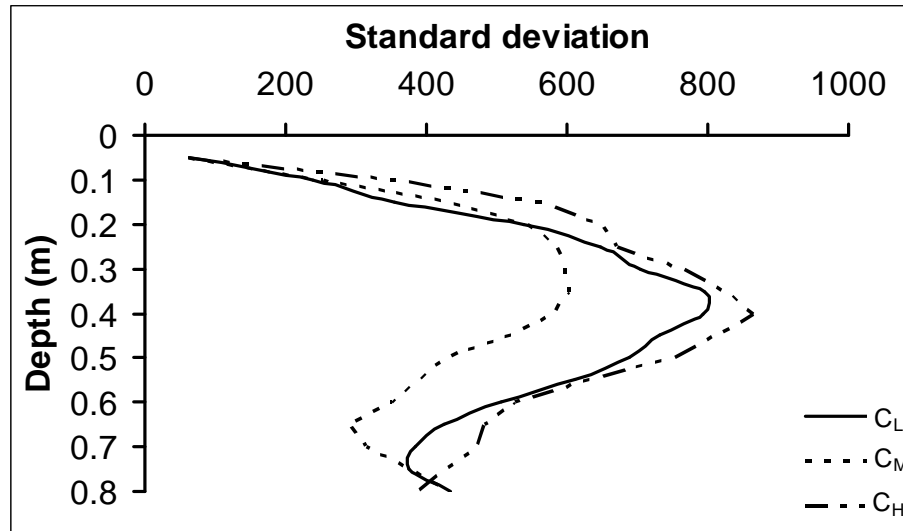
Figure 4.5: Standard deviation in PSS_1 with depth at Rattray. Treatments: C_L = low compaction, C_M = moderate compaction, C_H = high compaction.

d)   *Residue management effects*

In the analysis of treatment effects on PSS_1 data every 0.05 m down the soil profile, no significant residue management effects were found, with the exception of the soil depth of 0 - 0.05 m (**Appendix 4.5**; **A** - **C**). However, this was as a result of the PSS_1 values under the C_L compaction treatments, which did not change with residue management. If the relative increase in PSS_1 was calculated (**Equation 4.1**) for the C_M and C_H treatments, variation in the relative increases in PSS_1 in the top 0.3 m as a result of residue management then became significant (**Figures 4.6a** and **b**, **Table 4.4; Appendix 4.5D**). Below this depth, the effects of residue management diminished, and only compaction treatment differences remained.
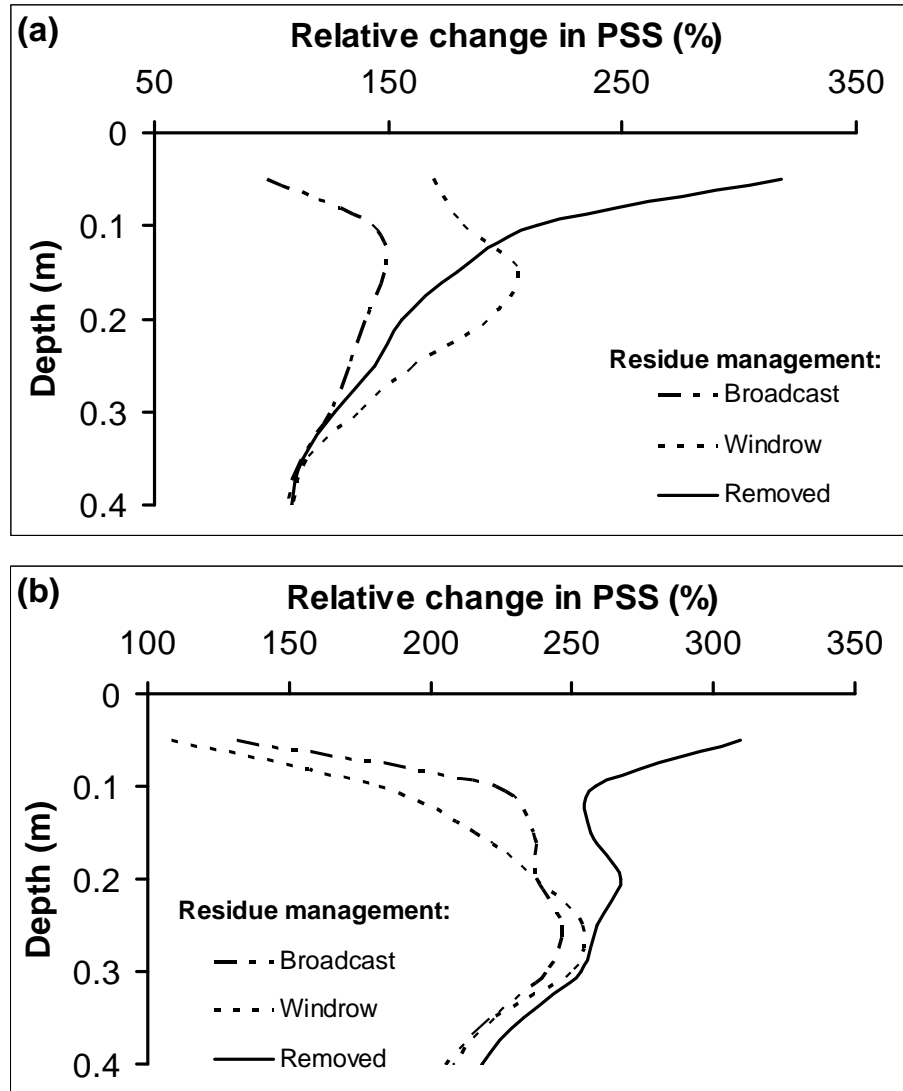
Figure 4.6: Average PSS_1 changes with depth (relative to average C_L treatment PSS_1 values) as a result of different residue management (a) under moderate compaction (C_M) and (b) under high compaction (C_H) at Rattray.

In each compaction treatment, relative PSS_1 decreased in the order R>W>B. In addition, the significance of the C_M and C_H treatment effects increased with increasing soil depth, while the significance of residue management effects were maintained (**Table 4.5**). However, there were no significant interaction effects. This indicates that residue retention diminished surface soil compaction by machinery.

Table 4.4: Mean relative PSS_1 of C_M and C_H treatments relative to the C_L treatment with different residue management at Rattray to a soil depth of 0.3 m.

Compaction/Residue management	Mean relative PSS_1 (%)
High	231.3[a]
Moderate	165.0[b]
Residue removed	228.5[a]
Windrowed residue	190.8[b]
Broadcast residue	175.1[b]

Treatments with different letters are significantly different ($p<0.01$).

Table 4.5: Level of significance (p) of compaction treatments (i.e. C_M and C_H) and residue management effects on relative (to the C_L treatment) PSS_1 values with soil depth at Rattray. Two-way ANOVA's were performed; blocking factor- soil depth.

Soil depth layer (m)	Compaction	Residue
0-0.10	0.580	<0.001
0.10-0.15	0.138	<0.001
0.15-0.20	0.006	<0.001
0.20-0.25	<0.001	<0.001
0.25-0.30	<0.001	<0.001

Residue removal resulted in significantly higher topsoil PSS_1 under both C_M and C_H treatments when compared to residue retention. Visual observation of the effect of the 3-wheel logger movement on topsoil in the R plots showed movement and mixing of the soil when compared to the B plots (**Plate 3.2**). A decrease in topsoil PSS_1 was therefore expected in these treatments. However, the direct pressure of the logger wheels on the soil (in contrast to the distribution of the logger mass over residue), as well as the vibration of the logger may have been responsible for higher topsoil PSS_1 compared to W or B residue management. The differences in PSS_1 between B and W residue management in the C_M treatment (**Figure 4.6a**) indicate that increasing residue retention reduces topsoil compaction. This is in contrast to that of the C_H treatment (**Figure 4.6b**), possibly as a result of the greater mass of the forwarder, as well as the manner of its movement. These results show that residue retention reduces topsoil compaction, and that broadcasting, rather than windrowing, of residues substantially reduces the effects of 3-wheel loggers on topsoil. These results are consistent with the bulk density results (**Section 3.3.2**).

4.3.3.2.   Shafton

a)   Residual compaction

The soil water content at Shafton (for the 0-0.3, 0.3-0.6 and 0.6-0.9 m depths) at the time of PSS_0 measurement was between 0.326 and 0.488 kg kg^{-1} and averaged 0.397 kg kg^{-1}.

Significant residual treatment effects on PSS_0 from the previous trial were apparent, decreasing in the order $C_H > C_M > C_L$ (average PSS_0 of 2457, 2251 and 2132 kPa, respectively) and from interrow to stumpline (average PSS_0 of 2357 and 2203 kPa, respectively; **Figure 4.7**). As a result of significant compaction treatment x plot position x depth interaction effects, comparative least significant differences could only be performed on combinations of these factors (**Appendix 4.6**).
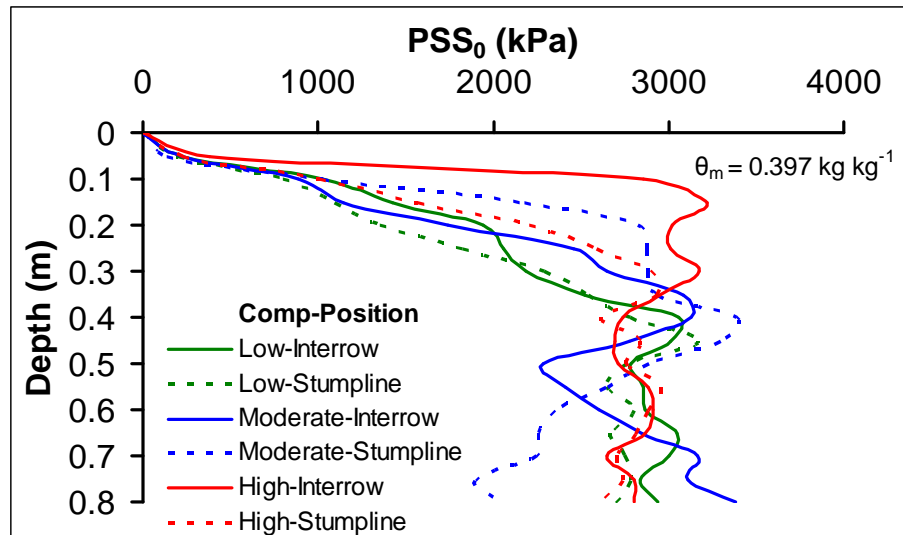
Figure 4.7: Compaction treatment (Comp) and plot position effects on average (28 points per treatment and position) penetrometer soil strength (PSS_0) with depth at Shafton.

Finer textured soils have been found to have higher PSS values than soils with a coarser texture (e.g. Gomez *et al.*, 2002a). This effect was reflected in the PSS results of Shafton, when they were compared to those of Rattray.

b)   *Effect of compaction treatments on PSS*

At PSS_1 measurement (after treatment implementation), soil water content ranged between 0.201 and 0.418 kg kg^{-1}, and averaged 0.344 kg kg^{-1}. The drier soil conditions during the measurement of PSS_1 resulted in PSS values outside the measuring range of the penetrometer (i.e. above 5000 kPa). These were often reached with increasing depth, and prevented measurement of PSS_1 to 0.8 m, for example, in the C_M-IR treatment (**Figure 4.8**). Despite this, there was a significant effect of compaction treatments on PSS_1 ($p<0.05$; **Figure 4.8***;* **Appendix 4.7A**), even with PSS_0 being accounted for (as a covariate). However, there was no significant difference in the increase in PSS_1 between the C_H and C_M compaction treatments, although the PSS_1 of these two treatments was significantly higher than that of the control at certain depths ($p<0.05$). This is shown in the resultant LSD's stemming from the significant interaction between compaction treatments, residue management and depth (**Appendix 4.7B**). The effect of residue management on PSS_1 is investigated later in the chapter. There was no significant difference between PSS_1 of interrows and stumplines, although the average trial interrow values were higher than the stumpline values (3149 and 3092 kPa, respectively). The significant effects of compaction treatments on PSS_1 were further confirmed by the analysis of treatment (both compaction and residue management) effects on PSS_1 every 0.05 m down the soil profile (**Appendix 4.8**; **A** - **C**). Penetrometer soil strength (PSS_1) decreased in the order $C_H>C_M>C_L$ in all instances.

The effect on PSS as a result of timber extraction treatments of the previous trial have been discussed (Smith, 1992; 2006). In that study, PSS was measured at a soil volumetric water content of between 0.23 and 0.28 m^3 m^{-3} (equivalent to between 0.20 and 0.35 kg kg^{-1}), i.e. much drier than when PSS_0 was measured prior to treatment implementation in the present study, but similar to when it was measured after treatment implementation. The lower values of PSS_0 obtained in this study (approximately 1000 kPa less) than those obtained by Smith (2006) may therefore be a result of differences in soil water content at the time of

measurement. Natural amelioration of compaction caused by the previous treatments does not appear to be the reason for the lower PSS_0, as significant differences between the previous treatments (and between the interrow and stumpline of the forwarder treatments) still remained. This confirms Smith's (2006) conclusion that the soil at this site would not naturally recover substantially from compaction, as the soil does not possess shrink/swell properties, i.e. the clay is mainly kaolinitic (Jakobsen, 1983; Murphy, 1984).
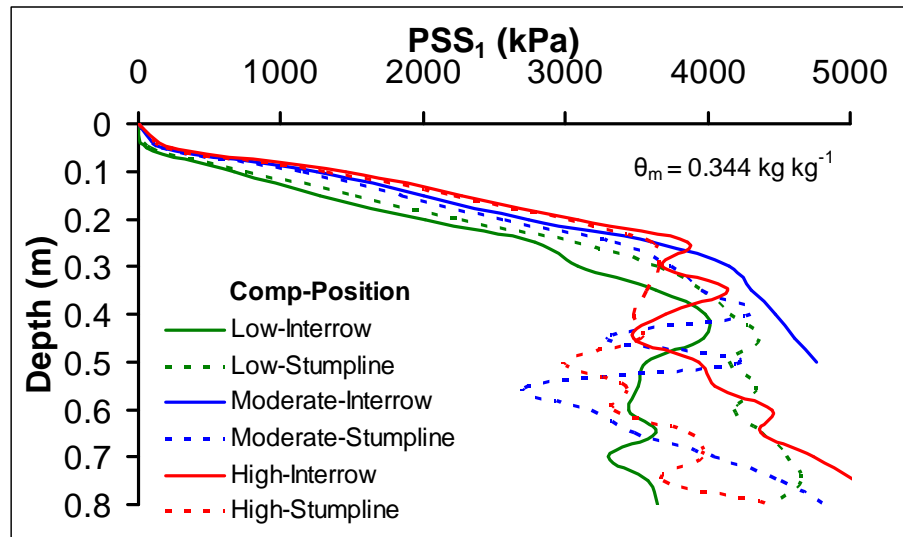
Figure 4.8: Compaction treatment (Comp) and plot position effects on average (28 points per treatment and position) penetrometer soil strength (PSS_1) with depth at Shafton.

The implementation of compaction treatments of this study significantly increased PSS (as accounted for by use of PSS_0 as a covariate), despite differences in soil water content, and resulted in significantly higher PSS_1 under the C_M and C_H treatments. The PSS_1 measurements are not reflected by Troxler bulk density, although significant effects of compaction treatments on PSS_1 were found within the top 0.3 m of soil (the same depth to which the Troxler measured). Although not apparent from **Figure 4.8**, PSS_1 in this top layer of soil increased rapidly over small increments in depth, and was quite different between the treatments. However, bulk density measurements were only taken every 0.1 m, while PSS_1 measurements were every 0.05 m (which was an average of five readings every cm). Secondly, a low number of measurements were taken for Troxler bulk density (four per plot,

compared to eight per plot for PSS_1). The slight differences between the treatments, in combination with the relatively small number of samples taken, may have meant that any treatment differences were masked by natural site variation. Visual observation of Rattray and Shafton indicated that the latter was more prone to microsite formation; an observation also noted by Smith (1992). This variability within a site and soil type often occurs as a result of small changes in topography that affect the transport and storage of water across and within the soil profile (Mulla and McBratney, 2000).

The lack of significant differences in interrow and stumpline PSS_1 values down the profile is in contrast to PSS_0 data in which the interrow C_H treatments attained higher values than C_M treatments (**Figure 4.7**). This could not be explained as being due to the soil reaching maximum bulk density, as this did not occur with treatment implementation (**Table 4.3**). However, it is likely that a level of soil strength was reached during treatment implementation that allowed the soil to resist further compaction, as evidenced by the high PSS_0 values at treatment implementation (**Section 4.3.3**).

In all treatments, PSS_1 was found to be above 2000 kPa below 0.25 m, and above 3000 kPa below 0.3 m, which may limit plant root growth (discussed in more detail in **Chapter 7**).

c)   Variation in PSS as a result of compaction treatments

The variation in PSS_1 values, quantified by standard deviation, showed that all treatments had extremely high values of standard deviation, particularly below 0.1 m (**Figure 4.9**). There was no significant difference in the amount of variation in PSS_1 between the treatments at any depth.
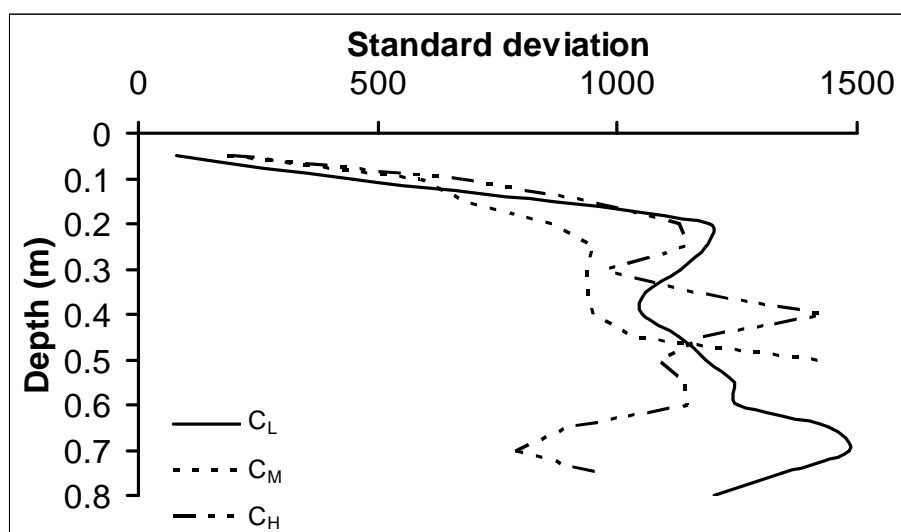
Figure 4.9: Standard deviation in PSS_1 with depth after compaction treatment implementation at Shafton. Treatments: C_L = low compaction, C_M = moderate compaction, C_H = high compaction.

d)   Residue management effects

When PSS_1 data (every 0.05 m) were analysed for both compaction treatment and residue management effects, significant residue management effects were only found at 0.05 and 0.1 m, and interaction (compaction x residue management) effects between 0 and 0.2 m (**Appendix 4.8A** - **C**). Although comparisons in treatment effects can only be performed separately if there are no significant treatment interaction effects, PSS_1 at these two depths declined from R>W>B.

As with Rattray, the lack of significant residue management effects on PSS_1 below 0.1 m were a result of there being no residue management effects on PSS_1 of C_L plots (data not shown). Therefore the relative change in PSS_1 from that of the C_L treatments in the C_M and C_H treatments were calculated (**Figure 4.10**, **Table 4.6**; **Appendix 4.8D**). The soil depths to which residue management altered the effects of machinery were 0.2 and 0.25 m in the C_M and C_H treatments, respectively.
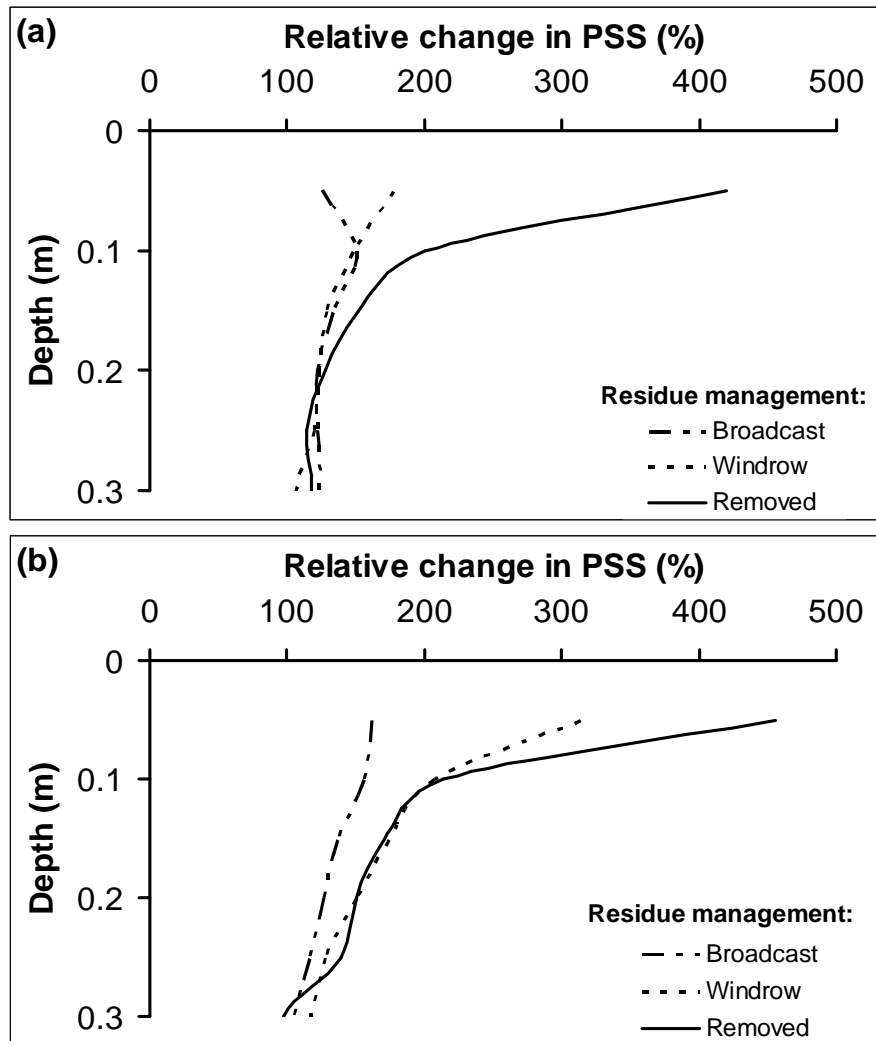
Figure 4.10: Average PSS_1 changes with depth (relative to average C_L treatment PSS_1 values) as a result of different residue management (a) under moderate compaction (C_M) and (b) under high compaction (C_H) at Shafton.

Table 4.6: Mean relative PSS_1 of C_M and C_H treatments relative to the C_L treatment under different residue management at Shafton to a soil depth of 0.25 m.

Compaction/Residue management	Mean relative PSS (%)
High compaction	186.7[a]
Moderate compaction	157.7[b]
Residue removed	214.4[a]
Windrowed residue	167.0[b]
Broadcast residue	135.2[c]

Treatments with different letters are significantly different ($p<0.01$).

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As at Rattray, the significance of C_M and C_H treatment effects on relative PSS_1 increased with increasing soil depth, while that of residue management remained highly significant until 0.25 m soil depth (**Table 4.7**). Again, there were no significant interaction effects. Relative PSS_1 decreased consistently in the order R>W>B, indicating (as at Rattray) that residue retention reduced surface soil compaction by machinery.

Table 4.7: Level of significance of (C_M and C_H) compaction treatments and residue management effects on relative (to the C_L treatment) PSS_1 values with soil depth at Shafton. Two-way ANOVA's were performed; blocking factor- soil depth.

Soil depth layer (m)	Compaction treatment	Residue management
0-0.10	0.019	<0.001
0.10-0.15	0.006	<0.001
0.15-0.20	0.003	<0.001
0.20-0.25	0.001	<0.001

Although at both Rattray and Shafton, relative PSS_1 was significantly higher with residue removal in the top 0.3 m of soil in the C_M and C_H treatments, at Shafton, this relative increase was greater under R residue management than at Rattray. This was probably due to the coarse textured and single grain soil at Rattray, which resulted in greater loosening of the surface soil with machinery movement when compared to Shafton (**Plate 3.2**).

Under the C_M treatment, broadcasting of residues reduced relative PSS_1 at both trials. However, this effect was only evident in the top 0.1 m at Shafton, but continued throughout the top 0.3 m of soil at Rattray. In the C_H treatment, similar relative changes in PSS_1 were recorded under B and W residue management at Rattray, unlike at Shafton, where the relative increase in PSS_1 was greater in W than in B residue management.

The difference in results between sites may be due to the variation in residue loads at the two trials when the compaction treatments were implemented. Evidence for this is discussed later (**Section 5.3.1**), but essentially Shafton had a

greater quantity of residues in B and W residue management plots, than Rattray. This thicker residue layer at Shafton decreased the effect of the C_M treatment and prevented substantial differentiation in the PSS_1 response between the B and W residue management. In contrast, the smaller residue load at Rattray resulted in a lower relative PSS_1 only in the C_MB treatment (when compared to the C_MW treatment with the smaller residue load). The importance of residue quantities on the reduction of PSS as a result of machinery movement is further supported by the response under R residue management plots, which was relatively much greater at Shafton than at Rattray. This indicates that if similar quantities of residue had been applied at Shafton as at Rattray, there may have been a greater difference in PSS_1 between the B and W residue management.

When a larger compactive effort (C_H) was applied to the sites, there were no differences in relative PSS_1 between B and W residue management at Rattray. However, at Shafton, the substantially thicker B residue resisted the compactive effects of the forwarder better than W residue management. These results indicate that the greater the quantity of residue left on a site, the lower the compaction of the upper layers of soil (in this case the top 0.3 m) by equipment.

4.4. Conclusions

The compaction treatments imposed may be representative of repetitive harvesting operations occurring over several rotations, particularly with the C_M treatment in which machinery movement was random (**Figure 3.2**). In C_H treatments, this is also true, if the orientation of the operation is maintained in the same manner from rotation to rotation (i.e. vehicle tracks travel over the same piece of ground). The lack of any amelioration of soil strength in response to harvesting treatments in the previous rotation indicates that continued use of machinery in forestry operations at both sites will result in a cumulative increase in soil bulk density and strength until a maximum level is obtained.

The compaction treatments applied at Rattray resulted in significant changes in bulk density and PSS. In the top 0.3 m soil, these effects were moderated by the

retention of residue. Bulk density and PSS increased in the order $C_L<C_M<C_H$. However, greater variability in compaction effects on soil bulk density and PSS were found under the C_H treatment when compared to the C_M treatment, and this may have implications for tree growth.

The lack of significant effects of the treatments on bulk density, as well as the highly variable PSS results at Shafton may imply that this site is more resistant to compaction than Rattray. However, significant increases in PSS in the order $C_L<C_M<C_H$ were still evident, and since they were greater in magnitude, were potentially more root limiting than those obtained at Rattray.

The PSS and bulk density results obtained at the two trials show the importance of measurement of more than one variable when determining the soil physical environment. Despite the substantially lower soil bulk densities at Shafton, PSS values were considerably greater than those at Rattray.

Despite the differences in natural soil physical properties between the sites and their response to compaction (as a result of textural differences), the trials had some features in common. At both trials, compaction treatments resulted in an increase in PSS i.e. $C_L<C_M<C_H$. Residue retention reduced compaction treatment effects on PSS of the top 0.3 m of soil at both trials, and seems to be a function of residue quantity. This mitigation of compaction effects in surface soils with residue retention has substantial implications for tree growth and seedling survival, as organic matter, nutrients and the majority of fine roots are often concentrated in this upper soil layer (Ampoorter *et al.*, 2007).

Chapter 5

Changes in Residues, Soil Organic Carbon
and Nutrients over Time

5.1. Introduction

Decreases in plantation productivity have often been attributed to decreases in soil organic matter and nutrient supply that occur mainly as a result of harvesting and site preparation practices. These reductions occur particularly in soils that depend on the decomposition of organic matter for a large portion of their nutrient supply (Powers *et al.*, 1990; 1995; Dyck and Cole, 1994; Johnson, 1994; Morris and Miller, 1994; Kelting *et al.*, 1999; Kazotti *et al.*, 2004). There is some evidence to suggest that suitable harvesting and site preparation practices may increase productivity, thereby increasing organic matter inputs to the soil (Laiho *et al.*, 2003). Despite this, declines in soil organic matter and nutrient supply are of particular concern in short-rotation plantations with high biomass and nutrient removal rates (Morris and Miller, 1994; Corbeels *et al.*, 2003; Gonçalves *et al.*, 2004b; Dovey *et al.*, 2007). However, studies of organic matter and nutrient dynamics in these short rotation plantations are severely lacking (Laiho *et al.*, 2003).

Soil organic matter forms only a small fraction of most forest soils, approximately between 1 and 12% (mass basis) in the total soil profile. Despite this it is considered to be crucial to the maintenance of soil productivity as a result of its effect on physical, chemical and biological properties of soils (Dudal and Deckers, 1991, Johnson, 1994; Powers *et al.*, 1995; Fisher and Binkley, 2000; Schoenholtz *et al.*, 2000). In addition, soils with high organic matter contents in the surface horizons are thought to be less susceptible to damage resulting from mechanised operations than those that have higher amounts of organic matter in the forest floor than in the soil (Jurgensen *et al.*, 1997).

Tree growth (and health) is directly linked to the availability of various nutrients (Johnston and Crossely, 2002; Dovey *et al.*, 2007). While nutrient deficiencies can be easily corrected by fertiliser application, reducing dependence on such additions would considerably lower costs of production and impact on the environment (Morris, 1987; du Toit and Carlson, 2000; Campion and du Toit, 2003).

5.1.1.   Management effects on soil organic matter and nutrients

Nutrient gains as a result of management can only occur by fertilisation and sometimes, by manipulation of the soil microbial population. However, the majority of processes contributing to site nutrient and organic matter losses, i.e. biomass removals, erosion, soil displacement, leaching and volatilisation, are substantially affected by management (Comerford *et al.*, 1994; Kimmins, 1994; Raison and Rab, 2001; Dovey and du Toit, 2006).

Removals of plant biomass in plantations occur through harvesting or residue management (including burning). Even in situations where only the utilisable stemwood is removed from the site, as in the majority of South African eucalypt plantations, considerable quantities of biomass and nutrients can still be removed (Nambiar and Brown, 1997; Kazotti *et al.*, 2004; Dovey, 2005). In such plantations after harvesting, the rates of biomass and nutrient removal or (displacement) are largely dependent on harvest residue management (Morris and Miller, 1994; Dovey, 2005; Powers *et al.*, 2005). This is because eucalypt harvest residues often contain substantial quantities of nutrients that may represent a large proportion of the total nutrient pool of a site (e.g. Spangenberg *et al.*, 1996; Sankaran *et al.*, 2005; Gonçalves *et al.*, 2007).

Residue removal may lead to an increased loss of soil nutrients through leaching (through a reduction in cation exchange sites due to loss of organic matter). Further losses of nutrients through leaching and volatilisation are often dependent on the timing at which nutrients are mineralised from organic compounds (Edwards and Ross-Todd, 1983; Henderson, 1995; Ballard, 2000;

Gómez-Rey *et al.*, 2008). Nutrients can also be lost through soil erosion and displacement, which often occur where harvest residues have been removed and the soil is left bare (Jones *et al.*, 1999; Ballard, 2000; Fernández *et al.*, 2004; Gómez-Rey *et al.*, 2008).

5.1.2. <u>Residue management</u>

In South Africa, *Eucalyptus* is harvested in a similar manner to that used in this study (**Section 3.1.4**). The resultant plant residues (i.e. branches, tops, bark and litter from the previous rotation) remaining on the site are then generally windrowed, broadcast or burnt (as described in **Section 3.1.4**), however increasing environmental pressures have increased the use of broadcasting, despite planting operation difficulties (Norris, 1992; 1993).

5.1.2.1. Eucalypt harvest residue

a)   Residue biomass (organic input)

In a summary of plantation studies in the tropics, Tiarks and Ranger (2008) reported that residue retention sometimes increased soil organic matter, but always prevented the loss of soil organic matter. Of the studies reviewed, several included those under eucalypts. In these studies, soil organic C content generally decreased with residue removal (e.g. Nzila *et al.*, 2004; Sankaran *et al.*, 2004) even if in some instances this was not significant (e.g. Mendham *et al.*, 2002; 2003; O'Connell *et al.*, 2004a; Gonçalves *et al.*, 2007).

Actual quantities of residues left on site as a result of harvesting and residue management operations for plantation eucalypts are well documented (e.g. du Toit, 2003; Gonçalves *et al.*, 2004a; Nzila *et al.*, 2004; Xu *et al.*, 2004). However, quantities varied substantially with species, age, site characteristics, harvesting and residue management operations, and season.

b)   *Factors affecting residue decomposition*

Although the same total mass of residue is left on a site, whether broadcast or windrowed, there are differences in both the distribution and quality of residues, and this therefore affects decomposition dynamics. The higher proportion of woody components in broadcast residues compared to residues in the inter-windrow area, results in higher C:N ratios and lignin and soluble phenol content of broadcast residues, so slowing their rate of decomposition (Bernhard-Reversat and Loumeto, 2002; O'Connell *et al.*, 2004b; Dovey *et al.*, 2007). On the other hand, the thicker layer of residues on the soil surface in broadcast residue management may result in a more favourable environment for decomposition, particularly from a temperature and moisture perspective. Machinery movement over any residues will increase the surface area of residues exposed to microbial attack, and therefore increase decomposition rates.

c)   *Residue nutrient concentrations and contents*

Nutrient concentrations of eucalypt harvest residues vary with site characteristics, species, age, silviculture (particularly fertilisation), decomposition period and rate, and harvesting and residue management operations (e.g. O'Connell and Sankaran, 1997; Bernhard-Reversat and Loumeto, 2002; O'Connell *et al.*, 2004b; Dovey, 2005; Safou-Matondo *et al.*, 2005). Residue management affects the distribution of those nutrients across a site. For example, in *Eucalyptus*, quantities of K are higher in large branches and tops, while Ca and Mg are higher in bark (per kg dry mass) than other components (O'Connell *et al.*, 2004a; Dovey, 2005; Sankaran *et al.*, 2005; Dovey *et al.*, 2007). It would be expected therefore, that inter-windrow areas would have less K, than if residues were broadcast.

For the purposes of this study, however, a comparison of the amount of nutrients contained in residues may be more appropriate. Therefore the nutrient content of *Eucalyptus* harvest residues including litter, from a site similar to Rattray (Nzila *et al.*, 2004; Deleporte *et al.*, 2008) and Shafton (du Toit *et al.*, 2001a; du Toit,

2003; du Toit *et al.*, 2004) were compared (**Table 5.1**). The former site, although located in the Congo, is on a sandy, low organic C, soil, and the previous rotation was a *Eucalyptus* clone that was harvested at about 7.7 years of age, with a stemwood volume of 129 m^3 ha^{-1}. This yielded approximately 31.4t ha^{-1} of residues in their broadcast residue treatment, of which about 50% had decomposed after 6 – 8 months. Close to Shafton, a study was performed using *E. grandis*, however, it was a considerably younger (7 years old) coppiced stand (when compared to the previous stand at Shafton) with a stemwood volume of 147 m^3 ha^{-1}. In that study, the residue mass in a broadcast treatment immediately after residue manipulation was approximately 116 t ha^{-1} (du Toit, 2003). Eight months later, residue mass decreased to 73 t ha^{-1} (du Toit, unpublished).

Table 5.1: Nutrient contents (kg ha^{-1}) of broadcast *E. grandis* harvest residues after felling (time).

Study	Nzila *et al.* (2004)			du Toit (2003)
Location	Congo			South Africa
Time (months)	**0**	**8**	**14**	**0**
N	250	108	62	1044
P	29	5	2	53
K	63	10	5	193
Ca	79	48	23	823
Mg	45	24	12	201

In addition, du Toit (2003) found that a total of 34.3 t ha^{-1} of the stand was branches, capsules and foliage biomass. These components contained a total of 180, 13, 123, 143 and 51 kg ha^{-1} of N, P, K, Ca and Mg, respectively, which since these are removed from the inter-windrowed areas, would result in lower site nutrient contents than areas with broadcast residue management.

Literature relating to windrowing effects on harvest residue nutrients and biomass in eucalypts is scarce. However, most nutrients in eucalypt harvest residues are contained in the foliage and bark and the former is often removed to windrows (Jones *et al.*, 1999; Shammas *et al.*, 2003; Dovey, 2005). Windrowing in other species often involves the removal of harvest residue, litter and some soil into windrows (Morris and Lowery, 1988).

5.1.2.2.   Effect of residue management on soil pH and nutrient availability

The effects of residue management on soil chemical properties under tropical plantations has been summarised by Tiarks and Ranger (2008). Soil pH changed with residue retention only at four sites out of nine, of which at three an increase in pH was measured. Residue retention either increased total soil N (at four sites), or had no effect (at seven sites), while available soil P only increased at one site (out of eight). Exchangeable soil K only decreased at one site out of fourteen with residue retention, the rest having measured no effect. Significant increases in soil exchangeable Ca with the retention of residues was only documented at four sites, with no effect at the remaining ten sites. Residue removal significantly decreased soil exchangeable Mg at one site, while at three other sites, residue retention increased it, and at the remaining ten sites, there was no effect.

Comparable studies to Rattray (Congo; Nzila *et al.*, 2004; Deleporte *et al.*, 2008) and Shafton (Karkloof; du Toit *et al.*, 2008) investigated the effect of residue management on soil pH and macronutrients. At the start of the Congolese study, 2878, 243, 255 and 40 kg ha^{-1} of total N, and exchangeable K, Ca and Mg, respectively, on average, was held in the top 1 m of soil. Broadcast residues (**Table 5.1**) therefore contained 9, 26, 31 and 113 % of the soil nutrient pools (Deleporte *et al.*, 2008). In contrast, the Karkloof soil (to a depth of 0.9 m) contained approximately 18650, 10, 465, 742, 771 kg ha^{-1} of N, P, K, Ca and Mg, respectively, resulting in broadcast residues representing 6% of total soil N, 530% of available soil P (Bray-2), and 42, 111 and 26% of exchangeable soil K, Ca and Mg, respectively, of soil nutrient pools (du Toit, 2003). The effect on soil pH and N, P, K, Ca and Mg of broadcast residue management relative to residue removal at these studies is summarised in **Appendix 5.1**.

5.1.3.   Effect of compaction on soil organic matter and nutrient dynamics

Since soil compaction affects the soil environment, it affects organic matter and nutrient dynamics (Greacen and Sands, 1980; Johnson and Curtis, 2001; Busse *et al.*, 2006). Although soil compaction generally increases soil water retention,

the concomitant decrease in aeration, and reduced accessibility of the residues, may decrease the activity of decomposer organisms (Edwards and Ross-Todd, 1983; Dick *et al.*, 1988; Whalley *et al.*, 1995; Marshall, 2000). Soil compaction alone has generally therefore been found to reduce populations of both soil macrofauna and microbes (Breland and Hansen, 1996; Marshall, 2000; Tan *et al.*, 2005; Busse *et al.*, 2006; Fleming *et al.*, 2006a). However, this is not always the case as the effects of compaction on different soil types vary (e.g. Jordan *et al.*, 2000; Shestak and Busse, 2005; Smith and du Toit, 2005).

Compaction can also reduce root growth and the diffusion rate of nutrients, reducing the ability of trees to obtain soil nutrients, and can result in increased leaching of nutrients (Powers *et al.*, 1990; Ballard, 2000; Johnston and Crossely, 2002). However, there is evidence that compaction can improve soil-root contact (Arvidsson, 1999). Therefore, compaction can have a positive, negative, or no effect on soil organic matter and nutrient availability. In addition, it must be noted, that if organic matter is expressed on a volume basis, an increase as a result of increasing bulk density is sometimes found, even though the quantity within the soil profile does not change (e.g. Johnson *et al.*, 1991).

Machinery movement over residues has been found to have both positive and negative effects on soil organic matter and nutrients. This is a result of the type of harvesting operation performed and the response of that particular soil (Laiho *et al.*, 2003). The weight and action of machinery results in the breaking up of residues and their incorporation with surface soil layers, so increasing the surface area of residues exposed to microbial attack (Johnson *et al.*, 1991; Rab, 1996; Eisenbies *et al.*, 2005). This incorporation results in considerable organic inputs into the soil and may initially increase surface soil organic matter content (Johnson and Curtis, 2001; Laiho *et al.*, 2003). The length of time after harvesting that this increase has been documented to persist varies between 4 and 18 years (Smethurst and Nambiar, 1990a; Knoepp and Swank, 1997). However, the overall consequence of the breaking up and incorporation of residues is generally an increase in the rate of residue decomposition, leading to a net loss of C as microbial communities release increased quantities of mineralised C with

heightened respiration (Salonis, 1982; Rab, 1994; Jones *et al.*, 1999; Pérez-Batallón *et al.*, 2001; Tan and Chang, 2007). This then leads to an overall drop in soil organic C content (Jurgensen *et al.*, 1997). In addition, machinery movement can displace residues, often leaving bare soil exposed, and can decrease organic matter input (Jones *et al.*, 1999; Ballard, 2000; Fernández *et al.*, 2004).

The effect of harvesting-induced compaction on organic matter (in the top 0.1 m soil) in eucalypts was investigated in an Australian young *E. regnans* stand (Rab, 1994). Logging significantly increased bulk density and decreased organic C and organic matter content. In the worst affected areas, bulk density increased between 39 and 65%, while organic C decreased between 27 and 66%. In contrast, no effect was found of compaction on soil C and N content determined across a range of sites (and under a range of species) in the USA (Sanchez *et al.*, 2006).

5.1.4. <u>Chapter rationale and objectives</u>

The objective of this section of the study was to determine the effect of compaction treatments and residue management on:
1. The biomass of residues at planting (TP) and harvesting (TH) of the sub-plot trees.
2. Soil organic C at TP, TH and TF.
3. The quantity of nutrients in residues and soil at TP, TH and TF.

5.2. Materials and methods

Refer to **Chapter 3** for details regarding materials and methods.

Soil nutrients are discussed as N, P, K, Ca and Mg, where N refers to total soil N, P to available soil P (Bray-2), and K, Ca and Mg to exchangeable K, Ca and Mg.

5.3.   Results and discussion

5.3.1.   Quantity of residues

5.3.1.1.   Rattray

There were no significant treatment effects on the total quantity of residues on each plot at TP, TH or TF (data not shown). However, the average total quantity of residues found under broadcast residue management was consistently higher than that under the windrow residue management at TP, TH and TF (**Figure 5.1**). In addition, the quantity of residues declined with time.
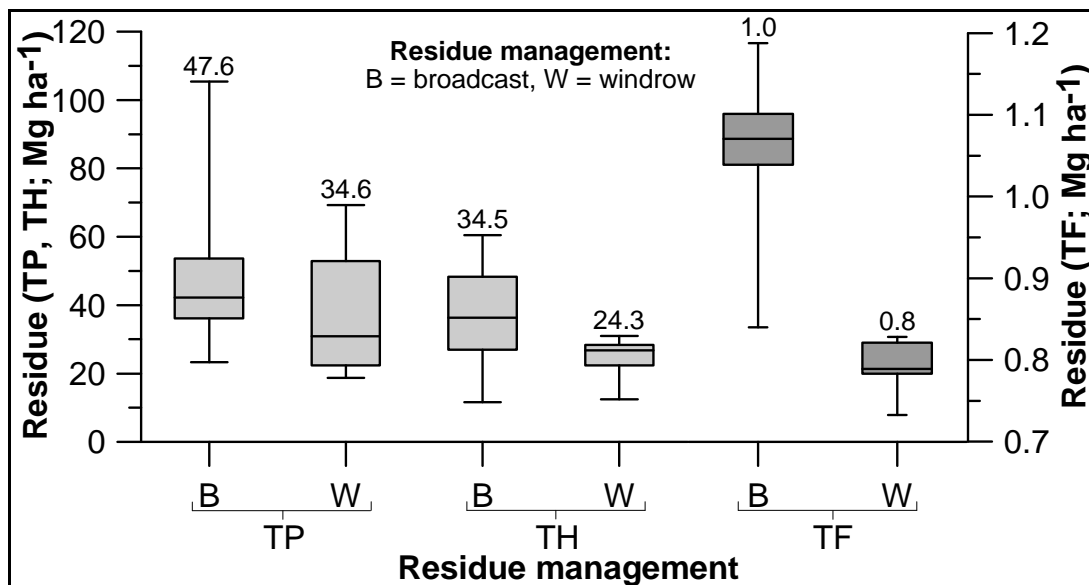
Figure 5.1:   Box whisker plot of the effect of residue management on quantities of residues at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF) at Rattray. Note that residues at TF were plotted on the second y-axis. Average values are displayed above each box whisker.

The average total quantity of residues found under broadcast residue management at Shafton were consistently, significantly ($p<0.01$) higher than that under the windrow residue management at both TP and TH (**Figure 5.2**, **Appendix 5.2**). Least significant differences are not shown as only two methods of residue management, broadcast and windrowed, were statistically tested, and they were significantly different from one another. There were significantly less residues at TP on C_M plots (38.4 Mg ha^{-1}), than either C_L or C_H plots (54.9 and 56.3 Mg ha^{-1}, respectively). This is probably due to sampling error, as at TH, there was a non-significant decrease in residue quantities from $C_M>C_L>C_H$. At no measurement time was there a significant effect of the interaction between compaction treatments and residue management on residue quantities.
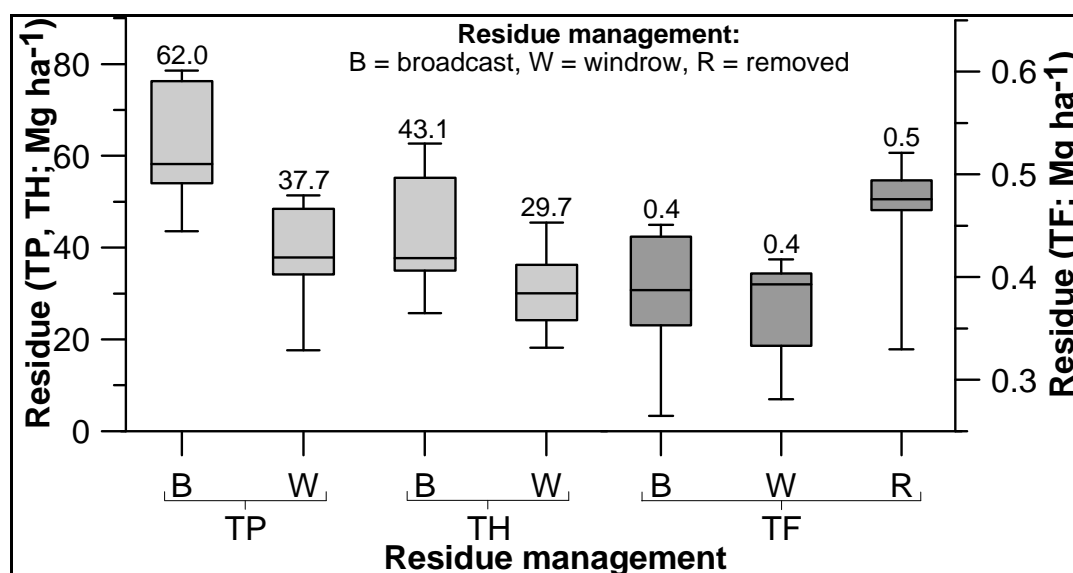
Figure 5.2: Box whisker plot of the effect of residue management on quantities of residues at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF) at Shafton. Note that residues at TF were plotted on the second y-axis. Average values are displayed above each box whisker.

The average quantity of residues within broadcast and windrow residue management decreased between TP and TH ($p<0.01$ and <0.1, respectively; **Appendix 5.2**). After the wildfire, no significant treatment effects were found on

the mass of burnt residues (data not shown). These residues included burnt litter, and therefore R plots were sampled at TF (**Figure 5.2**). The increased amount of residues present in the R plots is probably a result of the lower intensity of the wildfire in these plots (Rietz and Smith, 2009).

At Shafton, the harvesting and implementation of residue management took place well before planting (harvesting at 9 months, and residue manipulation 8.5 months prior to planting) when compared to Rattray (harvesting 2 months, and residue manipulation 1.5 months prior to planting). Despite this longer decomposition time, there was a lower mass of residues at planting with both broadcast and windrowed residue management at Rattray than at Shafton. This was probably a result of:

- The climate at Shafton is cooler than that of Rattray, and therefore less conducive to decomposition.
- The difference in tree species grown at the trials in the previous rotations. At Rattray, this was *E. grandis* x *camaldulensis* (Smith and du Toit, 2005), whereas at Shafton it was *E. grandis* (Smith, 2006). The former species is commonly known to have a smaller crown than that of *E. grandis* (L.J. Esprey, 2007, pers comm.[1]).
- Trees generally have smaller crowns, and a thinner litter layer in the Zululand (Rattray) area when compared to those in the Midlands (Shafton) area. This is due to the different growing conditions of these areas (L.J. Esprey, 2007, pers comm.[1]).

5.3.2.   Changes in soil organic carbon

5.3.2.1.   Rattray

Compaction treatments had a significant effect ($p<0.05$) on C (% m/m) at the 0-0.05 m soil depth at TH, but not at TF or other depths (**Appendix 5.3**). It was significantly higher in the C_H treatment (3.9%), than in the C_L treatment (2.8%), while the C_M treatment (3.3%) was not significantly different from either C_H or C_L treatments.

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[1] Dr L.J. Esprey, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

These treatment effects were maintained in the 0-0.05 m depth layer, even if the C values were adjusted for bulk density changes, i.e. values were expressed on a volume rather than mass basis (data not shown). Neither residue management alone, nor the interaction between residue management and compaction treatments had any significant effects on soil C.

Across the trial, soil C content between 0 and 0.05 m initially increased, and then decreased to a level similar to that at TP. Below this depth, however, C was fairly stable over the three sampling times (**Figure 5.3**).
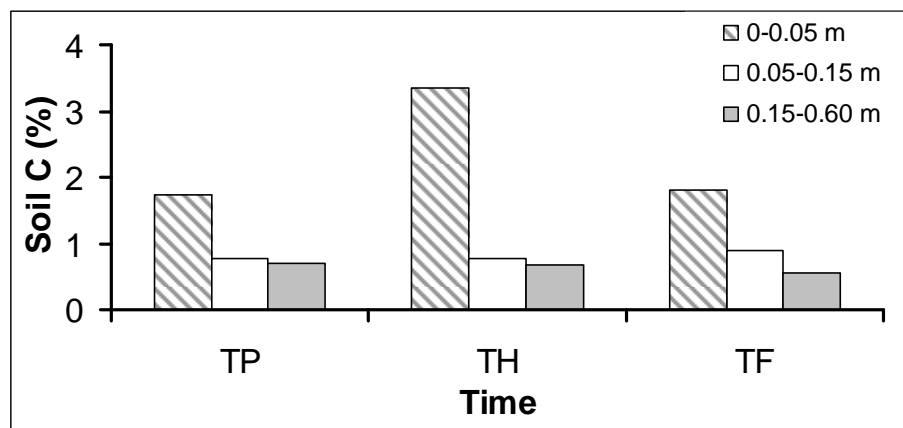
Figure 5.3:   Average soil carbon (C; % m/m) changes with depth at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF) at Rattray.

The increase in soil C with increasing compaction intensity at TH between 0 and 0.05 m may be a result of the incorporation of residues into this top layer of soil by machinery, and a contribution to soil C stocks. These differences became non-significant with time, as C contents returned to pre-trial levels (data not shown). The lack of residue management effects, despite the low organic C content of Rattray's soil may be a result of the climate of this site that enables rapid decomposition. The overall increase in C (0 – 0.05 m) measured at TH at Rattray is most likely a result of the input of organic matter from the previous rotation in the form of harvest residues, either broadcast or windrowed, and tree roots, particularly fine roots.

5.3.2.2.   Shafton

In the 0-0.05 m soil layer at TH, C was significantly ($p<0.01$) lower in residue removed plots, than in either broadcast or windrowed residue plots (**Figure 5.4**; **Appendix 5.4**). At other depths and at TF, however, there was no significant effect of residue management (**Appendix 5.4**). Similar results were obtained when C values were converted from a mass to a volume basis using bulk density data (data not shown). The final measurement may not reflect treatment effects due to the fire prior to TF that burnt all residues, and much of the decomposing organic layer on top of the mineral soil. Compaction treatments and the interaction between compaction treatments and residue management had no significant effect on C at any soil depth, or at any time. This is probably because residue loads were larger than those of Rattray at compaction treatment implementation, so reducing the mixing of residues and soil by the movement of the machinery. Soil C also decreased with depth and over the three sampling times (**Figure 5.5**).
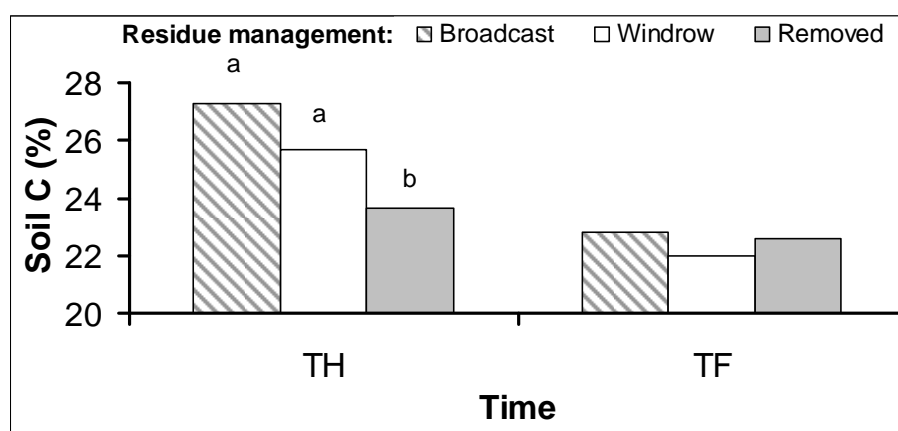
Figure 5.4:   Effect of residue management on soil carbon (C; % m/m) between 0 and 0.05 m residues harvesting of sub-plot trees (TH) and final soil measurement (TF) at Shafton. Treatments with different letters are significantly different ($p<0.05$).
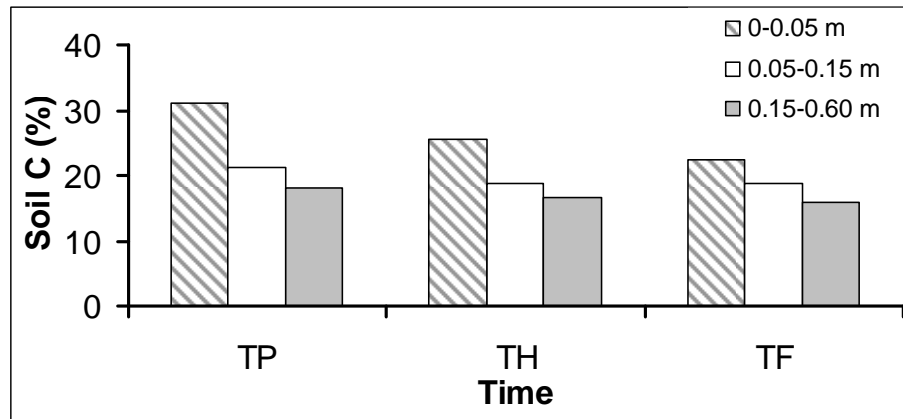
Figure 5.5: Soil carbon (C; % m/m) changes with depth at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF) at Shafton.

The decrease in soil C after treatment implementation at this site may be due to organic matter accumulation during the previous rotation as a result of relatively cool and dry soil conditions from shading and water uptake by trees. Once harvested, the soil environment may have become warmer and moister, so leading to organic matter decomposition, and a decrease in soil C. This effect would have been greater at Shafton than Rattray since 15 months, as opposed to 7 months at Rattray, passed between treatment implementation and TH.

5.3.3. Changes in soil pH and site nutrient pools

5.3.3.1. Rattray

a) Soil pH

Although not significant, soil pH across the trial changed over time. It initially increased in all soil depth layers between TP and TH, and then decreased between TH and TF (**Figure 5.6a**).

At TF, residue management had a significant ($p<0.05$) effect on soil pH in all depth layers. However, compaction treatments and the interaction between compaction

treatments and residue management, did not have any significant effect (**Figure 5.6b**, **Appendix 5.5.A-D**). In addition, no significant treatment effects were found in soil pH at TH (results not shown).
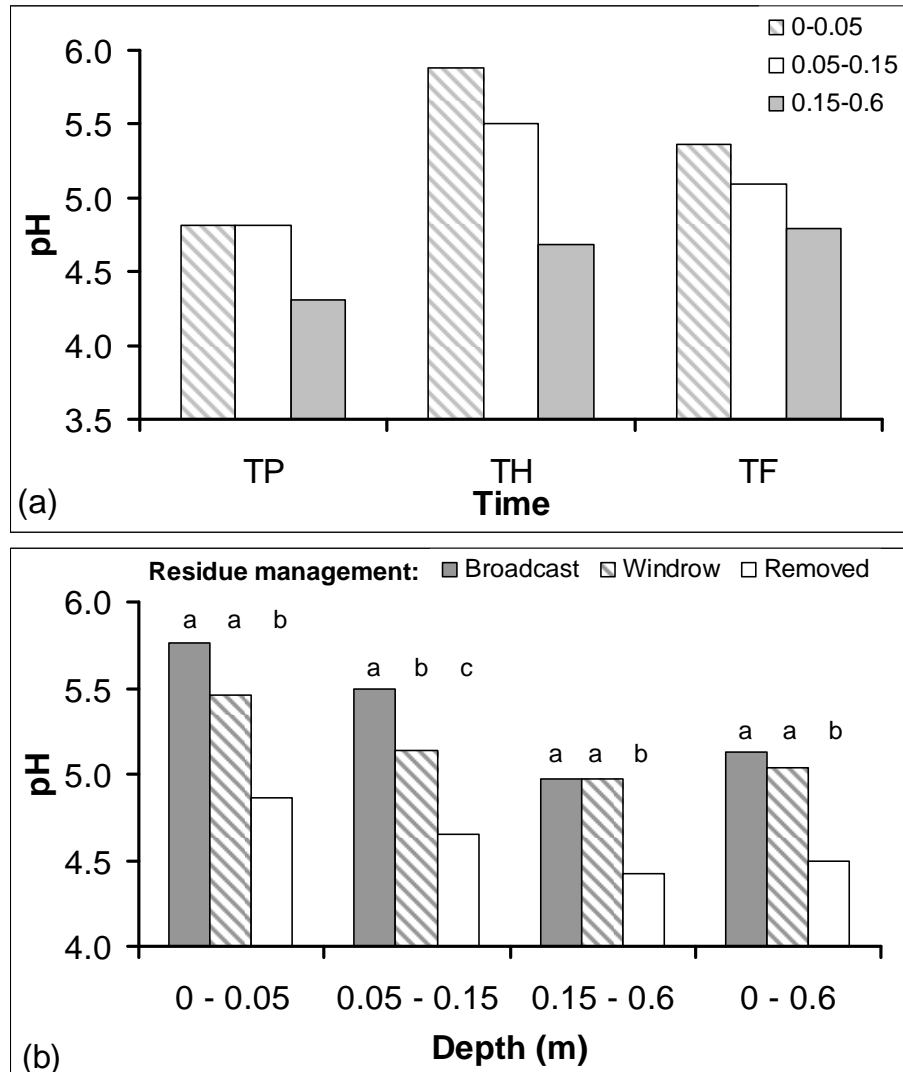
Figure 5.6: Change in soil pH in various depth layers at Rattray (a) at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF), and (b) with residue management at TF (0 – 0.6 m is a depth weighted average). Treatments with different letters are significantly different ($p<0.05$).

This increase in soil pH with increasing residue retention is due to the addition of plant material with a higher pH than that of the soil, and the contribution of this

plant material of K, Ca and Mg (as seen later in **Figures 5.7** and **5.8**), which results in an increase in soil pH (Wong and Swift, 2003). In addition, there is evidence that organic matter can buffer the pH of a soil through its CEC (Magdoff and Weil, 2004).

b)   Site Nutrient Pools

The site nutrient status of Rattray was assessed prior to treatment implementation (**Tables 3.3** and **3.5**). These results indicated that Rattray has a low soil C and clay content, resulting in a relatively low ECEC and total N concentration.

The total quantity of N, P, K, Ca and Mg measured in both soil and residues generally increased from TP to TH, and then decreased from TH to TF (**Figure 5.7**). However, these changes were not significant. These changes are most likely due to the differences in sampling strategies between TP and TH (and TF), as the nutrient rich 0 – 0.05 m layer was not directly sampled at TP. However, some other eucalypt studies (reviewed by Tiarks and Ranger, 2008) also found increases, particularly in soil cations, that were larger than could be accounted for by decomposing residues. They attributed this to the uptake of these nutrients from deep in the soil profile by tree roots. These nutrients are utilised by the tree and then deposited on the soil surface as litter that decomposes and so increases soil surface concentrations of those nutrients. This explanation is unlikely for this study, as trees were not large enough for roots to obtain nutrients from deep in the soil profile. In most instances, the amount of nutrients decreased from TH to TF, probably as a result of both plant uptake, and losses through leaching. Exceptions to this were overall site N and Ca pools that increased between TH and TF. These increases were mainly attributable to increases in N and Ca contained in the 0.05 – 0.15 and 0.15 – 0.6 m depth layers. This may indicate a contribution by decomposing root systems of the previous rotation to soil N and Ca.
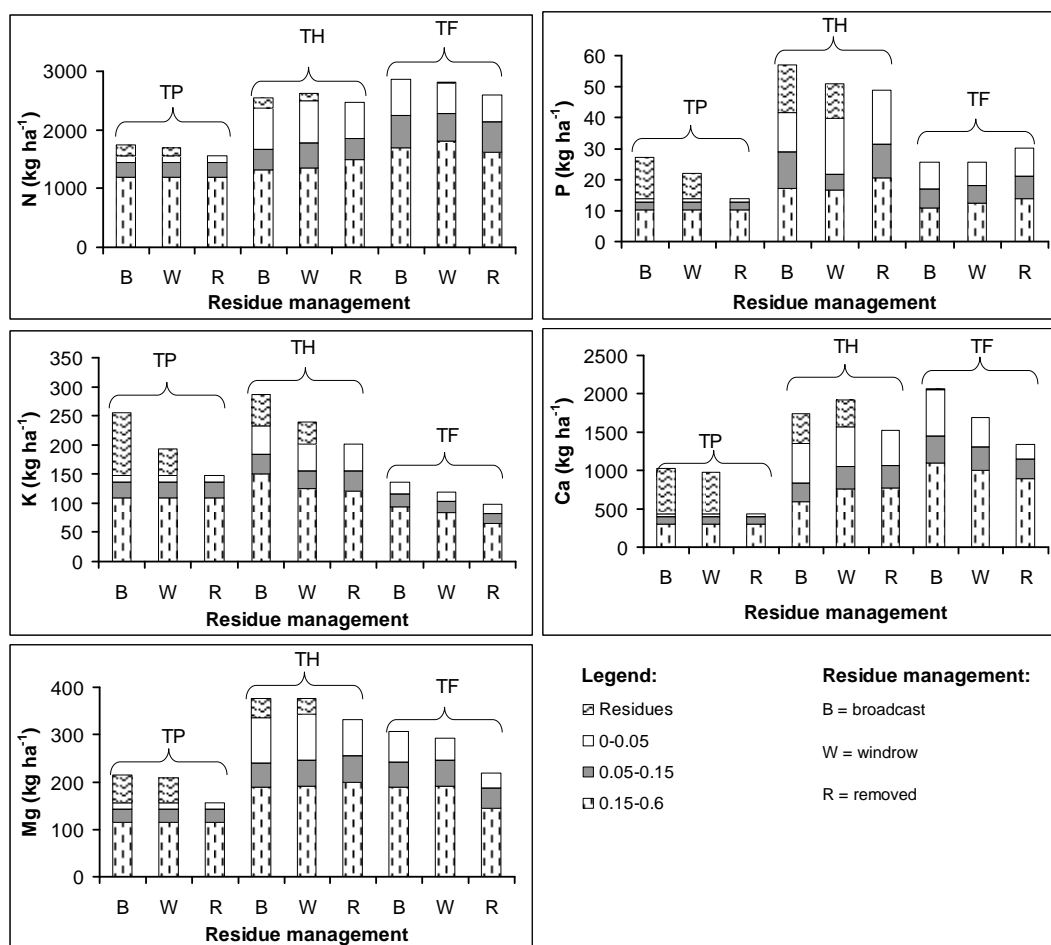
Figure 5.7: Effect of residue management on average total N, P (Bray-2) and exchangeable K, Ca and Mg quantities in soil (0 – 0.6 m) and elemental contents of residues at Rattray at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF). Soil sampling strategy at TP may have resulted in substantially lower quantities of nutrients being displayed as the individual 0 – 0.5, 0.5 – 0.15 and 0.15 – 0.3 m layers were determined from a bulked sample.

Windrowed residues consistently contained a lower proportion of nutrients when compared to that in broadcast residues (**Table 5.2**). However, residue management usually did not have a significant effect on site macronutrient pools, although the size of these pools generally decreased with decreasing residue retention (**Figure 5.7**). Significant residue management effects were found only at TF in soil Ca and Mg (expressed in kg ha^{-1}) in the 0 – 0.05 m depth layer, and the

total amount of Ca (kg ha^{-1}) between 0 and 0.6 m (**Figure 5.8**, **Appendix 5.5E-G**). This is most likely due to the large quantity of Ca added in residues, relative to that contained in the soil (**Table 5.2**). However residues contributed greater proportions of P and K, than Mg, yet no significant response was found in soil P and K pools. However, less soil Mg may have been taken up by plants or leached, as is likely in the case of P and K. The quantity of nutrients contained in residues was often significantly affected by residue management (**Appendix 5.6**). This is because residue nutrient quantities are the product of nutrient concentration and mass of residues.

Table 5.2: Nutrients held in broadcast or windrowed residues as a percentage of that held in the soil (0 – 0.6 m)[a] at TP at Rattray.

Nutrient	Broadcast (%)	Windrowed (%)
N	11.7	8.9
P	98.5	60.5
K	72.4	30.9
Ca	89.0	81.3
Mg	36.7	34.1

[a] Soil nutrients measured were total soil N, available soil P (Bray-2), and exchangeable soil K, Ca and Mg.
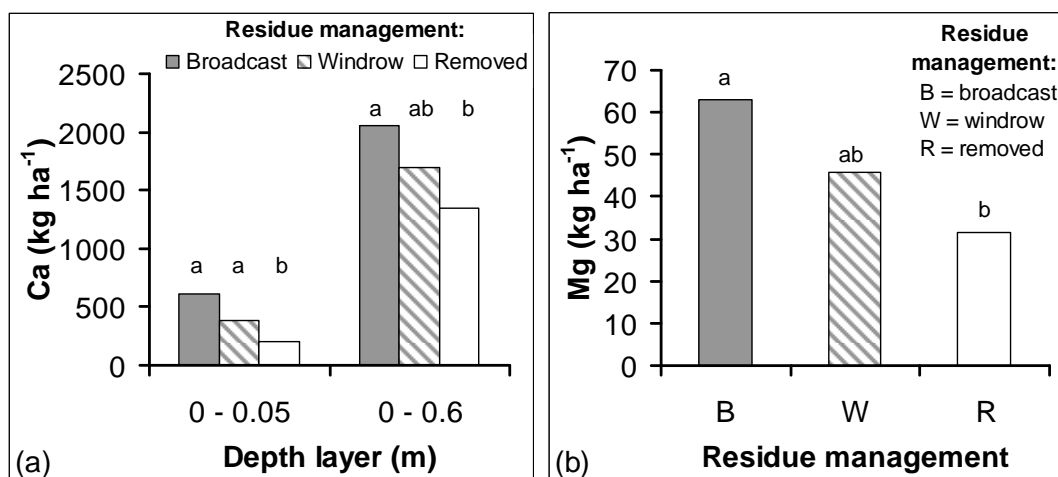
Figure 5.8: Effect of residue management on soil exchangeable (a) Ca (0 – 0.05 and 0 – 0.6 m), and (b) Mg (0 – 0.05 m) at the final soil measurement (TF) at Rattray. Treatments with different letters are significantly different ($p<0.05$).

No significant effect of compaction treatments, or the interaction between compaction treatments and residue management, on site macronutrient pools at any soil depth were found. This was despite the fact that significant compaction treatment effects on soil C at TH were found. It is therefore most likely that any additional nutrients (associated with organic matter) were either taken up by trees or leached from the soil profile.

Deleporte *et al.* (2008) found a significant effect of residue management on soil N. This was even though similar (to Rattray) amounts of N were measured in their residues and soil. However, soil N at Rattray was determined after the wet season, and it is possible that this nutrient, as well as K, was leached. Deleporte *et al.* (2008) did not find any significant effects of residue management on soil Ca. However, their soil and residues contained substantially lower quantities of Ca than those of Rattray. The lack of any significant response of soil P to residue management may be due to plant uptake of this nutrient, or the inability of the analysis to detect all plant-available soil P.

5.3.3.2.   Shafton

a)   Soil pH

No trends were seen in the soil pH data at the three sampling times (**Figure 5.9a**). Residue management significantly affected soil pH between 0 and 0.05 m at TH ($p<0.05$; **Figure 5.9b**; **Appendix 5.7**). However, there was no significant residue management effect at TF, nor were there any significant compaction treatment or interaction effects at any time or depth (data not shown).

The increase in soil pH with residue retention is at this trial is most likely for the same reasons as that found at Rattray. However, a similar response was not obtained at the trial comparable to Shafton (du Toit *et al.*, 2008), although there was a similar increase in soil pH across that trial after harvesting.
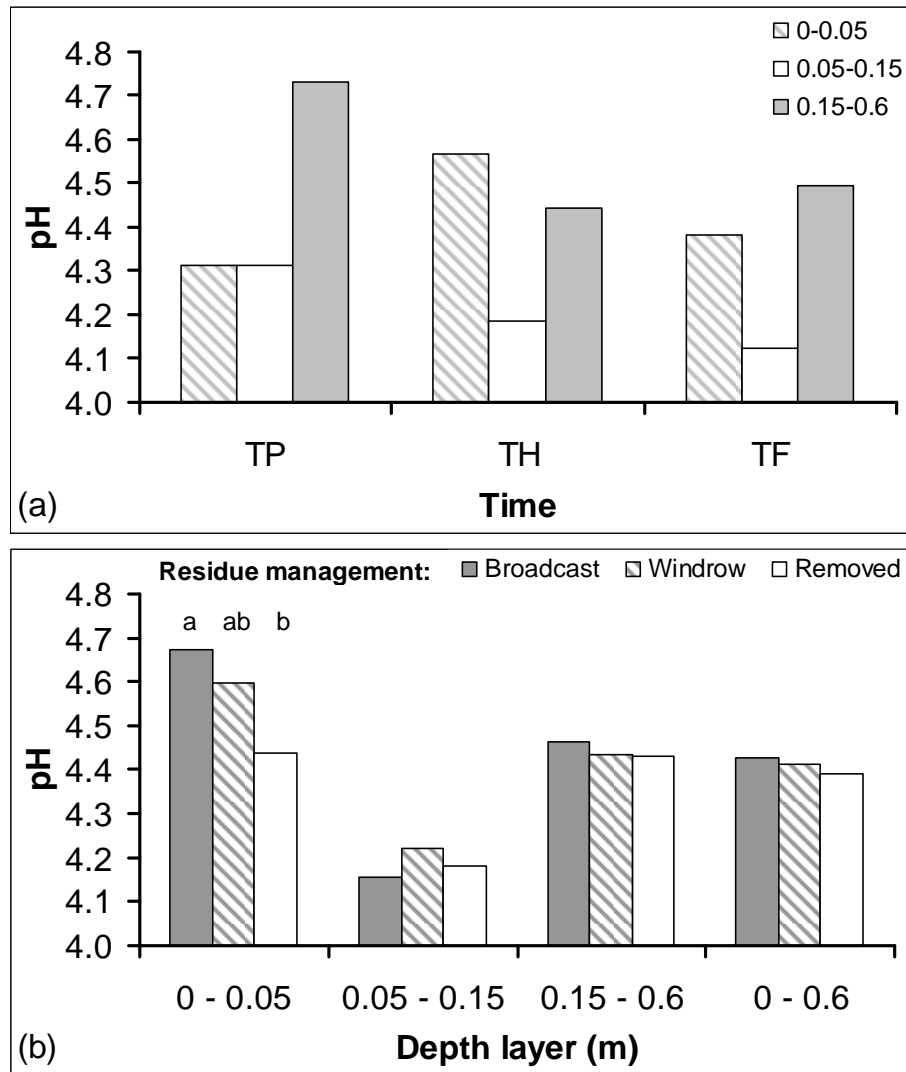
Figure 5.9: Change in soil pH in various depth layers at Shafton (a) at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF), and (b) with residue management at TH (0 – 0.6 m is a depth weighted average). Treatments with different letters are significantly different ($p<0.05$).

b)   Site Nutrient Pools

Initial assessment of the soil at Shafton (**Tables 3.4** and **3.5**) indicated that it is relatively high in organic C and clay, yielding a relatively high CEC. In addition, the high P fixing capacity of this soil was reflected in the low available soil P results.

The total quantity of N, P, K, Ca and Mg measured in both soil and residues did not significantly change over time (ANOVA data not shown). However, they were generally highest at TH (**Figure 5.10**). These increases in nutrient contents between TP and TH are most likely due to the reasons discussed earlier for this phenomenon at Rattray.
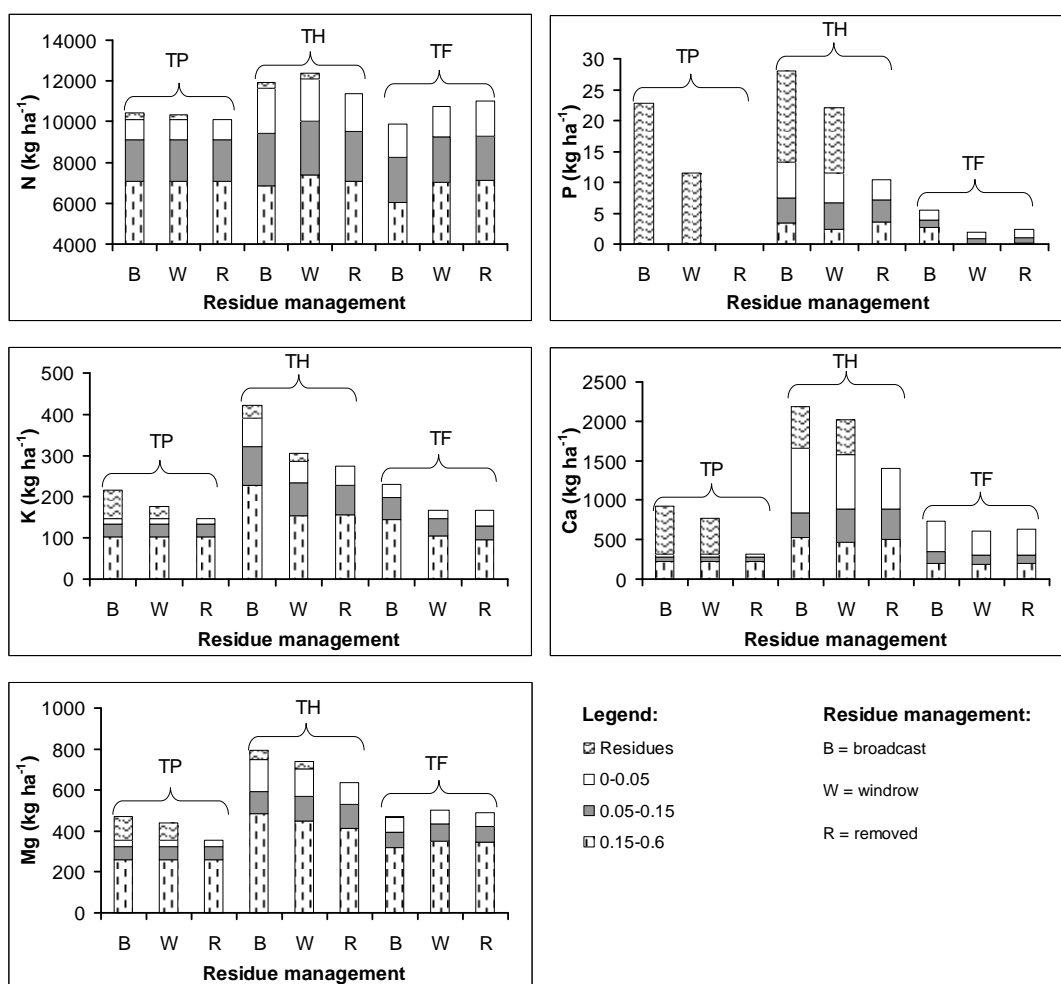
Figure 5.10: Effect of residue management on average total N, P (Bray-2) and exchangeable K, Ca and Mg quantities in soil (0 – 0.6 m) and elemental contents of residues at Shafton at planting (TP), harvesting of sub-plot trees (TH) and final soil measurement (TF). Soil sampling strategy at TP may have resulted in substantially lower quantities of nutrients being displayed as the individual 0 – 0.5, 0.5 – 0.15 and 0.15 – 0.3 m layers were determined from a bulked sample.

An extremely high proportion of total P was held in residues at TP, as a result of the small amount of plant-available P measured (**Table 5.3**). This is most probably due to the high P-fixing capacity of the Hutton soil, but may be exacerbated by the inability of the Bray-2 analysis to extract all plant available soil P. In contrast, soil N comprised the majority of site N (**Table 5.3**).

Table 5.3:   Nutrients held in broadcast and windrow residues as a percentage of that held in the soil $(0 – 0.6 \text{ m})^a$ at TP at Shafton.

Nutrient	Broadcast (%)	Windrowed (%)
N	3.1	2.3
P	31508.0	15823.0
K	46.6	20.0
Ca	196.1	146.5
Mg	34.1	24.1

[a]   Soil nutrients measured were total soil N, available soil P (Bray-2), and exchangeable soil K, Ca and Mg.

Compaction treatments and residue management (but not the interaction between them) often significantly affected soil and site macronutrient pools at TH and TF (**Table 5.4**; **Figure 5.10**; **Appendices 5.8** and **5.9**). At TH, significantly greater amounts of surface N and P, and total P, were found in C_M treatments than the other treatments. This may be a result of the soil environment, particularly soil water content, created by the moderate amount of compaction, for the decomposition of residues. It is also possible that the 3-wheel logger mixed the residues with soil which led to a faster decomposition of the residues. Although this same machine was used in the C_H treatments, the subsequent use of the forwarder may have reduced this effect. At TF after the fire, however, soil N was significantly affected by the interaction between compaction treatments and residue management (**Appendix 5.9**) as well as by compaction treatments alone. The interaction effects were rather complex, but overall, soil N content decreased with increasing compaction intensity. This may be due to the wildfire, as the intensity of the fire (measured by tree damage) was decreased in the order $C_L > C_M > C_H$, although this was not significant ($p = 0.098$; data not shown). In addition, compaction would have affected soil water characteristics, and may have increased the proportion of N transformed into forms that are easily leached or volatilised.

Table 5.4: Significant results of residue management and compaction treatment effects on mean macronutrient values (kg ha^{-1}) of soil depth layers[a] and total nutrients (residues + soil 0 - 0.6m) at Shafton at harvesting of sub-plot trees (TH) and final soil measurement (TF). Treatments with different letters are significantly different ($p<0.05$) for each nutrient.

TH			
Residue management:	**Broadcast**	**Windrow**	**Removed**
N (0 – 0.05 m)	2209[a]	2083[ab]	1840[b]
P (0 – 0.05 m)	5.72[a]	4.78[ab]	3.34[b]
P (total)	28.0[a]	22.1[a]	10.5[b]
K (0 – 0.05 m)	69.6[a]	50.6[b]	47.5[b]
K (total)	422[a]	305[b]	274[b]
Ca (0 – 0.05 m)	821[a]	688[ab]	512[b]
Ca (total)	2269[a]	2017[a]	1401[b]
Mg (0 – 0.05 m)	156.3[a]	134.9[a]	104.4[b]
Compaction:	**Low**	**Moderate**	**High**
N (0 – 0.05 m)	1914[b]	2257[a]	1962[b]
P (0 – 0.05 m)	4.32[b]	5.81[a]	3.70[b]
P (total)	21.7[a]	25.1[a]	13.8[b]
TF			
Residue management:	**Broadcast**	**Windrow**	**Removed**
K (0 – 0.05 m)	30.2[ab]	20.6[b]	37.2[a]
Compaction:	**Low**	**Moderate**	**High**
N (0 – 0.05 m)	1874[a]	1527[ab]	1442[b]

[a]   Soil nutrients measured were total soil N, available soil P (Bray-2), and exchangeable soil K, Ca and Mg.

At TH in the top 0 – 0.05 m of soil, all macronutrients were significantly and consistently reduced by residue removal. At that time, total (i.e. residues plus soil) site P, K and Ca were the only macronutrients significantly affected by residue management, probably because of the large proportion that residues contributed to these site pools (**Table 5.3**). The significant response of surface soil N to residue management was unexpected as a result of the very small contribution of residues to site N pools. However, the well-established positive relationship between soil organic C and total N content may have been the main cause (e.g. Herbert, 1991). In contrast at TF, only surface soil K was significantly affected by residue management, and was lowest in the W treatment, probably in response to the wildfire. In addition, residue management alone (i.e. not compaction treatments or interaction effects) significantly affected the quantity of several nutrients contained in the residues (**Appendix 5.10**).

Despite residues representing a very small proportion of some soil nutrients, particularly N, there was a significant increase in measured soil macronutrients, particularly in the surface 0 – 0.05 m, at TH with residue retention. Although generally not significant, du Toit *et al.* (2008) also found increased quantities of N, P and K in the soil (between 0 and 0.1 m) of broadcast residue plots compared to residue removed plots, particularly in the first 2 years of their trial. The significantly higher soil K at TF at Shafton with windrowed residues is most likely the result of indirect wildfire effects, rather than direct residue management effects.

Although Shafton's residues were sampled 9 months after felling of the previous rotation, they contained more nutrients (kg ha^{-1}), with the exception of K, than the residues at Rattray (sampled 2 months after felling). Even though trees at Shafton were slightly smaller; they probably had larger, more nutrient rich, canopies due to the slightly higher fertility of the site, and these would have decomposed more slowly than at Rattray due to the cooler climate of this site. In addition, a lower allocation of biomass to the canopy, and lower nutrient content of various components has been found in *E. camaldulensis* trees when compared to *E. grandis* (Pagano *et al.*, 2009). Although the previous stand at Rattray was *E. grandis* x *camaldulensis*, it could be assumed that biomass allocation and nutrient contents were between that found in *E. camaldulensis* and *E. grandis* trees alone. Since K is easily leached from plant residues, the longer the decomposition period, the lower the K content. This may explain the low K values of residues at Shafton when compared to that of Rattray.

5.4.   Conclusions

The results indicate that the effect of compaction and residue management on soil organic C varies with soil type, residue load and climate. Compaction only had a significant effect at Rattray at TH, while residue retention significantly increased soil C at Shafton at TH. The longevity of this latter response could not be determined due to the wildfire. The lack of significant residue management effects at Rattray is most likely due to the climate which encourages a more rapid decomposition of organic matter. The significant effect of compaction treatments,

in contrast, is a result of a change in the soil environment, and therefore decomposition dynamics. The indications are that residue removal, particularly on sites with large quantities of residues that slowly decompose, may be detrimental to soil organic C stores. It would be expected that on sites with inherently low soil organic C coupled with less residues that residue management would considerably affect long term soil C contents, and thus LTSP. However, on sites such as Rattray, where the climate and sandy soil leads to rapid decomposition of residues, residue management is not as central to LTSP, as on sites with higher inherent soil organic C, finer texture and with large residue loads, such as Shafton.

Neither compaction nor the interaction between compaction and residue management had any significant effect on soil pH at either trial. However, residue retention consistently increased soil pH, even if this was short-lived, as in the case of Shafton. Considering the generally acidic pH of many South African forestry soils, residue removal, without the application of ameliorants (such as lime) would further acidify soils, which has implications for nutrient availability and leaching, and plant growth. In contrast, residue retention may improve the pH status of currently acidic soils.

Compaction treatments only significantly affected soil N and P pools at Shafton, and again the occurrence of the wildfire has limited the prediction of longer-term effects. The results obtained at TH at Shafton, as well as the lack of compaction treatment effects on soil nutrient pools at Rattray at TH and TF, indicate that compaction effects on nutrient pools need to be determined across a range of soil types before its importance to long-term site productivity can be quantified.

Residue management often had significant effects on soil nutrient pools. At Rattray, these effects were only significant on soil Ca and Mg at TF, and can therefore be linked to the changes in soil pH. Although no significant residue management effects were found on N, P and K soil pools at Rattray, the substantial proportion of these nutrients, as well as Ca and Mg, contained in residues indicates that repeated residue removal will negatively affect long-term nutrient pools at similar sites. The lack of significant residue management effects

on N, P and K soil pools is most likely a result of either plant uptake or leaching of any additional nutrients supplied by residues. This would have occurred since not only does this soil have a low ECEC, but also because there were no significant residue management effects on soil C.

Although residues at Shafton represented a relatively small proportion of some soil nutrient pools, e.g. N and Mg, residue retention significantly increased, at least in the surface soil, quantities of N, P, K, Ca and Mg at TH. These increases are linked to the increases measured in soil C, as found by others (e.g. Jurgensen *et al.*, 1997; Gonçalves *et al.*, 2007, Tiarks and Ranger, 2008). Unless residue removal at similar sites is compensated by adequate applications of fertiliser, particularly P and Ca, it represents a large threat to productivity.

Finally, residue removal, even on sites with substantial soil nutrient pools, will negatively affect productivity from a nutritional stand-point, both in the short and long-term. Nutrients that are most at threat by residue removal appear to be P and Ca, and similar conclusions have been reached by others (Sanchez *et al.*, 2006; Gonçalves *et al.*, 2008; Mendham *et al.*, 2008; Tiarks and Ranger, 2008). Although signs of P deficiencies in plantations are becoming more common, Ca deficiencies are not often found. However, evidence from this and other studies is that if removals continue, Ca may become problematic in the future (Johnson, 1994; Fölster and Khanna, 1997; Dovey, 2005). Although quantities of site Mg are generally not substantially reduced by biomass removals, concentrations in a soil are often positively related to those of exchangeable Ca (Tiarks and Ranger, 2008). The retention of residues on cooler sites can also increase soil organic C, which has implications for nutrients, water, and the susceptibility to compaction of such sites. Compaction does not appear to affect soil nutrient pools as much as residue management, as its effects are through the alteration of the soil environment for organic matter decomposition, and the ability of plant roots to obtain, particularly immobile, nutrients.

Chapter 6

Effect of Compaction Treatments and Residue Management on Soil Water and Aeration

6.1.   Introduction

In South Africa, increased productivity of eucalypt plantations has been documented on sites with high annual rainfall or irrigation (Schönau and Grey, 1987; Smith *et al.*, 2005; Campion *et al.*, 2006). This, in conjunction with the relationships found between growth and soil water supply and availability (Boden, 1991; Smith and du Toit, 2005), has led to the conclusion that plantation growth in this country is substantially dependent on water supply and availability (Theron, 2000). Soil aeration status is also often considered important, as it affects the activity, size and community structure of soil microorganisms (particularly the nitrifying and general-purpose decay organisms), soil chemistry and plant root respiration (important for nutrient uptake), and therefore the growth of plants (Wolkowski, 1990; Brady and Weil, 1999).

In South African plantations, soil water supply is not easily affected by management as it is mainly dependent on rainfall and/or groundwater supply. However, soil water availability and aeration are greatly affected by any management practices that impact the soil.

6.1.1.   Soil water availability and aeration

Although the ideal measure of soil water availability and supply would be the continuous measurement of the water status of trees, this was not possible in this study, and therefore estimation of various soil water retention characteristics was performed. Available water capacity (AWC) is water held in the soil between field capacity, generally regarded as a matric potential of -10 kPa, and wilting point (-1500 kPa). It is considered to be the portion of soil water that is plant available and is therfore an index of the drought resistance of a soil and is one of

the most important determinants of soil productivity (Hall *et al.*, 1977; Bauer and Black, 1992). A portion of AWC is readily available to plants (RAW) and is the water held in the soil between field capacity and a matric potential of -100 kPa (Smith, 1995; Moodley *et al.*, 2004). Soil aeration is considered limiting to both plant growth and microbial activity, if air-filled porosity (ε_a) is less than 10% at field capacity (Grable and Siemer, 1968; Dexter, 1988; Topp *et al.*, 1997). The amount of water held in the soil at different matric potentials is dependent on the water retention characteristics of the soil which are affected by soil properties and management (Rawls *et al.*, 1991; Green *et al.*, 2003; Fernández-Gálvez and Barahona, 2005).

Comprehensive reviews of the many soil properties that affect water retention are available (e.g. Rawls *et al.*, 1991; Or and Wraith, 2000; Green *et al.*, 2003). Management effects on soil water retention are generally a result of changes in soil bulk density (or pore volume, size distribution and continuity) and organic carbon (often as a result of plant residue management; Rawls *et al.*, 1991; Jones *et al.*, 1999; Green *et al.*, 2003).

6.1.1.1.   *Total porosity and pore-size distribution*

Total porosity affects total soil water retention and is mainly affected by bulk density, decreasing proportionally with increases in bulk density (Kay and Angers, 2000). In contrast, pore-size distribution generally has greater effects on water retention characteristics, soil aeration, infiltration, hydraulic conductivity and plant root growth. It is substantially affected by management practices, especially those that result in changes in soil bulk density and organic carbon, and is an important property when understanding the response of soils to various management practices (Soane, 1990; Brady and Weil, 1999). Pore-size distribution can be determined from water retention data in conjunction with total porosity (Kay and Angers, 2000). Pores are usually categorised according to size and function as macro-, meso-, or micropores. Each of the categories of pores are affected to varying extents by different soil properties. Several authors (e.g. Blackwell *et al.*, 1990; Powers, 1990; Wolkowski, 1990; da Silva and Kay, 1997a; Kay and Angers, 2000; Miller *et al.*, 2004) have thoroughly discussed these aspects.

6.1.1.2.   Effect of soil bulk density and organic carbon on water retention

Changes in soil bulk density and organic carbon have effects on water retention at different matric potentials (and therefore soil water availability and aeration). Water retention at lower levels of matric potential (i.e. <-10 kPa) is mainly dependent on pore-size distribution and therefore soil structure, bulk density and porosity (Rawls *et al.*, 1991). As matric potential decreases with drying of the soil (> -150 kPa) water adsorption and specific surface properties such as soil texture, mineralogy and organic matter become increasingly important (Rawls *et al.*, 1991; Kern, 1995). Both organic carbon and soil bulk density have a strong effect on soil structure and porosity (Rawls *et al.*, 1991; Skopp, 2000), and have been used in the prediction of water retention (e.g. Schulze *et al.*, 1985; Kern, 1995; Smith, 1995). In addition, the magnitude of the effects of changes in soil bulk density and organic matter vary with texture, clay mineralogy and pore geometry (Rawls *et al.*, 1991; Or and Wraith, 2000; Smith *et al.*, 2001). Generally, increases in bulk density result in an increase in volumetric water content and water holding capacity, and a decrease in porosity, in particular macroporosity, which leads to a decrease in aeration (Ares *et al.*, 2005). In contrast, increases in soil organic matter result in decreases in bulk density, and increases in water holding capacity- particularly at increasingly negative values of matric potential (Henderson, 1995; Kay, 1998).

In general, coarse textured, low organic matter soils (such as that at Rattray) have a low total porosity, but a large proportion of macropores that result in high hydraulic conductivity and air permeability. In these soils, soil water is mainly held in the pore spaces between the individual soil particles. In contrast, finer textured, higher organic matter content soils (such as that at Shafton) often have high total porosities, but a lower proportion of macropores leading to lower hydraulic conductivity and air permeability. In addition, soil water is held in both the pore spaces between soil particles and aggregates (which are affected by organic matter) and in the pores in organic matter (Brady and Weil, 1999; Kay and Angers, 2000). When a soil is compacted, macroporosity decreases (and micro- and mesoporosity increase), lowering aeration, and often increasing water content at

field capacity (Greacen and Sands, 1980; Incerti *et al.*, 1987; Smith, 1995).

6.1.2. Least limiting water range

A number of measures have been proposed to integrate soil physical properties that affect plant growth. One of these is the least limiting water range (LLWR), originally termed by Letey (1985) as the "nonlimiting water range" (NLWR; da Silva *et al.*, 1994). This combines measures of soil strength and aeration at varying soil water contents, to define a range over which plant growth would not be restricted (**Figure 6.1**).

For each soil, the soil water retention characteristics and the variation in soil strength with varying soil water content must be determined. The soil water contents at which soil physical characteristics, specifically aeration, soil strength and matric potential, become restrictive to plant growth must be determined. The LLWR is the range of soil water contents within which a crop is not limited by soil water or air requirements, and is able to extend and proliferate its root system (Topp *et al.*, 1997; Reynolds *et al.*, 2002). It has been used in two ways:

1. As an indicator of management-induced changes in soil physical properties that would affect sustainable crop production (Topp *et al.*, 1994; Smith, 1995; da Silva and Kay, 1997a).
2. To determine the frequency with which soil water content falls within the LLWR; and the relationship between this and crop growth (da Silva and Kay, 1996; Kelting *et al.*, 2000).

Generally, soils with poor physical conditions have a small LLWR and require careful management for adequate plant growth and to prevent decreases in the LLWR (Zou *et al.*, 2000; Reynolds *et al.*, 2002). Therefore LLWR can be used to determine the most appropriate management of a particular soil to maintain or improve the LLWR (Letey, 1985; da Silva and Kay, 1997b). In South African forestry soils, Smith (1995) not only determined the LLWR, but extended its use and developed the "compaction envelope". This incorporates changes in soil water, air, bulk density and strength as a result of compaction for a particular soil.
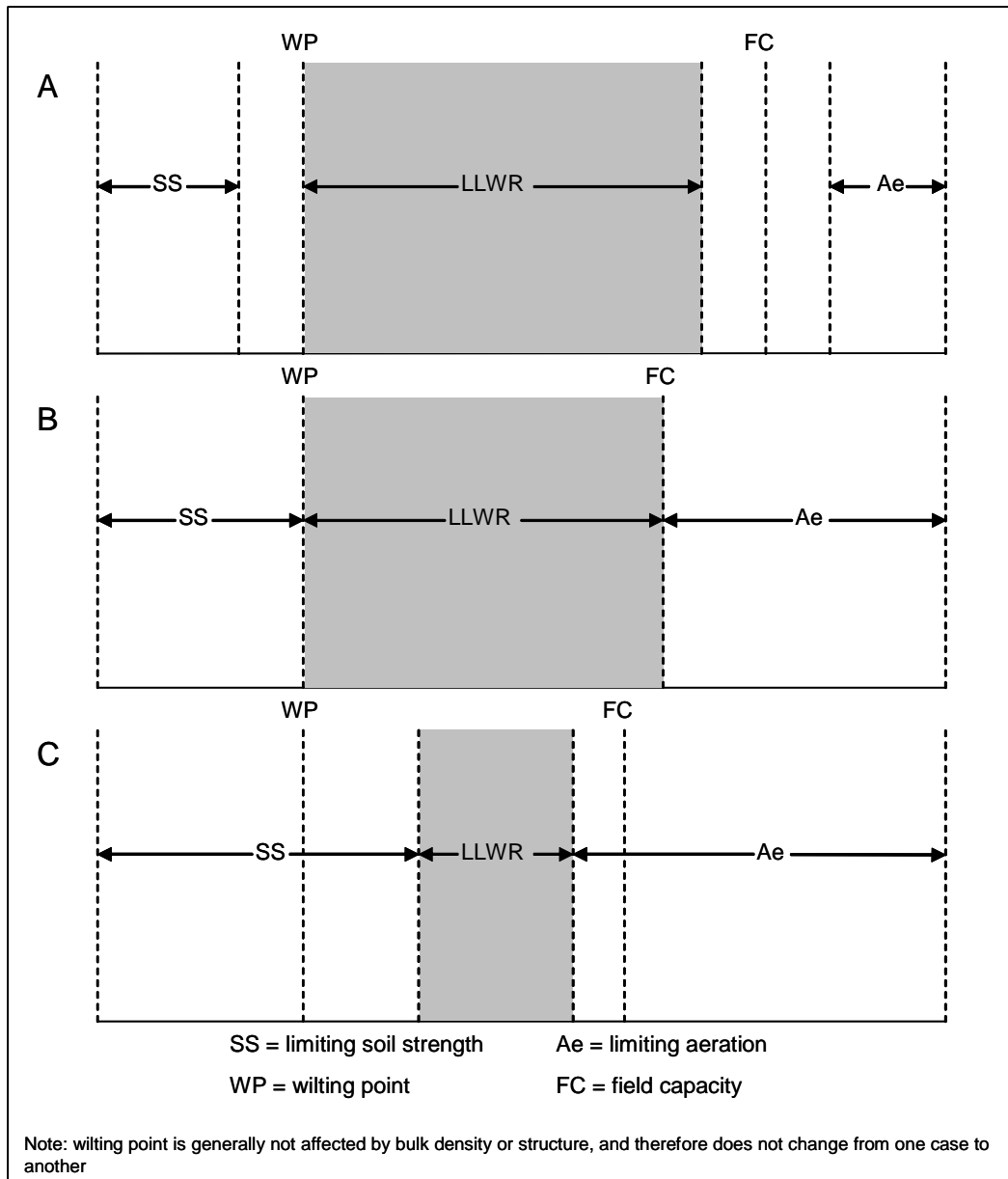
Figure 6.1: Generalised relationships between soil water content and soil physical factors that are limiting to plant growth. The effects of increasing bulk density and decreasing aggregation (structure) on the least limiting water range (LLWR) are demonstrated from A to C (adapted from Letey, 1985 and Smith, 1995).

6.1.3. Soil bulk density and organic carbon effects in forestry soils

Smith *et al.* (2001) quantified the effects of compaction on a range of South African forestry soils of varying texture and organic carbon content. This was performed by reconstitution of cores by packing of air-dry sieved (<2 mm) soil to desired bulk densities. It was found that in all cases compaction altered water retention characteristics of soils and therefore AWC. However, as a result of variation in soil properties resulting in complex responses of (and interactions between) pore geometry and compressive processes, a relationship between AWC and bulk density changes on different soil types could not be obtained.

Soil from the Shafton trial was included in the study by Smith (1995). It was found that in reconstituted cores increasing bulk density from 0.906 to 1.251 Mg m^{-3} decreased soil water content at matric potentials between 0 and -200 kPa and 0 and -2 kPa on a mass and volume basis, respectively. Thereafter, soil water contents increased with increasing bulk density, although not substantially when expressed on a mass basis. This resulted in a decrease in both AWC and RAW with increasing bulk density. The LLWR was limited at bulk densities above approximately 1.06 Mg m^{-3} by soil strength alone, and also at field capacity by aeration above a bulk density of 1.16 Mg m^{-3}.

During the previous rotation at Rattray, increases in soil bulk density were generally found with increasing intensity of harvesting operation (or machinery mass and movement). A concomitant increase in AWC was also found, although these changes could not be directly related to those reported in bulk density. Although air-filled porosity was also affected, it was not affected to a limiting level under any circumstances (Smith and du Toit, 2005).

As a result of the soil types occurring in forest plantations, and government restrictions regarding planting in water drainage areas, soil aeration in most South African forestry soils is generally adequate i.e. soils are rarely wet enough to attain ε_a values of less than 10% (Musto, 1994; Smith, 1995).

6.1.4. Soil water supply

Compaction can reduce soil water supply by reducing macroporosity which lowers the infiltrability of the soil and leads to runoff (Radcliffe and Rasmussen, 2000). However, plantations rarely have an even soil surface since they often do not undergo major tillage operations. This leads to "hollows" in the soil surface caused by trees (particularly roots and stumps from previous rotations), management practices (particularly machinery movement) and the natural activity of fauna. This results in any runoff ponding in these "hollows" and infiltrating into the soil.

Residue management may also affect soil water supply. Residue removal increases the likelihood of the formation of a soil surface crust due to raindrop impact that can reduce infiltration and increase runoff (Radcliffe and Rasmussen, 2000). Residue retention has had positive (e.g. Ginter *et al.*, 1979; Kelting, 1999; O'Connell *et al.*, 2004a; Roberts *et al.*, 2005) or initially positive, and later minor (e.g. Smethurst and Nambiar, 1990a; 1990b) effects on soil water content. These positive effects are thought to be a result of the:

a. Physical protection of the soil from evaporation by lowering soil surface temperature (through shading) and exposure to wind.
b. Mulching effect of residues (Smethurst and Nambiar, 1990b; O'Connell *et al.*, 2004a; Roberts *et al.*, 2005).

The prevention of soil surface sealing adds to this effect (Green *et al.*, 2003). In South Africa, the effect of plantation residue management on soil water characteristics has not been investigated.

6.1.5. Chapter rationale and objectives

The literature reviewed indicated that soil compaction and residue management may affect water retention, availability and capacity, as well as soil aeration. The response and magnitude of water retention, availability and capacity to these effects is dependent on inherent soil properties such as particle size distribution, organic matter and pore geometry. The objectives of this section of the study were

to determine the effect of soil compaction and residue management treatments at each trial on:

- Soil water retention characteristics.
- Soil water availability.
- Soil aeration.
- Least limiting water range.

However, as a result of time and logistical constraints, these effects could not be determined directly. The following investigations were therefore carried out prior to resolution of these objectives:

1. The effects of soil bulk density and organic carbon on soil water and aeration characteristics were first determined on selected soil cores.
2. The effects of soil compaction and residue management treatments on soil organic carbon and bulk density were ascertained (**Chapters 4** and **5**).

These results were then combined to estimate the effects of the treatments on soil water and aeration characteristics.

6.2.   Materials and methods

Soil compaction and residue management effects on soil C and bulk density have been discussed earlier (**Chapters 4** and **5**). The water and aeration characteristics of the 56 undisturbed soil cores taken at each trial (**Section 3.2.2.2**) were determined in the laboratory (**Section 3.3.1.3**).

6.2.1.   <u>Statistical analysis of the effect of soil bulk density and organic carbon on soil water retention and availability (undisturbed soil cores)</u>

In the undisturbed soil cores, both bulk density and C were found to have significant effects on soil water content (θ) at each matric potential measured at both sites (data not shown). However, significant relationships between bulk density and soil C at both sites prevented the use of multiple linear regression analysis to determine the combination of these factors on soil water retention (data

not presented). Therefore results from the cores were grouped according to their bulk density and C content (separately for each site). The groups were determined by percentiles, i.e. those falling below the 25th percentile, above the 75th percentile, and those between the 25th and 75th percentile. This resulted in three groups for bulk density, and three groups for C. These groups were then used in regression analysis of the data. In addition, the effects of the combination of bulk density and C values were determined by combining each bulk density group with each C group. This resulted in nine (3 * 3) groups, which were then used in the statistical analysis in the same manner. Water retention is generally discussed on a mass basis (i.e. kg kg^{-1}; θ_m), rather than a volume basis (m^3 m^{-3}; θ_v) as a result of the dependency of θ_v on bulk density. Where appropriate, information pertaining to θ_v is included.

6.2.2. Effect of soil bulk density and organic carbon on least-limiting water range (undisturbed soil cores)

To simplify the changes in the LLWR with bulk density and C, regression equations for the effect of combinations of three levels of bulk density and three levels of C were utilised to calculate θ_m and θ_v at field capacity and wilting point.

6.2.3. Treatment effects on soil water availability and least-limiting water range (undisturbed soil cores)

The effect of the treatments on soil water availability and LLWR were only determined where significant effects of the treatments were found in soil bulk density and C data (**Chapters 4** and **5**). Soil water contents at various values of bulk density and C were then calculated at field capacity, -100 kPa and wilting point from regression equations. Where r^2 values were low (i.e. r^2<0.5), θ values were calculated using available regressions and converted. For example, no regression is available to calculate the effect of bulk density in the 0 – 0.2 m layer on θ_v at field capacity at Rattray. Therefore the effect was calculated using the

corresponding regression for θ_m and then converted to θ_v. Statistical analysis of the resultant data was not performed as the results would be identical to those of treatment effects on bulk density and C.

6.2.3.1. Compaction treatments

Bulk density values (for each site) were estimated from Troxler bulk density values using the calibrations developed in **Appendix 3.6**. These were then averaged for each plot, at each plot position i.e. interrow or stumpline, at each depth. These values were then used to calculate the average changes in AWC and RAW (from data in **Chapter 4**) in the top 0.3 m of soil as a result of the compaction treatments at each site.

6.2.4.   Statistical analysis of treatment effects on soil water content (thetaprobe)

Thetaprobe measurements were taken on each plot on three separate occasions during the study at Rattray. In contrast, as a result of difficulties during sampling (**Section 3.2.4**), only on one occasion was θ_v measured with a thetaprobe at Shafton.

However, on all three occasions at Rattray, and the single occasion at Shafton, there were significant effects of compaction, residue management and their interaction on θ_v, but no significant differences between interrow and stumpline measurements (data not shown). The results were therefore analysed using a two-way ANOVA, with the variables being compaction treatment and residue management (for both trials).

6.3. Results and discussion

6.3.1. Effect of bulk density and organic carbon on soil water (undisturbed soil cores)

6.3.1.1. Rattray

a) Water retention

The range of values for soil bulk density and C (% m/m) are presented in **Table 6.1**. The levels of these factors were then used to group cores into nine classes, varying in bulk density and C.

Table 6.1: Ranges of bulk density and soil carbon (C; % m/m) values at Rattray grouped according to percentile ranges (undisturbed soil cores).

Percentile range	Bulk density (Mg m^{-3})
0 – 25%	1.376 – 1.522
25 – 75%	1.523 – 1.632
75 – 100%	1.633 – 1.724
	C (%)
0 – 25%	0.437 – 0.644
25 – 75%	0.645 – 0.954
75 – 100%	0.955 – 2.754

Increasing bulk density had a significantly negative effect on θ_m, particularly at higher matric potentials (i.e. > -10 kPa), while C significantly increased water retention throughout the water retention curve (**Figure 6.2**; **Table 6.2**; **Appendix 6.1**). The regression equations and associated statistical information for the data in **Figure 6.2,** and for the combination of both bulk density and C groups, are given in **Table 6.2**. With increasing bulk density, θ_v decreases at matric potentials greater than -4 kPa, whereas the effect of increasing C on θ_v mirrors the response found in θ_m (at any matric potential; **Appendix 6.2**).
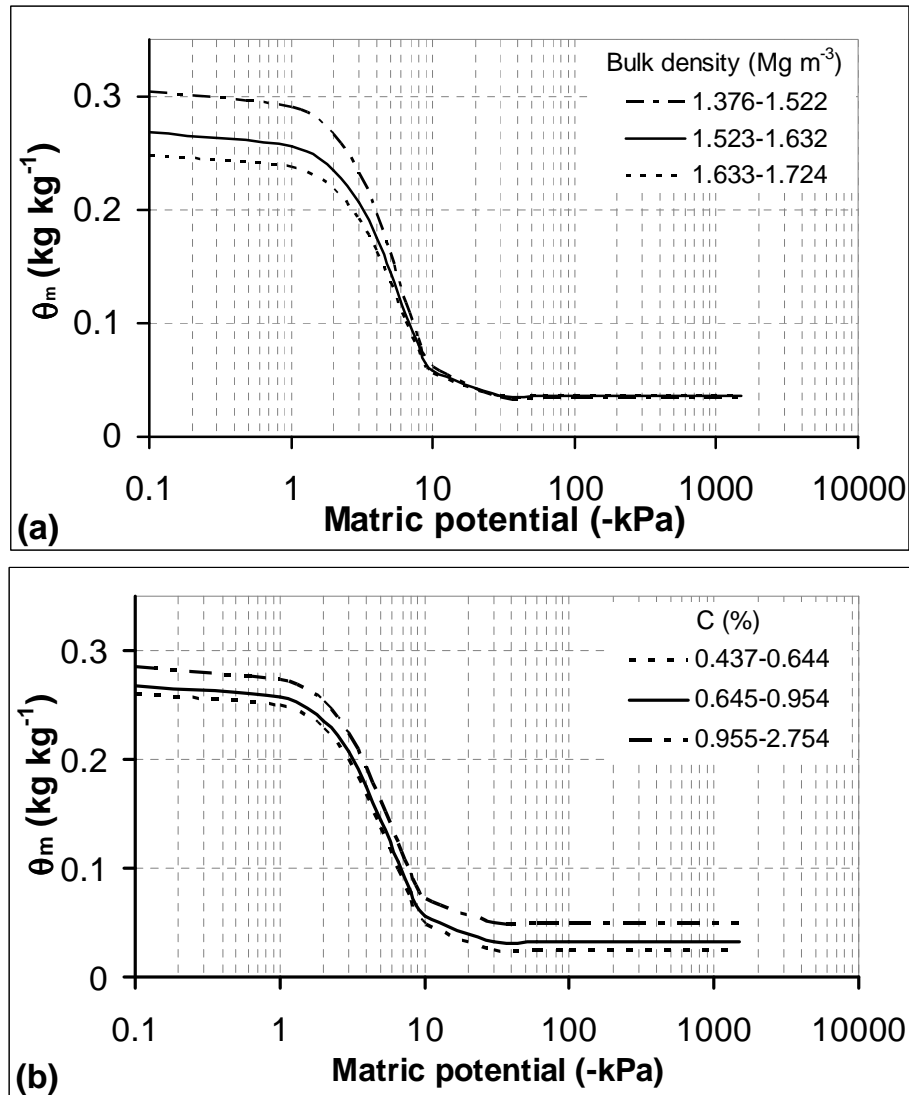
Figure 6.2: The effect on soil water content (θ_m) of ranges of (a) bulk density and (b) soil carbon (C; % m/m) at Rattray (of undisturbed soil cores taken between 0 and 0.5 m).

The effect of both bulk density and C at each matric potential measured on θ_m on all cores between 0 and 0.5 m was determined (**Table 6.3**; **Appendix 6.1**). These results show that bulk density had significant negative effects on θ_m from saturation to a matric potential of only -2 kPa. Soil C also had an effect over this upper range of matric potentials. However, the poorly correlated negative relationship between bulk density and C (r^2 = 0.324; data not shown) may have been the cause of this. The higher r^2 values of the relationships suggest that bulk density was the primary cause of changes in soil water retention over this high matric potential range.

Table 6.2: Coefficients of regression equations[†] and associated percentage of variance accounted for by equations (r^2) of the effects of ranges of bulk density (BD) and soil carbon (C), as grouped in **Table 6.1**, on mass soil water content (of undisturbed soil cores) at Rattray. All regression equations were highly significant ($p<0.001$); n = 56.

BD/C	Range (%)	a	c	b	m	r^2
BD	0 – 25	0.312	-0.278	-0.359	-3.624	
	25 – 75	0.275	-0.239	-0.359	-3.624	0.927
	75 – 100	0.254	-0.219	-0.359	-3.624	
C	0 – 25	0.269	-0.245	-0.359	-3.631	
	25 – 75	0.267	-0.229	-0.359	-3.631	0.927
	75 – 100	0.307	-0.266	-0.359	-3.631	
BD, C	0 – 25, 0 – 25	0.274	-0.249	-0.360	-3.609	
	25 – 75, 0 – 25	0.271	-0.246	-0.360	-3.609	
	75 – 100, 0 – 25	0.245	-0.227	-0.360	-3.609	
	0 – 25, 25 – 75	0.322	-0.275	-0.360	-3.609	
	25 – 75, 25 – 75	0.272	-0.234	-0.360	-3.609	0.936
	75 – 100, 25 – 75	0.257	-0.219	-0.360	-3.609	
	0 – 25, 75 – 100	0.329	-0.291	-0.360	-3.609	
	25 – 75, 75 – 100	0.288	-0.243	-0.360	-3.609	
	75 – 100, 75 – 100	0.241	-0.208	-0.360	-3.609	

[†] The regression equation used is of the Gompertz form i.e. y = a + c * EXP(-EXP(-b * (x – m))), where y = water content (θ_m; kg kg^{-1}), x = matric potential (kPa), and a, c, b and m are coefficients.

Table 6.3: Significant regression equations ($p<0.001$) and percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on soil water content (θ_m; kg kg^{-1}) of 0 – 0.2 and 0.4 – 0.5 m undisturbed soil cores at various matric potentials (Ψm) at Rattray. n = 56.

Ψm (kPa)	Regression equation	r^2
0	θ_m = 0.875 - 0.382 BD	0.871
-1	θ_m = 0.814 - 0.357 BD	0.838
-2	θ_m = 0.764 - 0.333 BD	0.741
0	θ_m = 0.228 + 0.043 C	0.543
-1	θ_m = 0.205 + 0.042 C	0.573
-2	θ_m = 0.193 + 0.047 C	0.620
-3	θ_m = 0.188 + 0.031 C	0.557
-1500	θ_m = 0.006 + 0.007 C	0.720

This exercise was repeated on the θ_v data (**Appendix 6.3A**). A similar negative effect of bulk density on θ_v between saturation and -2 kPa was found. Increasing C generally increased θ_v from -30 to -1500 kPa, however, several regressions were excluded as a result of their low r^2 values.

In both θ_m and θ_v data, no significant effects of either C or bulk density were found between -3 and -100 kPa. This may be a result of the change-over from bulk density to organic carbon as the principal factor affecting the relationship between θ and matric potential, or due to the heterogeneous nature of the undisturbed soil cores.

Similar effects of bulk density on water retention characteristics in South African forestry soils of sandy loam texture have been previously found (Smith, 1995). Decreases in the effect of bulk density with decreasing matric potential in other sandy soils, is also documented (Hill and Sumner, 1967; Rawls *et al.*, 1991; Rab, 1994). Similarly, organic carbon has been found to increase water retention at all matric potentials (Hall *et al.*, 1977; Rawls *et al.*, 1991; 2003).

The results indicate that soil bulk density only has a considerable effect on soil water retention under very wet conditions at this site. However, at wilting point, soil organic carbon strongly influences water retention. Even small increases in soil C (e.g. of 0.1%) result in a substantial increase in water retention at this matric potential.

b)   Porosity and pore-size distribution

From the water retention data, the effects of soil bulk density and C on total porosity and pore-size distribution were determined (**Table 6.4**). Total porosity decreased with increasing bulk density and decreasing C. These decreases were mainly through the loss of macroporosity, and an increase in mesoporosity, a phenomenon often associated with compaction (Smith, 1995; Brady and Weil, 1999). The results show that small increases in organic carbon may partially negate increases in soil bulk density by increasing mesoporosity. These increases in mesoporosity may increase AWC. Air-filled porosity was

consistently above 0.32 m^3 m^{-3} (data not shown), well above the minimum value of 0.1 m^3 m^{-3} considered adequate for aeration.

Table 6.4: Change in total soil porosity and pore-size distribution (PSD) with percentile ranges of soil bulk density and soil carbon (of undisturbed soil cores) at Rattray.

| Pores | Bulk density range | | | | | |
| | <25% | | 25%<BD<75% | | >75% | |
	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)
Micro-	0.001	0.1	0.001	0.1	0.001	0.1
Meso-	0.049	11.1	0.055	13.0	0.058	14.0
Macro-	0.393	88.8	0.369	86.8	0.356	85. 9
Total	0.443	100.0	0.425	100.0	0.415	100.0
	Carbon range					
	<25%		25%<C<75%		>75%	
	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)
Micro-	0.000	0.1	0.001	0.1	0.001	0.2
Meso-	0.038	9.4	0.056	13.1	0.067	15.2
Macro-	0.371	90.5	0.371	86.8	0.371	84.6
Total	0.409	100.0	0.428	100.0	0.439	100.0

Total porosity values approximately 0.06 m^3 m^{-3} smaller than those obtained in this study were found at the Rattray site in the previous trial (Sibisi, 1998). The discrepancies can be related to the higher bulk densities obtained in that study (**Section 4.3.2.1**).

c)   Water availability

From the water retention regression equations (**Table 6.2** and **Appendix 6.2**), AWC and RAW were calculated for the nine different combinations of soil bulk density and C. Water content was expressed on both a mass and volume basis, as the latter is important for practical applications (**Figure 6.3**).

Bulk density consistently had a negative effect on RAW and AWC on a mass basis. A similar trend was seen when soil water was expressed as θ_v, with the exception of low C soils. Soil C had similar effects on both RAW and AWC on mass and volumetric basis. At low bulk density, increasing C increased RAW and AWC. At high bulk density, increasing C decreased RAW and AWC. At medium

levels of bulk density, RAW and AWC initially decreased, and then increased with increasing C. To simplify the comparative process, RAW and AWC for high bulk density (75 – 100%), low C (0 – 25%; i.e. HL), medium bulk density (25 – 75%), medium C (25 – 75%; i.e. MM) and low bulk density (0 – 25%), high C (75 – 100%; i.e. LH) were compared (**Table 6.5**).
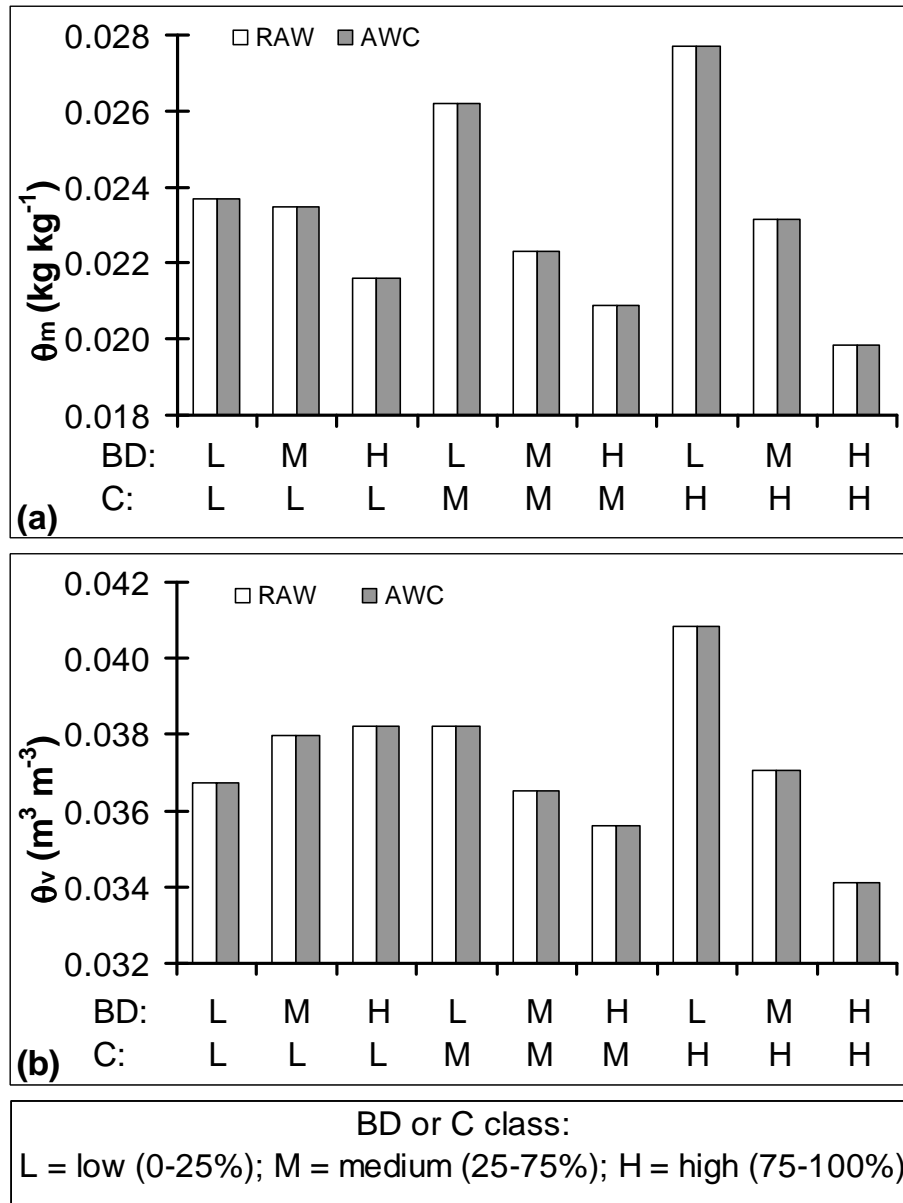
Figure 6.3: The effect of combinations of ranges of bulk density (BD) and soil carbon (C) on readily available water (RAW) and available water capacity (AWC) expressed as (a) mass basis (θ_m), and (b) volumetric basis (θ_v) at Rattray (of undisturbed soil cores between 0 and 0.5 m).

Table 6.5: Effect of selected combinations of bulk density and soil carbon on readily and available water capacity (RAW and AWC, respectively) in undisturbed soil cores between 0 and 0.5 m at Rattray.

Bulk density	Carbon	RAW	AWC	RAW	AWC
		(kg kg^{-1})		(m^3 m^{-3})	
75 – 100%	0 – 25%	0.022	0.022	0.038	0.038
25 – 75%	25 – 75%	0.022	0.022	0.037	0.037
0 – 25%	75 – 100%	0.028	0.028	0.041	0.041

The data in **Table 6.5** indicate that the greatest amount of RAW and AWC occurred when bulk density was at its lowest and C values at their highest. In addition, differences in AWC and RAW between the combinations of bulk density and C were greatest when water content was expressed on a mass basis. This may be a result of volume/bulk density interactions influencing θ_v. In addition, the lack of differences between RAW and AWC indicate the low number of micropores in this sandy soil available to hold water between −100 and −1500 kPa.

If, however, raw data (rather than values derived from regression equations developed from raw data) from the undisturbed soil cores are utilised, RAW averaged 0.036 kg kg^{-1} or 0.058 m^3 m^{-3}, while AWC averaged 0.057 kg kg^{-1} or 0.089 m^3 m^{-3} across all treatments and depths. When the data (not shown) were examined, there were indications that the regressions obtained for water retentivity at Rattray may have over-estimated water content at low matric potentials (i.e. -100 and -1500 kPa).

When data from the cores were interrogated by regression analysis, no significant relationships between water availability (either AWC or RAW) and either bulk density or C were obtained. This may be a result of the low correlation between bulk density and C ($r^2 = 0.324$). This indicates that, as a result of the treatments, there were some soil cores that had a relatively high organic C content- but with a high bulk density; and some with a low C content and low bulk density- perhaps due to disturbance from compaction treatments. This may have resulted in the lack of significant relationships between either soil C or bulk density and soil water availability.

Smith and du Toit (2005) determined AWC to range between approximately 0.050 and 0.085 m^3 m^{-3} at the same site. These values are similar to those determined directly from the soil cores, but substantially higher than those determined from the regressions in this study. However, in Smith and du Toit's (2005) study field capacity was taken at –8 kPa, whereas in this study it was at –10 kPa. If the AWC values of this study developed from the regressions, i.e. **Figure 6.3** and **Table 6.5**, are adjusted using a field capacity water content at –8 kPa, very similar values to those of Smith and du Toit (2005) are obtained.

Bulk density negatively affected AWC and RAW, except in low C soils when water was expressed volumetrically (**Figure 6.3**). Smith and du Toit's (2005) results also did not show a consistent effect of bulk density on AWC. This is in contrast to other studies on sandy soils, which found AWC increased with increasing bulk density (e.g. Smith, 1995; Gomez *et al.*, 2002a). Changes due to bulk density and C in AWC and RAW were mainly the result of changes in field capacity, rather than wilting point (**Table 6.2**). For example, an increase in C alone from the 25-75% range to the 75-100% range resulted in an increase in soil water content of 0.007 kg kg^{-1} and 0.003 kg kg^{-1} at field capacity and wilting point, respectively. This resulted in an increase in AWC of 0.004 kg kg^{-1}. Therefore the relationships between θ at field capacity, bulk density and C (**Table 6.3**; **Appendix 6.3**) were mainly responsible for changes in AWC and RAW. Since there was a changeover in the dominant effects, both within bulk density, and between bulk density and C, changes in RAW and AWC are not consistent.

d)   Least limiting water range

The LLWR extends the usefulness of AWC by restricting it to limiting levels of air-filled porosity and soil strength (both of which vary with θ). At Rattray, air-filled porosity at field capacity was consistently well above 0.1 m^3 m^{-3}, necessary for limitation of the LLWR at the upper end of $θ_v$. Although soil strength (as measured by PSS_0 and PSS_1) was significantly affected by θ (**Section 4.3.3.1**), this was not the case with the 0 – 0.3 m PSS data used to correlate Troxler bulk density, probably as a result of

too few measurements (data not shown). Due to the lack of effect of θ on PSS values, the effect of bulk density on PSS did not change with θ. Therefore bulk densities above 1.646 Mg m^{-3} resulted in PSS values above 2000 kPa, which then limit the LLWR. The effect of the various ranges of bulk density and organic C on LLWR was thus identical to that of AWC (**Figure 6.3**), with the exception that in classes with the high bulk density range (i.e. 1.633 – 1.724 Mg m^{-3}), the LLWR or AWC is reduced by soil strength. These classes already have low AWC values, particularly when θ is expressed on a mass basis. Therefore, a low bulk density (<1.522 Mg m^{-3}) combined with high C (0.955 – 2.754%) has the highest amount of AWC, while not limiting root growth.

6.3.1.2.   Shafton

a)   Water retention

As with the Rattray data, soil bulk density and C values from undisturbed soil cores formed the percentile groups to allow easier analysis of water retention and availability results (**Table 6.6**). The effect of these bulk density and C ranges on soil water retention curves were determined (**Figure 6.4** and **Table 6.7**; **Appendices 6.4** and **6.5**).

Table 6.6:   Ranges of bulk density and soil carbon (C; % m/m) values at Shafton grouped according to percentile ranges.

Percentile range	Bulk density (Mg m^{-3})
0 – 25%	0.893 – 0.994
25 – 75%	0.995 – 1.123
75 – 100%	1.124 – 1.167
	Carbon (%)
0 – 25%	13.539 – 15.975
25 – 75%	15.976 – 19.986
75 – 100%	19.987 – 21.961
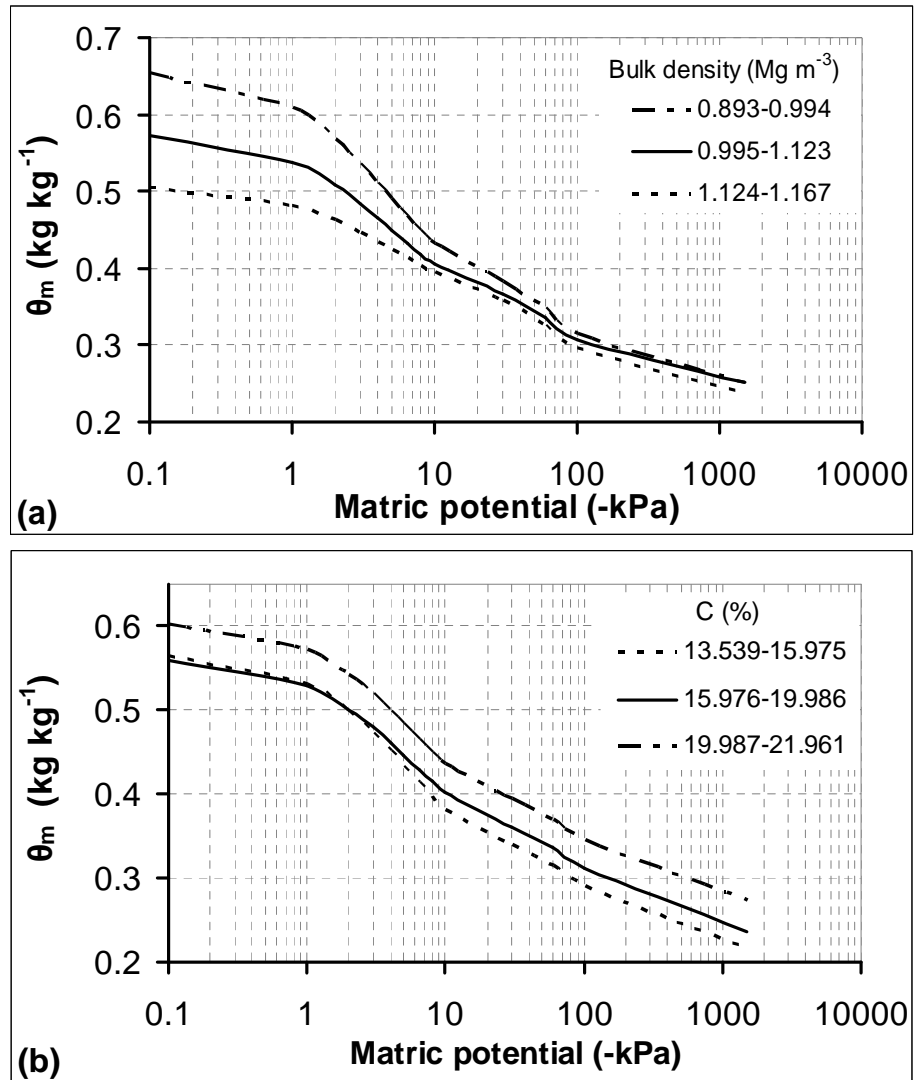
Figure 6.4: The effect on soil water content (θ_m) of ranges of (a) bulk density and (b) soil carbon (C; % m/m) at Shafton (of undisturbed soil cores taken between 0 and 0.5 m).

Increasing bulk density resulted in an increasing reduction in θ_m with decreasing matric potential (**Figure 6.4**). In contrast, soil C had a greater effect at high matric potentials, increasing θ_m with increasing C content. The effect on θ_v was quite different, particularly in the case of bulk density (**Appendix 6.5**). Increasing bulk density resulted in decreasing θ_v at high matric potentials, but increasing θ_v at low matric potentials, while the effects of C were not as pronounced as with θ_m.

Table 6.7: Coefficients of regression equations[†] and associated percentage of variance accounted for by equations (r^2) of the effects of ranges of bulk density (BD) and soil carbon (C; % m/m), as grouped in **Table 6.6**, on mass soil water content (of undisturbed soil cores) at Shafton. All regression equations were highly significant ($p<0.001$); n=56.

BD/C	Range (%)	a	b	r	c	s	r^2
	0 – 25	0.251	0.230	1.273	0.179	1.010	
BD	25 – 75	0.251	0.169	1.273	0.155	1.010	0.838
	75 – 100	0.237	0.104	1.273	0.165	1.010	
	0 – 25	0.217	0.201	1.234	0.151	1.007	
C	25 – 75	0.236	0.170	1.234	0.156	1.007	0.805
	75 – 100	0.274	0.183	1.234	0.151	1.007	
	0 – 25, 0 – 25	0.237	0.221	1.261	0.153	1.009	
	25 – 75, 0 – 25	0.217	0.194	1.261	0.158	1.009	
	75 – 100, 0 – 25	0.194	0.150	1.261	0.179	1.009	
	0 – 25, 25 – 75	0.227	0.256	1.261	0.200	1.009	
BD, C	25 – 75, 25 – 75	0.244	0.171	1.261	0.156	1.009	0.868
	75 – 100, 25 – 75	0.231	0.114	1.261	0.161	1.009	
	0 – 25, 75 – 100	0.263	0.238	1.261	0.181	1.009	
	25 – 75, 75 – 100	0.287	0.168	1.261	0.140	1.009	
	75 – 100, 75 – 100	0.289	0.0731	1.261	0.136	1.009	

[†] The regression equation used is of the double exponential form i.e. $y = a + b*r^x + c*s^x$, where y = water content (θ_m; kg kg^{-1}), x = matric potential (kPa), and a, b, r, c and s are coefficients.

Although often significant, low r^2 values excluded many relationships between water content and bulk density or C of soil cores at specific matric potentials. The few remaining relationships are presented in **Appendix 6.6**.

Almost identical effects of bulk density on both gravimetric and volumetric soil water retention curves were found at the same site in an earlier study (Smith, 1995). The effect of organic C on water retention was not tested in Smith's (1995) study, although increases in water retention throughout the retentivity curve with increasing organic carbon is well documented (Hall *et al.*, 1977; Rawls *et al.*, 1991; Rawls *et al.*, 2003).

However, despite the much wider range of C values at Shafton, compared to Rattray, relatively smaller increases in water retention per unit change in C were found. This phenomenon in clay soils, when compared to sandy soils, has been

found by others (e.g. Bauer and Black, 1992; Rawls *et al.*, 2003). Differences in the effects of both bulk density and organic C on the relative change in water retention (when compared to values from the lowest bulk density and highest C range) are therefore a result of soil textural differences between the two sites.

b)   Porosity and pore-size distribution

The effect of bulk density and C on total porosity and pore-size distribution were determined (**Table 6.8**). Compaction reduced total porosity of the soil at Shafton, the main loss being macroporosity, while mesoporosity increased. Increasing organic C did not increase total porosity substantially. However, C did increase mesoporosity, while having little effect on macro- and microporosity. Air-filled porosity was calculated from the same data and was at the very least 0.13 m^3 m^{-3}, i.e. above the 10% level considered adequate for plant growth.

Table 6.8:   Change in total soil porosity and pore-size distribution (PSD) with percentile ranges of bulk density and soil carbon (of undisturbed soil cores) at Shafton.

Pores	Bulk density range					
	<25%		25%<BD<75%		>75%	
	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)
Micro-	0.003	0.5	0.003	0.6	0.004	0.6
Meso-	0.352	56.0	0.373	61.6	0.397	68.4
Macro-	0.274	43.5	0.229	37.9	0.180	31.1
Total	0.629	100.0	0.606	100.0	0.581	100.0
	Carbon range					
	<25%		25%<C<75%		>75%	
	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)	(m^3 m^{-3})	PSD (%)
Micro-	0.003	0.5	0.003	0.6	0.004	0.6
Meso-	0.344	57.7	0.373	62.4	0.393	63.7
Macro-	0.250	41.8	0.221	37.0	0.221	35.8
Total	0.597	100.0	0.598	100.0	0.617	100.0

Total porosity, and the proportion of mesopores constituting total porosity is much higher at Shafton, than at Rattray, where in contrast both the quantity and proportion of macropores was much greater. Increases in bulk density led to similar decreases in total porosity and losses of macroporosity with some

increases in mesoporosity at both trials. Despite substantially greater increases in C at Shafton (i.e. approximately 2%, rather than 0.4% between groups), increases in total porosity with increasing C were not as great as those experienced at Rattray. Increases in total porosity with increasing organic C are well documented (Kay, 1998). At both trials, however, the main effect of organic C was to increase mesoporosity. Air-filled porosity at field capacity at both trials, was well above 10% of the total soil volume, even with increasing bulk density or decreasing C. Differences in changes in total porosity and pore-size distribution with compaction can be attributed to soil textural differences (Gomez *et al.*, 2002a).

c)   Water availability

From a plant perspective, changes in RAW and AWC are more important than those of θ. The effect of combinations of bulk density and C were determined on RAW and AWC (**Figure 6.5**).

At low C values, bulk density increased RAW and AWC. However, as C increased, increasing bulk density decreased RAW and AWC (**Figure 6.5**). Organic C decreased RAW and AWC at high bulk densities, had a slight negative effect at medium values of bulk density and initially increased, and then decreased RAW and AWC at low values of bulk density (**Figure 6.5**). These inconsistent effects are reflected in **Table 6.9** where, as for the Rattray data (**Section 6.3.1.1.c**), values relating to HL, MM and LH were compared.

When actual RAW and AWC values were determined on all of the undisturbed soil cores, RAW averaged 0.093 kg kg^{-1} or 0.098 m^3 m^{-3}, while AWC averaged 0.175 kg kg^{-1} or 0.184 m^3 m^{-3}. These values are fairly close to those obtained utilising the regression equations, indicating a good prediction by the equations, unlike at Rattray.
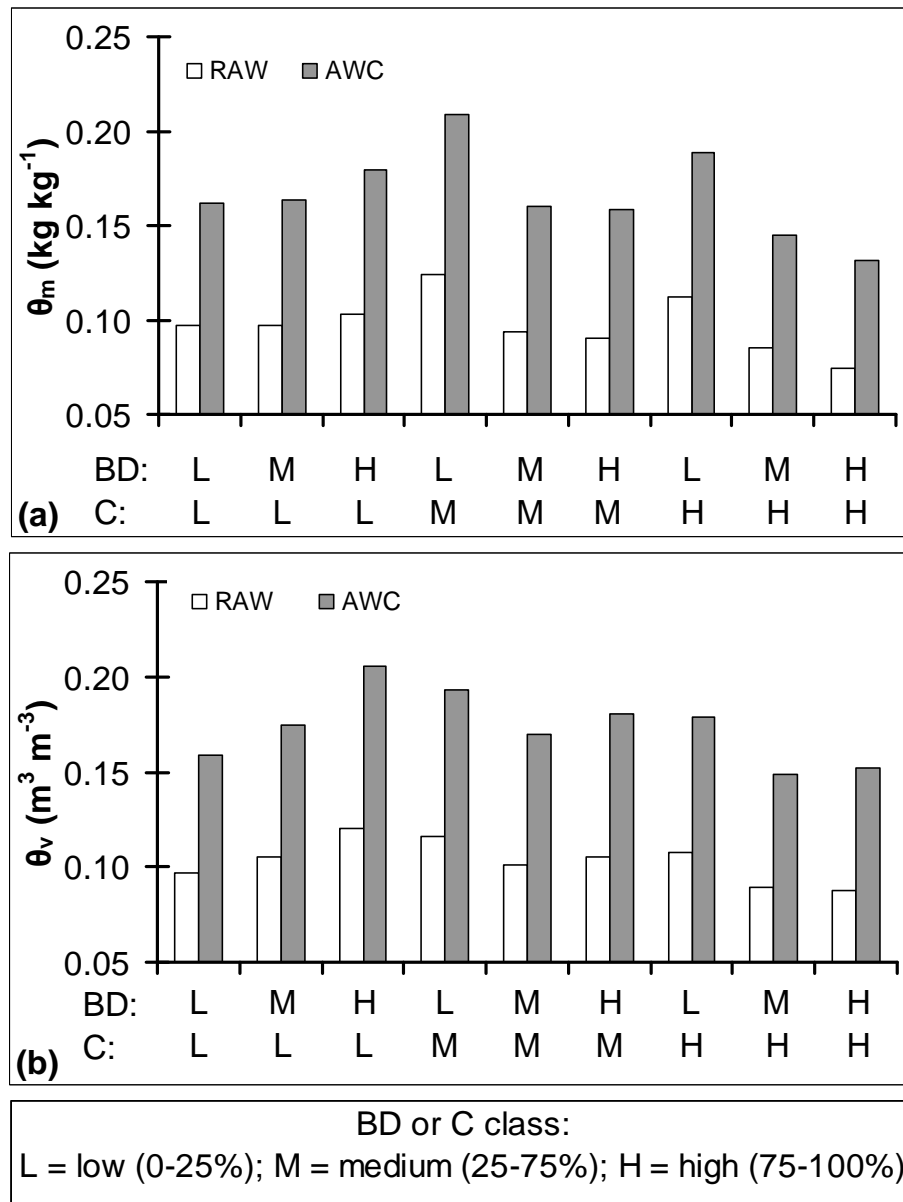
Figure 6.5: The effect of combinations of ranges of bulk density (BD) and soil carbon (C) on readily available water (RAW) and available water capacity (AWC) expressed as (a) mass basis (θ_m), and (b) volumetric basis (θ_v) at Shafton (of undisturbed soil cores between 0 and 0.5 m).

Table 6.9: Effect of selected combinations of bulk density and soil carbon on readily and available water capacity (RAW and AWC, respectively) in undisturbed soil cores between 0 and 0.5 m at Shafton.

Bulk density	Carbon	RAW	AWC	RAW	AWC
		$(kg^{-1}\ kg^{-1})$		$(m^3\ m^{-3})$	
75 – 100%	0 – 25%	0.103	0.179	0.121	0.205
25 – 75%	25 – 75%	0.094	0.160	0.101	0.170
0 – 25%	75 – 100%	0.113	0.189	0.108	0.179

Using the same soil, but in reconstituted cores, Smith (1995) found that compaction only had a negative effect on RAW and AWC, although this effect diminished as bulk density approached its maximum. However, the cores obtained from the field with low C content had a high proportion of very large, easily collapsible macropores (**Table 6.8**), a situation that would not necessarily occur in reconstituted cores. As these soils were compacted, although total porosity decreased, the proportion of mesopores increased, so increasing RAW and AWC. The cores with medium to high C had higher proportions of mesopores. Therefore, decreases in total porosity with compaction would have affected this size of pore to a greater extent than in the lower C content cores, probably leading to declines in RAW and AWC with increasing compaction.

The much higher RAW and AWC values at Shafton, compared to Rattray, are indicative that periods of plant water stress may be less likely at Shafton (if water supply and evapotranspiration at the two sites are similar). These differences can mainly, once again, be attributed to soil textural differences, as clay soils generally have much higher AWC than sands (Bauer and Black, 1992; Smith, 1995; Or and Wraith, 2000; Gomez *et al.*, 2002a). The greatest difference between RAW and AWC at Rattray when either bulk density or C were considered was 0.006 kg kg^{-1} or 0.004 m^3 m^{-3}, while at Shafton it was 0.029 kg kg^{-1} or 0.016 m^3 m^{-3}. This relatively low variation in water availability with either bulk density or C at both trials may indicate that other soil factors, such as soil texture, have a greater influence over RAW and AWC (e.g. Bauer and Black, 1992; Smith, 1995); or that the regressions developed for the retentivity curves may be over- or under-estimating a component of RAW or AWC, such as field capacity or wilting point.

Although increasing bulk density and decreasing organic C have generally been found to decrease RAW and AWC, there are some exceptions. In loamy sands and sandy loams, increasing bulk density has been found to initially increase, then decrease AWC. In medium textured soils AWC has been found to respond differently to organic C (Hall *et al.*, 1977; Bauer and Black, 1992; Hudson, 1994; Smith, 1995; Gomez *et al.*, 2002a). This has led to the conclusion that there is no "hard and fast" rule that can be applied to AWC and RAW (Hall *et al.*, 1977; Hutson, 1983; Kern, 1995; Smith, 1995; Gomez *et al.*, 2002a). Consistent responses in AWC and RAW to increasing bulk density or C were not found at either Rattray or Shafton. Similar results were obtained in a study in which both bulk density and organic C content were varied in different textured soils (Bauer and Black, 1992). In that study, AWC in sandy soils initially slightly increased and then slightly decreased as organic C increased with concomitant decreases in bulk density. However, in the fine textured soils, AWC decreased with increasing organic C and decreasing bulk density.

The variable response of AWC and RAW to bulk density and organic C has been attributed (Hall *et al.*, 1977; Hutson, 1983; Musto, 1994; Kern, 1995; Smith, 1995; Skopp, 2000; Smith *et al.*, 2001; Gomez *et al.*, 2002a) to one of the following:

- Other unmeasured soil variables. For example water repellency found in soils under eucalypts.
- The use of undisturbed soils obtained from the field (instead of reconstituted cores) that contain roots, small stones and soil organisms can create variability between cores of similar texture, bulk density and organic carbon content.
- Complex responses of (and interactions between) pore geometry and compressive processes with compaction due to variation in soil properties.

d)   Least limiting water range

Field PSS values were well above the root-limiting 2000 kPa level determined by da Silva *et al.* (1994), and therefore a second upper limit of PSS at 3000 kPa was also included (Sands *et al.*, 1979) in determination of the LLWR. The fact that PSS

was not significantly affected by θ (either with these data, or the data in **Section 4.3.3.2**) in this soil may be an indication of the variability associated with field measurements of PSS, as changes in PSS for this soil have previously been determined under laboratory conditions (Smith, 1995).

The LLWR was only limited at higher levels of θ by air-filled porosity at field capacity in one instance (high bulk density and high C, i.e. 1.124 – 1.167 Mg m^{-3}, 6.143 – 7.678%, respectively). The re-calculation of this value from volumetric to gravimetric terms is difficult, as a range of bulk densities are used to calculate the LLWR, rather than specific values.

Available water capacity and RAW for each of the nine combinations of bulk density and C were shown earlier (**Figure 6.5**). However, the results of this section indicate that if root-limiting levels of PSS are considered to be above 2000 kPa, all classes with the exception of the lowest range of bulk densities (i.e. 0.893 – 0.994 Mg m^{-3}) would be root-limiting. If PSS values above 3000 kPa are used, however, the only root-limiting classes would be those with the highest bulk densities. It is important to note that even though the Shafton soil has a considerably greater AWC than Rattray (0.130 – 0.230 and 0.019 – 0.027 kg kg^{-1}, respectively), it has an increased likelihood of plant growth being limited by soil strength.

Smith (1995) determined the LLWR on reconstituted cores, using the same soil, and found similar water contents at wilting point and field capacity. Only at bulk densities above approximately 1.15 Mg m^{-3} was aeration limiting at field capacity (i.e. similar to this study). Soil strength, however, varied with θ, and because of this, was limiting at wilting point and at field capacity at bulk densities above 1.00 Mg m^{-3} and above 1.20 Mg m^{-3}, respectively.

However, the data presented here may not be representative of LLWR in the field for the following reasons:

- The variation in PSS with θ needs to be determined more precisely (under laboratory conditions), and these values translated into field values. This is particularly the case at this trial, as field PSS values are well above that considered growth-limiting.

- Values for wilting point determined from regression equations in which both groups of bulk density and C are combined (**Table 6.7**) may be erroneous as it has been demonstrated (**Figure 6.4**) that bulk density in particular, has little influence at such low matric potentials. This effect was also seen at Rattray (**Table 6.2** and **Figure 6.2**).

6.3.2.   Treatment effects on soil water availability and least-limiting water range (undisturbed soil cores)

6.3.2.1.   Compaction treatments

a)   Rattray

Compaction treatments significantly affected both soil bulk density and C (**Chapters 4** and **5**). Therefore the effects on AWC, RAW and LLWR of changes in bulk density, C, and finally both bulk density and C were determined.

Bulk density

Compaction treatments, through their effect on bulk density, had a negative effect on AWC and RAW in comparison to the C_L treatment in the $0 - 0.3$ m soil layer (**Figures 6.6** and **6.7**). In addition, there were differences in AWC and RAW between interrow and stumpline of C_H treatments.

Considerably less water is plant or readily available in the top 0.3 m of soil in the C_M or C_H treatment plots than in the C_L treatment plots. The C_M treatment plots have on average 0.012 and 0.006 m^3 m^{-3} (or on a surface area basis, 12.1 and 5.9 ℓ m^{-2}) less AWC and RAW, respectively, in the top 0.3 m of soil than that of the C_L treatments. C_L treatments also have on average, 0.027 and 0.013 m^3 m^{-3} (or 26.7 and 13.0 ℓ m^{-2}) more AWC and RAW than C_H treatments.

Compaction: low = C_L; moderate = C_M; high = C_H
Plot position: interrow = IR; stumpline = SL
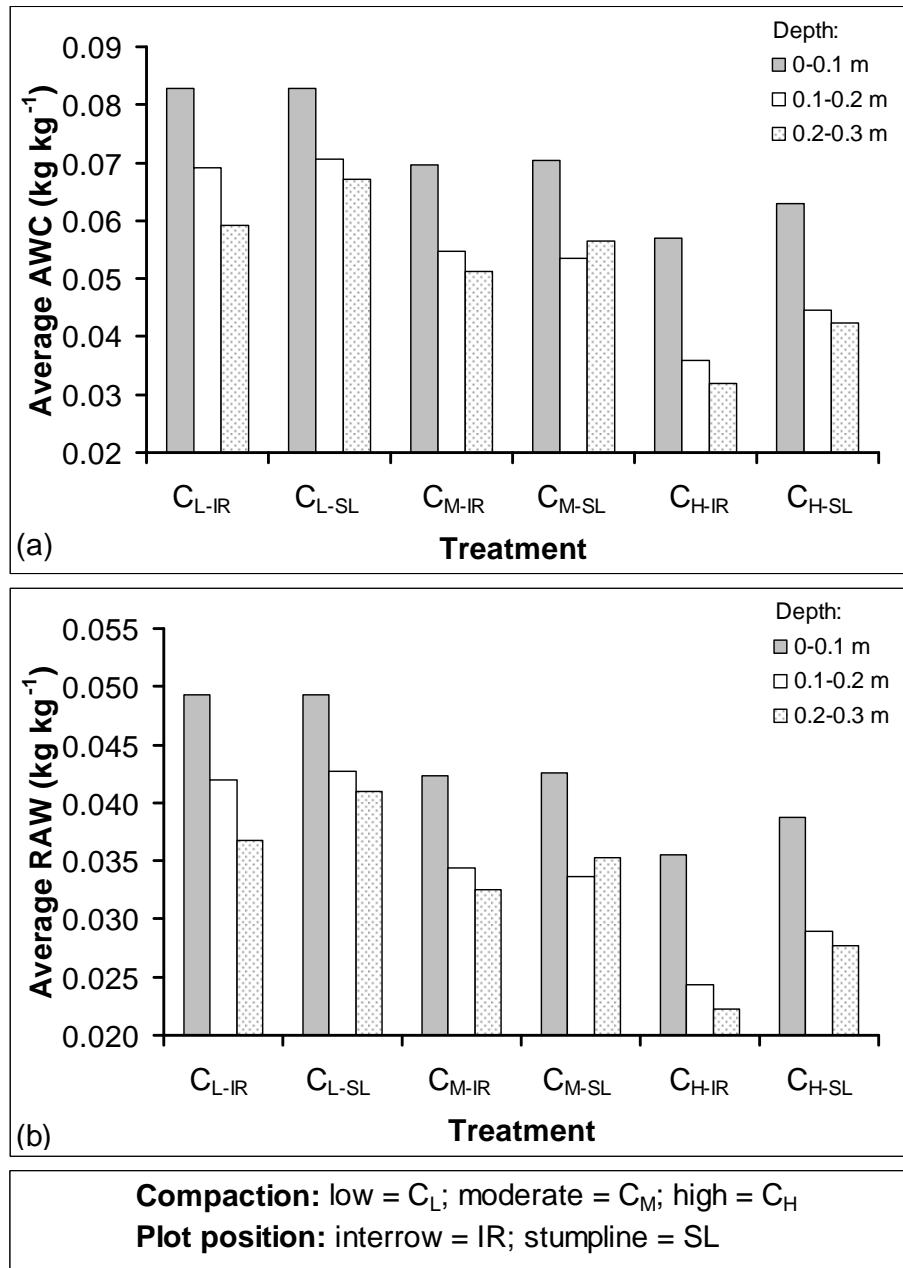
Figure 6.6: Effect of bulk density as affected by compaction treatments and plot position at Rattray on (a) AWC and (b) RAW (on a mass basis determined from undisturbed soil cores).
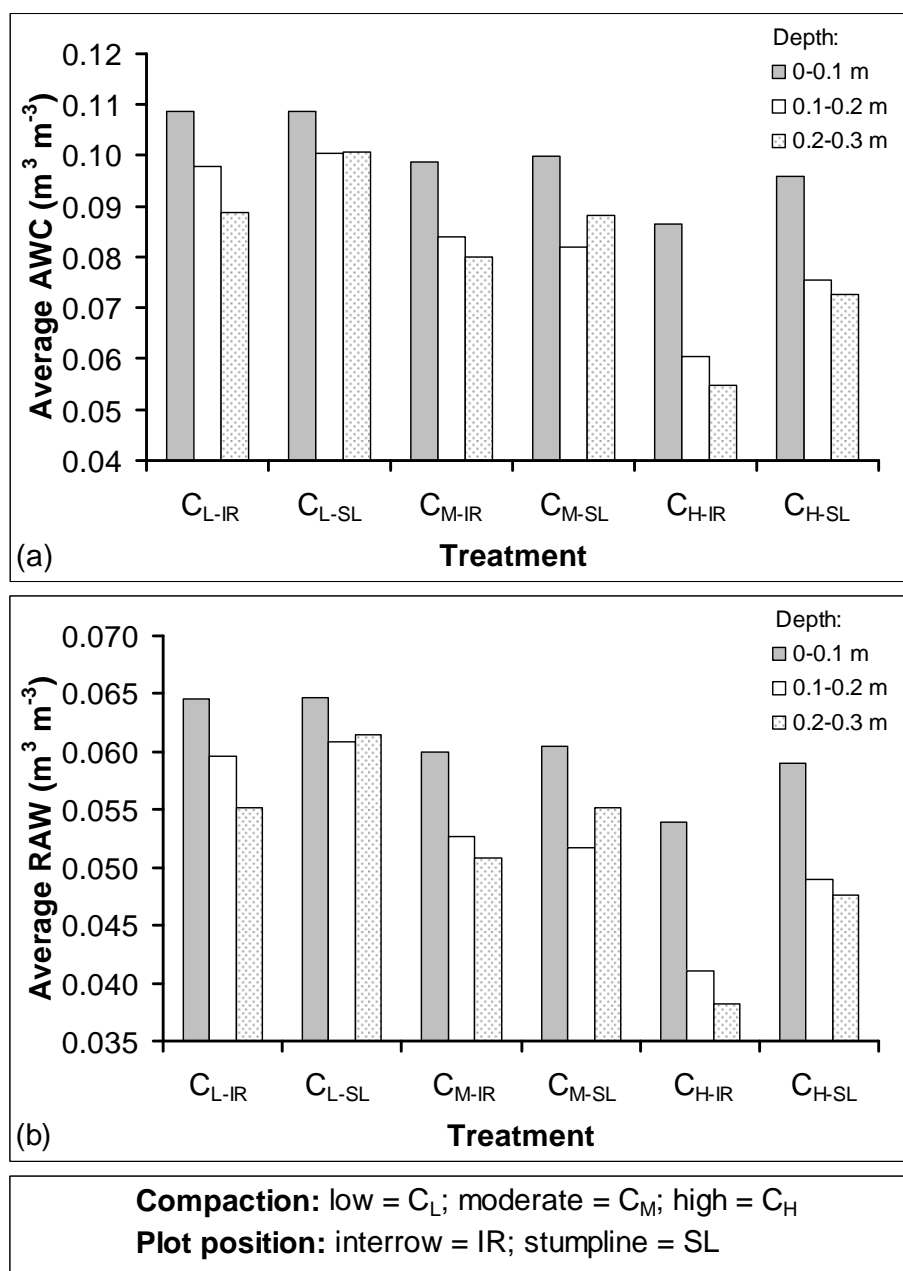
Figure 6.7: Effect of bulk density as affected by compaction treatments and plot position at Rattray on (a) AWC and (b) RAW (on a volume basis determined from undisturbed soil cores).

Organic carbon

Soil organic C at Rattray was significantly affected in the top $0 - 0.05$ m by compaction treatments at TH, increasing with increasing compaction intensity (**Section 5.3.2.1**). Using the average values (for each compaction treatment),

AWC and RAW were calculated. Carbon had little effect on RAW values that ranged between 0.405 and 0.406 kg kg^{-1}, or 0.382 and 0.383 m^3 m^{-3} (data not shown) However, AWC decreased with increasing C, or increasing compaction (**Figure 6.8**).
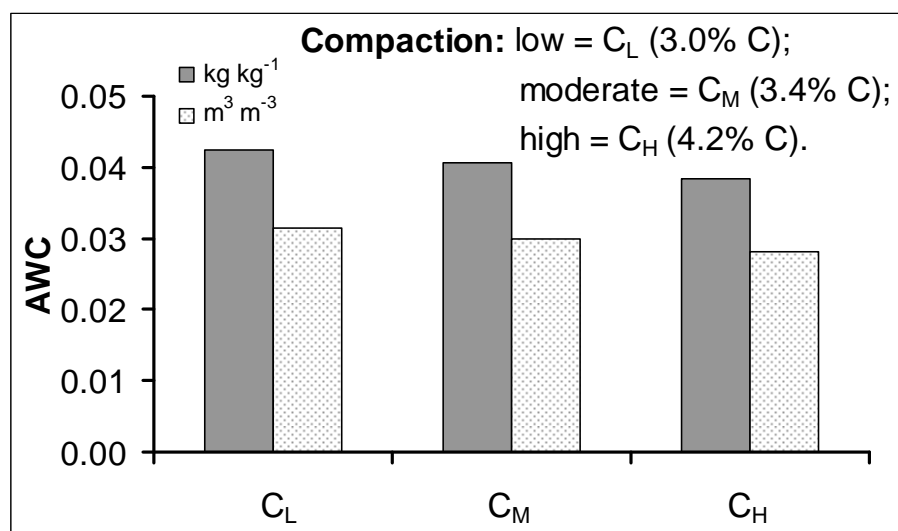
Figure 6.8: Effect of compaction treatments on AWC due to changes in soil carbon (C; % m/m) at Rattray (determined from undisturbed soil cores between 0 and 0.05 m).

Bulk density and organic carbon

Compaction treatment effects on *both* C *and* bulk density were only significant in the 0 - 0.05 m soil depth. Therefore compaction treatment effects on AWC (through their effect on bulk density *and* C) were only assessed in this layer. Since the effects of C on RAW were found to be extremely small, the combination of changes in bulk density and C (due to compaction treatments) were not determined, as they can be inferred from the effect of bulk density alone on RAW.

The effect of both bulk density and C on water retention at -10 and -1500 kPa in undisturbed soil cores between 0 and 0.1 m was determined earlier (**Section 6.3.1.1.a**). These results were used in the calculation of AWC (**Figure 6.9**).
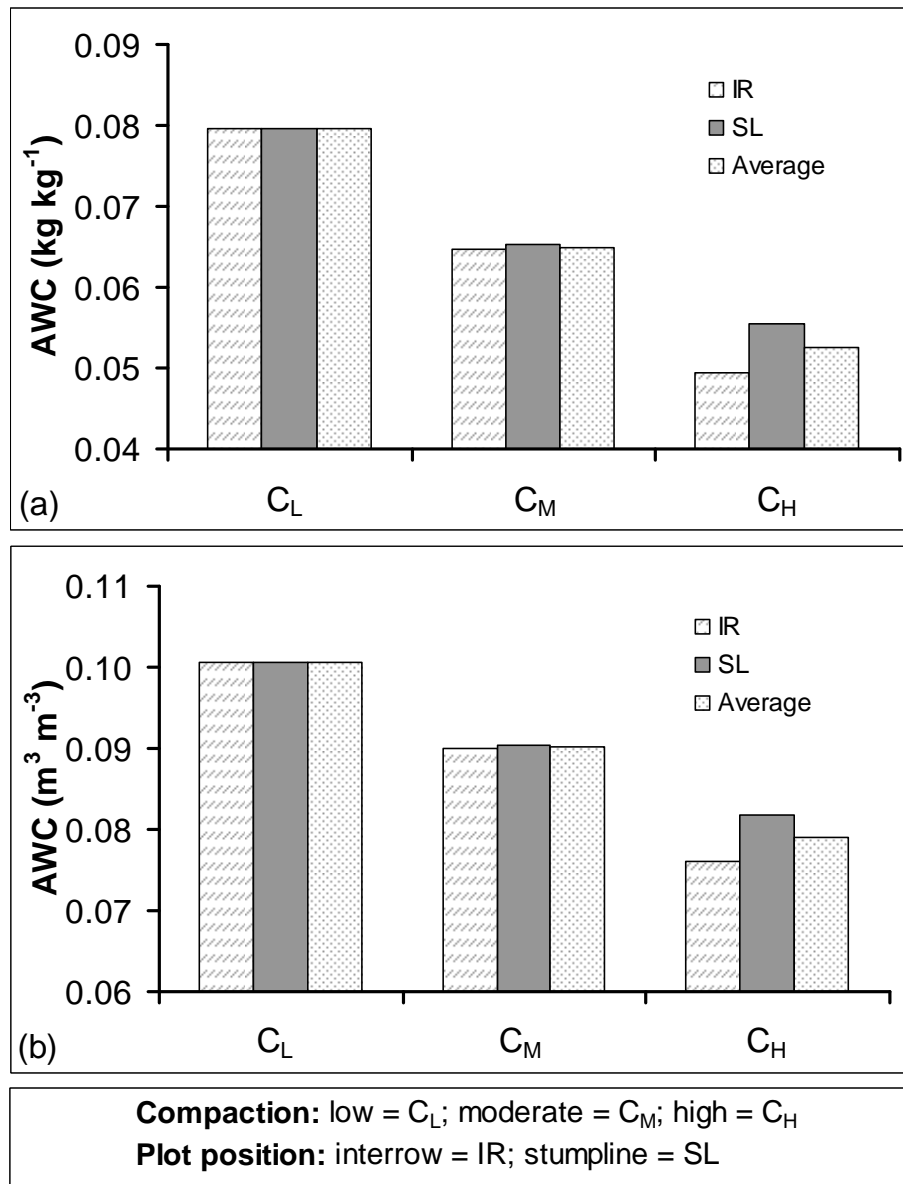
Figure 6.9: Effect of plot position within compaction treatments, and averaged across compaction treatments (Average), on AWC on (a) a mass basis, and (b) volume basis, at Rattray (determined from undisturbed soil cores between 0 and 0.05 m).

Since bulk densities attained in this 0 – 0.1 m soil layer were below that which would cause root-limiting levels of PSS, and soil aeration is adequate (**Section 6.3.1.1**), the LLWR in this soil layer is dependent solely on AWC (**Figure 6.9**).

b)   *Shafton*

Bulk density determined from soil cores had a significant effect on water retention at this trial (**Section 6.3.1.2**). However, no significant compaction treatment effects on bulk density measured with a Troxler were found (**Section 4.3.2.2**). Therefore the effect of the compaction treatments on AWC, RAW and LLWR could not be determined by extrapolation using Troxler bulk density results.

The results of **Chapter 5**, coupled with the LLWR data (**Section 6.3.1.2**), indicate that the majority of the site has bulk densities between 0 and 0.3 m depth that may cause some plant root-limiting levels of soil strength. Soil aeration is generally not limiting to plant growth. Therefore, changes in available water supply potentially have the greatest effect on plant growth at this site.

6.3.2.2.   *Residue management*

a)   *Rattray*

Residue management significantly affected soil bulk density, but not C at Rattray (**Chapters 4** and **5**). However, this significant effect was not as a result of residue management *per se*, but rather the reduction of compaction treatment effects with increasing residue retention. Therefore the effects of residue management on AWC and RAW were only determined along with those of compaction treatments (**Section 6.3.2.3**).

b)   *Shafton*

Soil organic C was significantly higher in the top 0.05 m of soil with increasing residue retention at TH (but not at soil depths between 0.05 and 0.6 m, nor at TF; **Section 4.3.2.b**). Therefore the effect of residue management on AWC and RAW was only determined for the 0 – 0.05 m soil depth at TH (**Figure 6.10**). Organic C values (averaged for each type of residue management) were used to calculate the amount of soil water held at -10, -100 and -1500 kPa (**Section 6.3.1.2**).

Residue management: B = broadcast (27.3% C);
W = windrow (25.7% C);
R = removed (23.6% C).
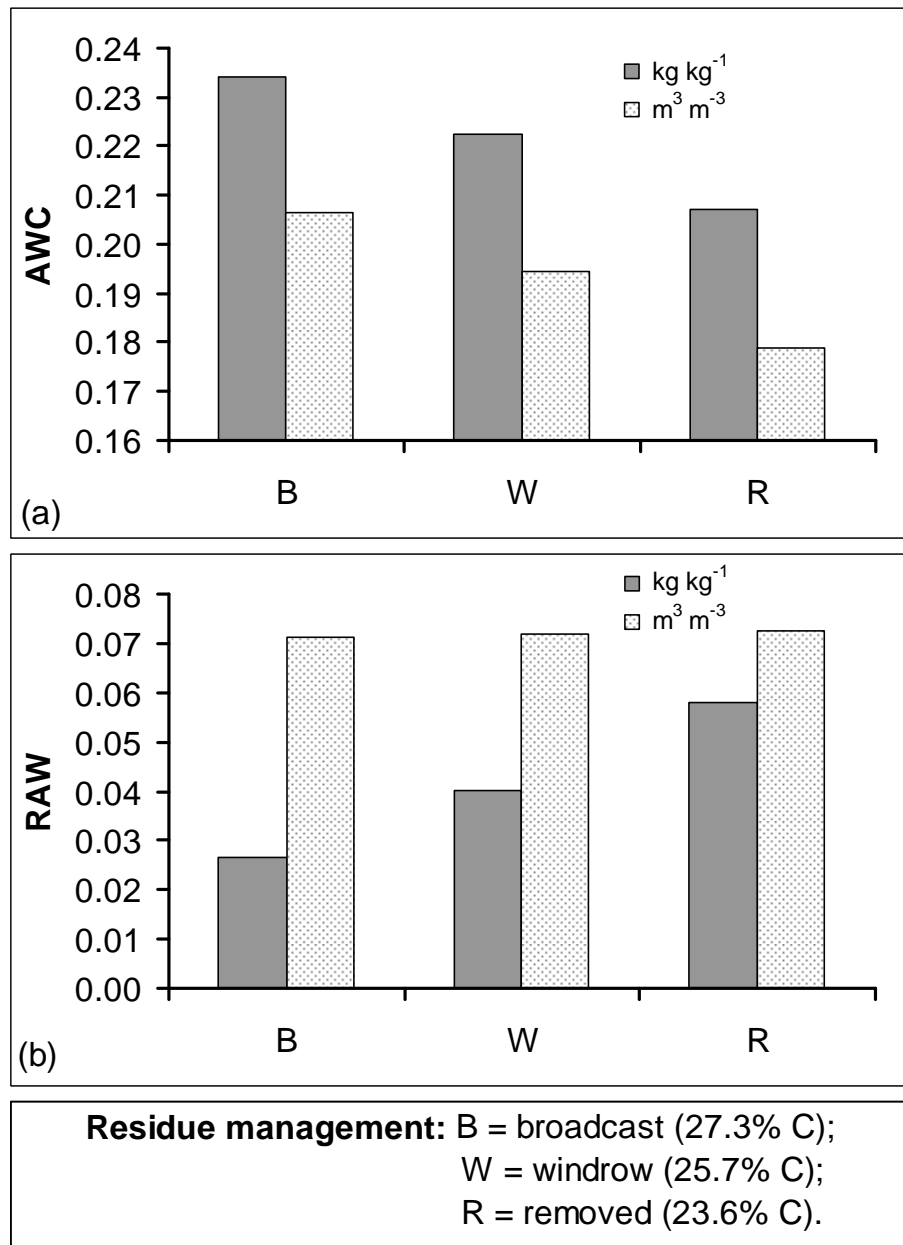
Figure 6.10: Effect of residue management on (a) AWC and (b) RAW due to changes in soil carbon at Shafton (determined from undisturbed soil cores 0 and 0.05 m).

However, the averaged C values were substantially higher (C range 20.82 – 31.98%) than those obtained in the soil cores (C range 15.14 - 21.96%). It was assumed that the regressions developed in **Section 6.3.1.2** could be extrapolated outside their range and utilised to determine organic carbon effects on AWC and RAW here.

Due to the effect of residue retention on C, decreasing residue retention led to a decrease in AWC, and a minor increase, i.e. <0.035 kg kg^{-1} from removed to retained residue management, in RAW. The increase in RAW with decreasing C, due to residue removal, is a result of C having a slightly smaller positive effect on θ at field capacity than the positive effect on θ at wilting point. These results (**Figure 6.10**) show that AWC is more affected than RAW by C, implying that only as the soils dry out, will C content become important to plant available soil water status.

The effect of C on the LLWR was not determined, as changes in bulk density and PSS with C were relatively small. The main effects on the LLWR would therefore be through AWC (**Figure 6.10**).

6.3.2.3.   Compaction treatment x residue management interaction

a)   Rattray

Average soil bulk density values (0 – 0.3 m) determined for each combination of compaction treatments and residue management (**Section 4.3.2.1**) were used in the calculation of AWC and RAW values (**Figure 6.11**).
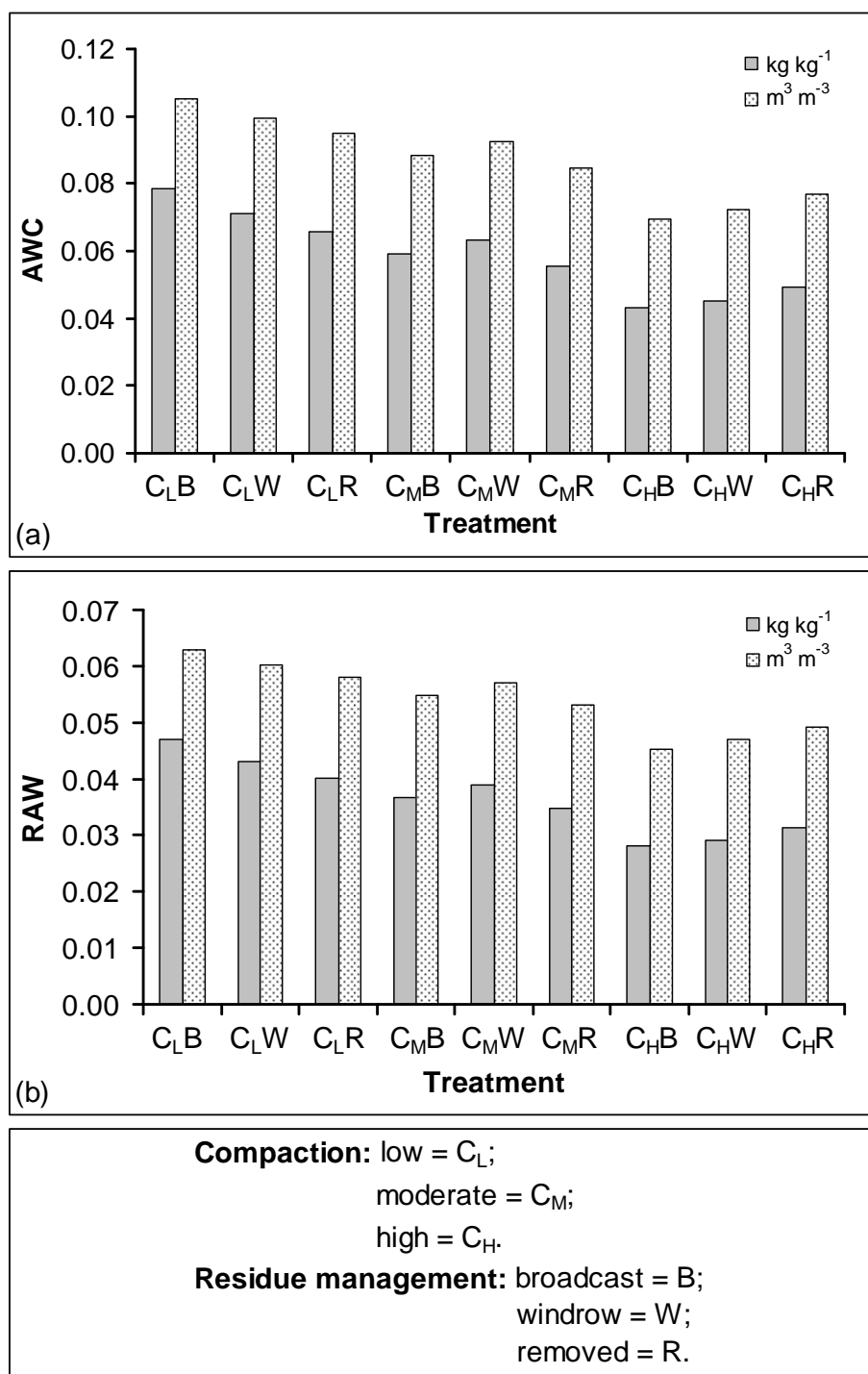
Figure 6.11: Effect of the interaction between compaction treatments and residue management on (a) AWC and (b) RAW due to changes in soil bulk density at Rattray (determined from undisturbed soil cores between 0 and 0.3 m).

b)   Shafton

No significant compaction treatment x residue management interaction effects were found on soil bulk density or C at Shafton. It was therefore assumed that this interaction had no effect on AWC or RAW.

6.3.3.   Soil water content (thetaprobe)

6.3.3.1.   Rattray

At each time measurements were taken with a thetaprobe (a total of three measurement occasions), θ_v values (0 – 0.05 m) increased with increasing compaction and quantity of residues present (**Figure 6.12**). However, the main effects of the compaction and residue management treatments were not always significant on each measurement occasion, and the interaction between compaction treatments and residue management was not significant at any measurement occasion (**Table 6.10**). The inconsistencies in statistical results between measurement occasions may be due to the changing site water content on each measurement occasion. Soil water content (0 - 0.5 m) measured by the thetaprobe showed that θ_v averaged 0.041, 0.056, and 0.026 m^3 m^{-3} on measurement occasion one, two and three, respectively. This indicates that the matric potential of the soil was in the –40 to –1500 kPa range (**Appendix 6.2**).

At measurement occasions one and two, statistical results were similar, i.e. residue management showed a highly significant effect ($p<0.001$), while compaction treatments were only moderately ($p<0.05$) or weakly ($p<0.1$) significant. The average θ_v over the trials was also similar at these measurement occasions. The positive response of soil water content to residue retention in the surface soil has been documented by others (e.g. Kelting, 1999; O'Connell *et al.*, 2004a; Roberts *et al.*, 2005). However, at measurement occasion three (at TH), the soil was considerably drier, and compaction treatment effects were significant, while residue management effects were not. This may be because this measurement was taken at the start of the dry season when the atmosphere was

probably so dry that residues could not prevent evaporation, and only the effects of compaction on porosity had an effect on soil water. In addition, the trees had grown considerably by this stage and were probably extracting as much available soil water as possible. The remaining water was less available and hence was affected by compaction treatments.

Table 6.10: Summary of ANOVA results of the effect of compaction treatments and residue management on average volumetric soil water content (θ_v) measured using the thetaprobe at Rattray on three different occasions.

Source of Variation	d.f.	F pr.		
Measurement occasion		1	2	3
Compaction	2	0.072	0.038	0.005
Residue	2	<0.001	<0.001	0.583
Compaction x residue	4	0.344	0.166	0.388
Residual	18			
Total	26			
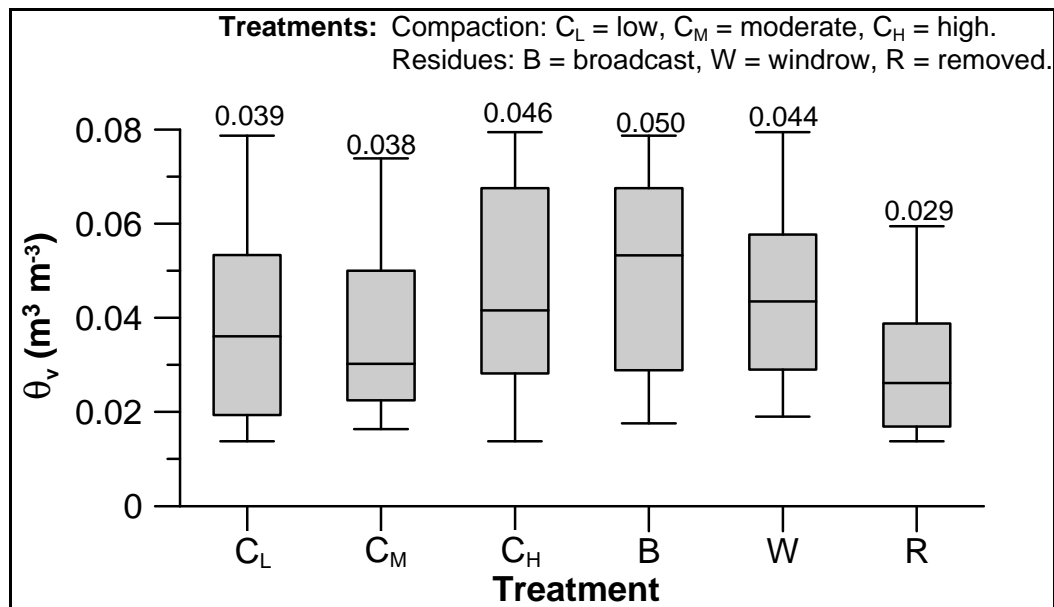
Figure 6.12: Box whisker plot of soil water content (θ_v; measured with a thetaprobe) between 0-0.05 m averaged over three separate measurement occasions under different compaction treatments and residue management at Rattray. Treatment means are displayed above the box whisker columns.

Significant effects of compaction treatments and residue management, but not the interaction between them were found on θ_v between 0 and 0.05 m ($p<0.001$; **Figure 6.13**; **Appendix 6.7)**. Residue management had a particularly obvious positive effect, with increasing θ_v with increasing residue retention. Compaction also increased θ_v slightly. The θ_v values obtained indicate that the soil at this time (65 DAP) of measurement ranged in matric potentials from −8 to −1500 kPa, the range in which bulk density positively affected θ_v in the retentivity curve (**Appendix 6.5**). However, the effects of compaction were not great enough to induce a significant difference between interrow and stumpline measurements of θ_v (data not shown).
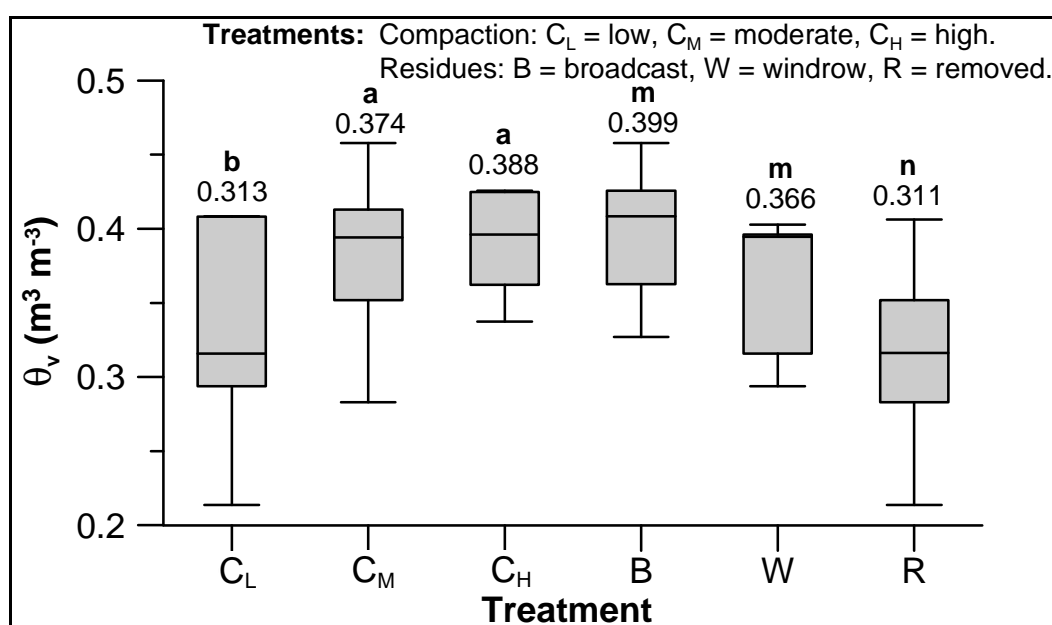
Figure 6.13: Box whisker plot of volumetric soil water content (θ_v; measured with a thetaprobe) between 0-0.05 m under different compaction treatments and residue management at Shafton. Treatment means are displayed above the box whisker columns. Treatments with different letters displayed above the box whisker are significantly different ($p<0.05$) within compaction treatments and residue management.

6.4. Conclusions

Measured treatment effects on soil water availability (AWC and RAW) at both sites were greatest in the top 0.05 m of soil. In this top layer of soil, soil strength and aeration were generally not limiting, and the LLWR was defined mainly by AWC and RAW. Although deeper in the soil profile (up to 0.5 m), treatment effects were not found on AWC and RAW, soil strength may be the main limiting factor of the LLWR.

At Rattray, compaction treatments reduced AWC and RAW (and LLWR) in the top 0.3 m of the profile, although increasing quantities of residues reduced this effect. The LLWR may be further limited by soil strength below 0.2 m, particularly in the C_H treatments. Although trees obtain water from below 0.5 m, the low AWC (and LLWR) and RAW values obtained for the top 0.5 m of soil may be problematic as the top layer of soil at this site contains most nutrients (**Chapter 4**) and fine roots and changes in soil water availability will affect both mineralisation and root uptake of these nutrients. Reductions in available water through compaction by machinery may limit site productivity, and therefore compaction should be limited where possible. Although residue management did not significantly affect soil water availability, residue retention significantly increased θ_v in the top 0.05 m of soil. This effect may only be significant either until the majority of residues have decomposed, after approximately 3 years, or until canopy closure. However, the results show that, at this site, compaction coupled with residue removal will be detrimental to water supply and availability to a young stand.

At Shafton, compaction generally reduced AWC and RAW. However, the effect of compaction treatments on these variables could not be quantified due to insufficient Troxler bulk density measurements. Residue management significantly affected organic C content in the top 0.05 m of soil which, in turn, affected AWC and RAW, the former particularly increased with increasing C. Therefore, the retention of residues has the potential to offset some of the effects of compaction on the quantity of available water. Although the LLWR in the top 0.05 m layer was not limited by soil strength or aeration, this was not the case at

depths below 0.1 m. The results indicate that compaction may have a substantial effect on long-term site productivity of similar sites, the effect worsening with decreasing water supply (i.e. rainfall). Residue retention, in particular, increased θ_v in the top 0.05 m of soil. These results, coupled with reduction in soil strength values in the top 0.3 m with residue retention, demonstrate the importance of residues at this site.

Both soil bulk density and organic C had significant effects on water retention and availability at both trials. These effects were not consistent and were probably a result of complex changes in porosity in response to the two variables. This indicates that both bulk density and organic C need to be carefully managed to obtain the best possible soil physical environment for maintaining LTSP. In addition, the increase in θ_v in the top 0.05 m of soil with residue retention at both sites indicates the importance of this management practice to maintain favourable soil water conditions, particularly in a young stand. The inclusion of LLWR information has also been useful to identify factors that may be limiting to plant growth besides those of water availability.

A further point to bear in mind is that the majority of the data in this chapter were derived from only 56 undisturbed soil cores at each site. Additional cores and continuous monitoring of soil water changes would have been ideal to understand where water restrictions on the trees lie as the data presented here is only an estimation of this. However this would have represented a considerable amount of field data collection which was not possible due to time and financial constraints.

Chapter 7

Tree Survival and Productivity

7.1.   Introduction

The use of plantation productivity as an indicator of long-term soil productivity has been discussed (**Chapter 2**). Plantation productivity can either be measured by non-destructive measures of growth, e.g. tree DBH and height, or by NPP_{-RT} at canopy closure (termed potential productivity). Although the latter measure is more accurate, it is destructive and time consuming. To adequately quantify productivity in this study, measurements were made of both growth and potential productivity.

7.1.1.   Productivity

Potential productivity can be considered as the amount of biomass produced when leaf area is at a maximum (usually close to canopy closure; Powers *et al.*, 1996). It is independent of stocking and occurs between canopy closure and stand maturity. It is constrained by climate, soils and the genetic potential of the stand (Powers *et al.*, 1996; Beadle, 1997; Landsberg and Gower, 1997). The findings of **Section 2.4.2** indicated potential productivity could be measured by the very dense stocking of plots with trees. This allows the rapid identification of key soil indicators of growth through placing an extreme demand on site resources (Kelting, 1999; Watt *et al.*, 2005).

7.1.2.   Factors affecting productivity

Plant productivity is essentially dependent on the uptake of water and nutrients by roots, and the capture of light and carbon dioxide by leaves to form photosynthates (Nadelhoffer *et al.*, 1985; Landsberg, 1986; Sheriff, 1992; Atkinson and Last, 1994). Leaf growth is dependent on the ability of roots to supply the

plant with nutrients and water, while the ability of roots to perform this function is in turn dependent on the ability of leaves to produce photosynthates for root growth and respiration. Therefore changes in allocation of resources to either roots or leaves will result in a change in photosynthate available for growth, and thus overall productivity. As a result, although the measurement of all stand components is important, productivity has been found to be particularly related to measurements of foliage and fine roots (Ruark and Blake, 1991; Sands *et al.*, 1992).

The study of the proportional allocation of resources to different plant parts is termed allometry, and is often reported as the difference between a particular component and total mass (Cromer and Jarvis, 1990; Medhurst *et al.*, 1999). The proportion of resources allocated to a plant part is a result of a combination of processes that are influenced by plant genetics, physiological age of the plant (ontogeny) and the conditions under which the plant is grown, including competition (Cannell and Dewar, 1994; Bernardo *et al.*, 1998; Reed and Tomé, 1998; Medhurst *et al.*, 1999). This is because resources are limited within a plant at any point in time and the allocation of resources to one plant part results in less resources going to another plant part, particularly under conditions of stress (Waring, 1983). In addition, from a plantation forestry perspective, the measurement of allometry is important as any change in allocation patterns will affect allocation to stemwood (Sands *et al.*, 1992; Cannell and Dewer, 1994; Misra *et al.*, 1998a; Teixeira *et al.*, 2002).

Therefore an understanding of the effects of variable growing conditions (or treatments) on allometry is important, as it gives insight into the mechanisms controlling allocation and the resultant growth patterns, and thus productivity (Landsberg, 1986; Landsberg and Gower, 1997). However, allometric relationships can also be affected by ontogeny, which is particularly prevalent in young trees and these effects must be separated from treatment effects (Amateis *et al.*, 2003a; 2003b).

7.1.2.1.   Measurements of foliage and fine roots

a)   Specific leaf area

Specific leaf area (SLA) is the (one-sided) leaf area of plants per unit mass of foliage. It is a measure of the balance between the capture of light and carbon dioxide and leaf structure limitations, water loss and herbivore resistance (Sheriff, 1992; Sefton *et al.*, 2002). High SLAs have been linked to greater plant efficiency, as higher leaf area for the same amount of resources (or carbon) increases light and carbon dioxide interception and therefore carbon assimilation (Sands *et al.*, 1992; Sheriff, 1992; Cromer *et al.*, 1993; Landsberg and Gower, 1997). Specific leaf area in *E. grandis* has been found to decrease with age; e.g. from 35 m^2 kg^{-1} in 2-month-old seedlings (supplied with ample nutrients and water) to 5 m^2 kg^{-1} in 12-month-old trees (Linder, 1985; Cromer *et al.*, 1993; Grove *et al.*, 1996; Job *et al.*, 2003). This ensures an efficient means of fast establishment, with low biomass cost in young trees (Linder, 1985).

b)   Leaf area index

The product of SLA and foliar biomass per unit area of land is the leaf area index, i.e. the single-sided leaf area per unit of land (Linder, 1985; Landsberg and Gower, 1997). Since productivity is related directly to light interception, productivity and LAI are in turn related (e.g. in eucalypt plantations, Cromer *et al.*, 1993; Beadle *et al.*, 1995; Cromer *et al.*, 1995; Hunt *et al.*, 1999). In young stands the more rapid the development of leaf area up to canopy closure, the greater the productivity early in the rotation (Beadle and Mummery, 1990).

c)   Foliar nutrients

Since foliage is where most physiological processes (such as photosynthesis) take place, some have suggested that foliar nutrients will be most directly related to plant productivity when compared to the analysis of other plant components (Schönau, 1981a; Mead, 1984; Bellote and da Silva, 2004; Silveira *et al.*, 2004). In

addition, foliar analysis can be used to give an indication of overall treatment effects on plant nutrition (Ulrich and Hills, 1967; Richards and Bevege, 1972; Needham *et al.*, 1990; Silveira *et al.*, 2004). This is particularly the case with trees in which the exploration of large volumes of soil by their extensive root systems makes the evaluation of available soil nutrients difficult (Barros *et al.*, 2004). To this end, foliar nutrient levels and ratios have been compared in vigorously and poorly growing trees, to determine where the nutrient imbalance lies, and is a common practice in forestry (Drechsel and Zech, 1991; Dell, 1996; Herbert, 1996; Bellote and da Silva, 2004).

The critical level approach (Ulrich and Hills, 1967) was used to assess foliar nutrients in this study. This approach considers that plant nutrients are required in certain quantities and forms for plant health (Dell, 1996). Critical levels are not single values, but narrow ranges in which a plant nutrient is deficient, sufficient or toxic (Smith and Loneragan, 1997). However, criticism of this approach exists, and has mainly originated from fertiliser trials in which no response in foliar nutrient levels to applications of specific nutrients has occurred, despite the fact that those specific nutrients were below the optimum (e.g. Birk and Turner, 1992; Misra *et al.*, 1998b; du Toit and Oscroft, 2003). In addition, the use of static critical levels may not be suitable in plantation trees because foliar nutrients have been found to vary with stand age, season, species, plant tissue age and site (Schönau, 1981a; Frederick *et al.*, 1986; Erasmus and Levin, 1991; Dell *et al.*, 1995; Barros *et al.*, 2004). However, the critical level approach is the simplest method of assessing nutrient levels. In South African eucalypt plantations, severe deficiencies/toxicities of foliar nutrients are not common despite trees being grown on highly weathered soils of low nutrient status. It has therefore been suggested that nutrient balance or ratios may be more important when investigating the nutritional status of these trees (Schönau, 1982; Herbert and Schönau, 1989; Herbert and Schönau; 1990). Critical levels of foliar nutrients for young *E. grandis* have been determined or reviewed by several authors for a range of sites and ages (Herbert, 1990; Boardman *et al.*, 1997; **Table 7.1**).

Table 7.1: Critical levels of foliar nutrient concentrations in *E. grandis* as determined by Boardman *et al.* (1997[‡]) and Herbert (1990[⊕]).

Study:	Boardman *et al.* (1997)				Herbert (1990; 1992)	
Nutrient	**Def**[†]	**Marg**[‡]	**Opt**[†]	**High**	**Range**	**Opt**[†]
N (g 100g^{-1})	<0.7	1.48-1.8	1.8-3.4	3.5+	1.30-2.91	>2.0
P (g 100g^{-1})	<0.07	0.09	0.1-0.3	0.3+	0.10-0.31	0.16
K (g 100g^{-1})	<0.5	*	0.6-1.8	*	0.59-0.99	0.70
Ca (g 100g^{-1})	<0.08	*	0.3-1.0	*	0.89-1.42	>1.0
Mg (g 100g^{-1})	<0.06	*	0.1-0.35	*	0.27-0.42	0.30
Fe (mg kg^{-1})	<17	*	60-130	300+	52-1021	110
Zn (mg kg^{-1})	<7	*	14-46	*	8-32	18
Mn (mg kg^{-1})	<8	*	220-700	1000+	129-6005	600
Cu (mg kg^{-1})	<2	*	6-15	*	2-26	12
Na (mg kg^{-1})	*	*	3000-4200	*	*	*

[†]   Def = deficient; Marg = marginal, Opt = optimal.
[‡]   From a review of juvenile plantation *E. grandis* foliar nutrient studies, i.e. between seedling stage and canopy closure.
[⊕]   From a summary of 4-year-old *E. grandis* fertiliser trials in the Zululand region of South Africa.

d)   *Root:shoot ratio*

The root:shoot ratio assumes that a functional equilibrium exists between the size and activity of shoots (foliage) and fine roots (Cannell, 1985; Johnson and Thornley, 1987; Gonçalves and Mello, 2004). Fine roots are generally classified as those smaller than 2 mm diameter. They absorb soil water and nutrients directly, and their biomass and distribution are sensitive to local environmental conditions (Ares and Peinemann, 1992; Fredericksen and Zedaker, 1995; Landsberg and Gower, 1997; Vogt *et al.*, 1997; Gonçalves and Mello, 2004).

7.1.2.2.   *Ontogeny*

The allometric relationships of a tree change with its development, i.e. the course of genesis, growth, maturation, and decline (Fitting *et al.*, 1921; Larcher, 2003). These changes are most easily observed in young trees, where resources are initially preferentially allocated to root growth for seedling establishment. As the trees grow and reach canopy closure, the majority of resources are then allocated to stemwood for the attainment of light (Cromer and Williams, 1982; Fabião *et al.*,

1995; Misra *et al.*, 1998a; Beets *et al.*, 2007). This change in allocation patterns due to natural growth and development is termed ontogeny (Cannell, 1985; Ruark and Blake 1991; Sands *et al.*, 1992; Sheriff, 1992).

Certain treatments will slow down tree growth and development, compared to other treatments, resulting in trees of different sizes, at different stages of development. Even though the trees in the study are of a similar species and chronological age, the simple comparison of allometric relationships (e.g. root:shoot ratios) across these treatments, can lead to incorrect conclusions regarding treatment effects on allometry (Sands *et al.*, 1992; Beets *et al.*, 2007). This is because the direct treatment effects on allocation patterns of trees must be distinguished from indirect treatment effects on rates of growth and development (Ledig *et al.*, 1970; Gebauer *et al.*, 1996). Several eucalypt studies have found that water and/or nutrient availability effects on allometry were significant until ontogenetic effects were accounted for (e.g. Cromer and Jarvis, 1990; Osório *et al.*, 1998; Reed and Tomé, 1998; Guiterrez *et al.*, 2002).

Three methods of determining if allometry has changed with treatments, and not ontogeny, are to:

  a) Compare allocation in similar size trees, i.e. in terms of height and ground line diameter, or biomass index in small trees, across treatments (Darrow, 1984; Eccles *et al.*, 1997).
  b) Adjust differences in plant size statistically (Osório *et al.*, 1998; Guiterrez *et al.*, 2002).
  c) Compare differences in parameters in allometric equations (Sands *et al.*, 1992).

7.1.3.   Compaction effects on survival and productivity

7.1.3.1.   Effect of compaction on survival and aboveground productivity

The effects of compaction in South African eucalypt stands were reviewed in **Section 2.4.1**. Results of the previous studies at specifically Rattray and Shafton found no significant effect of harvesting treatments on survival (Smith and du Toit,

2005; Smith, 2006). In addition, compaction had no significant effect on stand productivity (measured by basal area and stemwood volume) at Rattray. This was attributed to improved soil water availability, since PSS was not growth limiting. At Shafton however, only the logger and extraction route treatments (imposed in a similar manner to the C_M and C_H treatments of this study, respectively) had significantly lower growth at 12 years of age than their control treatments. This was despite the fact that the logger treatment did not have the highest PSS of all the treatments. In addition, although not always significant, the basal area of trees in most treatments was lower than that of the control treatments (Smith, 2006).

Only limited work has been conducted internationally on the effect of soil compaction on *Eucalyptus* growth (e.g. Misra and Gibbons, 1996; Williamson and Neilsen, 2003a; 2003b). Williamson and Neilsen (2003a) found that compaction, and the associated soil damage from machinery movement resulted in poorer survival and growth of naturally regenerating eucalypt forest on wetter sites. Under glasshouse conditions, eucalypt seedling growth was poorest on soils representing those with topsoil displacement and profile disturbance when compared to those representing compacted soils, although these also had poor growth relative to undisturbed soils (Williamson and Neilsen, 2003b). Surface compaction (i.e. top 0.2 m), has been found to more significantly decrease *E. camaldulensis* stem volume when compared to increases in bulk density in the subsoil (0.2 – 0.4 m; Pereira, 1990, cited by Gonçalves *et al.*, 1998). This is probably due to the concentration of water, and particularly nutrients, in the soil surface. Misra and Gibbons (1996) found that although eucalypt seedling root growth decreased from soil strengths of 400 to 4200 kPa (relating to bulk densities of between 0.7 and 1.0 Mg m^{-3} in a clay soil), seedling biomass was not significantly affected. This may be because adequate water and nutrients were supplied to the seedlings throughout the experiment.

In other non-eucalypt stands, tree survival and stand aboveground productivity have been positively, negatively, or not affected at all by compaction, or the effects have diminished with time (e.g. Corns, 1988; Powers, 1999; Kelting *et al.*, 2000; Miller *et al.*, 2004; Ares *et al.*, 2005; Fleming *et al.* 2006b; Tan *et al.*, 2006). The

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cause of these variable responses to compaction found both internationally and in South Africa (**Section 2.4.1**) were reviewed in **Chapter 1**.

7.1.3.2.   Effect of compaction on belowground productivity

Very few productivity studies have included measurements of roots. This is due to the difficulty (as roots vary substantially with soil variability) and expense involved in their measurement, and also the low level of precision of measurements when compared to those of aboveground biomass components (Sutton, 1991; Atkinson and Last, 1994; Misra *et al.*, 1998a; Bauhus and Messier, 1999; O'Grady *et al.*, 2005). However, roots represent a large (between 22 and 63%) portion of the NPP of a stand (Landsberg, 1986; Hendrick and Pregitzer, 1993; Waring *et al.*, 1998; Bauhus and Messier, 1999; Teixeira *et al.*, 2002). In South African *E. grandis*, belowground biomass represented approximately 30% of the total biomass of a coppiced 7-year-old stand in the KwaZulu-Natal Midlands (du Toit *et al.*, 1999).

No relationship between root growth and bulk density has been directly determined except under controlled conditions (e.g. Foil and Ralston, 1967; Misra and Gibbons, 1996). However, several workers have established root growth-limiting bulk densities for their sites and species by reviewing literature (e.g. Daddow and Warrington, 1983; Lousier; 1990). Even so, there is evidence from other studies that these limiting bulk density values are not infallible (Miller *et al.*, 2004; Page-Dumroese *et al.*, 2006). This is because changes in belowground productivity have been found to be a result of changes in soil strength, water availability, nutrient supply to roots and aeration, rather than bulk density *per se* (Grable and Siemer, 1968; Greacen and Sands, 1980; Gomez *et al.*, 2002a; Blouin *et al.*, 2004). Generally, increasing soil compaction decreases belowground productivity, due to either increasing soil strength or decreasing AWC, or a combination of the two.

Compaction increases soil strength, so reducing both tree root growth and the soil volume able to be explored by roots (Greacen and Sands, 1980; Page-Dumroese *et al.*, 1998; Williamson and Neilsen, 2003b; Blouin *et al.*, 2004). Severe root limiting levels of penetrometer soil strength (PSS) for *Pinus radiata* have been found to be 1300 kPa (Zou *et al.*, 2001), 2100 kPa (Theodorou *et al.*, 1991) and 3000 kPa (Sands *et al.*, 1979). While Greacen *et al.* (1969, cited by Greacen and Sands, 1980) found that over a range of penetrometers, plant species and soil types that an average soil strength above 2500 kPa severely limited root growth. In another review, root limiting values of PSS for a number of tree species were found to vary between 2000 and 4200 kPa (Miller *et al.*, 2004). Misra and Gibbons (1996) varied PSS in a well-aggregated clay soil and found that increasing PSS and bulk density (between 400 and 4200 kPa or 0.7 and 1.0 Mg m^{-3}) reduced root length and number in potted *E. nitens* seedlings. Any reduction in the soil volume able to be explored by roots also decreases the ability of roots to obtain soil water and nutrients, particularly immobile nutrients, further impacting growth (Froehlich and McNabb, 1984; Corns, 1988). In addition, the decrease in soil volume occupied by roots can also decrease the physical support to trees, so increasing the likelihood of windthrow (Hutchings *et al.*, 2002). Compaction often decreases the availability of soil water to plants (or the LLWR), which on drier sites will increase the risk of drought (Miller, 1985).

However, in some soils (particularly sandy soils) compaction may increase water retention and improve soil-root contact, and if supplies of air, water and nutrients are adequate, decreases in growth and productivity may not be found (Greacen and Sands, 1980; Taylor and Brar, 1991; Powers *et al.*, 1996).

Finally, as a result of the review in **Chapter 2**, it was determined that the effect of compaction on tree survival and productivity must be evaluated in conjunction with changes in soil properties affected (by compaction) and site and species characteristics (Powers *et al.*, 1996; Burger and Kelting, 1998; Gomez *et al.*, 2002a; 2002b; Williamson and Neilsen, 2003a).

7.1.3.3. Effect of compaction on SLA, LAI, foliar nutrients and root:shoot ratio in eucalypts

Pot studies have found that compaction does not affect SLA, LAI or root:shoot ratios of *Eucalyptus* seedlings (Williamson and Neilsen, 2003b), or root:shoot ratios of *E. nitens* seedlings (Misra and Gibbons, 1996). In *Picea* and *Pinus* seedlings, however, compaction has increased root:shoot ratios (Corns, 1988).

Contrasting effects of water supply on SLA values in eucalypts have been found. Decreasing water supply decreased SLA (Job *et al.*, 2003) or had no effect (Tuomela *et al.*, 2001). Although compaction had no effect on the LAI of *Eucalyptus* seedlings (Williamson and Neilsen, 2003b), water stress decreased LAI in *E. grandis* and other eucalypts (Cromer *et al.*, 1993; Beadle *et al.*, 1995; Osório *et al.*, 1998; Tuomela *et al.*, 2001; Stape *et al.*, 2004; Whitehead and Beadle, 2004). An increase in root:shoot ratio as a result of water stress is thought to occur through a reduction in shoot growth (Pereira and Pallardy, 1989; Pereira and Osório, 1995). However, variable results of water availability on root:shoot ratios in eucalypts have been found (Pereira and Kozlowski, 1976; Bachelard, 1986; Fabião *et al.*, 1995; Osório *et al.*, 1998; Guiterrez *et al.*, 2002). Lower productivity under water stressed situations have been explained by the death of fine roots during drought, and the allocation of greater quantities of carbon to replace these roots during times of adequate water supply than ordinarily necessary (Pereira and Pallardy, 1989).

In South Africa, coarse root biomass of 4-year-old *E. grandis* increased while fine root biomass decreased, in irrigated treatments relative to the control (Campion, 2005). In addition there was an increase in both fine and coarse root biomass relative to the control in treatments combining irrigation and fertilisation. However, it was not clear if the change in allocation was a result of the treatments or changes in tree size as a result of the treatments as the comparison of trees of similar size across the treatments was not performed. Overall, there was a decrease in carbon allocation to belowground biomass with increasing water supply.

No studies investigating the effect of soil compaction on eucalypt foliar nutrients were found. However, in other tree species compaction had varied effects, either increasing (e.g. in *P. contorta*; Blouin *et al.*, 2008), decreasing (e.g. in *P. radiata*; Sheriff and Nambiar, 1995), or having no effect (e.g. in *P. radiata*; Nambiar and Sands, 1992; Merino *et al.*, 2004) on several foliar nutrient concentrations.

7.1.4.   Residue management effects on growth, productivity and survival

7.1.4.1.   Effect of residue management on survival and aboveground productivity

Despite the long-term negative effects on soil organic carbon content of harvest residue removal, most review studies found that survival and early growth of seedlings increased with residue removal (Dyck and Cole, 1994; Johnson, 1994; Morris and Miller, 1994; Powers, 1999; Raison and Rab, 2001; Laiho *et al.*, 2003; Gonçalves *et al.*, 2004b). However, as trees grew, the effects of residue management on growth were reversed and residue removal resulted in decreases in growth (e.g. Proe *et al.*, 1999; Smith *et al.*, 2000). This was attributed to an initial greater availability of nutrients, particularly nitrogen, changes in soil temperature and moisture (not only affecting physical soil properties, but also microbial properties and nutrient availability) and reduced competition by weeds (Morris and Miller, 1994; Powers *et al.*, 1995; 1996; Powers, 1999). Later, however, as the residues decompose, nutrients originally "locked-up" are released, allowing trees on residue retained areas to surpass (in growth) trees on residue removed areas (Roberts *et al.*, 2005).

It has been suggested that the response of trees to the retention of residues may be partially dependent on climate (Powers *et al.*, 1996). In tropical or warm temperate climates, residue removal is thought to not only increase evaporative soil moisture loss, but also to lead to extremes in soil temperature that have negative effects on soil microbial populations and nutrient mineralisation rates (Powers, 1999). However, another review of *Eucalyptus* studies in tropical areas,

found in several cases that residue retention did not improve growth, although it was never reduced (Gonçalves *et al.*, 2004b). The positive effect of residues may be due to their influence on the temperature, aeration, nutritional and moisture status particularly of the topsoil (i.e. the principal area of fine root growth). Residues also affect the susceptibility of the soil surface to erosion, the reproduction of vegetation (including weed growth), microbial activity and their role in nutrient cycling and soil aggregation and structure (Zabowski *et al.*, 1994; Grigal and Vance, 2000).

In the previous study at Rattray, Smith and du Toit (2005) found no significant effect of either windrowing or broadcasting of residues on tree survival or volume. At a site close to Shafton, du Toit *et al.* (1999; 2004) reported the effects of residue management on *E. grandis* early tree survival, growth and biomass. They concluded that increased nutrient availability in the burnt and fertilised treatments positively affected early tree growth, although there were no effects on survival. However, du Toit and Scholes (2002), reporting on the soil nutrient status at the same trial, concluded that only burning of harvest slash residue resulted in a substantial loss of nutrients and that the soil was reasonably well buffered against major nutrient fluxes caused by residue management practices.

7.1.4.2. *Effect of residue management on belowground productivity*

Residue management has implications for soil organic matter and nutrient dynamics and soil moisture (**Chapters 4-6**). Fine root biomass increased with increasing residue retention (Oliveria *et al.*, 1997 cited by Gonçalves and Mello, 2004). However, some studies have found no effect of residue management on eucalypt root biomass (e.g. Jones *et al.*, 1999; Nkosana, 2002). In other plant species, however, fine root biomass and length have generally decreased in soil under residue removal in comparison to undisturbed soil (e.g. in *Pseudotsuga* and *Picea* tree species, Perry *et al.*, 1982; and in various crop species, Bathke *et al.*, 1992).

7.1.4.3.   Effect of residue management on SLA, LAI, foliar nutrients and root:shoot ratio in eucalypts

Residue management generally has a substantial effect on nutrient supply. Nutrient supply, particularly N and P, has also been linked to higher SLA in *E. grandis*, although this effect diminishes as the stand approaches canopy closure (Kirschbaum and Tompkins, 1990; Kirshbaum *et al.*, 1992; Cromer *et al.*, 1993; Grassi *et al.*, 2002). This has led to the conclusion that nutrition has the greatest effect on the SLA of eucalypts when SLA is high and trees are young (Cromer *et al.*, 1993). Nutrient uptake in *E. grandis* has also been found to strongly affect LAI (Cromer *et al.*, 1984; Linder, 1985; Sands *et al.*, 1992; Cromer *et al.*, 1993). However, increased nutrient supply does not always increase allocation of biomass to foliage (e.g. Sheriff and Nambiar, 1991), but rather purely increases SLA (e.g. Field and Mooney, 1986; Sheriff and Nambiar, 1991). Increases in nutrient availability have resulted in decreases in root:shoot ratios in *E. grandis* seedlings and trees (Cromer and Jarvis, 1990; Kirschbaum *et al.*, 1992; Dighton *et al.*, 1993; Fabião *et al.*, 1995; Misra *et al.*, 1998a; Campion, 2005) or a reduction in allocation of biomass belowground (relative to aboveground) (Grove *et al.*, 1996; Madeira *et al.*, 2002; Teixeira *et al.*, 2002). However, other studies (on both *Eucalyptus spp.* and other tree species) have found no effect of fertiliser on root:shoot ratios, as a result of proportional increases in each component with fertilisation (Nadelhoffer *et al.*, 1985; Santantonio, 1989; Sheriff and Nambiar, 1991; Smith *et al.*, 1994). However, the effect of residue management directly on SLA, LAI and root:shoot ratios has not been quantified in eucalypts.

Residue retention significantly increased the foliar concentrations of N, Ca and Mg of 1-year-old eucalypt stands in the Congo (Nzila *et al.*, 2004). A study close to the Shafton trial (du Toit *et al.*, 2008) also found that foliar nutrient concentrations were often significantly higher in trees (0.25 – 3-years-old) on broadcast than residue removed plots.

7.1.5. Compaction x residue management effects on survival and productivity

The combination of compaction and residue management (or movement as a result of operations) on tree growth has generally only been investigated overseas and on other tree species besides eucalypts. Studies reviewed by Morris and Miller (1994) generally found that seedling growth was greatest on plots with severe soil disturbance and mixing, and residue removal. As the stands matured, however, growth was negatively affected by soil compaction (and mixing) and residue removal. In other studies, increasing compaction in compaction x residue management studies generally led to a decrease in tree size (e.g. Powers *et al.*, 2005; Tan *et al.*, 2006), although natural amelioration occurred on some sites (e.g. Lacey and Ryan, 2000; Powers *et al.*, 2005). Decreasing residue retention in these interaction studies either had no effect (e.g. Powers *et al.*, 2005), initially increased growth which then "washed out" (e.g. Lacey and Ryan, 2000), or decreased growth (e.g. Tan *et al.*, 2006). The results from these and other trials indicate that compaction and residue retention effects are site and species specific.

At Rattray in the previous study, no interaction effects were found on either tree survival or productivity (Smith and du Toit, 2005). Improved early *E. grandis* productivity was found in residue retained treatments where logger movement mixed residues and soil, when compared to residue retained treatments alone, at a site close to Shafton (du Toit *et al.*, 1999; 2004). However, the results may be more due to the mixing effect of the logger on nutrient availability, than actual compaction. In addition, there were no significant effects on tree survival.

7.1.6. Chapter rationale and objectives

The effect of soil compaction and residue management on eucalypt stand productivity and allometric relationships, as well as tree survival and growth has not been adequately investigated in South Africa. Therefore the objective of this

section of the study was to determine if, and in what manner, stand productivity was influenced by compaction treatments and residue management through their effects on soil properties at the two sites. This was achieved by evaluating:

- compaction and residue management treatment effects on the NPP_{-RT} of sub-plot trees;

- changes in this productivity and the relationship with SLA, LAI, foliar nutrient concentrations or root:shoot ratios;

- the changes found in SLA, LAI, foliar nutrient concentrations or root:shoot ratios and their relationship to the compaction treatments and the imposed residue management strategies;

- the relationship between non-destructive measures of tree growth (such as GLD, DBH, height or biomass index) and destructive measures of NPP_{-RT} or stand allometry; and

- growth and survival responses to compaction treatments and residue management in sub-plots and main plots.

7.2.   Materials and methods

Full details of planting, other silvicultural operations and measurements are given in **Chapter 3**. However, the effect on the results of the accidental herbicide application to trees at Shafton is discussed here more fully.

7.2.1.   Herbicide application effects on trees at Shafton

The accidental application of herbicide at Shafton resulted in defoliation, and in some cases death, of some of the sub-plot trees in certain plots. On an individual young tree basis, those that survived would have had a lower growth rate as a result of the loss of vital leaf area in the early stages of growth. There is evidence that lower survival of young eucalypts as a result of external factors (such as defoliation by browsing) is later compensated for on a plot basis by the better growth rates of surviving trees (Wilkinson and Neilsen, 1995). That study found

that young trees that lost half of their crown had lower total volume growth than un-browsed trees, while those that lost the entire crown either died or were severely suppressed by competing vegetation. In this study, competing vegetation would not have impacted growth, only once the trees reached canopy closure would poorer growth have become an issue. Therefore during statistical analyses of the Shafton results mortality due to herbicide application was used as a covariate.

7.2.2. Statistical analysis of effects of soil properties on tree growth and productivity

Although significant (p<0.001) relationships were sometimes obtained between various soil properties and tree growth or productivity, these were excluded as a result of their low r^2 values (r^2<0.5).

7.3. Results and discussion

7.3.1. Productivity and allometry

7.3.1.1. Effect of biomass index on total and component productivity

There were significant relationships between the biomass index (BI = ground-line diameter^2 * height; mm^3) of trees harvested from the sub-plots and their various biomass components at both Rattray and Shafton (**Table 7.2**; **Appendices 7.1** and **7.2**, respectively). Biomass index was therefore utilised as the independent variable in the relationships rather than height or GLD because it produced higher r^2 values with the dependent variables.

Table 7.2:   Regression equations, percentage variance accounted for (r^2) and levels of significance (p) of relationships between biomass index (BI; mm^3) and various biomass components (kg dry mass; y-variate) of *E. grandis* trees at Rattray (209 DAP) and Shafton (211 DAP).

Component	Regression equation	r^2	p
Rattray			
Total	y = 0.019 + 5.15E-07 * BI	0.944	<0.001
Aboveground	y = 0.044 * 3.15E-07 * BI	0.945	<0.001
Stem + Branches	y = 0.019 + 1.90E-07 * BI	0.961	<0.001
Foliage	y = 0.025 + 1.25E-07 * BI	0.901	<0.001
Belowground	y = 0.017 + 7.48E-08 * BI	0.835	<0.001
Belowground Stem	y = 0.005 + 0.40E-07 * BI	0.940	<0.001
Coarse Roots	y = 0.011 + 2.07E-08 * BI	0.810	<0.001
Fine Roots	-	-	NS
Shafton			
Total	y = 0.039 + 4.65E-07 * BI	0.967	<0.001
Aboveground	y = 0.034 + 3.74E-07 * BI	0.915	<0.001
Stem + Branches	y = 0.014 + 2.05E-07 * BI	0.938	<0.001
Foliage	y = 0.019 + 1.71E-07 * BI	0.891	<0.001
Belowground	y = 0.016 + 6.76E-08 * BI	0.836	<0.001
Belowground Stem	y = 0.004 + 3.81E-08 * BI	0.825	<0.001
Coarse Roots	y = 7.95E-03 + 3.05E-08 * BI	0.610	<0.001
Fine Roots	-	-	NS

NS: not significant.

The high r^2 values (**Table 7.2**) suggest that changes in allocation of biomass occurred principally as a result of tree size, rather than as a direct result of the treatments, with the possible exception of fine root biomass. The lack of relationships with fine roots may also be due to the difficulties associated with sampling and recovery of fine roots from trees in the field, as found by others (e.g. Sutton, 1991; Misra *et al.*, 1998a). It is likely that the treatments did not significantly alter the allometry of trees, although they may have a significant effect on the size of trees. It could thus be expected that treatments with smaller trees at the time of harvest would have similar allometry once the trees grow to the size of the larger trees in other treatments.

Of the studies investigating allometry in *E. grandis*, only two were of a similar age to this study (Cromer *et al.*, 1993; Nkosana, 1999). In these studies the effects of fertilisation and irrigation treatments were investigated on 4- and 8-month-old trees

(Cromer *et al.*, 1993), and 5-month-old trees (Nkosana, 1999), this latter study site being close to Shafton. From the results presented in both studies, it was not apparent if there were changes in allometry with the treatments, although certain treatments did have larger trees. However, it was found that in *E. globulus* growing under different irrigation and fertiliser or purely irrigation regimes that there were no structural changes in trees as a result of the treatments (Madeira *et al.*, 1989; Osório *et al.*, 1998; Reed and Tomé, 1998). Treatments affected DBH and height of the trees, and it was tree size that affected allocation to different aboveground parts. Highly significant correlations of aboveground components with DBH were obtained in an *E. diversicolor* age-series study (Grove and Malajczuk, 1985).

These results indicate that total biomass and that of the components (with the exception of fine roots) from planting to canopy closure of the sub-plot trees were mainly, and significantly, affected by ontogeny (**Table 7.2**). Therefore treatment effects on productivity were statistically tested only on BI data.

7.3.1.2. *Allometric relationships*

Significant relationships were found between the proportion of biomass allocated above- and belowground, between foliage and stem plus branch biomass and between coarse root and stem plus branch biomass at the two trials (**Table 7.3**; **Appendix 7.3**). No significant relationship was found between foliage and fine root biomass at either trial (data not presented).

Linear relationships between above- and belowground biomass, as well as the percentage of biomass allocated aboveground were similar at Rattray and Shafton. (**Table 7.3**; **Appendix 7.3**). However, the allocation to foliage at Shafton was only slightly higher than that at Rattray, while allocation of biomass to stem plus branches was considerably lower than Rattray (**Appendix 7.3**). This discrepancy is probably not due to the occurrence of canopy closure at Rattray. This is because although the trees were bigger at Rattray (average total harvested tree biomass was 0.27 kg at Rattray; 0.21 kg at Shafton), with a larger average

crown diameter (0.95 m, in contrast to Shafton's 0.83 m), spacing at Rattray was wider (1 x 1 m, in comparison to 0.8 x 0.8 m at Shafton), and the majority of trees had not quite reached canopy closure, unlike at Shafton. However, this discrepancy may be due to site or genetic differences as allometric equations have been found to vary with species and geographical region (Schönau and Boden, 1982; Sheriff, 1992; Medhurst *et al.*, 1999).

Almost identical relationships were obtained between coarse roots and stem plus branch biomass at both trials, as has been found by others (Misra *et al.*, 1998a in *E. nitens*; and Jackson and Chittenden, 1981; van Miegroet *et al.*, 1994; Drexhage and Colin, 2001, in other tree species). The highly significant relationships ($p<0.001$) between these parameters in this and other studies may indicate that coarse root biomass can be reliably estimated from measurements of stem variables. The lack of a relationship between foliage and fine root biomass at both Rattray and Shafton was probably due to the difficulties associated with sampling and recovery of fine roots from trees in the field or treatment effects.

Table 7.3: Regression equations and percentage variance accounted for (r^2) of relationships between biomass components (kg dry mass) of *E. grandis* trees 209 DAP at Rattray ($_{RAT}$) and 211 DAP at Shafton ($_{SH}$). All relationships are highly significant ($p<0.001$).

Component (y)	Component (x)	Regression equation	r^2
Aboveground$_{RAT}$	Belowground$_{RAT}$	$y = 2.902x + 0.041$	0.837
Aboveground$_{SH}$	Belowground$_{SH}$	$y = 5.509x - 0.040$	0.851
Stem+branches$_{RAT}$	Foliage$_{RAT}$	$y = 1.624x - 0.033$	0.920
Stem+branches$_{SH}$	Foliage$_{SH}$	$y = 1.117x - 0.002$	0.976
Stem+branches$_{RAT}$	Coarse roots$_{RAT}$	$y = 2.086x - 0.014$	0.852
Stem+branches$_{SH}$	Coarse roots$_{SH}$	$y = 2.709x - 0.013$	0.870

Despite some slight differences between relationships at the two trials, the high r^2 values indicate that allocation of biomass at the trials over the first 6 months of growth was probably not substantially affected by the treatments (**Table 7.3**). Other studies have reported significant treatment effects on both biomass components and total biomass, but not on the relative proportions allocated to each component at a particular tree size (e.g. Cromer *et al.*, 1993; 1995).

7.3.1.3.   Effect of SLA, LAI, foliar nutrients and root:shoot ratio on productivity

a)   SLA

Specific leaf area at Rattray varied between 12.3 and 16.2 m^2 kg^{-1}, while at Shafton it ranged between 12.2 and 16.8 m^2 kg^{-1}. No significant relationship between total biomass and SLA was obtained at either trial (data not shown). This similar range of SLA values at both trials is indicative of the similar age (when sampled) of the trees at the trials. The lack of significant relationships with biomass is most likely a result of the trees having been sampled either close to, or at canopy closure. This is because SLA has been found to be initially very high in *E. grandis* seedlings, decreasing with age (Cromer *et al.*, 1993; Grove *et al.*, 1996; Job *et al.*, 2003).

b)   LAI

Since LAI was calculated as the product of SLA and foliage biomass per unit land area, and SLA values did not vary greatly across the trials, LAI values were directly related to foliar biomass values (data not shown). Foliar biomass was significantly related to other biomass components of the trees, and therefore highly significant relationships (p<0.001) on an individual tree basis between aboveground biomass and tree leaf area were obtained at both Rattray and Shafton (**Figure 7.1**; **Appendix 7.4**). These data indicate that for a similar amount of leaf area, a tree at Rattray would have a larger amount of biomass than a tree at Shafton, and therefore that trees at Rattray are more efficient, probably due to greater resource availability. Linear relationships between aboveground biomass and intercepted radiation (based on leaf area) in a range of young (i.e., <3 years-old) eucalypt species has been found (Beadle *et al.*, 1995; Osório *et al.*, 1998). Both studies concluded that differences in aboveground biomass (Beadle *et al.*, 1995) and total biomass (Osório *et al.*, 1998) were directly related to canopy development (or LAI). Similar results were seen in *E. grandis* of a similar age range (Cromer *et al.*, 1993). In this study, the initial linear relationship was similar to that of Beadle *et al.* (1995). As the trees grew, however, increases in

biomass with increasing LAI tapered off. This often occurs as canopy closure and intra-specific competition sets in (Cromer *et al.*, 1993). Although LAI can be used to distinguish between stands of varying management (or age or species), this was not performed in this study, as a result of the relationship of total biomass with biomass index. However, at Rattray LAI at 208 DAP was calculated to vary in the treatment plots between 0.309 and 2.818 m^2 m^{-2} and average 1.511 m^2 m^{-2} across the trial, while at Shafton it varied between 1.157 and 2.605 m^2 m^{-2} and averaged 1.851 m^2 m^{-2} at 211 DAP. Variation in LAI within species of young eucalypts has been found to be low, i.e. between different provenances and less than 4-years-old (Beadle and Mummery, 1990), but significant between species (e.g. Honeysett *et al.*, 1992).

Rattray $y = 0.351(1.398^x) - 0.305; r^2 = 0.924^{***}$
Shafton $y = 3.27 - 3.280(0.942^x); r^2 = 0.958^{***}$
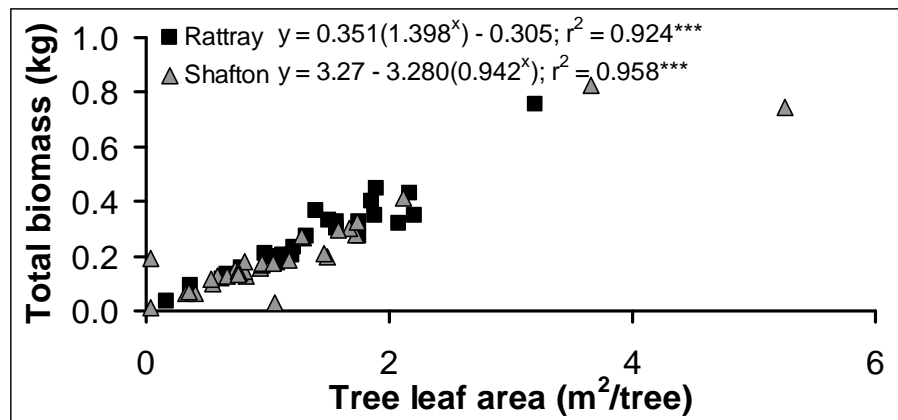
Figure 7.1:   Relationship between total biomass and tree leaf area of individual trees at Rattray (209 DAP) and Shafton (211 DAP).

c)   *Foliar nutrient concentrations*

Although foliar N values at Rattray (**Table 7.4**) were similar to those obtained by du Toit *et al.* (2001b) and Schönau (unpublished), on average they would be considered below optimum (Herbert, 1990; 1992; Boardman *et al.*, 1997). Foliar Mn concentrations covered a wide range. The majority of plots would be considered to have below optimum Mn (Herbert, 1992), although some had very high values (greater than 1000 mg kg^{-1}; Boardman *et al.*, 1997). However, foliar Mn can vary widely without trees showing signs of deficiency or toxicity

(e.g. Schönau, 1981b; Carlson *et al.*, 1998).The majority of other foliar nutrients at Rattray, i.e. P, K, Ca, Mg, Cu, Fe, Zn, Na and Al, were all generally within the range of values in the literature (Herbert, 1990; 1992; Boardman *et al.*, 1997; du Toit *et al.*, 2001b; Schönau, unpublished). Despite several nutrient concentrations and ratios being below optimal, there were no significant relationships with total biomass (data not shown).

At Shafton, foliar N concentrations (**Table 7.4**) were well within the range found by other researchers from the same vicinity (i.e. Campion, 2005; Dovey *et al.* 2007). They were also well above the optimum value quoted by Herbert (1990). Foliar P concentrations were generally low compared to other sources, and some values would be considered marginal (Boardman *et al.*, 1997) or below the range previously found in South Africa (Herbert, 1990). A much wider range of foliar K concentrations were obtained than those given by Herbert (1990) and several values would be considered deficient or marginal (Boardman *et al.*, 1997), despite being similar to those of a nearby trial (Campion, 2005). Foliar S, Ca, Mg, Cu and Zn concentrations were within the majority of the ranges found in the literature (Herbert, 1990; 1992; Boardman *et al.*, 1997; Campion, 2005; Dovey *et al.*, 2007) However, foliar concentrations of Fe, Mn and Al of several plots would be considered high (Herbert, 1992; Boardman *et al.*, 1997). High foliar Mn levels in *E. grandis* have been attributed to adverse growing conditions (Schönau, 1982). As at Rattray, despite there being evidence of deficiencies in certain foliar nutrients, no significant effects of foliar nutrient concentrations or ratios were found on tree biomass (data not shown).

As at Rattray, the lack of significant relationships between foliar nutrient concentrations with tree biomass, particularly those considered below optimal for *E. grandis* trees of a similar age, reinforces the view that the diagnosis of nutrient deficiencies in eucalypts using foliar analysis is often unreliable (Cromer, 1996). However, it must be borne in mind that even if nutrients are not limiting poor growth may still occur due to some other limiting factor(s). When poor growth is due only to some limiting nutrient(s) then foliar analysis can be of importance in highlighting such deficiency.

Table 7.4: Range and average of foliar nutrient concentrations of sub-plot trees at Rattray and Shafton.

Foliar nutrient	Rattray		Shafton	
	Range	Average	Range	Average
N (g 100g^{-1})	1.35 – 2.22	1.80	2.10 – 3.02	2.49
N (g m^{-2})	0.90 – 1.66	1.25	1.51 – 2.21	1.71
P (g 100g^{-1})	0.10 – 0.14	0.12	0.08 – 0.12	0.10
K (g 100g^{-1})	0.62 – 0.88	0.74	0.47 – 1.04	0.67
Ca (g 100g^{-1})	0.76 – 1.17	0.95	0.64 – 1.06	0.79
Mg (g 100g^{-1})	0.30 – 0.39	0.35	0.25 – 0.33	0.28
C (g 100g^{-1})	49.1 – 51.4	50.5	48.7 – 50.9	50.1
Cu (mg kg^{-1})	3.6 – 11.6	8.2	7.3 – 13.5	11.6
Zn (mg kg^{-1})	13.0 – 26.0	17.0	14 - 24	18
Fe (mg kg^{-1})	102 – 224	136	150 – 358	206
Mn (mg kg^{-1})	249 - 1039	535	519 – 1195	713
Na (mg kg^{-1})	3368 - 4693	3974	2032 - 3659	2650
Al (mg kg^{-1})	97 - 178	130	208 - 472	254

d)   Root:shoot ratio

As with SLA and foliar nutrients, no significant relationship was obtained between root:shoot ratios and total biomass (NPP$_{-RT}$) at either trial.

7.3.1.4.   Effect of treatments on SLA, LAI, foliar nutrients and root:shoot ratio

a)   SLA and LAI

No significant treatment effects were found on SLA (data not shown). Since LAI was highly, significantly related to total biomass (and therefore BI), treatment effects were not determined, as these will be similar to those found on BI (**Section 7.3.3**).

b)   Foliar nutrient concentrations

No significant effects of compaction treatments, residue management, or the interaction between them were found on foliar nutrient concentrations at Rattray (data not shown). This is probably due to the overall lack of significant effects on

soil and residue nutrient levels, with the exception of Ca and Mg, at Rattray at TH (**Section 5.3.3.2**). However, at Shafton, both compaction and residue removal treatments had a significant negative effect on foliar N (**Figure 7.2**; **Appendix 7.5**). Although significant interaction effects were found with foliar P concentrations at Shafton, the main effects of compaction treatments and residue removal were also negative, and these main effects are rather discussed for ease of explanation (**Figure 7.2**; **Appendix 7.5**). This was despite foliar N concentrations generally being optimal at Shafton, although foliar P concentrations were lower than that found to be optimal in the literature. Soil N and P contents were decreased by residue removal (**Section 5.3.3.3**), however residues contributed a substantially larger proportion of P to the site, than N (**Figure 5.11**). This, in combination with the foliar nutrient concentrations and ratios indicate that at Shafton, the principle growth-limiting nutrient was P. Foliar N, but not P, concentrations were significantly higher in 0.5-year-old *E. grandis* grown in broadcast residue treatments, when compared to residue removed treatments at a trial close to Shafton (du Toit *et al.*, 2008). However, residue management was applied to plots 2 months prior to planting at that trial. Therefore the foliar nutrient concentrations determined when the trees were 1-year-old, may be more applicable to the results of this study. At that age, trees in the broadcast residue plots had higher foliar N and P concentrations, but the power of the statistical test was insufficient to show significance.

The effect of compaction treatments on foliar N and P at Shafton was almost the opposite of that on site N and P (**Section 5.3.3.3**). Under the compaction treatments, soil N significantly decreased in the order $C_M > C_H \geq C_L$, while for available soil P (0 – 0.05 m) the order was $C_M > C_L \geq C_H$, and for total P it was $C_M \geq C_L > C_H$. This may imply that higher levels of soil nutrients in the more compacted treatments may be a result of lower plant uptake, possibly due to the restrictive effect of compaction on soil strength (**Section 6.3.2.1**) and/or soil water availability (**Section 6.3.1.2**). No comparable eucalypt studies investigating the effect of compaction on foliar nutrients were found, although one showed no significant effect of soil water availability on foliar N and P concentrations of 1-year-old *E. grandis* grown at a site similar to Shafton (Campion, 2005).
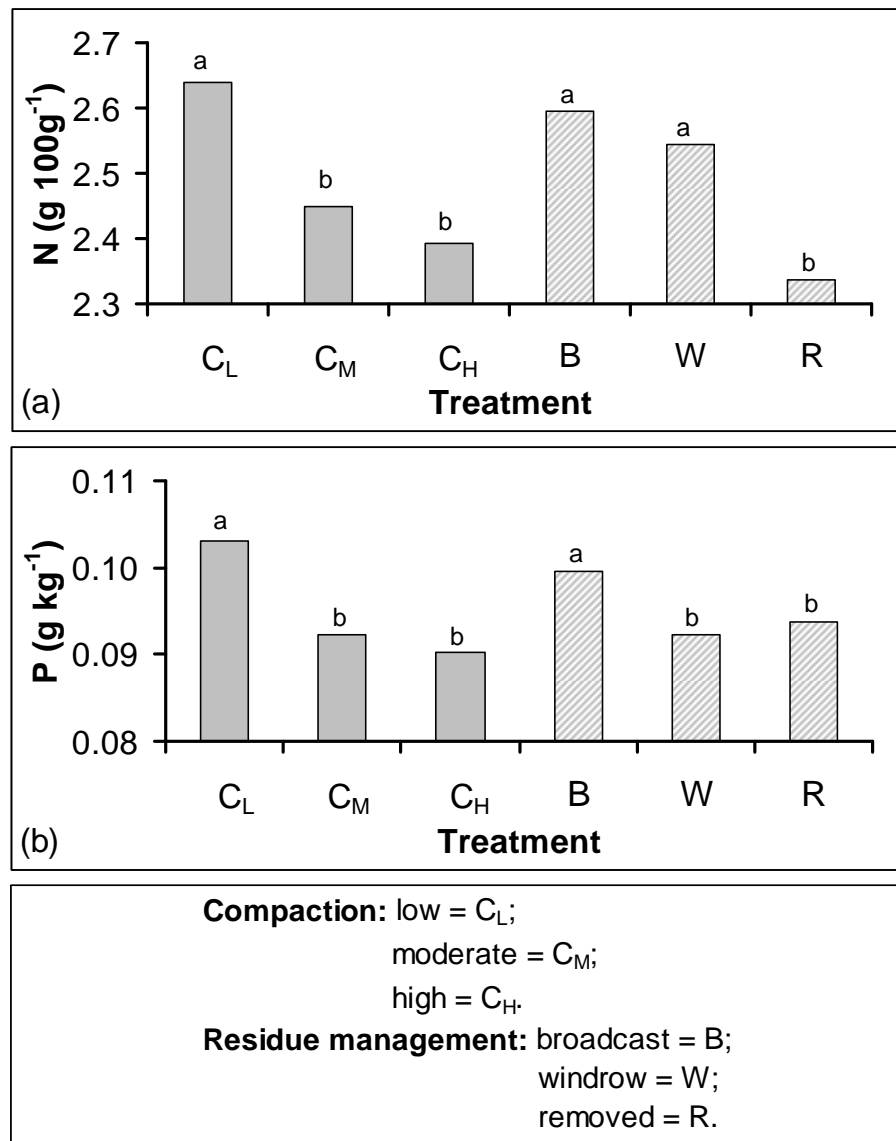
Figure 7.2: Effect of compaction treatments and residue management on concentrations of foliar (a) N, and (b) P at Shafton. Treatments with different letters are significantly different ($p<0.005$).

c)   *Root:shoot ratio*

No significant relationships were obtained between BI and fine root biomass (**Table 7.2**). Therefore root:shoot data were analysed for compaction treatment, residue management and interaction effects (ANOVA) at both trials. Compaction treatments significantly affected root:shoot ratios at Rattray (**Figure 7.3**; **Appendix 7.6**), whereas at Shafton no significant treatment effects were found (data not shown).

The results displayed in **Figure 7.3** led to the multiple linear regression analysis of fine root and foliage data with topsoil PSS or topsoil Troxler bulk density, i.e. between 0 – 0.1 m soil depth, the same depth in which fine roots were measured. This was possible since there was no significant correlation between foliage biomass and topsoil PSS or bulk density. Both topsoil PSS and topsoil Troxler bulk density significantly affected the relationship between fine roots and foliage at Rattray (PSS: **Equation 7.1**). However, a low r^2 (r^2 = 0.440) was obtained when topsoil Troxler bulk density was used (data not shown).
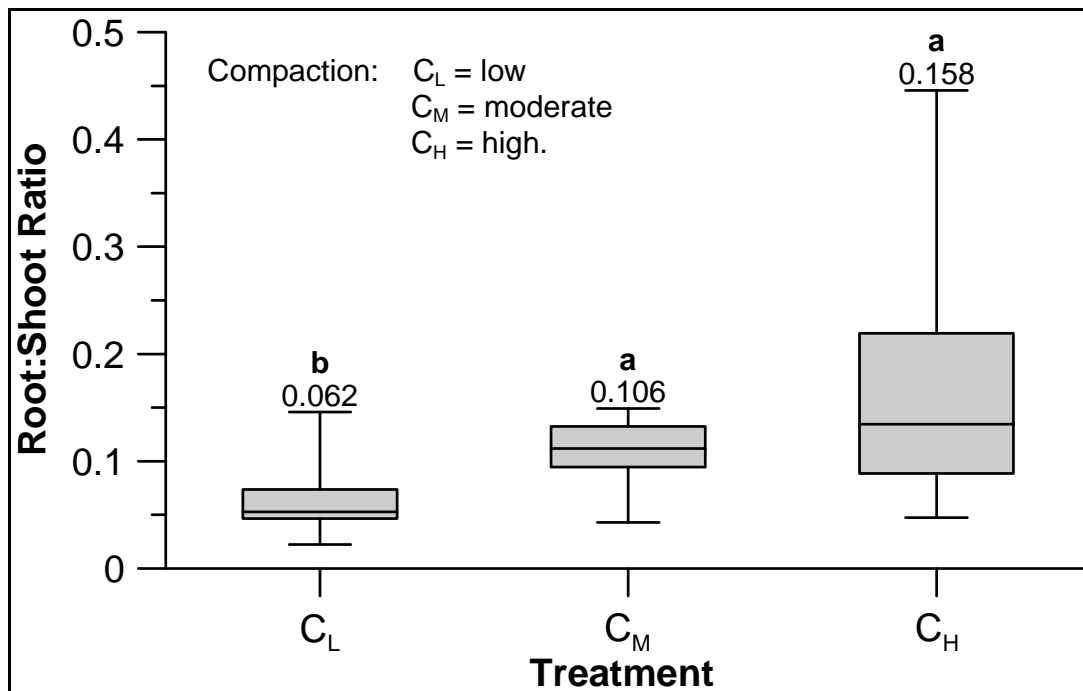
Figure 7.3: Box whisker plot of root:shoot ratios of *E. grandis* trees 209 DAP at Rattray. Treatment means are displayed above the box whisker. Treatments with different letters displayed above the box whisker are significantly different (*p*<0.05).

FR = 0.066Fol + 2.328E-05PSS – 3.600E-03 **Equation 7.1**
(r^2 = 0.505; *p*<0.001)

where FR is fine root biomass (kg); Fol is foliage biomass (kg); PSS is average PSS between 0 and 0.1 m (kPa). PSS in the 0 – 0.1 m depth layer ranged between 53 and 596 kPa and averaged 259 kPa.

These results indicate that there is an increase in biomass allocated to fine roots relative to foliage with increasing compaction. This relationship does not appear to be affected by ontogeny since foliage biomass is highly significantly related to biomass index, while fine root biomass is not. Therefore trees with similar foliage biomass are of a similar physiological age, but can have varying fine root biomass due to compaction.

The range of PSS values for which **Equation 7.1** is valid is extremely narrow (between 53 and 596 kPa), and would not normally be considered to have an effect on fine root growth (Sands *et al.*, 1979; Misra and Gibbons, 1996; Zou *et al.*, 2001). Bulk density values, however, are high (between 1.28 and 1.58 Mg m^{-3}). Since PSS in the top 0.03 m of soil was below 40 kPa, the averaging of PSS values over the top 0.1 m of soil (measurements were taken every 0.01 m) may have resulted in extremely low values in this layer of soil, substantially lowering the average value.

Penetrometer soil strength was better able to predict the effects of compaction on fine root biomass than bulk density. This is most likely due to PSS being related to the resistance of a soil to root growth, unlike bulk density (Greacen and Sands, 1980; Bengough *et al.*, 1997). Increasing soil strength generally reduces root elongation rate exponentially, until a critical value, after which root penetration ceases (Greacen and Sands, 1980). In addition, a greater number of measurements were made per plot of PSS, perhaps increasing the accuracy of the measurement of PSS relative to bulk density in each plot. The significant effects of soil strength on fine roots in the top 0.1 m of soil has important implications for processes such as nutrient and water uptake.

Sibisi (1998) measured fine root density and biomass under compaction treatments at Rattray in the previous rotation. Although no other tree components were measured, compaction increased fine root density and root biomass, supporting the results of this study.

The lack of response of fine roots or root:shoot ratios at Shafton to treatments is probably a result of the error associated with the measurement of the fine roots. In addition, no effects of residue management on fine roots were found at either trial. A similar lack of root responses to residue management has been found by others (e.g. Jones *et al.*, 1999; Nkosana, 2002), despite the effect of residue management on the soil environment (Perry *et al.*, 1982; Gonçalves and Mello, 2004).

7.3.2.   Survival

7.3.2.1.   Rattray

a)   Sub-plot trees

Sub-plot tree survival (at every measurement date) was not significantly affected by compaction treatments and/or residue management (**Table 7.5**).

Table 7.5:   Mean sub-plot tree survival (%) as affected by compaction treatments and residue management at Rattray at various measurement dates (DAP).

DAP	Compaction			Residue management		
	Low	**Moderate**	**High**	**Broadcast**	**Windrow**	**Removed**
70	88.4	95.1	90.7	88.4	92.9	92.9
133	88.3	91.2	87.2	86.8	90.1	89.8
167	87.7	91.1	87.1	86.4	89.6	89.8
209	87.5	90.9	87.1	86.3	89.4	89.8

b)   Main plot trees

Survival of the main plot trees was good (**Table 7.6**). At 6 months of age there was a weakly significant ($p<0.10$) effect in which survival was slightly higher in the C_H treatments than the C_M or C_L treatments. The significance of this effect decreased, however, as the trees grew (data not shown). In the previous trial, there were also no significant treatment effects (three harvesting operations x two residue management) on survival (Smith and du Toit, 2005).

Table 7.6: Mean main plot tree survival (%) as affected by compaction treatments and residue management at Rattray at various ages (months).

Age	Compaction			Residue management		
	Low	Moderate	High	Broadcast	Windrow	Removed
6	95.4	94.8	98.1	96.6	95.4	96.3
13	95.4	94.8	97.2	96.3	95.4	95.7
18	95.1	93.8	96.6	95.1	94.8	95.7
23.5	95.1	93.8	94.4	94.1	94.1	95.1
31.5	94.4	93.5	94.8	94.1	93.8	94.8
41.5	93.2	92.0	93.2	91.7	92.9	93.8

7.3.2.2. *Shafton*

The accidental application of herbicide at 106 DAP in several plots at Shafton affected sub-plot tree growth (and mortality). However, this was not significant (data not shown), and the effect of this herbicide application was therefore excluded from the analyses. The lack of significant herbicide effects on survival and growth imply that, overall, herbicide application did not have a substantial effect on productivity, and confirms that productivity determined at canopy closure is not affected by stocking (Powers *et al.*, 1996; 1998).

a) Sub-plot trees

Increasing compaction and decreasing residue retention generally improved the survival of sub-plot trees at Shafton (**Tables 7.7** and **7.8**). Since some plots were more affected by herbicide application, this was included as a covariate in the ANOVAs, with the exception of the 70 DAP measurement. However, the covariate did not have a significant effect. This is because in some cases herbicide application was severe enough to cause mortality, particularly in the $C_L B$ plots, whereas in other plots herbicide application was light, and although it caused defoliation, trees survived (in several C_M and C_H plots).

Table 7.7: Level of significance (*p*) determined by ANOVA of the effects of compaction treatments and residue management, and the interaction between them on the survival of sub-plot trees at Shafton at three measurement dates (DAP).

Treatment	70 DAP	120 DAP	211 DAP
Compaction	0.032	0.001	<0.001
Residue	NS	<0.001	<0.001
Compaction x residue	NS	NS	0.010

Table 7.8: Effect of compaction and residue management (res man) on mean survival (%) of sub-plot trees at Shafton at three measurement dates (DAP). Treatments with different letters are significantly different (*p*<0.05) within measurement dates, and only significant results are shown.

70 DAP		120 DAP		211 DAP		
Compaction	**Mean**	**Compaction**	**Mean**	**Compaction**	**Res man**	**Mean**
High	98.7^a	High	94.8^a	High	Removed	98.6^a
Moderate	96.9^{ab}	Moderate	93.7^a	Moderate	Removed	97.3^{ab}
Low	94.7^b	Low	83.0^b	Low	Removed	95.9^{ab}
				High	Windrow	94.6^{abc}
		Res man		Moderate	Windrow	90.5^{bc}
		Removed	97.3^a	Moderate	Broadcast	90.5^{bc}
		Windrow	89.6^b	High	Broadcast	88.4^c
		Broadcast	84.6^b	Low	Windrow	80.3^d
				Low	Broadcast	70.1^e

b)   Main plot trees

Main plot tree survival varied substantially (between 75 and 100%), and there were no significant treatment effects on any of the measurement dates (**Table 7.9**). A similar lack of significant treatment effects (of seven harvesting operations) on survival were found in the previous rotation at Shafton (Smith, 2006).

Table 7.9: Mean main plot tree survival (%) as affected by compaction treatments and residue management at Shafton at various ages (months).

Age	Compaction			Residue management		
	Low	Moderate	High	Broadcast	Windrow	Removed
6	90.3	93.1	97.2	92.1	94.0	94.4
12	90.3	92.6	96.8	91.7	93.5	94.4
18	89.4	90.7	95.8	89.8	93.1	93.1
25.5	88.4	90.7	94.9	89.4	91.7	93.1
30.5	88.0	90.7	94.4	89.4	90.7	93.1

7.3.3.   Growth

7.3.3.1.   *Rattray*

a)   *Effect of compaction treatments and residue management on tree growth in sub-plots*

Compaction treatments significantly ($p<0.05$) affected average sub-plot tree GLD, except at 209 DAP. Significant effects were also found on sub-plot tree height, biomass index and crown diameter, except at 70 and 209 DAP (**Figure 7.4**; **Table 7.10**; **Appendices 7.7** - **7.10**). Compaction reduced growth with the exception of GLD (and therefore BI) at 70 DAP. It is suggested that the lack of a relationship between compaction treatments and GLD at the early stage of growth is possibly due to the small trees not utilising all soil resources and thus not being affected by changes in soil resource supply. The lack of significant effects on crown diameter at the 209 DAP measurement is a result of this measurement coinciding with canopy closure of the sub-plot trees.

Although residue management (or the interaction between compaction treatments and residue management) did not have a significant effect, growth was generally better in residue removed plots, than residue retained plots (**Table 7.11**).
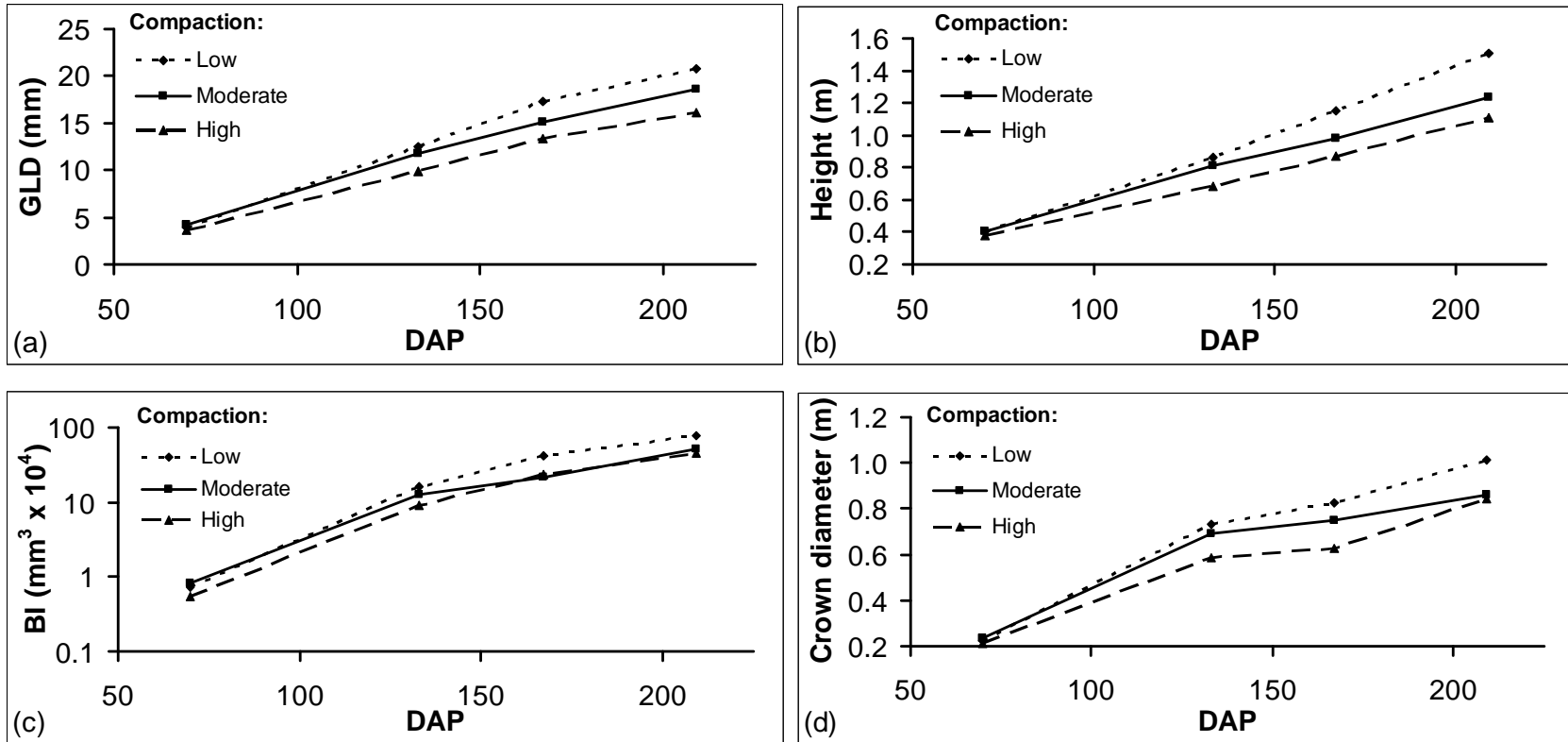
Figure 7.4: Effect of compaction treatments on mean (a) ground-line diameter (GLD), (b) height, (c) biomass index (BI), and (d) crown diameter of sub-plot trees over time (days after planting; DAP) at Rattray.

Table 7.10: Effect of compaction treatments on mean ground-line diameter, height, biomass index, and crown diameter of sub-plot trees at Rattray at four measurement dates; days after planting (DAP). Treatments with different letters in the same column are significantly different ($p < 0.05$).

Compaction	70 DAP	133 DAP	167 DAP	209 DAP
Ground-line diameter (mm)				
Low	3.92^b	12.43^a	17.24^a	20.72
Moderate	4.21^a	11.74^a	15.14^{ab}	18.56
High	3.58^b	9.90^b	13.42^b	16.15
Height (m)				
Low	0.404^a	0.859^a	1.151^a	1.503^a
Moderate	0.407^a	0.815^a	0.977^b	1.235^{ab}
High	0.375^b	0.686^b	0.874^b	1.104^b
Biomass index (mm^3)				
Low	7190^a	159900^a	418000^a	794000^a
Moderate	8400^a	128500^{ab}	217000^{ab}	508000^{ab}
High	5540^b	90400^b	234000^b	453000^b
Crown diameter (m)				
Low	0.225	0.825^a	0.735^a	1.011
Moderate	0.235	0.751^a	0.690^{ab}	0.862
High	0.210	0.624^b	0.584^b	0.841

Table 7.11: Effect of residue management on ground-line diameter, height, biomass index, and crown diameter of sub-plot trees at Rattray at four measurement dates; days after planting (DAP). Treatments are not significantly different.

Residue management	70 DAP	133 DAP	167 DAP	209 DAP
Ground-line diameter (mm)				
Broadcast	3.75	10.81	14.68	17.49
Windrow	3.99	10.92	14.61	18.07
Removed	3.98	12.34	16.51	19.87
Height (m)				
Broadcast	0.399	0.778	0.979	1.235
Windrow	0.405	0.75	0.971	1.259
Removed	0.383	0.833	1.052	1.348
Biomass index (mm^3)				
Broadcast	6440	119700	296000	544000
Windrow	7740	110400	269000	532000
Removed	6950	148600	354000	679000
Crown diameter (m)				
Broadcast	0.216	0.641	0.700	0.853
Windrow	0.220	0.639	0.720	0.920
Removed	0.234	0.729	0.780	0.941

Using regressions developed in **Table 7.1** and accounting for mortality, total biomass, or NPP$_{-RT}$ at 209 DAP, was calculated to be 0.374, 0.255 and 0.220 kg m^{-2} for C$_L$, C$_M$ and C$_H$ treatments, respectively. Broadcasting, windrowing or removal of residues, resulted in an average NPP$_{-RT}$ of 0.258, 0.262 and 0.331 kg m^{-2}, respectively.

It was observed that some plots had considerable variation in tree growth. The coefficient of variation (CV) was therefore calculated for both tree GLD and height for each plot at each measurement date. Compaction treatments had a significant ($p<0.05$) effect on GLD variability at 167 and 209 DAP (**Table 7.12**), while residue management had an almost significant ($p<0.10$) effect on GLD variability after 70 DAP (data not shown). No significant treatment interaction effects on GLD variability were found at any measurement date. In all instances where significant treatment effects were recorded, variation in tree GLD decreased in the order of C$_H$>C$_L$>C$_M$ (C$_L$ and C$_M$ treatments were not significantly different from one another), and B>W>R residue management.

Table 7.12: F probability values[†] of compaction treatment and residue management effects on sub-plot tree GLD and height coefficient of variation (GLD-CV and Ht-CV, respectively) from ANOVA at Rattray 133, 167 and 209 days after planting (DAP). Data were either transformed by ([a]) natural logarithm (ln x) or ([b]) square root ($\sqrt{x}$) to prevent violation of normality or error assumptions.

Source of Variation	133 DAP		167 DAP		209 DAP	
	GLD-CV[a]	Ht-CV[b]	GLD-CV	Ht-CV	GLD-CV	Ht-CV
Compaction	NS	0.007	0.018	NS	0.011	NS
Residue	0.055	0.008	0.073	NS	0.056	NS
Comp x Resid	NS	NS	NS	NS	NS	NS

[†] NS: not significant; i.e. $p>0.1$

At 133 DAP there were significant ($p<0.01$) compaction treatment and residue management effects (although no significant interaction effects) on tree height variability. At this measurement date, and at 167 DAP and 209 DAP, the variation in tree height decreased in the order of C$_H$>C$_L$>C$_M$ and B>W>R (**Table 7.12**).

In terms of the variation in BI, only residue management had a significant effect ($p<0.05$) at 133 and 209 DAP (data not shown). Broadcast residue management had a significantly higher CV than W or R residue management. There was no significant difference in CV of BI between W and R residue management, but CV values from W residue management were consistently higher than those from R residue management.

b)   Effect of compaction treatments and residue management on tree growth in main-plots

Compaction treatments had a significant effect on the GLD and DBH of the main plot trees at six, 13 and 18 months of age (**Figure 7.5**; **Table 7.13**; **Appendix 7.11**). The level of this significance diminished with time from 6 months ($p<0.01$), to 13 and 18 months ($p<0.05$), finally becoming non significant at 23.5 months of age and thereafter. Compaction treatments also had a significant effect on tree height, that also decreased with time from 6 months ($p<0.01$), to 13 months ($p<0.05$), to 18 months (non-significant; **Figure 7.5**; **Table 7.13**; **Appendix 7.12**). Ground-line diameter, DBH and height consistently decreased with increasing compaction intensity. Residue management, and the interaction between compaction treatments and residue management, had no significant effect on tree GLD, DBH or height at any time.

No significant treatment effects were found on the variation in main plot tree GLD/DBH or height (CV) at any measurement date.
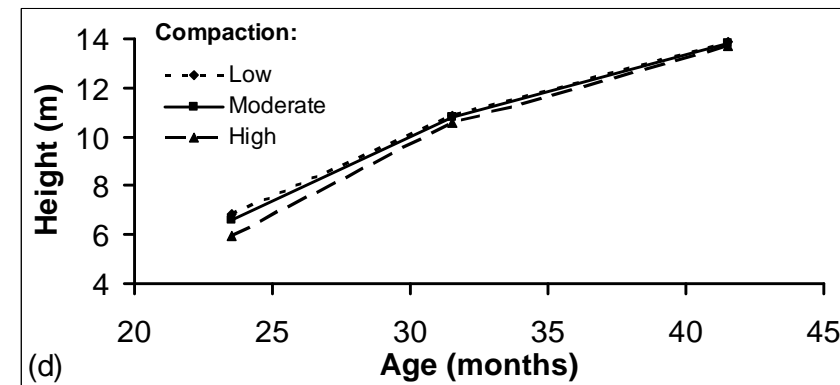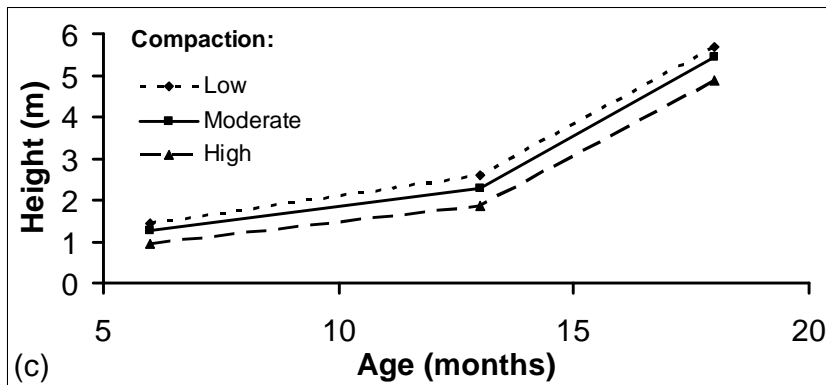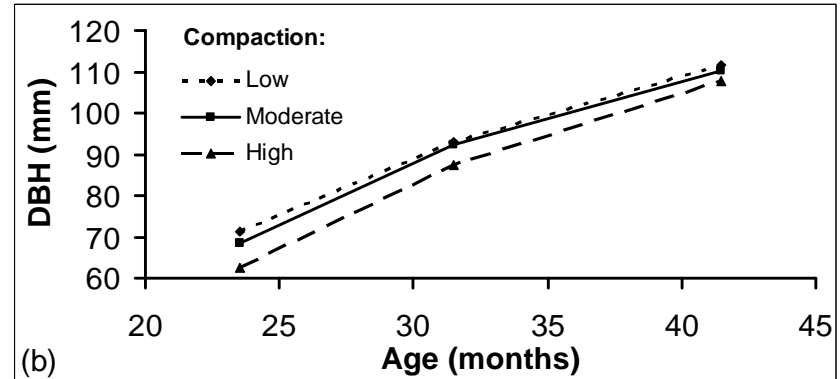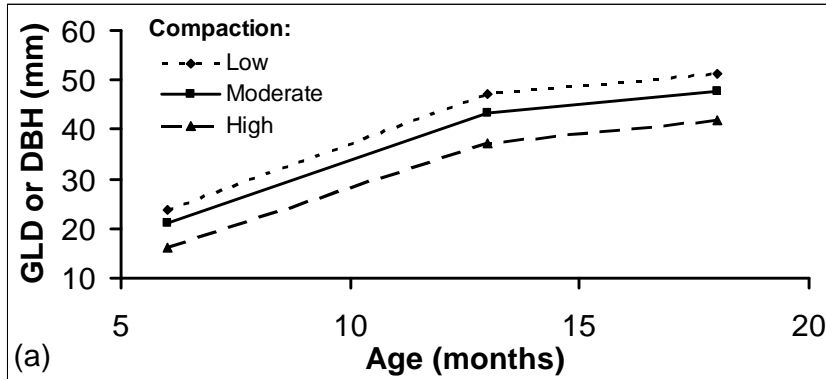
Figure 7.5: Effect of compaction treatments on mean (a) ground-line diameter (GLD) at 6 and 13 months of age and diameter at breast height (DBH) at 18 months of age, (b) DBH between 23.5 and 41.5 months of age, (c) height between 6 and 18 months of age, (d) height of main plot trees between 23.5 and 41.5 months of age (31.5 and 41.5 month heights determined from regressions in **Appendix 3.4**) at Rattray.

Table 7.13: Compaction treatment effects on mean GLD or DBH (mm), and height (m) of main-plot trees at Rattray at six measurement dates (months). Treatments with different letters in the same row are significantly different ($p<0.05$).

Months-GLD/DBH/Height	Compaction		
	Low	**Moderate**	**High**
6-GLD	23.8[a]	21.3[a]	16.2[b]
13-GLD	47.1[a]	43.4[ab]	37.3[b]
18-DBH	51.3[a]	47.8[ab]	41.9[b]
23.5-DBH	71.4	68.5	62.4
31.5-DBH	93.0	92.4	87.4
41.5-DBH	111.5	110.3	107.7
6-Height	1.5[a]	1.3[a]	1.0[b]
13-Height	2.6[a]	2.3[ab]	1.8[b]
18-Height	5.7	5.4	4.9
23.5-Height	6.8	6.6	5.9
31.5-Height[a]	10.8	10.8	10.6
41.5-Height[a]	13.9	13.8	13.7

[a] Heights not directly measured but determined from regressions developed in **Appendix 3.4**.

c)   *Effect of compaction treatments and residue management on overall tree growth*

At Rattray, tree growth and productivity was consistently negatively affected by increasing compaction intensity. These negative effects became non-significant as the trees grew. This may be due to the growing tree roots being more easily able to overcome soil strength, or the decomposition of tree roots from the previous rotation yielding areas of lower soil strength (Nambiar and Sands, 1992; Laclau *et al.*, 2001). In addition, increasing compaction intensity increased the amount of variation in the growth of sub-plot trees. This can have negative implications for stand stemwood productivity at rotation end (Tomé *et al.*, 1994; Little *et al.*, 2003; Little and van Staden, 2005). However, no significant treatment effects were found on the variability of main plot tree growth at Rattray.

d)   *Effect of compaction treatments and residue management on basal area and volume of trees in main-plots*

The basal area and stemwood volume (per unit land area) were calculated for interest for the last two measurements performed at Rattray (**Table 7.14**). Statistical

analyses could not be performed on these values as it may result in erroneous conclusions as particularly volume was estimated using a simple equation (**Equation 3.10**), and can only be reliably determined at rotation end. Increasing intensity of compaction resulted in a considerable loss of stemwood volume which increased substantially between the 31.5 and 41.4 month measurements. Residue management had variable effects, with trees with windrow residue management having the highest volume initially, but later falling behind those with broadcast residue management.

Table 7.14: Estimated average stand basal area (SBA), stemwood volume and volume loss relative to low compaction treatment or broadcast residue management as a result of compaction treatments (Comp) or residue management (Residue) of main plot trees at Rattray at 31.5 and 41.4 months of age.

Comp	SBA (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Loss (%)	Residue	SBA (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Loss (%)
31.5 months							
Low	10.699	38.475	0	Broadcast	10.012	42.924	0
Moderate	10.452	37.441	2.688	Windrow	10.496	45.444	-5.871
High	9.477	32.871	14.566	Removed	10.102	43.331	-0.946
41.5 months							
Low	15.197	71.043	0.000	Broadcast	14.390	66.838	0.000
Moderate	14.654	66.984	5.713	Windrow	14.887	68.667	-2.736
High	14.162	63.946	9.990	Removed	14.723	67.683	-1.264

7.3.3.2.   Shafton

a)   Effect of compaction treatments and residue management on tree growth in sub-plots

Residue management had a significant effect on GLD, height, BI and crown diameter of sub-plot trees at certain measurements times after planting (**Figure 7.6**; **Table 7.15**, **Appendices 7.13** - **7.16**). Trees in R plots initially grew better than those in B or W plots. However, as the trees grew, these differences decreased in significance until at 211 DAP they became non-significant (**Figure 7.6**). In contrast, compaction treatments did not have a significant effect on GLD, height, BI or crown diameter of the sub-plot trees at any measurement time (**Appendices 7.13** - **7.16**).
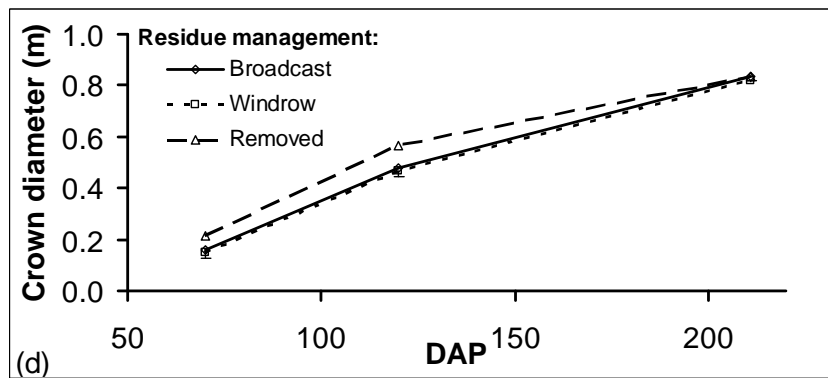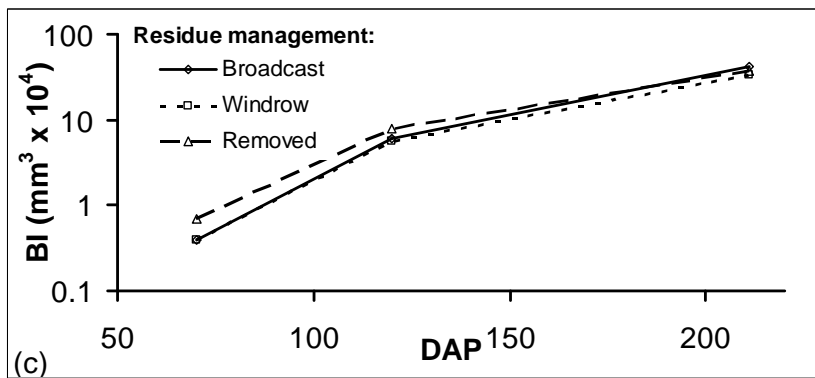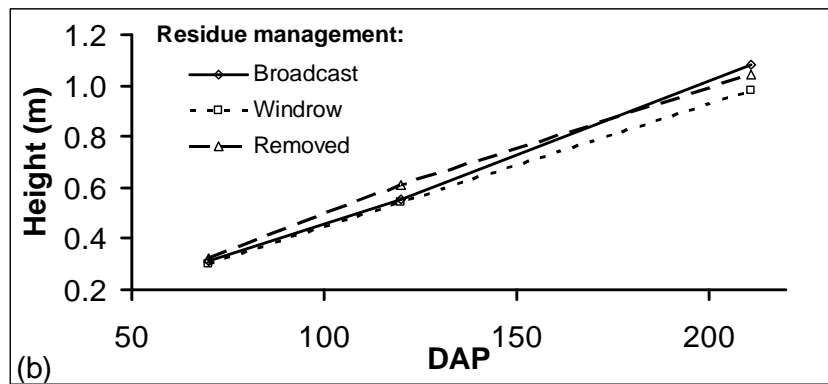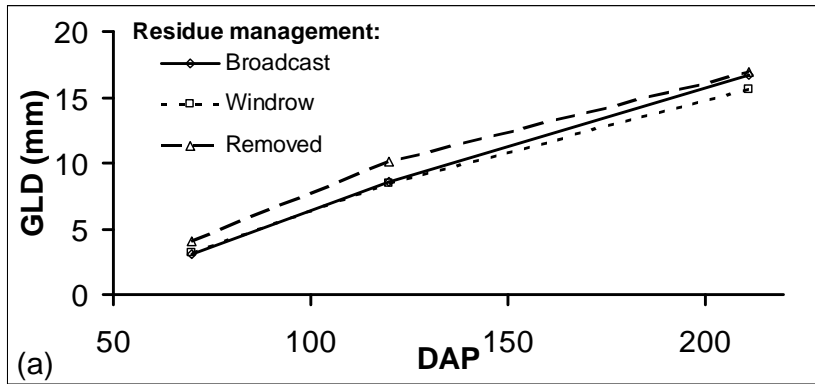
Figure 7.6: Effect of residue management on mean (a) ground-line diameter (GLD), (b) height, (c) biomass index (BI), and (d) crown diameter of sub-plot trees over time (days after planting; DAP) at Shafton.

Table 7.15: Effect of residue management on mean ground-line diameter, height, biomass index, and crown diameter of sub-plot trees at Shafton at three measurement dates; days after planting (DAP). Treatments with different letters in the same column are significantly different ($p<0.05$).

Residue management	70 DAP	120 DAP	211 DAP
Ground-line diameter (mm)			
Broadcast	3.07[b]	8.54[b]	16.71
Windrow	3.14[b]	8.47[b]	15.59
Removed	4.01[a]	10.09[a]	16.89
Height (m)			
Broadcast	0.3126	0.5555[b]	1.081
Windrow	0.2991	0.5419[b]	0.982
Removed	0.3235	0.6089[a]	1.045
Biomass index (mm^3)			
Broadcast	3990[b]	59600[b]	417000
Windrow	3980[b]	56500[b]	337000
Removed	6910[a]	78100[a]	375000
Crown diameter (m)			
Broadcast	0.157[b]	0.479[b]	0.836
Windrow	0.149[b]	0.469[b]	0.817
Removed	0.216[a]	0.565[a]	0.834

At 211 DAP, NPP_{-RT} was calculated (using regression equations in **Table 7.2** and survival) to average 0.302, 0.270 and 0.324 kg m^{-2} under broadcast, windrowed and removed residue plots, respectively, while it averaged 0.284, 0.329 and 0.283 kg m^{-2} in C_L, C_M and C_H treatments respectively.

Certain treatments were observed to have an effect on tree uniformity as determined by calculation of the CV of the growth measurements in each plot. At no stage did the inclusion of herbicide application as a covariate show significant effects on tree uniformity (data not shown). At the first measurement date (70 DAP) only compaction treatments had a significant effect ($p<0.01$ and $p<0.05$) on the CV of tree GLD and height (**Table 7.16**). For both GLD and height, CV values decreased in the order $C_L>C_M>C_H$. At the next two measurement dates, however, it was only residue management that had a significant effect on the CV of tree GLD (at 120 and 211 DAP; $p<0.001$ and $p<0.05$, respectively) and height (only at 120 DAP; $p<0.01$). In all instances, R plots had significantly lower CV values than the other residue management plots.

Table 7.16: F probability values of compaction treatment and residue management effects on sub-plot tree GLD and height coefficient of variation (GLD-CV and Ht-CV, respectively) from ANOVA at Shafton at 70, 120 and 211 days after planting (DAP). Data was power transformed (either [a:] x^3, or [b:] x^2) to prevent violation of normality assumptions.

Source of variation	70 DAP		120 DAP		211 DAP	
	GLD-CV	**Ht-CV**	**GLD-CV**[a]	**Ht-CV**	**GLD-CV**[b]	**Ht-CV**
Compaction	0.008	0.031	NS	NS	NS	NS
Residue	NS	NS	<0.001	0.007	0.018	NS
Comp x Res	NS	NS	NS	NS	NS	NS

b)   Effect of compaction treatments and residue management on tree growth in main-plots

Unlike the sub-plot trees, main plot tree GLD or DBH responded significantly ($p<0.05$) to compaction treatments, as well as residue management (but not the interaction between them) at all measurement dates except 6 months (**Figure 7.7**, **Tables 7.17** and **7.18**; **Appendix 7.17**). Increasing compaction intensity consistently reduced tree GLD or DBH. Similar effects were found with residue removal. At 6 months of age trees under R residue management had a higher, but not significantly so, GLD than those under W residue management. However, trees under these (R) treatments lost this advantage, eventually having a significantly ($p<0.05$) lower GLD or DBH than trees in the W or B treatments (at 30.5 months of age).

There was no significant effect of either compaction treatments or residue management on main plot tree height, except at 12 months of age (**Tables 7.17** and **7.18**; **Appendix 7.18**). Since similar trends to those in the GLD and DBH data were seen, these results may be due to the error associated with the difficulty of accurate measurement of tree heights above 3 m.
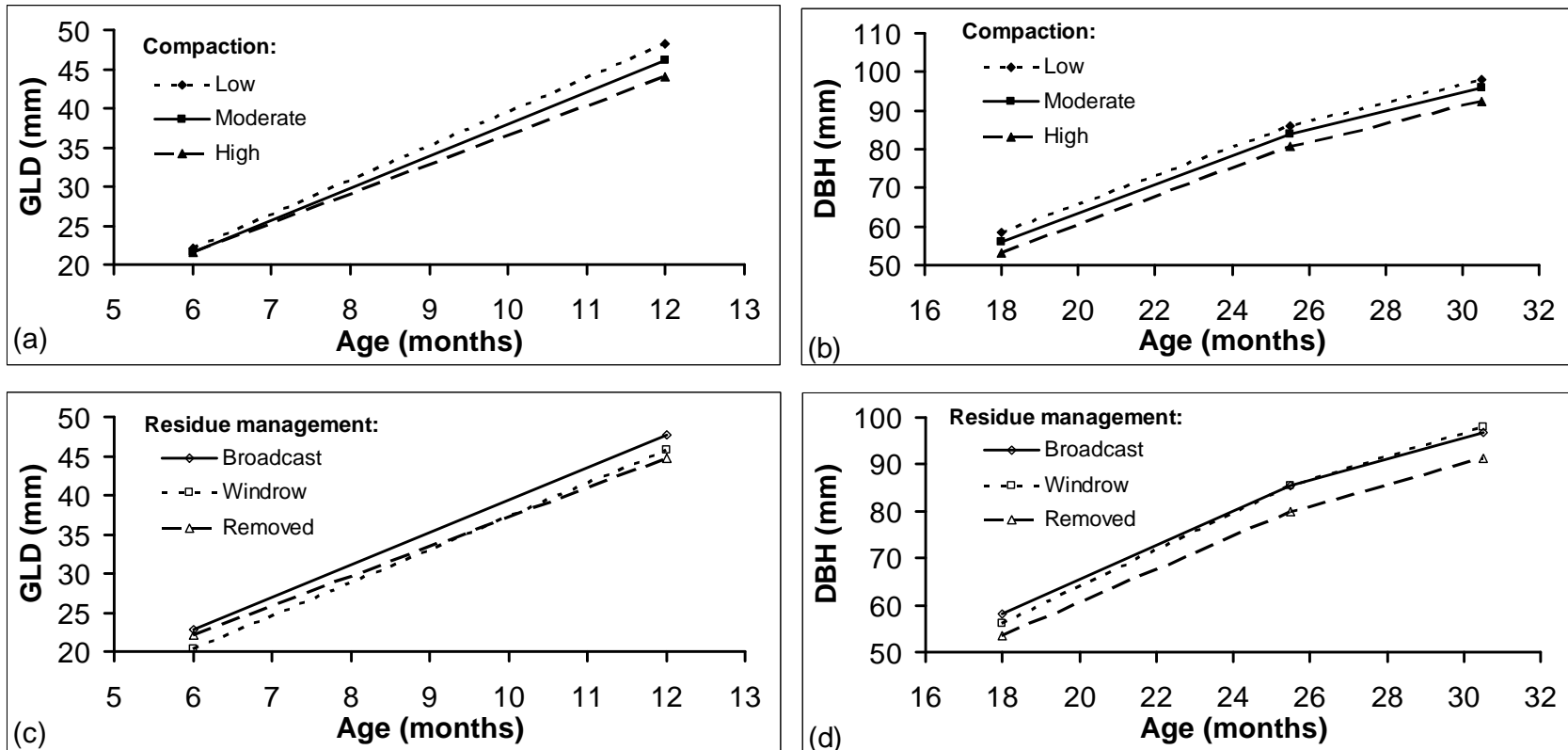
Figure 7.7: Effect of compaction treatments on mean (a) ground-line diameter (GLD) at 6 and 12 months of age, (b) diameter at breast height (DBH) between 18 and 30.5 months of age, and effect of residue management on mean (c) GLD at 6 and 12 months of age, and, (d) DBH between 18 and 30.5 months of age of main plot trees at Shafton.

Table 7.17: Effect of compaction treatments on mean GLD or DBH (mm), and height (m) of main-plot trees at Shafton at five measurement dates (months). Treatments with different letters in the same row are significantly different ($p<0.05$).

Months-GLD/DBH/Height	Low	Moderate	High
6-GLD	22.10	21.62	21.50
12-GLD	48.33[a]	46.08[ab]	43.96[b]
18-DBH	58.52[a]	56.00[ab]	53.13[b]
25.5-DBH	86.09[a]	84.01[a]	80.69[b]
30.5-DBH	97.96[a]	95.72[ab]	92.51[b]
6-Height	1.2	1.2	1.1
12-Height	2.4[a]	2.3[ab]	2.1[b]
18-Height	6.1	5.8	5.6
25.5-Height	9.9	9.6	9.5
30.5-Height[a]	11.6	11.5	11.3

[a] Heights not directly measured but determined from regressions developed in **Appendix 3.4**.

Table 7.18: Effect of residue management on mean GLD or DBH (mm), and height (m) of main-plot trees at Shafton at five measurement dates (months) Treatments with different letters in the same row are significantly different ($p<0.05$).

Months-GLD/DBH/Height	Broadcast	Windrow	Removed
6-GLD	22.74	20.33	22.15
12-GLD	47.75[a]	45.87[ab]	44.73[b]
18-DBH	58.10[a]	56.12[ab]	53.44[b]
25.5-DBH	85.38[a]	85.44[a]	79.96[b]
30.5-DBH	96.86[a]	98.05[a]	91.27[b]
6-Height	1.3	1.1	1.2
12-Height	2.4[a]	2.2[ab]	2.2[b]
18-Height	6.0	5.8	5.8
25.5-Height	9.7	9.9	9.4
30.5-Height[a]	11.6	11.7	11.3

[a] Height not directly measured but determined from regressions developed in **Appendix 3.4**.

No significant treatment effects were found in the variation (CV) in mean main plot tree GLD/DBH or height (data not shown).

c)   Effect of compaction treatments and residue management on overall tree growth

At Shafton, residue management had a more pronounced effect on tree growth and productivity than compaction treatments. Initially, residue removal increased

tree growth, and uniformity. Later, residue removal negatively affected tree growth and productivity. These results are probably due to changes in the soil environment and nutrient availability over time. Compaction treatments did not have a significant effect during the first 6 months of growth, however, from 12 months of age, compaction significantly, negatively affected tree growth and productivity. In the main plots this was around the time of canopy closure when nutrient demand from the soil is at its highest, and when restrictions, due to soil compaction and strength, in the ability of roots to obtain nutrients will have a substantial impact. In addition, the growth of the trees may have necessitated the growth of roots into deeper soil layers, where they encountered considerable levels of soil strength.

d)   *Effect of compaction treatments and residue management on basal area and volume of trees in main-plots*

At Shafton, basal area and stemwood volume (per unit land area) were only determined for the final measurement at 30.5 months of age (**Table 7.19**). As at Rattray, an compaction had a negative effect on stemwood volume while trees with windrow residue management had a larger volume than other trees (similar to the 31.5 month measurement at Rattray).

Table 7.19: Estimated average stand basal area (SBA), stemwood volume and volume loss relative to low compaction treatment or broadcast residue management as a result of compaction treatments (Comp) or residue management (Residue) of main plot trees at Shafton at 30.5 months of age

Comp	SBA (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Loss (%)	Residue	SBA (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Loss (%)
Low	11.509	44.890	0	Broadcast	11.430	44.343	0
Moderate	11.336	43.730	2.584	Windrow	11.894	46.413	-4.668
High	11.020	41.810	6.863	Removed	10.569	39.827	10.184

7.3.4. Comparison between sub-plot and main plot tree survival and growth

At Rattray, there was no significant effect of treatments on survival in either the sub-plots or main plots. At Shafton, tree survival in the sub-plots did not follow the same pattern, or was not related to that of the main plots.

Overall growth responses to compaction treatments at Rattray indicate that the sub-plot trees responded in a similar manner to that of the main plot trees. However, the residue responses seen in the sub-plot trees were not seen in the main plot trees. At Shafton, no significant response to compaction treatments was found in the sub-plot trees but this was not the case in the main plot trees. In addition, responses to residue management treatments were reversed in the main plot trees. These results were reflected in statistical analyses when regressions were performed between the final plot average GLD of sub-plots (i.e. at 209 and 211 DAP at Rattray and Shafton, respectively) and at all measurement times of main plot average GLD or DBH (**Table 7.20**). These analyses indicated that while sub-plot GLD measures at Rattray were significantly related to subsequent GLD and DBH measurements of main plot trees, that the percentage variance accounted for by the regressions (r^2) was quite low, especially in the 41.5 month regression. Regressions between data at Shafton were non-significant, with the exception of the 6 month measurement, but this had an extremely low r^2 value, and should therefore be discarded. Regressions between heights were not performed as latter heights were determined from regression equations.

Of the studies using densely stocked plots to predict future effects on stands, only one trial has correlated growth with that in commercially stocked plots (Amateis *et al.*, 2003a; 2003b; Sharma *et al.*, 2003). Although the only variable in that trial was tree stocking, trees in densely stocked plots did follow the same pattern of growth as those in more commercially stocked plots.

Table 7.20: Summary of statistical results of linear regressions performed between final average GLD of sub-plot trees (at 209 and 211 DAP at Rattray and Shafton, respectively) and subsequent measurements of GLD and DBH of main plot trees (months after planting; Month) at Rattray and Shafton.

| | Rattray | | | Shafton | |
Month	r^2	F pr.	Month	r^2	F pr.
6	0.568	<0.001	6	11.1	0.050
12	0.648	<0.001	12	NS	NS
18	0.629	<0.001	18	NS	NS
23	0.564	<0.001	25	NS	NS
31.5	0.503	<0.001	30.5	NS	NS
41.5	0.216	0.008			

Kelting (1999) and Watt *et al.* (2008) were the only studies found that used densely stocked plots to determine the effects of changes in soil properties. In both trials the growth of the densely stocked seedlings was substantially affected by the treatments as a result of changes in soil properties. However, tree growth in these densely stocked plots was not compared to the growth of commercially spaced trees.

Although measurements of tree productivity and growth at rotation end have not yet been made, the results of this study indicate that the use of densely stocked sub-plots for the assessment of residue management effects on tree productivity or for the prediction of responses in commercially spaced trees may not be reliable. This is probably as a result of changes in residues and the effects they exert over time. Even where growth of trees in such sub-plots are used to assess the effect of soil properties that are relatively stable over time, such as compaction, results must be viewed with extreme caution. This is because very young trees require relatively small volumes of soil for their nutrient and water needs. As the trees grow, the volume of soil required increases and, depending on the soil type and amount of compaction, this could be problematic. In addition, previous rotation root systems may influence the responses obtained, and as with residues, these decompose over time, and may further lead to variable responses.

7.4.   Conclusions

The assessment of productivity using non-destructive measures of growth (such as GLD, height and BI) and LAI in young (<6-months-old) eucalypt stands as an alternative to destructive measurements of NPP_{-RT} appears to be feasible. Although soil conditions alter the allocation of biomass to fine roots, this is not substantial enough to greatly affect total measurements of NPP_{-RT}. Productivity in the young eucalypt stands was not significantly affected by SLA, foliar nutrient concentrations, or root:shoot ratios as has been suggested (e.g. Sands *et al.*, 1992; Gonçalves and Mello, 2004; Silveira *et al.*, 2004). However, compaction, through soil strength, did affect root:shoot ratios at Rattray, indicating that over a rotation, a considerable amount of GPP may be allocated (and lost) to fine root respiration and turnover in compacted stands. Although foliar nutrient concentrations were not significantly related to productivity, they were significantly affected by compaction treatments and residue management at Shafton. The trends in foliar N and P concentrations measured when the trees were 6-months-old were similar to the trends in GLD/DBH measured when the trees were 12 months old, and older. At Rattray, no significant treatment effects were found on foliar nutrient concentrations, and after 18 months of age, no significant differences in DBH were measured. This may imply that foliar nutrient concentrations are linked to the future growth of the stand.

Despite similar treatments being imposed at both sites, tree growth and productivity responses were quite different. Compaction was detrimental to growth at both sites at different stages of growth. Indications are that compaction is more detrimental to LTSP at sites similar to Shafton. At sites such as Rattray, compaction appears to have a negative initial effect which may delay canopy closure, but that may not affect rotation-end productivity, or LTSP. However, these responses may be due to insufficient replication of treatments. If losses in stemwood volume due to compaction are considered, a loss of 14.6% under C_H treatments relative to C_L treatments at Rattray 31.5 months after planting is over double the loss of 6.9% under the same treatments at 30.5 months after planting at Shafton. This indicates that compaction at sites such as Rattray may

be more detrimental than those similar to Shafton. However, stemwood volume loss under high compaction at Rattray decreased to 10.0% at 41.5 months after planting, which may indicate that the negative effect of compaction may not be apparent at rotation end.

Residue management only significantly affected growth at Shafton, and residue removal was found to initially improve growth, but later decreased it. This trend, found by others (e.g. Proe *et al.*, 1999; Smith *et al.*, 2000), has been attributed to nutrient dynamics, particularly the availability of N. However, foliar nutrient results indicate that, at Shafton, P availability may have a larger effect than N availability. In addition, the results indicated that residue management has important implications for current stand productivity, as well as LTSP. If stemwood volumes were compared, residue removal slightly improved growth at Rattray, although this was generally very small (<2.7% at 41.5 months after planting). At Shafton however, stemwood volume at 30.5 months after planting was reduced by approximately 10.2% if residues were removed. Windrowing of residues actually increased stemwood volume by 4.7%, however, it is possible that this trend would not continue to rotation end.

The inability of measures of tree growth and productivity in this study to separate the effects of climate, soils and management suggest that there is a need for the development of such an indicator of stand performance.

The variation in growth and productivity results show that the effect of compaction and residue management on tree productivity cannot be predicted from responses obtained from one site, but should be assessed across site types. Unfortunately, it seems that this assessment cannot be performed by using densely stocked sub-plots, as these cannot predict growth responses of commercially spaced trees in LTSP studies.

Chapter 8

General Discussion and Conclusions

The first main objective of this study was to evaluate the effect of different levels of soil compaction (implemented through harvesting practices) and residue management on soil properties. The second objective was to determine if the productivity of young, fast-growing *Eucalyptus* stands could be used as indicators of the changes in soil properties as a result of the treatments. Each objective is addressed in this chapter separately. Thereafter the implications for the forestry industry and possible future research are discussed.

8.1 Effect of Compaction Treatments and Residue Management on Soil Properties

8.1.1 Compaction Treatments

Assessment of the trial sites prior to treatment implementation showed that there were still significant effects of the treatments imposed in the previous rotations on PSS. Analysis and comparison of the PSS values with those obtained during the preceding studies (Smith and du Toit, 2005; Smith, 2006) led to the conclusion that there had been no natural amelioration of soil compaction over the previous rotation. It is therefore assumed that the sites have minimal capacity to self-ameliorate, and that the effects of compaction are maintained well into the future. In addition, due to the soil texture and organic C content of the Rattray soil, this site had a much higher soil maximum bulk density and was considered to be more susceptible to compaction, than the soil of Shafton.

Application of the C_M and C_H treatments resulted in a significant increase in PSS at both trials, and in soil bulk density at Rattray. These increases were considerably higher in the C_H than C_M treatments. However, as a result of the

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manner in which these treatments were applied, compaction across the site was more variable in the C_H, than the C_M plots. Although the implementation of compaction treatments resulted in higher average bulk density values, average PSS was lower at Rattray than at Shafton. This implies that despite the relatively low soil bulk densities at Shafton, root growth may be limited by soil strength, more than at Rattray.

At Rattray, compaction treatments significantly increased soil C between 0 and 0.05 m at TH in the order $C_L > C_M > C_H$. This is probably a result of the incorporation of residues by machinery into the topsoil, and this effect was non-significant by TF. A similar effect was not seen at Shafton probably because the soil type did not lend itself to substantial mixing of residues and soil when the compaction treatments were implemented, and because a considerable period of time elapsed between treatment implementation and soil sampling at TH. However, the compaction treatments at Shafton did have a significant effect on the amount of total N and available P (Bray 2) in the 0 – 0.05 m soil depth at TH. Total N and available P (Bray 2) were significantly higher in the C_M treatment than either the C_H or C_L treatments, which were not significantly different from one another. This may be due to differences in the soil environment creating different rates of decomposition of residues, or due to variable uptake of nutrients.

At both sites, increasing bulk density led to a decrease in AWC and RAW. At Rattray, the increase in soil C between 0 and 0.05 m with compaction treatments also further reduced AWC with increasing compaction intensity. However, at both sites, θ_v between 0 and 0.05 m significantly increased with increasing compaction intensity. This indicates that although a greater quantity of water is held in the soil with increasing compaction, a smaller proportion was available to plants. At Rattray, the amount of water available to plants (LLWR) may be further limited by soil strength below a depth of 0.2 m, while at Shafton, this limitation will be below 0.1 m.

8.1.2   Residue Management

The quantity of residues at both sites decreased in the order B>W>R. Despite the application of residue management in a similar manner at both sites Rattray had lower initial quantities of residues than Shafton. This was probably due to differences in site and previous rotation species affecting the initial quantity of residues at each site. Also the amount that these residues would have decomposed would have varied with climate and the length of time between harvesting of the previous rotation and planting. Only at Shafton did soil C measured at TH between 0 and 0.05 m, significantly increase with residue retention. Due to the wildfire at this trial, effects of residue management on soil C at TF could not be determined. The lack of residue management effects on soil C at Rattray is probably due to the relatively low mass of residues, even in the B plots, and the climate, which is conducive for rapid decomposition of residues.

Where significant, residue removal reduced the nutrient content of residues and soil at a site. This impact on site nutrients was greatest at Shafton. At Rattray, significant effects were only found at TF on Ca and Mg. This was despite Rattray having a lower content of available macronutrients in the soil than Shafton, with the exception of P and Ca. However, the total nutrient content of residues at Rattray was much lower than that of Shafton, resulting in smaller additions of nutrients to the site from residues. At Shafton, a significant decrease at TH in soil N, P, K, Ca and Mg contents was found with residue removal, while effects found at TF were excluded due to the wildfire. Residues at Shafton contained a substantial proportion of site P, as a result of the high P-fixing nature of the soil. In addition, where soil pH was significantly affected by residue management at both sites, it decreased with increasing residue removal. This has implications for the availability (e.g. P) and leaching potential of nutrients (e.g. N).

The significant effect of residue management on soil C at Shafton (at TH between 0 and 0.05 m) resulted in a change, mainly in AWC, which decreased with decreasing residue removal. In addition, at both sites, residue retention also increased θ_v between 0 and 0.05 m. However, this effect may only be significant

until either the majority of residues have decomposed, or until canopy closure. Nonetheless, residue retention has an important role in maintaining favourable soil water conditions in a young stand.

Although a similar study of the effect of residue management on soil C and nutrients was performed at a site close to Shafton (du Toit *et al.*, 2008), minimal research has been performed on sites similar to Rattray. Thus while some of these results are not new, they were necessary to attempt to quantify as many of the major variables as possible that would affect tree growth at both sites. In addition, this study was unique in that it included interaction effects between compaction and residue management.

8.1.3   Interaction between Compaction Treatments and Residue Management

At both sites, the effects of the C_M and C_H treatments were reduced by residue retention and resulted in a lower PSS in the top 0.4 m of soil, and at Rattray this was reflected in the bulk density results. This reduction was related to the quantity of residues left on the plot prior to compaction treatment implementation.

No significant effects of the interaction between compaction treatments and residue management were found on the quantity of residues, soil C content, soil pH, or the nutrient content of either residues or soil at Rattray or Shafton.

Both soil bulk density and C were found to have a significant effect on soil water retention characteristics, and therefore on AWC and RAW at both trials. However, significant interaction effects of compaction treatments and residue management were only found on soil bulk density at Rattray. Residue retention at this site could thus be used to reduce the negative effects of compaction on AWC. Significant interaction effects on θ_v (between 0 and 0.05 m) were found at both Rattray and Shafton. Both increasing compaction and residue retention increased θ_v between 0 and 0.05 m, which on soils such as those of Rattray due to their inherently low AWC and RAW could be particularly advantageous to seedling establishment.

8.1.4   <u>Conclusions</u>

The results clearly show that the soils at the two sites are susceptible to compaction; more so at Rattray than at Shafton. Also, neither soil possesses the ability to naturally ameliorate the effects of compaction. This means that any management practice that leads to compaction on these sites will have long-lasting effects that can only be ameliorated by human intervention. The effects of this compaction on other soil properties not only vary with soil type, but are also dependent on the quantity of organic C in the soil.

Residue management effects also varied between the two sites. However, the initial source of variation was the residues themselves. Despite identical types of residue management at the two sites, initial quantities of residues, their nutrient content and the time the residues were able to decompose before planting, varied. In addition, decomposition rates during the study at the two sites would have varied due to differences in climate. Nonetheless, some key conclusions can be drawn.

Residues reduced the amount of compaction inflicted by machinery in the top 0.4 m of soil. The greater the quantity of residues, the lower was the compactive effect of machinery on the soil. In addition, residue retention increases soil water content in the top 0.05 m of soil, at least in the first 8 months after felling, which has implications for nutrient mineralisation, seedling establishment and early tree growth. Residue management did not necessarily substantially affect soil organic C and nutrient levels in the short term (<3.5 years). However, residues do contain considerable quantities of nutrients, and removal of residues will negatively affect site nutrient capital in the long-term.

Although the implementation of compaction treatments and residue management at both trials was almost identical, differences in residue quantities, residue decomposition state and rate, as well as soil type, often resulted in dissimilar

effects on soil properties. This indicates that the effect of compaction and residue management on the LTSP of soils cannot be assumed to be similar, but needs to be assessed over a range of sites.

8.2 *Eucalyptus* Productivity as an Indicator of Changes in Soil Properties

At Rattray, tree productivity until 18 months of age was significantly affected by compaction treatments, and decreased in the order $C_L>C_M>C_H$. This was probably in response to increasing soil strength and decreasing water availability, despite the increases in soil C content with compaction intensity. Although not significant, this negative effect of compaction treatments was measured until 41.5 months of age, particularly in the DBH data. The decrease in the significance of compaction treatments over time may be a result of the ability of roots to explore areas within the soil with a favourable environment that were previously unavailable. This would occur with the decomposition of the previous rotation roots, yielding zones with a low PSS, high organic C and available soil water and nutrients. It is also possible that the tree roots of the current stand have grown to a size that can more easily overcome the soil strength levels. Compaction treatments also increased the variability in growth within sub-plots. This was most likely a result of the variability in soil strength demonstrated by the significant differences in bulk density and PSS values between interrows and stumplines.

This change in response to compaction by trees as they grow gives new insights when data are compared with the previous study at Rattray (Smith and du Toit, 2005). They did not find any significant compaction effects on tree productivity at any time. Similar results were found in this study in the older trees, i.e. 2 years and over. However, the significant responses in younger trees obtained in this study, coupled with the significant increases in soil bulk density, PSS and other related soil variables, indicate that perhaps compaction of the site has reached the threshold level for trees.

Residue management had no significant effect on tree productivity at Rattray. This is probably because the effect of residue management on site nutrients was relatively small, significantly affecting only soil Ca and Mg, and some non-significant decreases in other site nutrients with residue removal.

Tree productivity (main plots) at Shafton was significantly negatively affected by compaction treatments between 12 and 30.5 months of age. This (relatively) late growth response to compaction treatments may be a result of either:

   a. Season, as the majority of the period of growth of sub-plot trees was during the wet season, unlike the main plot trees that grew through several seasons.

   b. The growing tree roots required larger volumes of soil to support aboveground growth, and these then encountered considerable soil strength. This would have also lowered the ability of the trees to access nutrients, particularly immobile nutrients such as P. Foliar results showed that P concentrations were highest in C_L treatments, while soil available P contents were highest in C_M treatments at the same sampling time. In addition, it is assumed that although significant effects on bulk density from compaction treatments were not found, increases in bulk density with increasing soil strength did occur. These increases in bulk density, would have generally also led to a decrease in AWC and RAW, further decreasing tree growth. Since these decreases in growth were found only in older trees, this implies that, initially, site resources were not limiting to the younger trees with lower water and nutrient requirements.

In contrast, residue management had a substantial effect on tree growth at Shafton. Residue removal significantly increased tree growth until 120 DAP, and then significantly decreased growth from 12 months of age, until the final measurement at 30.5 months of age. Similar responses in other studies have been attributed to changes in soil nutrient availability, particularly N. The soil sampling regime, however, was not intense enough to detect when changes in available nutrients occurred. However, foliar nutrient concentration results suggest that by the time the trees were six months old, considerably greater amounts of N and P were available to trees in the residue retained plots.

Tree productivity, around six months of age, at both Rattray and Shafton, was significantly related to non-destructive growth measurements (e.g. GLD, height and BI), and these relationships were not affected by the treatments, with the exception of the (fine) root:shoot ratio at Rattray. However, treatment effects on tree productivity changed as the trees grew. Therefore, while trees can be used as indicators of soil conditions, the specific conditions that they respond to will vary through their growth cycle. In addition, although trees may overcome some soil conditions with growth, such as compaction at Rattray, the initial effects may have rotation-end effects on the stand, such as poor uniformity, which ultimately lead to lower productivity. From a management perspective, poor initial growth of trees leads to late canopy closure, and either increases costs through additional weed control, or increases losses through poor uniformity (Little and van Staden, 2005).

8.3   Implications of the study and future work

8.3.1   Compaction treatments

A previous study at Rattray concluded that the effect of soil compaction on tree growth was negligible and that only in soils with a subsoil clay content above 10%, could growth losses be anticipated with soil compaction (Smith and du Toit, 2005). This effect was mainly attributed to an increase in AWC with soil compaction. Although the effects of compaction on growth from two years of age were not significant in the present study, this appears to be due to inadequate replication. The current results show that high levels of soil compaction lead to a reduction in productivity and growth, resulting in an almost 10% loss of stemwood volume at 3.5 years of age. In addition, reductions in growth and productivity were also measured on moderately compacted plots despite PSS in these plots only attaining a maximum value of 1529 kPa, well below the threshold of 2000 kPa quoted in the literature (**Section 7.1.3.2**). Growth reductions due to compaction at Rattray are most likely due to decreasing AWC with increasing compaction (**Section 6.3.2.1**), a result that contrasted with the findings of Smith and du Toit (2005). The results indicate that once compaction at similar sites reaches a

threshold level, this will negatively affect growth. This alters conclusions of previous studies that at sites similar to Rattray soil compaction has minimal effect on plantation productivity.

The previous study at Shafton (Smith, 2006) found that increasing soil compaction reduced stemwood volume, although this was not always significant. A significant, but also negative effect on growth and productivity, until 2.5 years of age (at which stage, stemwood volume was 6.9% less in C_H than in C_L treatments) was also found in the present study. This was despite only a 7% increase in PSS in C_H than in C_L treatments, in contrast to an 89% increase in PSS in C_H than in C_L treatments at Rattray. The lack of a more pronounced effect of compaction at Shafton is most likely a result of the site's high soil carbon content. Should this decrease in time, this site may be more prone to growth reductions due to soil compaction.

8.3.2   Residue management

No studies in South Africa have quantified the effects of residue retention in the reduction of the compactive effects of machinery. It was found that topsoil PSS increased less with increasing residue retention at both sites. Topsoil compaction is considered highly detrimental to LTSP, as it is in this part of the soil that most nutrients, water, and therefore tree roots are concentrated.

A previous study (du Toit and Scholes, 2002) at a site close to Shafton concluded that similar sites were well buffered against nutrient depletion in the short and long term due to considerable soil stores and addition from atmospheric deposition. However, the present results at Shafton indicate that residue removal negatively impacts tree growth (an estimated 10% loss in stemwood volume was found in residue removed than broadcast residue treatments at 2.5 years of age), and although nutrient dynamics were not intensively monitored, residue removal did significantly decrease foliar concentrations of N and P. In addition, residue management did affect soil C content almost 16 months after implementation, however this effect could not be confirmed two years later due to a wildfire.

Nonetheless, this effect has implications not only for soil nutrient sustainability, but also soil water availability, as the loss of soil C reduced AWC (**Section 6.3.2.2**). In addition, soil C assists in a soils ability to resist compaction, and losses will increase the susceptibility of the site to compaction. In contrast, the Rattray site is considered to be less fertile due to its low CEC, and was thus expected to show a greater response in tree growth to residue management than at Shafton. This, however, was not the case, and growth and productivity at Rattray were found to be relatively unaffected by residue management. In the future however residue removals may affect productivity at Rattray. For example, site Ca is currently sufficient for tree growth, but continued residue removals at Rattray will result in this nutrient eventually becoming deficient, unless atmospheric deposition or weathering is sufficient to maintain soil Ca levels.

The results of this study have considerable implications for the management of plantations on similar sites. At sites such as Rattray, compaction will negatively affect LTSP, and these effects can be reduced by the retention of as much residues as possible, at least for the duration of machinery movement. However, residue management does not appear to be essential for LTSP. In contrast, residue retention is necessary at sites such as Shafton to maintain LTSP, and to maintain soil C levels to aid in the reduction of the effects of compaction on tree productivity.

8.3.3   Use of densely planted sub plots and tree productivity

From a plant physiology perspective, although compaction and residue management affected tree growth and productivity, it did not affect the allometry of the densely planted trees, once the effects of ontogeny were accounted for. This is in contrast to other studies e.g. in South African plantation *E.grandis*, Campion (2005) concluded that water and nutrient availability affected allometry.

The productivity of densely planted trees was found not to be a good indicator of LTSP, as these trees responded to short-term changes in the soil environment that may not affect LTSP.

8.3.4 Future work

8.3.4.1 Future of the trials at Rattray and Shafton

The continued re-implementation and monitoring of the Rattray trial is essential for understanding the effects of compaction and residue management on the long term productivity of such sites. With re-implementation it is likely that factors that currently do not limit growth may become growth limiting, and can then be identified. Should additional funding be available, the monitoring of soil water and tree water status would substantially aid in understanding the main factors affecting this site. Unfortunately the occurrence of the wildfire at Shafton has limited the utility of this rotation for its original purpose. However, it may be useful to re-implement the residue management treatments in the next rotation to try to tease out the actual reasons for improved growth with residue retention, and to determine if this effect is continued to rotation end. The investigation of the effects of residue management on nutrient and soil water dynamics would yield some new insights that would further understanding on the role of residues in LTSP.

An additional use of the current and future data resulting from these trials is for the parameterisation and verification of process-based forest productivity and carbon storage/sequestration models.

8.3.4.2 Further LTSP Research

The results of this study show clearly that different sites respond differently to similar management practices, with equally variable effects on tree productivity and growth. Thus the work should be continued to investigate the range of sites used for plantation forestry in South Africa. For instance no data are currently available on the effect of compaction and residue management on the productivity of eucalypts or soil physical/nutritional properties on granite-derived soils. Over 150,000 ha of such soils exist in the south-eastern Mpumalanga region alone, and about 24% of the total area under forestry is on these soils. These soils are easily

compacted and have a tendency to hard-set when dry. In addition, they are often deficient in plant available P. Therefore future work should concentrate on such sites, as productivity losses may be substantial if the effects of compaction and residue management are not understood. In addition, the role of residues in reducing the compactive effects of machinery across different sites with different residue loads needs to be established, as does the potential of practices that can ameliorate compaction, such as ripping. Should time and financial constraints be removed, an ideal study would include detailed monitoring of soil water, the effects on tree water status, and a focus on nutrient dynamics.

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Appendix 3.1. Monthly rainfall data for the duration of the study.

A.   Rattray

Fifty year monthly mean rainfall (from 1950 - 2000 records) and total monthly rainfall from September 2004 – April 2008 for a nearby site[a].

Month	50 yr mean	2004/2005	2005/2006	2006/2007	2007/2008
September	73.0	94.5	16.4	20.5	36
October	102.7	53.8	58.0	89.7	94.9
November	113.6	111.6	84.3	87.1	168.2
December	107.9	31.6	56.5	133.1	35.9
January	139.1	167.0	101.6	83.5	53
February	142.8	123.7	165.2	27.4	129
March	107.6	122.3	108.1	34.0	108
April	76.4	18.5	170.8	125.0	141.5
May	54.3	31.2	46.1	1.2	
June	39.7	81.3	31.9	176.3	
July	46.2	12.3	2.5	3.0	
August	42.7	13.5	77.4	10.2	
Total	**1046.1**	**861.3**	**918.8**	**791.0**	

[a]   Detailed in **Table 3.1**.

B.   Shafton

Fifty year monthly mean rainfall (from 1950 - 2000 records) and total monthly rainfall from November 2004 – June 2007 for a nearby site[a].

Month	50 yr mean	2004/2005	2005/2006	2006/2007
November	108.0	120	103.9	135.1
December	130.8	128.2	68.4	113.8
January	136.0	232.3	187.1	72.4
February	108.4	127.5	122.8	18.2
March	100.3	160.4	84.1	98.6
April	48.5	25.0	85.8	31.6
May	25.0	6.4	17.3	0.4
June	11.7	11.2	5.8	31.8
July	14.1	0.4	0.0	
August	29.7	25.9	46.7	
September	45.3	23.3	37.2	
October	83.6	93.5	108.6	
Total	**841.4**	**954.1**	**867.7**	

[a]   Detailed in **Table 3.1**.

Appendix 3.2. Specifications of vehicles used to implement the compaction treatments.

Property	3-Wheel Logger	Forwarder
Name	225A Logger	T17D Articulated Timber Truck
Engine net power (kW)	46	198
Front tyre size	18.4 x 26 10 Ply	20.5R25
Front tyre pressure (kPa/psi)	unladen: 51.1/7.4	laden: 134 kPa/19
Rear tyre size	4.00 x 15.5 10 Ply	20.5R25
Rear tyre pressure (kPa/psi)	unladen: 94.7/13.7	laden: 134/19
Mass (unladen; t)	5.2	17.82
Mass (laden; t)	5.8	33.24

Source: www.bell.co.za, Bell Equipment Co. SA (Pty) Ltd, 7 Van Eck Place, Mkondeni, Pietermaritzburg, 3201, South Africa.

Appendix 3.3. Trial diary of forestry operations and main plot growth measurements carried out at Rattray and Shafton.

A.   Rattray trial

Date	DAP[a]	Operation
24 Jul– 03 Aug 2004	-57	Previous rotation manually felled, branches removed and stemwood cross-cut into 5.5 m lengths. Bark stripped from wood.
04-05 Aug 2004	-47	Wood stacked in appropriate positions in trial.
05-10 Aug 2004	-46	Residue management treatments implemented.
11 Aug 2004	-40	Old coppice stumps (from many rotations prior to previous rotation) cut to allow machinery movement.
02-03 Sep 2004	-18	Moderate compaction treatments implemented.
13-16 Sep 2004	-7	High compaction treatments implemented and stacked wood removed from trial.
16-18 Sep 2004	-4	Densely planted sub-plot positions marked and entire trial manually pitted with hoes. Pre-plant spraying operation also performed to kill competing vegetation.
20-21 Sep 2004	0	Trial planted, one litre of water applied to each seedling during planting. Seedlings in poor condition.
12 Oct 2004	20	First blanking operation. Hot, dry weather conditions noted.
15 Oct 2004	23	Two litres of water applied to every plant in trial to improve tree survival during continued hot, dry weather.
25 Oct 2004	33	Second blanking operation.
9 Nov 2004	48	Third blanking operation. Very hot weather conditions noted.
10 Nov 2004	49	Chemical spraying of weeds.
11 Nov 2004	50	Rain.
12-14 Nov 2004	51	Coppice from previous rotation reduced.
10 Dec 2004	79	Chemical spraying and hand removal of weeds.
10 Jan 2004	110	Coppice from previous rotation reduced.
11 Jan 2004	111	Chemical spraying and hand removal of weeds.
23 Feb 2005	154	Coppice from previous rotation reduced.
24 Feb 2005	155	Chemical spraying and hand removal of weeds.
29 Mar 2005	188	Coppice from previous rotation reduced.

Date	DAP[a]	Operation
14 Apr 2005	204	Chemical spraying and hand removal of weeds.
19-20 Apr 2005	209	Biomass harvest of densely planted sub-plot trees and thinning of plots to main plot espacement.
21 Apr 2005	211	Main plot tree measurement.
25 Oct 2005	398	Main plot tree measurement.
20 Apr 2006	575	Main plot tree measurement.
05 Sep 2006	715	Main plot tree measurement.
06 Jun 2007	987	Main plot tree measurement.
07 Apr 2008	1292	Main plot tree measurement.

[a] Negative DAP values are equivalent to days before planting.

B. Shafton trial

Date	DAP[a]	Operation
17-20 Feb 2004	-279	Previous rotation manually felled, branches removed and stemwood cross-cut into 2.4 m lengths. Bark stripped from wood.
23-27 Feb 2004	-273	Wood stacked in appropriate positions in trial.
04-11 Mar 2004	-264	Residue management treatments implemented.
22-23 Mar 2004	-246	Compaction treatments implemented and stacked wood removed from trial.
06-10 Oct 2004	-48	Coppice from previous rotation reduced.
13-14 Oct 2004	-41	Densely planted sub-plot positions marked and entire trial manually pitted with hoes.
23-24 Nov 2004	0	Pre-plant spraying operation to kill competing vegetation followed by planting. One litre of water applied to each seedling during planting.
30 Nov 2004	6	Wet cold conditions coupled with hail damage causes poor survival of trees.
10 Dec 2004	16	First blanking operation.
20 Dec 2004	26	Second blanking operation
14 Feb 2005	82	Coppice from previous rotation reduced.
10 Mar 2005	106	Accidental herbicide application in several plots by labour working in surrounding compartment.
24 Mar 2005	120	Herbicide damage fully assessed during tree measurement.
31 Mar 2005	127	Chemical spraying of weeds.
07-08 Jun 2005	134	Chemical spraying of weeds and remaining coppice.
22 Jun 2005	211	Biomass harvest of densely planted sub-plot trees and thinning of plots to main plot espacement.
23 Jun 2005	212	Main plot tree measurement.
30 Nov 2005	372	Main plot tree measurement.
18 May 2006	541	Main plot tree measurement.
09 Jan 2007	778	Main plot tree measurement.
07 Jun 2007	927	Main plot tree measurement.
25 Jun 2007	945	Fire through trial.

[a] Negative DAP values are equivalent to days before planting.

Appendix 3.4. Relationship between tree DBH and height at Rattray and Shafton.

A. Relationship between tree DBH and height at Rattray at 31.5 and 41.5 months after planting.

Legend inside chart:
31.5: ln y = 2.759 - 3.487/x; r^2 = 0.712***; + ——
41.5: ln y = 2.949 - 3.558/x; r^2 = 0.727***; ✕ - - - -

Y-axis: Height (m); X-axis: DBH (cm)
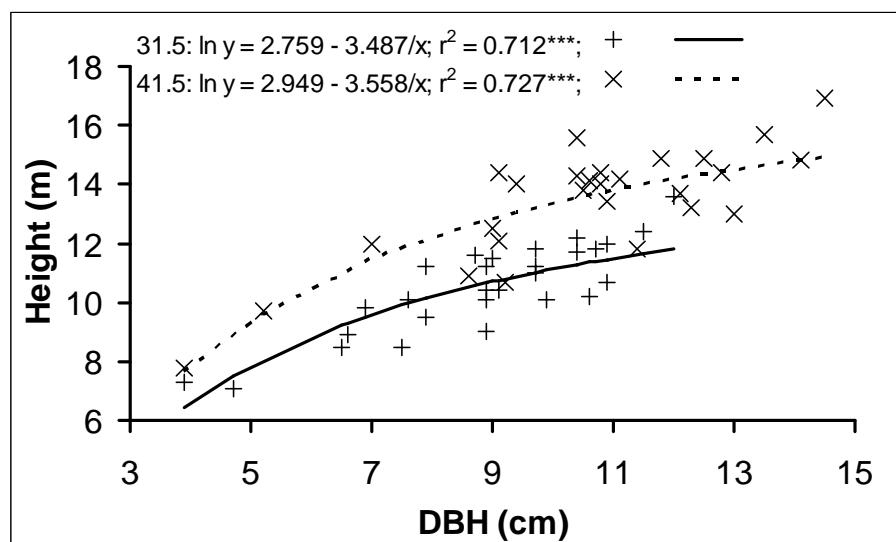
Estimates of parameters

Parameter	estimate	s.e.	t(26)	t pr.
		31.5 months		
Constant	2.759	0.053	51.69	<0.001
x	-3.487	0.424	-8.22	<0.001
		41.5 months		
Constant	2.949	0.047	62.95	<0.001
x	-3.558	0.425	-8.38	<0.001

B. Relationship between tree DBH and height at Shafton at 30.5 months after planting.

The chart shows $\ln y = 2.930 - 4.607/x; \ r^2 = 0.689{***}$, with Height (m) on the y-axis (9 to 14) and DBH (cm) on the x-axis (6 to 14).
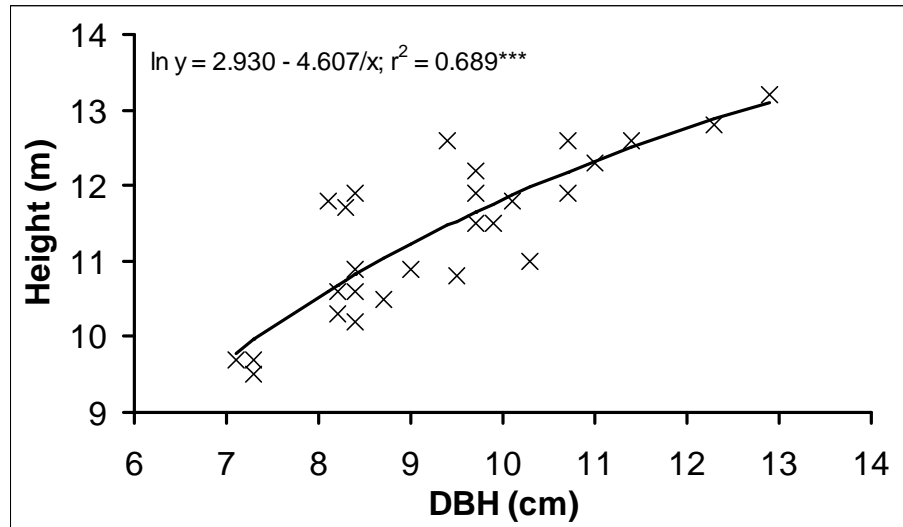
Estimates of parameters

Parameter	estimate	s.e.	t(25)	t pr.
Constant	2.930	0.066	44.13	<0.001
x	-4.607	0.602	-7.66	<0.001

Appendix 3.5. Calculation of soil water content, porosity, air-filled porosity and pore-size distribution.

A. Soil water content

The conversion of mass water content (θ_m) to volume water content (θ_v) was calculated using the following equation:

$$\theta_v = \theta_m * \rho_b/\rho_w$$

where ρ_b is soil bulk density, and ρ_w = density of water (0.998 Mg m^{-3} at 20 ℃).

B. Soil porosity, air-filled porosity and pore-size distribution

Total porosity can be determined from bulk density, as follows:

$$\varepsilon_t = 1 - (\rho_b / \rho_s)$$

where ε_t is the total porosity (m^3 m^{-3}); ρ_b is the bulk density (Mg m^{-3}) and ρ_s is the particle density, assumed to be 2.65 Mg m^{-3} for most soils, as total porosity is not very sensitive to variations in particle density found in the field (Kay and Angers, 2000).

Air-filled porosity can be determined as below:

$$\varepsilon_a = \varepsilon_t - \theta v_{(FC)}$$

where $\theta v_{(FC)}$ is the volumetric water content at field capacity.

Pore-size distribution can be determined from water retention data in conjunction with total porosity (Kay and Angers, 2000). The matric potentials at which water is held in certain size pores can be determined from the capillary equation:

$$P = 2\gamma / r$$

where P is matric suction in kPa; γ is the surface tension of water (estimated to be pure water at 20 ℃ = 0.073 N m^{-1}); r is the radius of the pores in question. Macropores are considered as pores greater than 0.75 mm radius, micropores are considered smaller than 0.3 mm radius, and mesopores occupy the radii between the two (Blackwell *et al.*, 1990; Brady and Weil, 1999; Kay and Angers, 2000).

From the matric potentials determined by the capillary equation, the corresponding volumetric water contents at various bulk densities are determined from water retention curves. These are then used to calculate the quantity or percentage of total pore volume occupied by the range of pores at various bulk densities.

Appendix 3.6. Calibration of the Troxler surface moisture density gauge.

A. Introduction

The Troxler has a single probe which contains a ^{137}Cs gamma radioactive source, which is lowered into a hole (made by hammering a sharpened rod into the soil) to the desired depth and a one minute count taken. This measures the radiation transmitted and backscattered through the soil between the source and the detector on the base of the machine (at the soil surface). Since soil is heterogeneous, certain components such as rock fragments and carbon (and therefore organic matter), affect the thermalisation of neutrons released by the source more than others (e.g. aluminium, silicon and oxygen; Hignett and Evett, 2002). Consequently, bulk density measurements obtained using a Troxler should be calibrated for different soils (King and Haines, 1979; Steele *et al.*, 1983; Cássaro *et al.*, 2000). Therefore in this study, Troxler bulk density values were regressed against their corresponding undisturbed soil core bulk density values to yield a calibration for the Troxler. The improvement in this regression by the inclusion of soil C values as a predictor variable was also evaluated.

B. Rattray

A significant relationship between bulk density measured on undisturbed soil cores (0 – 0.2 m) and Troxler bulk densities was obtained (**Figure 3.6.1**, **Table 3.6.1**). This was despite the recommendation by Steele *et al.* (1983) that at least 83 soil cores would be required to obtain a correlation coefficient of at least 0.65 (only 20 cores were used in this study). Soil C did not have a significant effect on bulk density measured by the Troxler, probably as a result of the very low concentration of organic carbon (between 0.12 and 0.78% m/m).
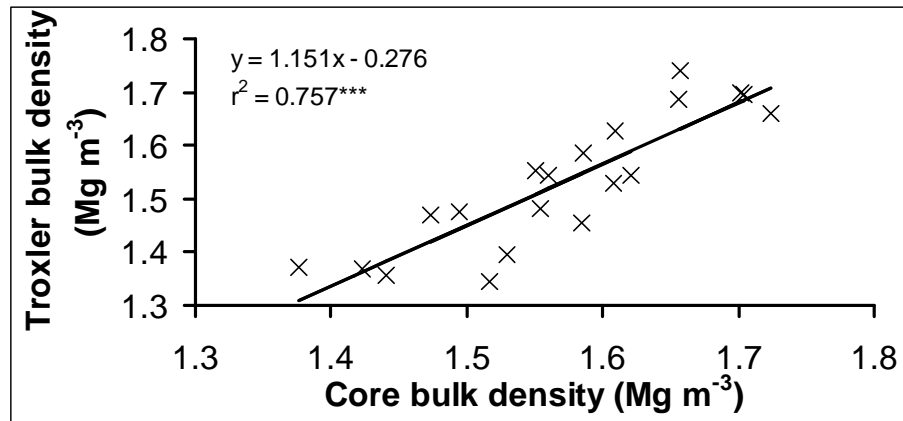
Figure 3.6.1: Relationship between bulk density determined on undisturbed soil cores and that measured with a Troxler at Rattray.

Table 3.6.1: Estimates of parameters of the regression between undisturbed soil core bulk density and that measured with a Troxler at Rattray.

Parameter	estimate	s.e.	t(19)	t pr.
Constant	-276	233	-1.18	0.252
x	1.151	0.148	7.77	<.001

C.   Shafton

Although topsoil Troxler bulk density was significantly positively related to bulk density determined on undisturbed soil cores, this relationship was extremely weak (data not shown; $r^2 = 0.182$; $0.001 < p < 0.01$). This was despite the use of 27 undisturbed soil cores (as opposed to 20 in the Rattray trial) for the calibration. Inclusion of C content of the soil cores improved the correlation (data not shown; $r^2 = 0.549$ $p < 0.01$). In this relationship, a positive effect of C on Troxler bulk density values was found. There was a much greater scatter in the data obtained between 0.1 and 0.2 m soil depth when compared to the 0 – 0.1 m soil depth (**Figure 3.6.2**). If the data from 0.1 – 0.2 m soil depth are excluded, the relationship between core bulk density and Troxler bulk density (excluding C values) improved ($r^2 = 0.581$ $p < 0.001$; **Table 3.6.2**).
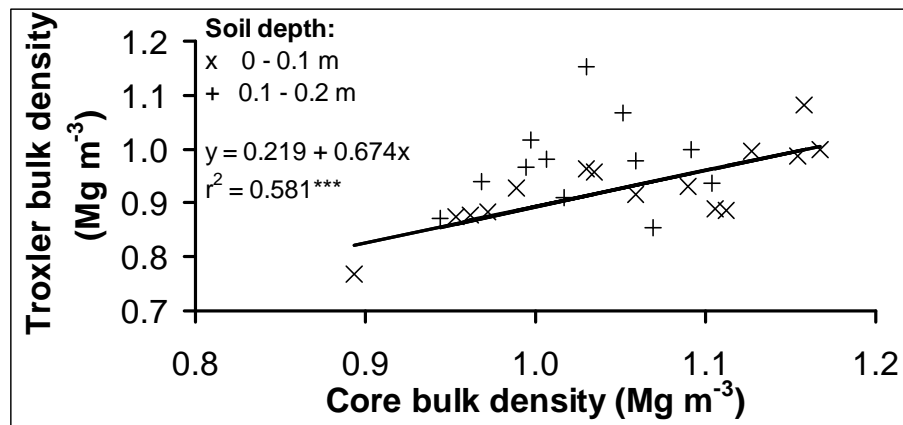
Figure 3.6.2: Relationship between bulk density determined on undisturbed soil cores and that measured with a Troxler in the topsoil at the Shafton trial. The regression displayed is for the 0-0.1 m values only.

Table 3.6.2: Estimates of parameters of the regression between undisturbed soil core bulk density and that measured with a Troxler at Shafton between 0 and 0.1 m.

Parameter	estimate	s.e.	t(13)	t pr.
Constant	0.219	0.158	1.39	0.188
x	0.674	0.149	4.52	<.001

D. Discussion

At both trials, there were discrepancies between bulk density measured with a soil core, and that with a Troxler. At Rattray, the Troxler generally underestimated bulk densities below 1.47 Mg m^{-3}. At Shafton, the Troxler underestimated bulk density over the range measured. The low C content and more homogeneous soil at Rattray may have reduced the noise in the data around the relationship between bulk densities measured with the Troxler and soil cores, unlike at Shafton. At the latter trial, C had a positive effect on Troxler bulk density (i.e. overestimation of bulk density when compared to soil core values). The reason for the difference between the two trials for the range of values at which the Troxler measured accurately was probably the result of differences in soil C, and perhaps texture and structure.

The greater scatter in Shafton trial bulk density data from the 0.1-0.2 m layer when compared to that of the 0-0.1 m layer may be a result of higher soil C combined with the different angle that the radiation travels from the source to the detector in the Troxler that may result in some error. In addition, Troxler bulk density values for the 0.1-0.2 m layer were calculated from the values given by the Troxler for the 0-0.1 m and 0-0.2 m soil layer. These results also indicate that in soils high in organic C, reliable determination of bulk density using a Troxler requires a greater number of core samples.

The underestimation of bulk density by a Troxler surface moisture density gauge has been found in some studies. Bulk density measured by a Troxler was consistently 0.3 Mg m^{-3} lower than that measured with soil cores (King and Haines, 1980). However, no mention of soil organic carbon contents was made, and bulk densities (measured with soil cores) ranged between 1.36 and 1.76 Mg m^{-3} (similar to those at Rattray). A slight underestimation (with one exception) of bulk density by a Troxler when compared to that measured by soil cores was also found at a South African sugarcane site (between 1.5 and 2.0 Mg m^{-3}; Swinford and Meyer, 1985). Page-Dumroese *et al.* (1999) found that a Troxler overestimated soil bulk density on a soil containing rock fragments. A positive effect of organic carbon on Troxler bulk density values leading to an overestimation of bulk density has also been found by others (King and Haines, 1979; Steele *et al.*, 1983; Hignett and Evett, 2002).

Appendix 3.7. Comparison between soil organic carbon methods.

A. Introduction

Soil organic carbon content was determined both by the WB and LOI methods. Two methods were used because of their relative (to one another) dis/advantages (Donkin, 1991; Schulte, 1995):

WB: determines easily oxidisable organic carbon content and is used to estimate (by calculation) total soil organic carbon content as well as soil organic matter content. A disadvantage is that a factor (generally 1.33) is used to calculate total soil organic carbon content, and this factor has been found to vary (Nelson and Sommers, 1996; Kamara *et al.*, 2007).

LOI: determines soil organic matter content which can be converted into soil organic carbon content by a factor. A drawback of this method is that in high (2:1) clay soils ignited at temperatures above about 440°C, structural water or hydroxyl groups are lost which result in an increased loss in mass and an overestimation of organic C (Schulte and Hopkins, 1996; Wang *et al.*, 1996; Konan *et al.*, 2002). In South African forestry soils a factor of 0.284 has been determined only for soils with an easily oxidisable organic carbon content (WB) of less than 5 % (Donkin, 1991).

As a result, relationships were sought between soil organic carbon content determined by WB and LOI to allow the conversion of LOI values (reported throughout this study as C) into total organic carbon values.

B. Rattray

A significant regression was obtained between raw LOI values (i.e. not adjusted using the factor of 0.284) and WB total organic carbon values obtained for the same samples (**Figure 3.7.1**; **Table 3.7.1**).
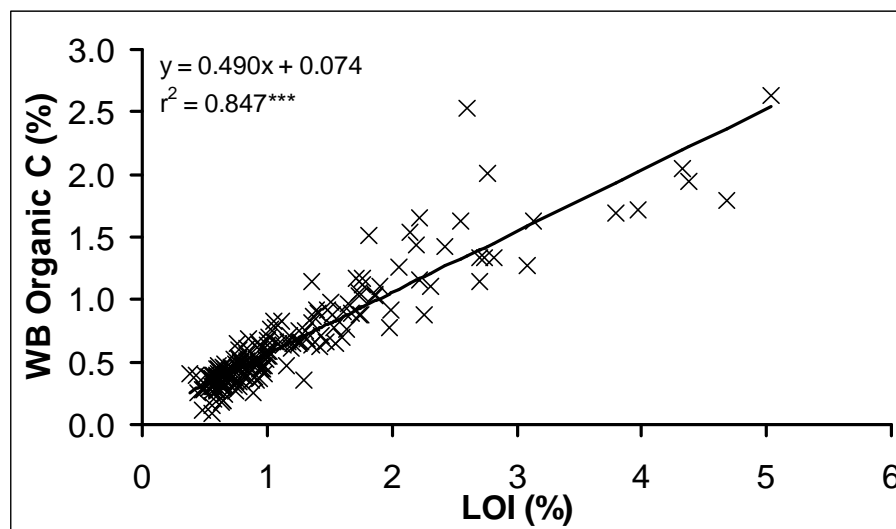
Figure 3.7.1: Relationship between Walkley-Black organic carbon (WB; % m/m) and loss (of mass) on ignition (LOI; % m/m) at Rattray.

Table 3.7.1: Estimates of parameters of the regression between Walkley-Black organic carbon and loss (of mass) on ignition at Rattray.

Parameter	estimate	s.e.	t(196)	t pr.
Constant	0.0743	0.0213	3.49	<.001
x	0.4902	0.0149	32.99	<.001

C. Shafton

Raw LOI values (i.e. not adjusted using the factor of 0.284) were significantly and positively related to WB total organic carbon values at Shafton (**Figure 3.7.2**; **Table 3.7.2**).
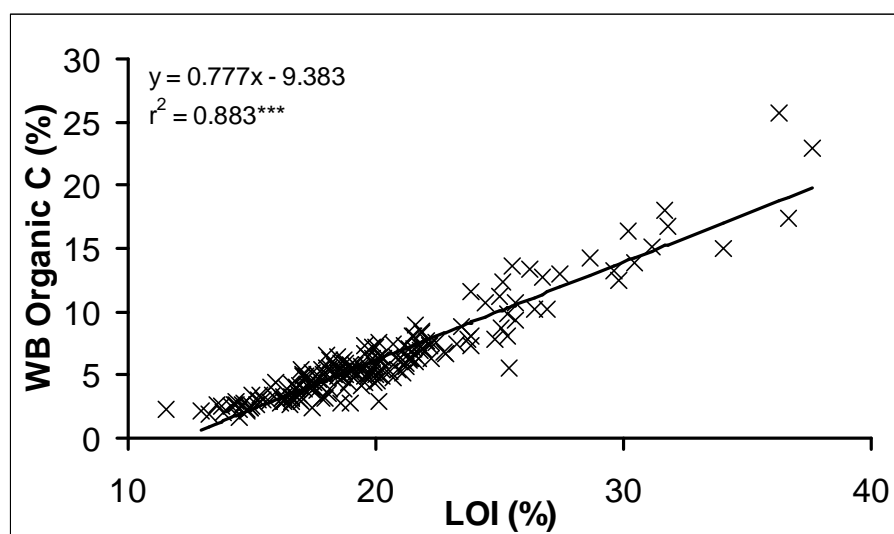
Figure 3.7.2: Relationship between Walkley-Black organic carbon (WB; % m/m) and loss (of mass) on ignition (LOI; % m/m) at Shafton.

Table 3.7.2: Estimates of parameters of the regression between Walkley-Black organic carbon and loss (of mass) on ignition at Shafton.

Parameter	estimate	s.e.	t(200)	t pr.
Constant	-9.383	0.408	-23.02	<.001
x	0.7768	0.02	38.89	<.001

D. Discussion

Significant positive relationships between LOI and WB values have been found in other studies (e.g. Wang *et al.*, 1996; Konan *et al.*, 2002; Cresser *et al.*, 2007). The lower intercept and steeper slope of the relationship obtained at Shafton when compared to Rattray may indicate that a greater loss of structural water or hydroxyl groups took place during LOI. However, the good correlation coefficients of these relationships (r^2>0.8) indicate that total organic carbon (WB) at the trials can be determined from raw LOI values.

Appendix 3.8. Determination of coarse root biomass.

A.   Introduction

Roots are generally classified as either fine (<2mm diameter) or coarse (>2 mm diameter) (Ares and Peinemann, 1992; Fredericksen and Zedaker, 1995; Landsberg and Gower, 1997; Vogt *et al.*, 1997; Gonçalves and Mello, 2004). Tree and sroots, particularly fine roots, are generally concentrated in the upper soil layers, and this has been well documented across a number of species in mixed and monoculture plantations (Nambiar, 1983; Fabião *et al.*, 1990; Ares and Peinemann, 1992; Bouillet *et al.*, 2002; O'Grady *et al.*, 2005). This high surface concentration of roots is attributed to efficient water and nutrient uptake as accretion of organic matter, availability of nutrients and warmer temperatures are found in this surface soil layer (Davis *et al.*, 1983; Strong and La Roi, 1985; Fredericksen and Zedaker, 1995). The distribution of roots in the soil has been studied in the previous rotation at Rattray, and at two sites in the KwaZulu-Natal Midlands close to Shafton. At Rattray almost double the biomass of roots were found in the 0 – 0.1 m versus the 0.1 – 0.2 m soil depth layer of the previous *E. grandis* x *camaldulensis* stand (Sibisi, 1998), while 60% of fine, and 40% of coarse roots of three year-old *E. grandis* trees were found in the top 0.3 m of soil at the Midlands sites (Nkosana, 2002).

B.   Materials and methods

Refer to **Sections 3.2.6.1** and **3.3.3.2**.

C.   Results and discussion

Significant (*p*<0.001) relationships were obtained between the approximate volume of roots and their mass at both trials (**Figure 3.8.1**; **Tables 3.81** and **3.82**). Rates of taper of roots with an end diameter of 2 mm were not related to their start

diameter (data not shown), and were therefore averaged. At Rattray and Shafton, root taper averaged 37.5 and 23.6 mm length mm diameter^{-1}, respectively.
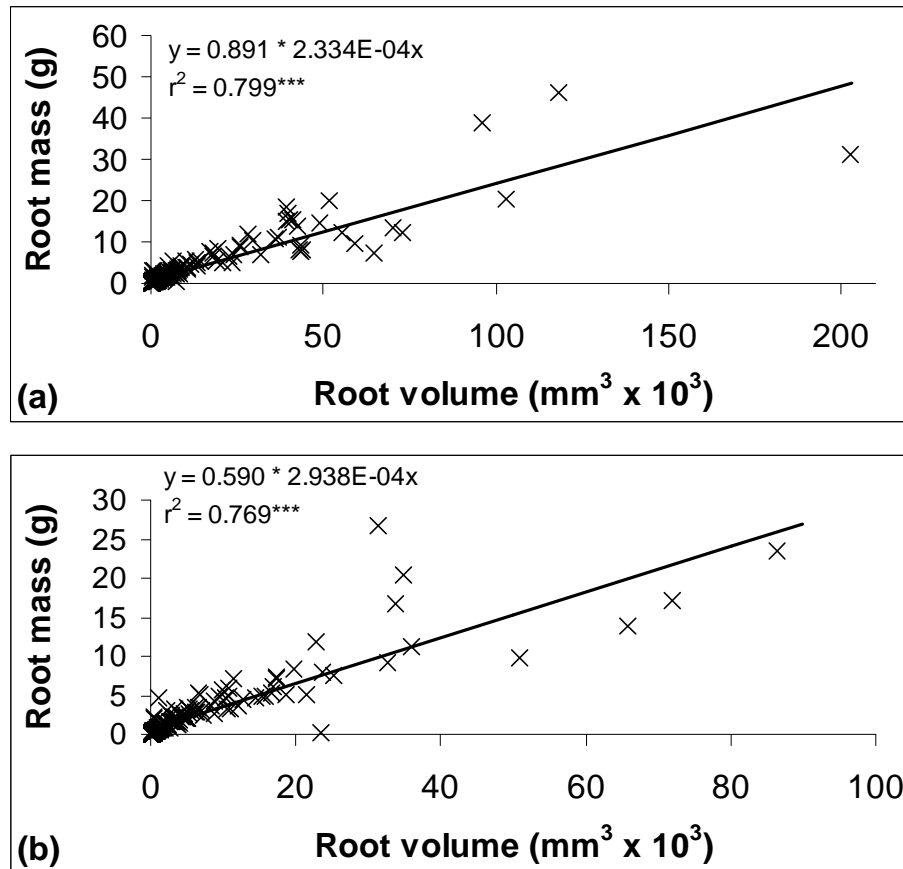
Figure 3.8.1: Relationship between coarse root mass and volume of *E. grandis* trees at (a) Rattray, and (b) Shafton.

Table 3.8.1: Estimates of parameters of the regression between coarse root mass and volume of *E. grandis* trees at Rattray.

Parameter	estimate	s.e.	t(211)	t pr.
Constant	0.891	0.200	4.460	<0.001
x	2.334E-04	8.040E-06	29.050	<0.001

Table 3.8.2: Estimates of parameters of the regression between coarse root mass and volume of *E. grandis* trees at Shafton.

Parameter	estimate	s.e.	t(220)	t pr.
Constant	0.590	0.132	4.470	<0.001
x	2.938E-04	1.080E-05	27.140	<0.001

This method of determination of the coarse root biomass in trees was not found in eucalypt literature. Highly significant correlations between root length and mass were obtained for coarse roots of *P. radiata* (Jackson and Chittenden, 1981) and between root diameters and mass of *P. sylvestris* L. (Helmisaari *et al.*, 2002). The majority of studies investigating this portion of biomass in the field generally did so through extensive excavation of the root system (e.g. Fabião *et al.*, 1995; Bernardo *et al.*, 1998; Misra *et al.*, 1998a; Campion, 2005) or by using root coring methodology (e.g. Misra *et al.*, 1998a; Nkosana, 2002). However, the results indicate that the method used here may have potential for use in other studies of small trees.

Appendix 4.1. Results of statistical analyses of Troxler soil bulk density at Rattray.

A. ANOVA of the effect of compaction treatments (Comp), residue management, plot position (interrow and stumpline; IR/SL) and soil depth of measurement on Troxler bulk density at Rattray. Blocking factor: replicate (Rep), whole plots: treatment (i.e. compaction x residue; trt).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1165	582	0.19	
Rep x trt					
Comp	2	888547	444273	142.20	<0.001
Residue	2	70741	35370	11.32	<0.001
Comp x residue	4	38755	9689	3.10	0.046
Residual	16	49988	3124	1.13	
Rep x trt x IR/SL stratum					
IR/SL	1	36121	36121	13.02	0.002
IR/SL x comp	2	16814	8407	3.03	0.073
IR/SL x residue	2	1814	907	0.33	0.725
IR/SL x comp x residue	4	1341	335	0.12	0.973
Residual	18	49937	2774	1.48	
Rep x trt x IR/SL x depth stratum					
Depth	2	563801	281900	150.68	<0.001
IR/SL x depth	2	11818	5909	3.16	0.048
Depth x comp	4	18881	4720	2.52	0.048
Depth x residue	4	2997	749	0.40	0.808
IR/SL x depth x comp	4	2516	629	0.34	0.853
IR/SL x depth x residue	4	2624	656	0.35	0.843
Depth x comp x residue	8	8761	1095	0.59	0.787
IR/SL x depth x comp x residue	8	7701	963	0.51	0.842
Residual	72	134702	1871		
Total	161	1909024			

B. Mean Troxler bulk density values between compaction treatments and three soil depths at Rattray.

Compaction	Depth (m)	Troxler bulk density[†] (Mg m^{-3})
High	0.2 – 0.3	1.70^a
High	0.1 – 0.2	1.68^a
Moderate	0.2 – 0.3	1.58^b
Moderate	0.1 – 0.2	1.58^b
High	0 – 0.1	1.54^c
Low	0.2 – 0.3	1.52^c
Low	0.1 – 0.2	1.47^d
Moderate	0 – 0.1	1.47^d
Low	0 – 0.1	1.38^e

[†] Treatments with different letters are significantly different ($p<0.05$).

C. Mean Troxler bulk density values between plot position (interrow/stumpline) and three soil depths at Rattray.

Plot position	Depth (m)	Troxler bulk density[†] (Mg m^{-3})
Interrow	0.2 – 0.3	1.63^a
Interrow	0.1 – 0.2	1.59^b
Stumpline	0.2 – 0.3	1.57^b
Stumpline	0.1 – 0.2	1.57^b
Interrow	0 – 0.1	1.47^c
Stumpline	0 – 0.1	1.46^c

[†] Treatments with different letters are significantly different ($p<0.05$).

D. Selected results of ANOVA's of the effect of compaction and residue management on Troxler bulk density at three soil depths at Rattray.

Source of variation	df	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.
Depth (m):		0 – 0.1		0.1 – 0.2		0.2 – 0.3	
Compaction	2	227502	<0.001	371390	<0.001	300831	<0.001
Residue	2	21636	0.002	33465	<0.001	21078	0.052
Comp x residue	4	12117	0.009	6251	0.150	5748	0.509
Residual	99	3374		3619		6920	
Total	107						

E. Mean Troxler bulk density values (Troxler) between compaction treatments and residue management at three soil depths at Rattray.

Depth (m)	Compaction	Residue management	Troxler (Mg m^{-3})	LSD† ($p<0.05$)	LSD† ($p<0.01$)
	High	Windrow	1.57	a	a
	High	Removed	1.55	ab	ab
	High	Broadcast	1.50	bc	abc
	Moderate	Removed	1.49	c	bcd
0 – 0.1	Moderate	Broadcast	1.48	cd	cde
	Moderate	Windrow	1.44	de	def
	Low	Removed	1.42	ef	def
	Low	Windrow	1.38	f	fg
	Low	Broadcast	1.34	fg	g
	High		1.68	a	a
	Moderate		1.58	b	b
0.1 – 0.2	Low		1.47	c	c
		Broadcast	1.55	a	a
		Windrow	1.57	b	ab
		Removed	1.61	c	b
	High		1.70	a	a
	Moderate		1.58	b	b
0.2 – 0.3	Low		1.52	c	c
		Broadcast	1.58	a	NS
		Windrow	1.59	b	NS
		Removed	1.63	b	NS

† Treatments with different letters are significantly different.

F. Mean Troxler bulk density values between compaction treatments and plot position (interrow/stumpline) at Rattray between 0 and 0.3 m.

Compaction	Plot position	Troxler bulk density† (Mg m^{-3})
High	Interrow	1.67[a]
High	Stumpline	1.61[b]
Moderate	Interrow	1.55[c]
Moderate	Stumpline	1.54[c]
Low	Interrow	1.47[d]
Low	Stumpline	1.45[d]

† Treatments with different letters are significantly different ($p<0.1$).

Appendix 4.2. Results of statistical analyses of Troxler soil bulk density at Shafton.

A.   ANOVA of the effect of compaction treatments (Comp), residue management, plot position (interrow and stumpline; IR/SL) and soil depth of measurement on Troxler bulk density at Shafton. Blocking factor: replicate (Rep), whole plots: treatment (i.e. compaction x residue; trt).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	35623	17812	1.78	
Rep x trt					
Comp	2	14850	7452	0.74	0.493
Residue	2	907	453	0.05	0.956
Comp x residue	4	18493	4610	0.46	0.764
Residual	16	160434	10027	1.89	
Rep x trt x IR/SL stratum					
IR/SL	1	1338	1338	0.25	0.622
IR/SL x comp	2	6549	3274	0.62	0.551
IR/SL x residue	2	29696	14848	2.79	0.088
IR/SL x comp x residue	4	2046	511	0.10	0.982
Residual	18	95706	5317	1.01	
Rep x trt x IR/SL x depth stratum					
Depth	2	899013	449507	85.57	<0.001
IR/SL x depth	2	13473	6736	1.28	0.284
Depth x comp	4	15599	3900	0.74	0.566
Depth x residue	4	24297	6074	1.16	0.337
IR/SL x depth x comp	4	9113	2278	0.43	0.784
IR/SL x depth x residue	4	5165	1291	0.25	0.911
Depth x comp x residue	8	24906	3113	0.59	0.781
IR/SL x depth x comp x residue	8	24716	3089	0.59	0.785
Residual	72	378242	5253		
Total	161	1760111			

B.   Mean Troxler bulk density values at three soil depths at Shafton.

Depth (m)	Troxler bulk density[†] (Mg m^{-3})
0.2 – 0.3	1.11[a]
0.1 – 0.2	1.03[b]
0 – 0.1	0.93[c]

[†]   Treatments with different letters are significantly different ($p<0.05$).

Appendix 4.3. Statistical analyses of treatment effects on mean PSS$_0$ at Rattray.

A. ANOVA of the effect of compaction treatments, plot position (interrow and stumpline; IR/SL) and soil depth of measurement on PSS$_0$ at Rattray. Blocking factor: replicate (Rep), whole plots: treatment (i.e. compaction x residue; trt); covariate: soil water content.

Source of variation	df	s.s.	m.s.	v.r.	cov.ef	F pr.
Rep stratum						
Covariate	1	21793	21793	0.00		0.948
Residual	6	28264926	4710821	2.60	0.86	
Rep x trt stratum						
Comp	2	11034456	5517228	3.04	0.97	0.083
Covariate	1	1862216	1862216	1.03		0.329
Residual	13	23583057	1814081	3.41	1.00	
Rep x trt x IR/SL stratum						
IR/SL	1	133610	133610	0.25	1.00	0.621
IR/SL x com	2	556541	278271	0.52	0.93	0.600
Covariate	1	681853	681653	1.28		0.271
Residual	20	10624866	531243	8.21	1.01	
Rep x trt x IR/SL x depth stratum						
Depth	16	171086159	10692885	165.21	0.89	<0.001
IR/SL x depth	16	7371618	460726	7.12	1.00	<0.001
Depth x comp	32	11387915	355872	5.50	1.00	<0.001
IR/SL x depth x comp	32	1974539	61704	0.95	1.00	0.543
Covariate	1	21174	21174	0.33		0.568
Residual	671	43429203	64723		1.00	
Total	815	371614902				

B.   Mean PSS_0 (kPa) values in the interrow and stumpline at Rattray.

Depth (m)	Interrow		Stumpline	
	Mean PSS_0	$LSD^{\dagger}$	Mean PSS_0	$LSD^{\dagger}$
0.05	31.5	q	42.1	q
0.10	221.1	p	239.9	p
0.15	545.3	n	486.8	o
0.20	1114.6	l	846.0	m
0.25	1540.0	abcd	1155.9	kl
0.30	1697.0	ab	1370.5	defghij
0.35	1710.9	a	1444.6	defgh
0.40	1633.8	abc	1446.0	defgh
0.45	1522.0	bcd	1473.7	cde
0.50	1426.4	defghij	1485.3	cde
0.55	1343.1	efghij	1481.0	cde
0.60	1285.2	ghijkl	1471.6	cde
0.65	1259.4	ijkl	1449.8	defg
0.70	1248.4	jkl	1432.8	defghi
0.75	1268.0	hijkl	1430.4	defghi
0.80	1291.2	fghijk	1469.3	cdef

† Treatments with different letters are significantly different ($p<0.05$).

C.   Mean PSS_0 (kPa) values different compaction treatments at Rattray.

Depth (m)	High		Moderate		Low	
	Mean PSS_0	$LSD^{\dagger}$	Mean PSS_0	$LSD^{\dagger}$	Mean PSS_0	$LSD^{\dagger}$
0.05	30.9	l	34.8	l	44.6	l
0.10	233.1	kl	235.4	kl	223.0	kl
0.15	553.2	j	500.6	jk	494.3	jk
0.20	1151.3	ghi	904.3	i	885.2	i
0.25	1734.5	abc	1162.9	ghi	1146.4	hi
0.30	2004.5	a	1291.9	efgh	1304.8	efgh
0.35	2004.4	a	1314.2	efgh	1414.8	defgh
0.40	1892.8	ab	1337.7	efgh	1389.1	defgh
0.45	1755.6	abc	1365.1	defgh	1372.7	defgh
0.50	1609.1	bcd	1414.5	defgh	1343.9	defgh
0.55	1532.7	cde	1420.7	defgh	1282.7	efgh
0.60	1468.6	cdef	1410.5	defgh	1256.1	efgh
0.65	1418.7	defgh	1395.9	defgh	1249.2	fgh
0.70	1378.8	defgh	1381.8	defgh	1261.2	efgh
0.75	1357.6	defgh	1411.9	defgh	1278.1	efgh
0.80	1365.7	defgh	1451.5	defg	1323.6	efgh

† Treatments with different letters are significantly different ($p<0.05$).

Appendix 4.4. Statistical analyses of treatment effects on mean PSS$_1$ at Rattray.

A. ANOVA of the effect of compaction treatments (Comp), residue management, plot position (interrow and stumpline; IR/SL) and soil depth of measurement on PSS$_1$ at Rattray. Blocking factor: replicate (Rep), whole plots: treatment (i.e. compaction x residue; trt); covariate: PSS$_0$.

Source of variation	df	s.s.	m.s.	v.r.	cov.ef.	F pr.
Rep stratum						
Covariate	1	126	126	0.06		
Residual	1	2175	2175	8.25	0.53	0.850
Rep x trt stratum						
Comp	2	16648	8324	31.59	0.91	<.001
Residue	2	204	102	0.39	0.99	0.686
Comp x residue	4	150	37	0.14	0.99	0.964
Covariate	1	133	133	0.51		0.489
Residual	14 (1)	3689	263	3.61	0.97	
Rep x trt x IR/SL stratum						
IR/SL	1	282	282	3.87	1.00	0.067
IR/SL x compaction	2	29	15	0.20	0.97	0.821
IR/SL x residue	2	561	280	3.84	0.77	0.043
IR/SL x comp x residue	4	269	67	0.92	0.96	0.476
Covariate	1	786	786	10.77		0.005
Residual	16 (1)	1168	73	7.85	1.57	
Rep x trt x IR/SL x depth stratum						
Depth	16	35387	2212	237.79	0.73	<.001
IR/SL x depth	16	57	3	0.38	0.99	0.986
Depth x comp	32	6962	218	23.39	1.00	<.001
Depth x residue	32	448	14	1.51	1.00	0.039
IR/SL x depth x comp	32	326	10	1.09	1.00	0.334
IR/SL x depth x residue	32	227	7	0.76	1.00	0.824
Depth x comp x residue	64	672	10	1.13	1.00	0.240
IR/SL x depth x comp x residue	64	476	7	0.80	1.00	0.868
Covariate	1	26	26	2.79		0.095
Residual	543 (32)	5050	9		1.00	
Total	883 (34)	182242				

B.   Mean PSS$_1$ (kPa) values in different compaction treatments at Rattray.

Depth (m)	High Mean PSS$_1$	LSD[†]	Moderate Mean PSS$_1$	LSD[†]	Low Mean PSS$_1$	LSD[†]
0.05	48.6	u	51.8	u	26.5	u
0.10	561.9	s	456	s	254.4	t
0.15	1279	op	962.9	qr	541.8	s
0.20	2011.5	ef	1322.8	klmno	814.1	r
0.25	2596.5	bc	1495.7	hijklm	1026	pq
0.30	2927.2	ab	1529.1	hijk	1181.6	op
0.35	3017.9	a	1524.2	hijk	1341	jklmno
0.40	2916.4	ab	1500.4	hijkl	1386.2	ijklmno
0.45	2734.3	abc	1447.8	hijklmn	1348.1	ijklmno
0.50	2456.5	cd	1375.6	ijklmno	1292.2	klmno
0.55	2214.3	de	1292.5	klmno	1279.5	klmno
0.60	2003	ef	1251.5	lmno	1265.7	klmno
0.65	1822.8	fg	1229.7	lmnop	1217	mnop
0.70	1703.6	fgh	1230.9	lmnop	1210.3	nop
0.75	1618.8	ghi	1216.4	mnop	1234.1	lmnop
0.80	1597.4	hij	1237.2	lmno	1235.7	mnop

[†]   Treatments with different letters are significantly different ($p<0.05$).

C.   Mean PSS$_1$ (kPa) values in under different residue management at Rattray.

Depth (m)	Broadcast Mean PSS$_0$	LSD[†]	Windrow Mean PSS$_0$	LSD[†]	Removed Mean PSS$_0$	LSD[†]
0.05	29.4	p	32.6	p	64.9	p
0.10	375.8	o	393	no	503.4	n
0.15	833.7	m	924	lm	1026	kl
0.20	1251.7	jk	1413.6	ij	1483.1	ghij
0.25	1589.5	defghi	1724.6	bcdefgh	1804.1	abcde
0.30	1806.5	abcde	1866.7	abcde	1964.7	ab
0.35	1950.4	ab	1927.6	ab	2005.1	a
0.40	1936.5	ab	1913.3	abc	1953.2	ab
0.45	1849.5	abcd	1815.2	abcde	1865.5	abcd
0.50	1747.4	abcdef	1675.2	bcdefg	1701.7	abcdef
0.55	1650.1	bcdefg	1556.6	defghi	1579.7	cdefghi
0.60	1542.3	defghi	1502.7	efghi	1475.2	fghi
0.65	1414.9	ghij	1453.4	fghi	1401.2	ghij
0.70	1366.5	ghij	1409.2	ghij	1369.2	ghij
0.75	1328.3	ij	1385.7	ghij	1355.3	hij
0.80	1329.3	ij	1379.5	ghij	1361.5	hij

[†]   Treatments with different letters are significantly different ($p<0.05$).

Appendix 4.5. Statistical analyses of treatment effects on PSS_1 at Rattray.

A. Summary of ANOVA levels of significance of treatment effects on PSS_1 averaged every 0.05 m down the soil profile at Rattray. Blocking factor-position of measurement, i.e. interrow or stumpline.

Depth (m)	Compaction	Residue	Compaction x residue
0.05	0.071	0.006	0.227
0.10	<0.001	0.127	0.750
0.15	<0.001	0.245	0.503
0.20	<0.001	0.221	0.421
0.25	<0.001	0.303	0.646
0.30	<0.001	0.567	0.797
0.35	<0.001	0.885	0.980
0.40	<0.001	0.972	0.945
0.45	<0.001	0.948	0.772
0.50	<0.001	0.882	0.749
0.55	<0.001	0.715	0.735
0.60	<0.001	0.774	0.634
0.65	<0.001	0.801	0.307
0.70	<0.001	0.818	0.354
0.75	<0.001	0.745	0.526
0.80	<0.001	0.795	0.692

B. ANOVA of the effect of compaction treatments and residue management on penetrometer soil strength at 0.05 m after treatment implementation at Rattray. Blocking factor- position of measurement, i.e. interrow or stumpline.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
IR/SL	1	721	721	0.60	
Compaction	2	6790	3395	2.81	0.071
Residue	2	13880	6940	5.75	0.006
Compaction x residue	4	7109	1777	1.47	0.227
Residual	44	53085	1206		
Total	53	81585			

C.   Residue management effects on PSS_1 (kPa) at 0.05 m at Rattray.

Residue management	Mean PSS_1 (kPa)
Removed	64.9[a]
Windrowed	32.4[b]
Broadcast	29.4[b]

[a]   Treatments with different letters are significantly different ($p<0.05$).

D.   ANOVA of the effect of C_M and C_H treatments and residue management on PSS_1 relative to that measured under C_L treatments to a soil depth of 0.3 m at Rattray. Blocking factor- soil depth.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Depth	5	10806	2161	0.32	
Compaction	1	237751	237751	35.21	<0.001
Residue	2	108377	54.189	8.03	<0.001
Compaction x residue	2	30325	15163	2.25	0.108
Residual	205	1384176	6752		
Total	215	1771435			

Appendix 4.6. Statistical analyses of treatment effects on mean PSS$_0$ at Shafton.

A. ANOVA of the effect of compaction treatments (Comp), plot position (interrow and stumpline; IR/SL) and soil depth of measurement on PSS$_0$ at Shafton. Blocking factor: replicate (Rep), whole plots: treatment (i.e. compaction x residue; trt); covariate: soil water content.

Source of variation	df	s.s.	m.s.	v.r.	cov.ef.	F pr.
Rep stratum						
Covariate	1	1212	1212	3.56		0.310
Residual	1	341	341	1.60	2.28	
Rep x trt stratum						
Comp	2	754	377	1.77	0.95	0.195
Covariate	1	657	657	3.09		0.094
Residual	21	4471	213	2.14	1.09	
Rep x trt x IR/SL stratum						
IR/SL	1	417	417	4.20	0.93	0.052
IR/SL x com	2	496	248	2.49	0.92	0.105
Covariate	1	170	170	1.71		0.204
Residual	23	2286	99	6.02	1.03	
Rep x trt x IR/SL x depth stratum						
Depth	16	72367	4523	274.06	0.43	<.001
IR/SL x depth	16	298	19	1.13	1.00	0.323
Depth x comp	32	1119	35	2.12	1.00	<.001
IR/SL x depth x comp	32	864	27	1.64	1.00	0.016
Covariate	1	0	0	0.00		0.989
Residual	711 (56)	11734	17		1.00	
Total	861 (56)	220351				

B.   Mean PSS_0 values (kPa) in different compaction treatments and plot positions (IR = interrow; SL = stumpline) at Shafton.

Depth (m)	IR/ SL	High PSS_0	High LSD[†]	Moderate PSS_0	Moderate LSD[†]	Low PSS_0	Low LSD[†]
0.05	IR	315	D	246	D	338	D
0.10	IR	2032	vwxyz	1308	C	1512	ABC
0.15	IR	2633	fghijklmnopqrst	1866	yzA	2159	uvwxyz
0.20	IR	2827	abcdefghijklmnopq	2199	tuvwxyz	2406	qrstuvwx
0.25	IR	3009	abcdefghijklm	2406	qrstuvwx	2614	hijklmnopqrstu
0.30	IR	3139	abcdef	2728	efghijklmnopqrs	2838	cdefghijklmnopqr
0.35	IR	3366	ab	3023	abcdefghijklmno	3003	abcdefghijklmn
0.40	IR	3286	abc	3216	abcdefghi	3129	abcdefghij
0.45	IR	2984	abcdefghijklmn	2914	defghijklmnopqr	3032	abcdefghijklm
0.50	IR	3068	abcdefghij	2648	jklmnopqrstu	3016	abcdefghijklm
0.55	IR	3049	abcdefghijkl	2550	mnopqrstuv	2963	abcdefghijklmn
0.60	IR	2969	abcdefghijklmn	2660	ghijklmnopqrstu	2902	abcdefghijklmnop
0.65	IR	3115	abcdefghij	2846	cdefghijklmnopqr	2892	abcdefghijklmnopq
0.70	IR	2898	abcdefghijklmnopq	2786	defghijklmnopqrs	2981	abcdefghijklmn
0.75	IR	2965	abcdefghijklmn	2837	cdefghijklmnopqr	3134	abcdefg
0.80	IR	3099	abcdefghij	2912	bcdefghijklmnopqr	3195	abcde
0.05	SL	314	D	243	D	334	D
0.10	SL	1402	BC	1349	C	1451	BC
0.15	SL	1842	yzA	2031	xyz	1836	zAB
0.20	SL	2205	stuvwxy	2426	pqrstuvwx	2105	wxyz
0.25	SL	2521	klmnopqrstu	2637	ijklmnopqrstu	2417	rstuvwx
0.30	SL	2834	abcdefghijklmnopq	3070	abcdefghijklm	2723	fghijklmnopqrstu
0.35	SL	2840	abcdefghijklmnopq	3273	abcdefgh	3009	abcdefghijklmnop
0.40	SL	2848	abcdefghijklmnopq	3447	a	3224	abcdef
0.45	SL	2686	defghijklmnopqrs	3281	abcde	3200	abcdefghi
0.50	SL	2591	fghijklmnopqrstu	3008	abcdefghijklmno	3017	abcdefghijklmn
0.55	SL	2670	efghijklmnopqrs	2606	klmnopqrstu	2879	cdefghijklmnopqr
0.60	SL	2691	defghijklmnopqrs	2488	opqrstuvwx	2850	cdefghijklmnopqr
0.65	SL	2783	cdefghijklmnopqr	2548	nopqrstuvw	2795	defghijklmnopqrs
0.70	SL	2828	abcdefghijklmnopq	2399	rstuvwx	3077	abcdefghijklmn
0.75	SL	2912	abcdefghijklmno	2580	mnopqrstuv	3146	abcdefghijk
0.80	SL	3076	abcdefghij	2607	lmnopqrstuv	3347	abcd

[†]   Treatments with different letters or status (capitals vs not capitals) are significantly different ($p<0.05$).

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Appendix 4.7. Statistical analyses of treatment effects on mean PSS$_1$ at Shafton.

A.   ANOVA of the effect of compaction treatments (Comp), residue management, plot position (interrow and stumpline; IR/SL) and soil depth of measurement on PSS$_1$ at Shafton. Blocking factor: replicate (Rep), whole plots: treatment (i.e. compaction x residue; trt); covariate PSS$_0$.

Source of variation	df	s.s.	m.s.	v.r.	cov.ef.	F pr.
Rep stratum						
Covariate	1	0.059	0.059	0.87		0.522
Residual	1	0.068	0.068	0.59	0.93	
Rep x trt stratum						
Comp	2	1.084	0.542	4.63	1.00	0.027
Residue	2	0.098	0.049	0.42	0.95	0.666
Comp x residue	4	0.852	0.213	1.82	0.95	0.177
Covariate	1	0.180	0.180	1.54		0.234
Residual	15	1.755	0.117	1.13	1.03	
Rep x trt x IR/SL stratum						
IR/SL	1	0.110	0.110	1.06	0.68	0.317
IR/SL x comp	2	0.595	0.298	2.89	0.64	0.083
IR/SL x residue	2	0.124	0.062	0.60	0.90	0.559
IR/SL x comp x residue	4	0.265	0.066	0.64	0.99	0.639
Covariate	1	0.022	0.022	0.22		0.647
Residual	17	1.753	0.103	9.64	0.96	
Rep x trt x IR/SL x depth stratum						
Depth	16	109.140	6.821	637.85	0.45	<0.001
IR/SL x depth	16	0.968	0.060	5.66	0.96	<0.001
Depth x comp	32	4.770	0.149	13.94	0.96	<0.001
Depth x residue	31 (1)	2.498	0.081	7.53	0.98	<0.001
IR/SL x depth x comp	25 (7)	0.679	0.027	2.54	0.99	<0.001
IR/SL x depth x residue	31 (1)	0.687	0.022	2.07	0.99	0.001
Depth x comp x residue	46 (18)	1.228	0.027	2.50	0.99	<0.001
IR/SL x depth x comp x residue	27 (37)	0.307	0.011	1.06	0.99	0.383
Covariate	1	0.030	0.030	2.77		0.097
Residual	286 (289)	3.059	0.011		1.01	
Total	564 (353)					

B.   Mean PSS_1 values (kPa) in different compaction treatments (C_L = low; C_M = moderate; C_H = high) and residue management at Shafton.

Depth (m)	Comp	Broadcast PSS_1	Broadcast $LSD^{\dagger}$	Windrow PSS_1	Windrow $LSD^{\dagger}$	Removed PSS_1	Removed $LSD^{\dagger}$
0.05	C_H	109	P	210	O	307	N
0.10	C_H	1124	JKL	1490	HIJK	1540	HIJK
0.15	C_H	1906	EFGHI	2430	ABCDEF	2385	ABCDEF
0.20	C_H	2717	uvwxyzABCDEF	3225	qrstuvwxyzAB	3217	pqrstuvwxyzAB
0.25	C_H	3399	mnopqrstuvwxyzAB	3733	jklmnopqrstuvwxy	4056	hijklmnopqrst
0.30	C_H	3606	lmnopqrstuvwxyz	4017	hijklmnopqrstuvw	3466	qrstuvwxyzAB
0.35	C_H	3484	pqrstuvwxyzAB	4396	fghijklmnopqr	4087	jklmnopqrstuvwxy
0.40	C_H	2898	yzABCDEF	4309	fghijklmnopqrs	4185	ijklmnopqrstuvwx
0.45	C_H	3094	stuvwxyzABCD	4315	fghijklmnopq	3578	rstuvwxyzABC
0.50	C_H	3468	nopqrstuvwxyzAB	4534	defghijklmn	2598	EFGHI
0.55	C_H	3820	jklmnopqrstuvwxyz	4854	cdefghij	2434	CDEFGH
0.60	C_H	4140	ghijklmnopqrst	4850	fghijklmnopq	3493	lmnopqrstuvwxyzAB
0.65	C_H	4571	fghijklmnopqr	4772	cdefghi	3756	jklmnopqrstuvwx
0.70	C_H	4847	defghijklmnopq	5743	bc	4112	fghijklmnopqrs
0.75	C_H	5072	defghijklm	5381	cdefgh	4523	defghijklmnopq
0.80	C_H	5407	cdefg	6059	bc	5350	bcde
0.05	C_M	85	PQ	119	P	282	NO
0.10	C_M	1087	KL	1066	JKL	1446	IJK
0.15	C_M	1857	FGHI	1795	EFGHI	2116	DEFGHI
0.20	C_M	2612	xyzABCDEF	2634	tuvwxyzABCDE	2727	vwxyzABCDEF
0.25	C_M	3569	lmnopqrstuvwxyzA	3514	jklmnopqrstuvwxyz	3347	opqrstuvwxyzAB
0.30	C_M	4202	ghijklmnopqrs	3616	jklmnopqrstuvwxyz	4019	hijklmnopqrstuv
0.35	C_M	4140	jklmnopqrstuvwxyz	3984	hijklmnopqrstu	4236	ghijklmnopqrs
0.40	C_M	4334	jklmnopqrstuvwx	4401	fghijklmnopqr	4456	ghijklmnopqrs
0.45	C_M	4900	defghijkl	3542	mnopqrstuvwxyzAB	4604	fghijklmnopqr
0.50	C_M	6708	defghijklmnop	3878	hijklmnopqrstu	5869	bc
0.55	C_M	2930	BCDEFG	3292	nopqrstuvwxyzAB	2291	BCDEFGH
0.60	C_M	3944	ijklmnopqrstuvw	3907	fghijklmnopqr	3677	fghijklmnopqrs

Appendix 4.7B (continued)

Depth (m)	Comp	Broadcast PSS$_1$	LSD[†]	Windrow PSS$_1$		Removed PSS$_1$	
0.65	C$_M$	4362	ghijklmnopqrs	3871	ghijklmnopqrs	3923	hijklmnopqrstu
0.70	C$_M$	4434	fghijklmnopqr	4484	defghijkl	3768	fghijklmnopqrs
0.75	C$_M$	6077	abc	5332	bcd	5183	bc
0.80	C$_M$	6296	ab	5973	a	6071	a
0.05	C$_L$	62	Q	34	R	105	P
0.10	C$_L$	861	L	501	M	799	L
0.15	C$_L$	1809	GHIJ	902	L	1472	IJK
0.20	C$_L$	2759	zABCDEF	1582	GHIJ	2076	DEFGHI
0.25	C$_L$	3484	opqrstuvwxyzAB	2585	vwxyzABCDEF	2710	wxyzABCDEF
0.30	C$_L$	3991	ghijklmnopqrst	3010	rstuvwxyzABC	3371	qrstuvwxyzAB
0.35	C$_L$	4346	fghijklmnopqr	3660	jklmnopqrstuvwx	3782	klmnopqrstuvwxyz
0.40	C$_L$	4547	defghijklmnopq	4253	fghijklmnopqrs	3863	jklmnopqrstuvwxyz
0.45	C$_L$	4962	defghijkl	4317	fghijklmnopqr	3995	ijklmnopqrstuvw
0.50	C$_L$	3668	jklmnopqrstuvwxy	4316	defghijklmno	4040	hijklmnopqrstuvw
0.55	C$_L$	3974	jklmnopqrstuvwxy	4607	cdefghijk	4065	ghijklmnopqrs
0.60	C$_L$	3870	lmnopqrstuvwxyzAB	4026	fghijklmnopqrs	3988	hijklmnopqrstu
0.65	C$_L$	4393	defghijklm	4140	fghijklmnopqrs	4334	fghijklmnopqr
0.70	C$_L$	4561	defghijk	4699	defghijklmn	3969	ghijklmnopqrs
0.75	C$_L$	5334	bcdef	4477	fghijklmnopqrs	4100	fghijklmnopqr
0.80	C$_L$	4554	efghijklmnopq	4227	jklmnopqrstuvwxyz	4174	fghijklmnopqr

[†]   Treatments with different letters or status (capitals vs not capitals) are significantly different ($p<0.05$).

Appendix 4.8. Statistical analyses of treatment effects on PSS_1 at Shafton.

A. Summary of ANOVA levels of significance of treatment effects on PSS averaged every 0.05 m down the soil profile at Shafton. Blocking factor- position of measurement, i.e. interrow or stumpline.

Depth (m)	Compaction	Residue	Compaction x residue
0.05	<0.001	<0.001	0.034
0.10	<0.001	0.031	0.057
0.15	<0.001	0.218	0.014
0.20	<0.001	0.494	0.018
0.25	<0.001	0.618	0.058
0.30	<0.001	0.352	0.248
0.35	<0.001	0.924	0.578
0.40	<0.001	0.233	0.286
0.45	<0.001	0.607	0.112

B. ANOVA of the effect of compaction treatments and residue management on PSS_1 at 0.05 m at Shafton. Blocking factor- position of measurement, i.e. interrow or stumpline.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
IR/SL	1	673	673	0.13	
Compaction	2	186834	93417	18.60	<0.001
Residue	2	207446	103723	20.65	<0.001
Compaction x residue	4	57682	14421	2.87	0.034
Residual	44	221046	5024		
Total	53	673681			

C. The combined effect of compaction treatments and residue management on PSS_1 at 0.05 m at Shafton.

Compaction	Residue Management	Mean PSS_1 (kPa)
High	Removed	306.5^a
Moderate	Removed	281.5^{ab}
High	Windrowed	210.3^b
Moderate	Windrowed	119.1^c
High	Broadcast	109.0^{cd}
Low	Removed	105.0^{cd}
Moderate	Broadcast	84.6^{cd}
Low	Broadcast	62.4^{cd}
Low	Windrowed	34.1^d

[a] Treatments with different letters are significantly different ($p<0.05$).

D. ANOVA of the effect of C_M and C_H treatments and residue management on PSS_1 relative to that measured under C_L treatments to a soil depth of 0.25 m at Shafton. Blocking factor - soil depth; data was square root transformed to prevent violation of normality assumptions.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Depth	4	7.977	1.994	20.90	
Compaction	1	1.046	1.046	10.96	0.001
Residue	2	3.601	1.800	18.87	<0.001
Compaction x residue	2	0.403	0.202	2.11	0.124
Residual	170	16.218	0.095		
Total	179	29.245			

Appendix 5.1. Responses obtained on selected soil properties of the effect of broadcast residues compared to residue removal at studies in the Congo (Nzila *et al.*, 2004; Deleporte *et al.*, 2008) and Karkloof (du Toit *et al.*, 2008).

Soil property	Study	Soil depth (m)	Response
pH	Karkloof	0-0.1	No significant difference between treatments but pH increased in all treatments until 2 years after harvest, then decreased to initial levels.
Total N	Congo	0-0.1	Significantly higher N in B than R plots one year into the study, thereafter no significant difference, but N decreased in R plots in the first 3 years of the study.
	Congo	0.1-1.0	No significant differences.
	Karkloof	0-0.1	No significant difference between treatments but N increased in all treatments and this was maintained until rotation end.
Available P	Karkloof	0-0.1	No significant difference between treatments but P initially increased in all treatments and then declined to levels below that measured at the start of the study.
Exch K	Congo	0-0.1	No significant differences.
	Congo	0.1-1.0	No significant differences.
	Karkloof	0-0.1	No significant difference between treatments but K was higher in B than R plots.
Exch Ca	Congo	0-0.1	No significant differences.
	Congo	0.1-1.0	No significant differences.
	Karkloof	0-0.1	Significantly higher Ca in B than R plots at rotation end. Overall increase in Ca in all treatments from the start to the end of the study.
Exch Mg	Congo	0-0.1	Significantly higher Mg in B than R plots at rotation end.
	Congo	0.1-1.0	No significant differences.
	Karkloof	0-0.1	No significant difference between treatments or from the start to the end of the study.

Note: soil pH and available P were not measured in the Congolese study.

Appendix 5.2. **Statistical analyses of changes in quantities of residues between TP and TH within broadcast or windrow residue management at Shafton.**

A. ANOVA of the effect of compaction treatments and residue management on the total quantity of residues at TP at Shafton.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	11.867	5.934	8.55	0.005
Residue Management	1	26.478	26.478	38.14	<0.001
Compaction x Residue	2	0.566	0.283	0.41	0.674
Residual	12	8.333	0.694		
Total	17	47.242			

B. ANOVA of the effect of compaction treatments and residue management on the total quantity of residues at TH at Shafton.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	6.014	3.007	3.55	0.062
Residue Management	1	8.075	8.075	9.53	0.009
Compaction x Residue	2	0.464	0.232	0.27	0.765
Residual	12	10.169	0.847		
Total	17	24.721			

C. ANOVA of changes in the total quantity of residue between TP and TH within broadcast residue management at Shafton.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time	1	16022248	16022248	11.02	0.004
Residual	16	23269831	1454364		
Total	17	39292078			

D. ANOVA of changes in the total quantity of residue between TP and TH within windrow residue management at Shafton.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time	1	2885572	2885572	3.27	0.090
Residual	16	14140053	883753		
Total	17	17025624			

Appendix 5.3. Statistical analyses of treatment effects on soil carbon at Rattray.

A. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0 and 0.05 m at harvesting of sub-plot trees (TH) at Rattray. Blocking factor- position of measurement, i.e. interrow or stumpline (IR/SL).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
IR/SL	1	0.007	0.007	0.01	
Compaction	2	10.975	5.487	4.16	0.022
Residue	2	1.039	0.519	0.39	0.677
Compaction x residue	4	2.773	0.693	0.53	0.718
Residual	44	58.079	1.320		
Total	53	72.872			

B. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.05 and 0.15 m at TH at Rattray. Blocking factor- position of measurement, i.e. interrow or stumpline (IR/SL).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
IR/SL	1	0.054	0.054	0.95	
Compaction	2	0.020	0.010	0.18	0.835
Residue	2	0.244	0.122	2.16	0.128
Compaction x residue	4	0.284	0.071	1.25	0.302
Residual	44	2.488	0.057		
Total	53	3.090			

C. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.15 and 0.60 m at TH at Rattray.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.001	0.000	0.28	0.761
Residue	2	0.002	0.001	0.52	0.606
Compaction x residue	4	0.002	0.001	0.33	0.854
Residual	18	0.031	0.002		
Total	26	0.036			

D. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0 and 0.05 m at TF at Rattray.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.000	0.000	0.00	1.000
Residue	2	0.198	0.099	0.99	0.389
Compaction x residue	4	0.288	0.072	0.72	0.587
Residual	18	1.794	0.010		
Total	26	2.280			

E. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.05 and 0.15 m at TF at Rattray.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.044	0.022	1.32	0.292
Residue	2	0.001	0.001	0.04	0.961
Compaction x residue	4	0.030	0.008	0.45	0.768
Residual	18	0.301	0.017		
Total	26	0.377			

F. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.15 and 0.60 m at TF at Rattray.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.006	0.003	0.53	0.599
Residue	2	0.014	0.007	1.20	0.324
Compaction x residue	4	0.033	0.008	1.40	0.274
Residual	18	0.106	0.006		
Total	26	0.160			

Appendix 5.4. Statistical analyses of treatment effects on soil carbon at Shafton.

A. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0 and 0.05 m at harvesting of sub-plot trees (TH) at Shafton. Blocking factor- position of measurement, i.e. interrow or stumpline (IR/SL).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
IR/SL	1	22.597	22.597	3.69	
Compaction	2	15.246	7.623	1.24	0.298
Residue	2	96.073	48.037	7.84	0.001
Compaction x residue	4	31.558	7.889	1.29	0.289
Residual	44	269.497	6.125		
Total	53	434.971			

B. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.05 and 0.15 m at TH at Shafton. Blocking factor- position of measurement, i.e. interrow or stumpline (IR/SL).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
IR/SL	1	0.011	0.011	0.19	
Compaction	2	0.198	0.099	1.74	0.187
Residue	2	0.081	0.041	0.72	0.494
Compaction x residue	4	0.167	0.042	0.74	0.572
Residual	44	2.501	0.057		
Total	53	2.959			

C. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.15 and 0.60 m at TH at Shafton.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.163	0.081	0.72	0.500
Residue	2	0.023	0.012	0.10	0.904
Compaction x residue	4	0.828	0.207	1.83	0.166
Residual	18	2.030	0.113		
Total	26	3.044			

D. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0 and 0.05 m at TF at Shafton.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	9.664	4.832	1.53	0.243
Residue	2	4.560	2.280	0.72	0.499
Compaction x residue	4	17.822	4.456	1.41	0.270
Residual	18	56.820	3.157		
Total	26	88.866			

E. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.05 and 0.15 m at TF at Shafton.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.438	0.219	0.76	0.482
Residue	2	0.256	0.128	0.44	0.648
Compaction x residue	4	0.757	0.189	0.66	0.630
Residual	18	5.186	0.288		
Total	26	6.637			

F. ANOVA of the effect of compaction treatments and residue management on soil carbon between 0.15 and 0.6 m at TF at Shafton.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.168	0.084	0.23	0.796
Residue	2	0.000	0.000	0.00	0.999
Compaction x residue	4	0.660	0.165	0.45	0.768
Residual	18	6.540	0.363		
Total	26	7.368			

Appendix 5.5. Significant statistical analyses of treatment effects on soil pH and exchangeable soil Ca and Mg at TF at Rattray.

A.   ANOVA of the effect of compaction treatments and residue management on soil pH between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.335	0.168	0.68	0.521
Residue	2	3.822	1.911	7.71	0.004
Compaction x residue	4	0.797	0.199	0.8	0.539
Residual	18	4.464	0.248		
Total	26	9.418			

B.   ANOVA of the effect of compaction treatments and residue management on soil pH between 0.05 and 0.15 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.399	0.199	2.02	0.162
Residue	2	3.226	1.613	16.31	<0.001
Compaction x residue	4	0.701	0.175	1.77	0.179
Residual	18	1.780	0.099		
Total	26	6.105			

C.   ANOVA of the effect of compaction treatments and residue management on soil pH between 0.15 and 0.6 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.890	0.445	2.99	0.076
Residue	2	1.804	0.902	6.06	0.010
Compaction x residue	4	0.805	0.201	1.35	0.290
Residual	18	2.680	0.149		
Total	26	6.179			

D.   ANOVA of the effect of compaction treatments and residue management on soil pH between 0 and 0.6 m (weighted average).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.581	0.290	2.46	0.114
Residue	2	2.087	1.044	8.84	0.002
Compaction x residue	4	0.424	0.106	0.9	0.486
Residual	18	2.124	0.118		
Total	26	5.216			

E.   ANOVA of the effect of compaction treatments and residue management on soil exchangeable Ca (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.675	0.337	1.21	0.321
Residue	2	3.972	1.986	7.14	0.005
Compaction x residue	4	1.434	0.359	1.29	0.311
Residual	18	5.007	0.278		
Total	26	11.088			

Data natural log transformed to prevent violation of error assumptions.

F.   ANOVA of the effect of compaction treatments and residue management on soil exchangeable Ca (kg ha^{-1}) between 0 and 0.6 m (weighted average).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.073	0.036	2.36	0.123
Residue	2	0.137	0.068	4.46	0.027
Compaction x residue	4	0.020	0.005	0.33	0.856
Residual	18	0.276	0.015		
Total	26	0.506			

Data log transformed to prevent violation of error assumptions.

G.   ANOVA of the effect of compaction treatments and residue management on soil exchangeable Mg (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.042	0.021	0.46	0.636
Residue	2	0.435	0.218	4.85	0.021
Compaction x residue	4	0.227	0.057	1.26	0.320
Residual	18	0.807	0.045		
Total	26	1.511			

Data log transformed to prevent violation of error assumptions.

Appendix 5.6. Average residue nutrient quantities showing significant residue management effects at TP, TH and TF at Rattray.

A. Significance (*p* values) of ANOVA results of the effect of compaction treatments and residue management (broadcast and windrow) on quantity of nutrients held in residues at TP, TH and TF.

Nutrient	Compaction	Residue	Compaction x residue
		TP	
P	0.203	0.025	0.820
K	0.177	0.007	0.555
		TH	
N	0.968	0.031	0.325
		TF	
N	0.577	0.023	0.461
P	0.862	0.001	0.731

B. Average quantities of macronutrients held in broadcast and windrowed residues at Rattray at TP, TH and TF.

Residue management	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
			TP		
Broadcast	183.4	15.4	107.2	580.8	57.3
Windrowed	138.9	11.4	45.7	542.2	53.3
			TH		
Broadcast	162.9	13.5	54.1	391.3	40.8
Windrowed	120.6	8.3	37.1	357.8	32.3
			TF		
Broadcast	5.0	3.8E-05	0.3	10.6	0.9
Windrowed	2.9	2.0E-05	0.2	6.0	0.5

Appendix 5.7. Significant statistical analyses of treatment effects on soil pH at TH at Shafton.

A. ANOVA of the effect of compaction treatments and residue management on soil pH between 0 and 0.05 m at Shafton at TH.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.200	0.100	2.75	0.091
Residue	2	0.262	0.131	3.60	0.048
Compaction x residue	4	0.141	0.035	0.97	0.448
Residual	18	0.655	0.036		
Total	26	1.258			

Appendix 5.8. Significant statistical analyses of treatment effects on macronutrients at TH at Shafton.

A.   ANOVA of the effect of compaction treatments and residue management on total soil N (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	619103	309551	3.78	0.043
Residue	2	633746	316873	3.87	0.040
Compaction x residue	4	284621	71155	0.87	0.502
Residual	18	1475265	81959		
Total	26	3012735			

B.   ANOVA of the effect of compaction treatments and residue management on available soil P (kg ha^{-1}, Bray-2) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	21.260	10.630	4.87	0.020
Residue	2	25.964	12.982	5.94	0.010
Compaction x residue	4	4.999	1.250	0.57	0.686
Residual	18	39.307	2.184		
Total	26	91.529			

C.   ANOVA of the effect of compaction treatments and residue management on available soil P (kg ha^{-1}, Bray-2) contained in residues and soil between 0 and 0.6 m (weighted average).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	609.95	304.97	6.18	0.009
Residue	2	1431.09	715.54	14.50	<0.001
Compaction x residue	4	35.45	8.86	0.18	0.946
Residual	18	888.05	49.34		
Total	26	2964.54			

D.   ANOVA of the effect of compaction treatments and residue management on soil exchangeable K (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	160.7	80.4	0.46	0.640
Residue	2	2577.9	1288.9	7.35	0.005
Compaction x residue	4	1067.6	266.9	1.52	0.238
Residual	18	3156.9	175.4		
Total	26	6963.1			

E.   ANOVA of the effect of compaction treatments and residue management on K (kg ha^{-1}) contained in residues and soil (exchangeable K) between 0 and 0.6 m (weighted average).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	19340	9670	0.76	0.481
Residue	2	108627	54313	4.28	0.030
Compaction x residue	4	44398	11100	0.88	0.498
Residual	18	228166	12676		
Total	26	400531			

F.   ANOVA of the effect of compaction treatments and residue management on soil exchangeable Ca (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	316463	158232	3.01	0.075
Residue	2	430999	215500	4.10	0.034
Compaction x residue	4	230256	57564	1.09	0.389
Residual	18	946492	52583		
Total	26	1924211			

G.   ANOVA of the effect of compaction treatments and residue management on Ca (kg ha^{-1}) contained in residues and soil (exchangeable Ca) between 0 and 0.6 m (weighted average).

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	929298	464649	2.45	0.114
Residue	2	3587306	1793653	9.47	0.002
Compaction x residue	4	483715	120929	0.64	0.642
Residual	18	3407692	189316		
Total	26	2964.54			

H.   ANOVA of the effect of compaction treatments and residue management on soil exchangeable Mg (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	4036.1	2018.1	2.35	0.123
Residue	2	12262.5	6131.2	7.15	0.005
Compaction x residue	4	6049.2	1512.3	1.76	0.180
Residual	18	15425.9	857.0		
Total	26	37773.7			

Appendix 5.9. Significant statistical analyses of treatment effects on soil macronutrients at TF at Shafton.

A. ANOVA of the effect of compaction treatments and residue management on total soil N (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	942868	471434	3.75	0.044
Residue	2	300863	150432	1.20	0.326
Compaction x residue	4	1720244	430061	3.42	0.030
Residual	18	2265403	125856		
Total	26	5229379			

Data log transformed to prevent violation of error assumptions.

B. The combined effect of compaction treatments and residue management on total soil N (kg ha^{-1}) between 0 and 0.05 m.

Compaction	Residue Management	Mean total soil N (kg ha^{-1})
Low	Broadcast	2254[a]
Low	Removed	2052[ab]
Moderate	Removed	1699[abc]
High	Windrowed	1666[abc]
High	Removed	1501[bc]
Moderate	Windrowed	1499[bc]
Moderate	Broadcast	1381[c]
Low	Windrowed	1315[c]
High	Broadcast	1159[c]

[a] Treatments with different letters are significantly different ($p<0.05$).

C. ANOVA of the effect of compaction treatments and residue management on soil exchangeable K (kg ha^{-1}) between 0 and 0.05 m.

Source of variation	df	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.188	0.094	0.66	0.531
Residue	2	1.229	0.614	4.30	0.030
Compaction x residue	4	0.462	0.115	0.81	0.537
Residual	18	2.573	0.143		
Total	26	4.451			

Data log transformed to prevent violation of error assumptions.

Appendix 5.10. Summary of significant statistical analyses of treatment effects on residue nutrient quantities at TP, TH and TF at Shafton.

A. Significance (*p* values) of ANOVA results of the effect of compaction treatments and residue management (broadcast and windrow) on quantity of nutrients (kg ha^{-1}) held in residues at Shafton at TP and TH.

Nutrient	Compaction	Residue	Compaction x residue
		TP	
N	0.086	0.047	0.738
P	0.094	<0.001	0.139
K	0.005	<0.001	0.694
Ca	0.443	0.156	0.030
Mg	0.093	0.003	0.252
		TH	
N	0.017	0.855	0.271
P	0.002	0.014	0.583
K	0.009	0.004	0.109
Ca	0.008	0.021	0.613
Mg	0.005	0.073	0.769

B. Significance (*p* values) of ANOVA results of the effect of compaction treatments and residue management (broadcast, windrow and residue removed) on quantity of nutrients (kg ha^{-1}) held in residues at Shafton (TH).

Nutrient	Compaction	Residue	Compaction x residue
N	0.17	<0.001	0.772
P	0.113	0.005	0.699
Ca	0.208	0.004	0.209
Mg	0.413	0.043	0.680

C.　　Average quantities of macronutrients held in broadcast and windrowed residues at TP and TH at Shafton. In addition, macronutrient quantities in burnt residue+litter samples taken at TF are given (including residue removed plots).

Residue management	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
TP					
Broadcast	317.8	22.9	68.6	609.1	120.1
Windrowed	228.3	11.5	29.5	455.0	84.9
TH					
Broadcast	273.5	14.8	31.5	528.3	46.0
Windrowed	220.7	10.5	19.4	442.8	35.8
TF					
Broadcast	3.6	7.0E-06	0.2	4.0	0.4
Windrowed	3.4	6.1E-06	0.2	3.9	0.4
Removed	2.6	2.4E-06	0.2	2.0	0.3

Appendix 6.1. Standard error values of regression equations between soil bulk density and soil carbon (combined) on mass soil water content (θ_m) at Rattray.

A. Standard error values of regression equations displayed in **Table 6.2** of the effects of ranges of bulk density (BD) and soil carbon (C), as grouped in **Table 6.1**, on mass soil water content (of undisturbed soil cores) at Rattray.

Parameter	BD	C	BD,C
b	0.011	0.011	0.010
m	0.089	0.088	0.083

B. Standard error values of regression equations displayed in **Table 6.3** of the effect of bulk density and soil carbon on soil water content (θ_m) of 0 – 0.2 and 0.4 – 0.5 m undisturbed soil cores at various matric potentials (Ψm) at Rattray.

Ψm (kPa)	Parameter	estimate	s.e.	t(54)	t pr.
			BD		
0	Constant	0.875	0.031	28.01	<0.001
	x	-0.382	0.020	-19.26	<0.001
-1	Constant	0.814	0.033	24.43	<0.001
	x	-0.357	0.021	-16.91	<0.001
-2	Constant	0.764	0.042	18.33	<0.001
	x	-0.333	0.026	-12.6	<0.001
			C		
0	Constant	0.228	0.007	34.72	<0.001
	x	0.043	0.005	7.99	<0.001
-1	Constant	0.205	0.006	33.87	<0.001
	x	0.042	0.005	8.49	<0.001
-2	Constant	0.193	0.006	33.83	<0.001
	x	0.044	0.005	9.35	<0.001
-3	Constant	0.188	0.005	40.4	<0.001
	x	0.031	0.004	8.23	<0.001
-1500	Constant	0.006	0.001	7.98	<0.001
	x	0.007	0.001	11.71	<0.001

Appendix 6.2. Soil bulk density and soil carbon effects (combined) on volumetric soil water content (θv) at Rattray.

A. The effect on soil water content (θ_v) of ranges of (a) bulk density and (b) soil carbon (C; % m/m) at Rattray (of undisturbed soil cores between 0 and 0.5 m).
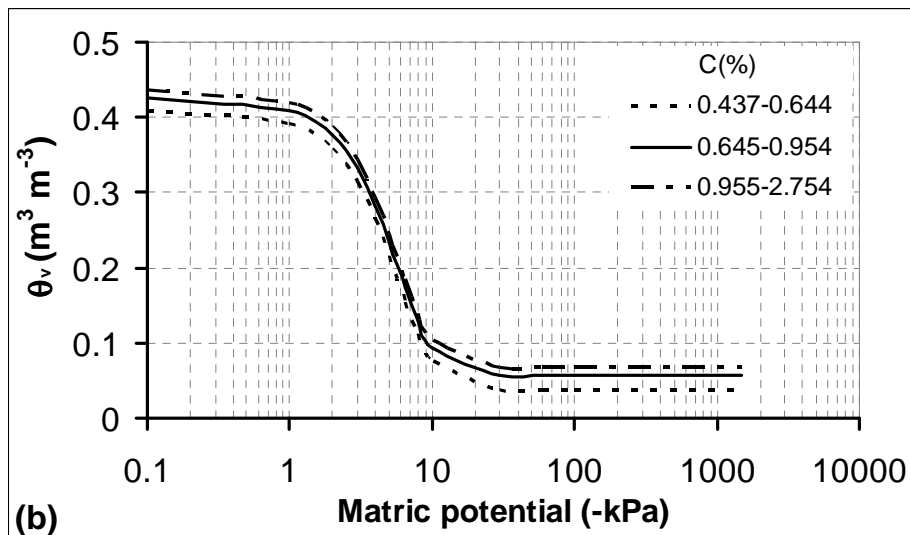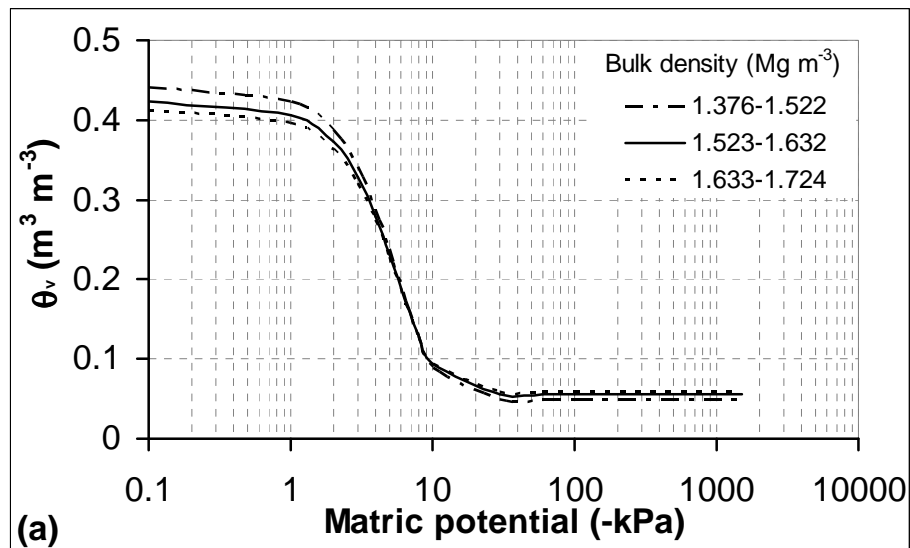
B. Coefficients of regression equations[†] and associated percentage of variance accounted for by equations (r^2) of the effects of ranges of bulk density (BD) and soil carbon (C), as grouped in **Table 6.1**, on volumetric soil water content Rattray (of undisturbed soil cores) at Rattray. All regression equations were highly significant ($p<0.001$); n = 56.

BD/C	Range (%)	a	c	b	m	r^2
BD	0 – 25	0.453	-0.403	-0.358	-3.675	
	25 – 75	0.434	-0.378	-0.358	-3.675	0.932
	75 – 100	0.423	-0.364	-0.358	-3.675	
C	0 – 25	0.422	-0.385	-0.356	-3.668	
	25 – 75	0.431	-0.370	-0.356	-3.668	0.935
	75 – 100	0.458	-0.397	-0.356	-3.668	
BD, C	0 – 25, 0 – 25	0.413	-0.375	-0.359	-3.668	
	25 – 75, 0 – 25	0.426	-0.388	-0.359	-3.668	
	75 – 100, 0 – 25	0.421	-0.390	-0.359	-3.668	
	0 – 25, 25 – 75	0.456	-0.390	-0.359	-3.668	
	25 – 75, 25 – 75	0.433	-0.373	-0.359	-3.668	0.937
	75 – 100, 25 – 75	0.425	-0.364	-0.359	-3.668	
	0 – 25, 75 – 100	0.471	-0.417	-0.359	-3.668	
	25 – 75, 75 – 100	0.450	-0.378	-0.359	-3.668	
	75 – 100, 75 – 100	0.402	-0.348	-0.359	-3.668	

[†] The regression equation used is of the Gompertz form i.e. $y = a + c * EXP(-EXP(-b * (x - m)))$, where y = water content (θ_v; $m^3 m^{-3}$), x = matric potential (kPa), and a, c, b and m are coefficients.

Standard error values of regression equations displayed in **Table B** above of the effects of ranges of bulk density (BD) and soil carbon (C), as grouped in **Table 6.1**, on volumetric soil water content (of undisturbed soil cores) at Rattray.

Parameter	BD	C	BD,C
b	0.011	0.010	0.010
m	0.085	0.082	0.082

Appendix 6.3. Soil bulk density and soil carbon effects (separate) on soil water content (θ_m and θ_v) at Rattray.

A.   Significant regression equations and associated percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on volumetric soil water content (θ_v; m^3 m^{-3}) of 0 – 0.2 and 0.4 – 0.5 m undisturbed soil cores at various matric potentials at Rattray. All relationships were highly significant ($p<0.001$); **n = 56.**

Ψm (kPa)	Regression equation	r^2
0	$\theta_v = 0.906 - 0.302$ BD	0.669
-1	$\theta_v = 0.848 - 0.288$ BD	0.616
-2	$\theta_v = 0.789 - 0.262$ BD	0.447
0	$\theta_v = 0.387 + 0.040$ C	0.587
-1	$\theta_v = 0.350 + 0.041$ C	0.613
-2	$\theta_v = 0.329 + 0.044$ C	0.626
-1500	$\theta_v = 0.012 + 0.010$ C	0.587

Estimates of parameters of regression equations displayed in **Table A** above of the effect of bulk density (BD) and soil carbon (C) on soil water content (θ_v) of 0 – 0.2 and 0.4 – 0.5 m undisturbed soil cores at various matric potentials (Ψm) at Rattray.

Ψm (kPa)	Parameter	estimate	s.e.	t(54)	t pr.
		BD			
0	Constant	0.906	0.045	20.15	<0.001
	x	-0.302	0.029	-10.6	<0.001
-1	Constant	0.848	0.048	17.61	<0.001
	x	-0.288	0.031	-9.44	<0.001
-2	Constant	0.789	0.061	12.86	<0.001
	x	-0.262	0.039	-6.74	<0.001
		C			
0	Constant	0.387	0.006	68.72	<0.001
	x	0.040	0.005	8.74	<0.001
-1	Constant	0.350	0.005	64.23	<0.001
	x	0.041	0.005	9.22	<0.001
-2	Constant	0.329	0.006	57.75	<0.001
	x	0.044	0.005	9.48	<0.001
-3	Constant	0.319	0.006	50.14	<0.001
	x	0.028	0.005	5.35	<0.001
-1500	Constant	0.012	0.001	8.57	<0.001
	x	0.010	0.001	8.74	<0.001

B. Significant regression equations and associated percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on mass and volumetric soil water content (θ_m; kg kg^{-1} and θ_v; m^3 m^{-3}) of 0 – 0.2 m undisturbed soil cores at various matric potentials at Rattray. All relationships were highly significant ($p<0.001$); n = 20.

Ψm (kPa)	Regression equation	r^2
0	$\theta_m = 0.908 - 0.400\ BD$	0.939
-1	$\theta_m = 0.835 - 0.368\ BD$	0.905
-2	$\theta_m = 0.792 - 0.346\ BD$	0.852
-3	$\theta_m = 0.559 - 0.209\ BD$	0.636
-60	$\theta_m = 0.058 - 0.090 * 0.058^C$	0.513
-100	$\theta_m = 0.052 - 0.087 * 0.162^C$	0.507
-1500	$\theta_m = 0.037 - 0.037 * 0.654^C$	0.885
0	$\theta_v = 0.948 - 0.326\ BD$	0.847
-1	$\theta_v = 0.872 - 0.299\ BD$	0.758
-2	$\theta_v = 0.822 - 0.277\ BD$	0.632
-1500	$\theta_v = 0.044 - 0.045 * 0.528^C$	0.823

Estimates of parameters of regression equations displayed in **Table B** above of the effect of bulk density on mass and volumetric soil water content (θ_m and θ_v) of 0 – 0.2 m undisturbed soil cores at various matric potentials (Ψm) at Rattray.

Ψm (kPa)	Parameter	estimate	s.e.	t(26)	t pr.
		θ_m			
0	Constant	0.9081	0.0302	30.03	<0.001
	x	-0.4003	0.0196	-20.46	<0.001
-1	Constant	0.8352	0.0353	23.63	<0.001
	x	-0.3677	0.0229	-16.08	<0.001
-2	Constant	0.7917	0.0429	18.46	<0.001
	x	-0.3463	0.0277	-12.48	<0.001
-3	Constant	0.5586	0.0465	12.01	<0.001
	x	-0.2089	0.0301	-6.94	<0.001
		θ_v			
0	Constant	0.9478	0.041	23.11	<0.001
	x	-0.3256	0.0265	-12.27	<0.001
-1	Constant	0.872	0.05	17.44	<0.001
	x	-0.2989	0.0323	-9.24	<0.001
-2	Constant	0.822	0.0622	13.22	<0.001
	x	-0.2769	0.0402	-6.88	<0.001

Standard error values of regression equations displayed in **Table B** above of the effect of soil carbon on mass and volumetric soil water content (θ_m and θ_v) of 0 – 0.2 m undisturbed soil cores at various matric potentials (Ψm) at Rattray. Equations are exponential in the form $y = a + br^x$.

Ψm (kPa)	Parameter:	a	b	r
		θ_m		
-60		0.006	0.047	0.166
-100		0.005	0.048	0.157
-1500		0.01	0.008	0.151
		θ_v		
-1		0.008	0.005	0.166

C. Significant regression equations and associated percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on mass soil water content[a] (θ_m; kg kg^{-1}) of 0.4 – 0.5 m undisturbed soil cores at various matric potentials at Rattray. All relationships were highly significant ($p<0.001$); n=36.

Ψm (kPa)	Regression equation	r^2
0	$\theta_m = 0.596 – 0.210$ BD	0.531
-1	$\theta_m = 0.529 – 0.184$ BD	0.514

[a] All relationships with θ_v had r^2 values < 0.5 and were excluded.

Estimates of parameters of regression equations displayed in **Table C** above of the effect of bulk density on mass soil water content (θ_m) of 0.4 – 0.5 m undisturbed soil cores at various matric potentials (Ψm) at Rattray.

Ψm (kPa)	Parameter	estimate	s.e.	t(26)	t pr.
0	Constant	0.5958	0.0601	9.91	<0.001
	x	-0.2101	0.0374	-5.62	<0.001
-1	Constant	0.5294	0.0542	9.77	<0.001
	x	-0.1835	0.0337	-5.44	<0.001

Appendix 6.4. Standard error values of regression equations between soil bulk density and soil carbon (combined) on mass soil water content (θ_m) at Shafton.

A.   Standard error values of regression equations displayed in **Table 6.7** of the effects of ranges of bulk density (BD) and soil carbon (C), as grouped in **Table 6.6**, on mass soil water content (of undisturbed soil cores) at Shafton.

Parameter	BD	C	BD,C
r	0.023	0.025	0.031
s	0.001	0.001	0.001

Appendix 6.5. Soil bulk density and soil carbon effects (combined) on volumetric soil water content (θ_v) at Shafton.

A. The effect on soil water content (θ_v) of ranges of (a) bulk density and (b) soil carbon (C; % m/m) at Shafton Rattray (of undisturbed soil cores between 0 and 0.5 m).
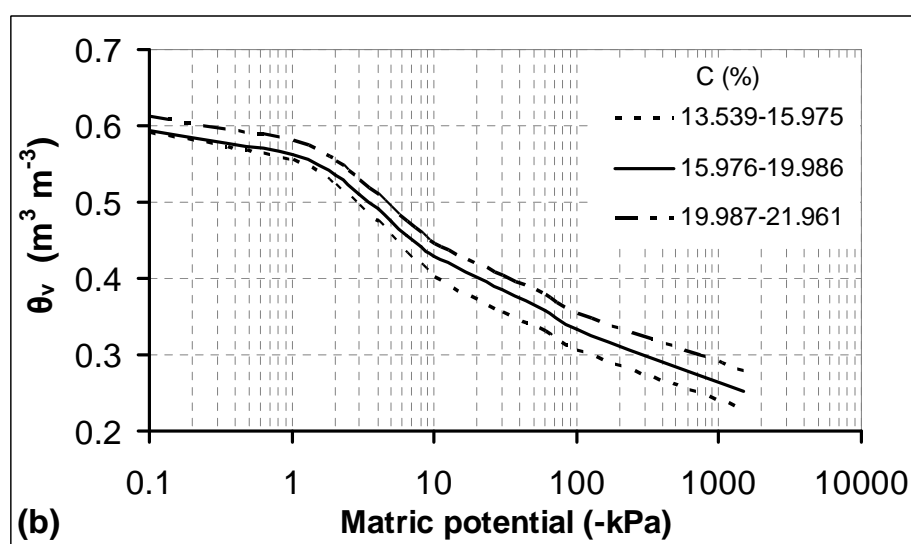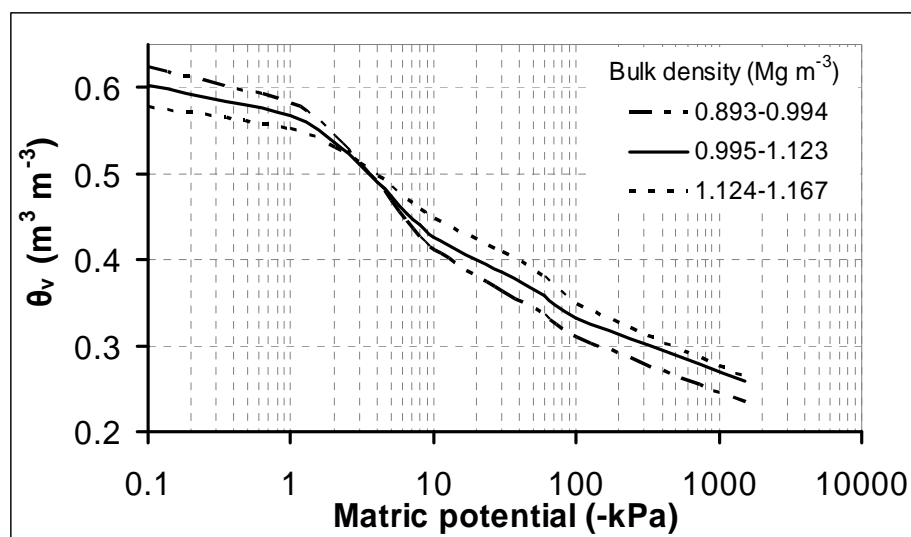
B. Coefficients of regression equations[†] and associated percentage of variance accounted for by equations (r^2) of the effects of ranges of ranges of bulk density (BD) and soil carbon (C; % m/m), as grouped in **Table 6.6**, on volumetric soil water content (of undisturbed soil cores) at Shafton. All regression equations were highly significant ($p<0.001$); n=56.

BD/C	Range (%)	a	b	r	c	s	r^2
	0 – 25	0.234	0.231	1.250	0.164	1.008	
BD	25 – 75	0.258	0.188	1.250	0.160	1.008	0.857
	75 – 100	0.265	0.132	1.250	0.184	1.008	
	0 – 25	0.228	0.212	1.225	0.157	1.007	
C	25 – 75	0.253	0.182	1.225	0.163	1.007	0.865
	75 – 100	0.280	0.184	1.225	0.154	1.007	
	0 – 25, 0 – 25	0.233	0.214	1.271	0.152	1.009	
	25 – 75, 0 – 25	0.230	0.201	1.271	0.171	1.009	
	75 – 100, 0 – 25	0.221	0.167	1.271	0.208	1.009	
	0 – 25, 25 – 75	0.213	0.238	1.271	0.187	1.009	
BD, C	25 – 75, 25 – 75	0.260	0.178	1.271	0.168	1.009	0.881
	75 – 100, 25 – 75	0.264	0.127	1.271	0.185	1.009	
	0 – 25, 75 – 100	0.250	0.224	1.271	0.173	1.009	
	25 – 75, 75 – 100	0.298	0.172	1.271	0.146	1.009	
	75 – 100, 75 – 100	0.337	0.083	1.271	0.158	1.009	

[†] The regression equation used is of the double exponential form i.e. $y = a + b*r^x + c*s^x$, where y = water content (θ_v; $m^3\ m^{-3}$), x = matric potential (kPa), and a, b, r, c and s are coefficients.

Standard error values of regression equations displayed in **Table B** above of the effects of ranges of bulk density (BD) and soil carbon (C), as grouped in **Table 6.6**, on volumetric soil water content (of undisturbed soil cores) at Shafton.

Parameter	BD	C	BD,C
r	0.007	0.020	0.006
s	0.001	0.001	0.001

Appendix 6.6. Soil bulk density and soil carbon effects (separate) on soil water content (θ_m and θ_v) at Shafton.

A. Significant regression equations and associated percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on mass soil water content[a] (θ_m; kg kg^{-1}) of 0 – 0.2 and 0.4 – 0.5 m undisturbed soil cores at various matric potentials at Shafton. All relationships were highly significant ($p<0.001$); n = 56.

Ψm (kPa)	Regression equation	r^2
0	$\theta_m = 1.442 - 0.813\ BD$	0.889
-1	$\theta_m = 1.256 - 0.684\ BD$	0.752
-2	$\theta_m = 1.153 - 0.612\ BD$	0.580

[a] All relationships with θ_v had r^2 values < 0.5 and were excluded.

Estimates of parameters of regression equations displayed in **Table A** above of the effect of bulk density (BD) on soil water content (θ_v) of 0 – 0.2 and 0.4 – 0.5 m undisturbed soil cores at various matric potentials (Ψm) at Shafton.

Ψm (kPa)	Parameter	estimate	s.e.	t(52)	t pr.
0	Constant	1.442	0.042	34.62	<0.001
	x	-0.813	0.039	-20.62	<0.001
-1	Constant	1.256	0.057	22.07	<0.001
	x	-0.684	0.054	-12.71	<0.001
-2	Constant	1.153	0.075	15.37	<0.001
	x	-0.612	0.071	-8.62	<0.001

B. Significant regression equations and associated percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on mass soil water content[a] (θ_m; kg kg^{-1}) of 0 – 0.2 m undisturbed soil cores at various matric potentials at Shafton. All relationships were highly significant ($p<0.001$); n=27.

Ψm (kPa)	Regression equation	r^2
0	$\theta_m = 1.453 - 0.819\,BD$	0.876
-1	$\theta_m = 0.461 + 108 * 0.001^{BD}$	0.726
-2	$\theta_m = 0.484 + 77094 * 5.60E\text{-}07^{BD}$	0.520
-3	$\theta_m = 0.475 + 3.10E\text{+}08 * 0.53E\text{-}10^{BD}$	0.509
-5	$\theta_m = 0.440 + (3.21E\text{-}15 + 1.93E\text{-}19\,C) + 4^C$	0.544
-30	$\theta_m = 0.85 + (-1.15 + 11.7\,C) + 0.854^C$	0.648
-60	$\theta_m = 0.302 + (-2.29E\text{-}09 + 5.3E\text{-}08\,C) + 2.20^C$	0.593
-100	$\theta_m = 0.539 + (-6.7 + 87\,C) + 0.760^C$	0.593

[a] All relationships with θ_v had r^2 values < 0.5 and were excluded.

Standard error values of regression equations displayed in **Table B** above of the effect of bulk density and soil carbon on mass soil water content (θ_m) of 0 – 0.2 m undisturbed soil cores at various matric potentials (Ψm) at Shafton. Standard error values are given in the order in which they appear in the regression equations above.

Ψm (kPa)	s.e.	s.e.	s.e.	s.e.
0	0.063	0.060		
-1	0.041	274	0.003	
-2	0.017	322164	2.61E-06	
-3	0.012	2.12E+09	4.06E-10	
-5	0.0175	4.41E-11	1.23E-12	58121
-30	1.25	3.96	52	0.215
-60	0.024	2.13E-08	5.01E-07	1.030
-100	0.285	26.5	364	0.188

C. Significant regression equations and associated percentage of variance accounted for by equations (r^2) of the effect of bulk density (BD; Mg m^{-3}) and soil carbon (C; % m/m) on mass soil water content[a] (θ_m; kg kg^{-1}) of 0.4 – 0.5 m undisturbed soil cores at various matric potentials at Shafton. All relationships were highly significant ($p<0.001$); n=29.

Ψm (kPa)	Regression equation	r^2
0	$\theta_m = 0.383 + 12 * 0.020^{BD}$	0.912
-1	$\theta_m = 0.414 + 78 * 0.002^{BD}$	0.829
-2	$\theta_m = 0.428 + 1031 * 9.2E\text{-}05^{BD}$	0.745
-3	$\theta_m = 0.426 + 7797 * 8.4E\text{-}06^{BD}$	0.664
-4	$\theta_m = 0.417 + 21959 * 2.52E\text{-}06^{BD}$	0.661
-5	$\theta_m = 0.410 + 57227 * 7.7E\text{-}07^{BD}$	0.592
-6.5	$\theta_m = 0.406 + 535151 * 5.6E\text{-}08^{BD}$	0.500

[a] All relationships with θ_v had r^2 values < 0.5 and were excluded.

Standard error values of regression equations displayed in **Table C** above of the effect of bulk density and soil carbon on mass soil water content (θ_m) of 0.4 – 0.5 m undisturbed soil cores at various matric potentials (Ψm) at Shafton. Standard error values are given in the order in which they appear in the regression equations above.

Ψm (kPa)	s.e.	s.e.	s.e.
0	0.081	14.5	0.031
-1	0.042	149	0.004
-2	0.025	2674	2.67E-04
-3	0.018	25837	3.08E-05
-4	0.015	75852	9.64E-06
-5	0.014	236751	3.54E-06
-6.5	0.012	2920969	3.36E-07

Appendix 6.7. ANOVA (two-way) of the effect of compaction treatments and residue management on average volumetric soil water content (θ_v) measurements using the thetaprobe at Shafton.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.028	0.014	11.02	<0.001
Residue	2	0.036	0.018	13.85	<0.001
Compaction x residue	4	0.007	0.002	1.44	0.262
Residual	18	0.023	0.001		
Total	26	0.095			

Appendix 7.1. Relationship between biomass index and various biomass components of *E. grandis* trees 209 DAP at Rattray.

A.   Foliage

Plot of Foliage mass (kg) versus Biomass Index (mm³ x 10⁴).
$y = 0.02495 + 1.25E\text{-}07x$
$r^2 = 0.901^{***}$

B.   Stem + Branches

Plot of Stem+Branch (kg) versus Biomass Index (mm³ x 10⁴).
$y = 0.01874 + 1.90E\text{-}07x$
$r^2 = 0.961^{***}$

C. Aboveground biomass

$y = 0.04369 + 3.15\text{E-07}x$
$r^2 = 0.945^{***}$

Aboveground (kg) vs Biomass Index (mm^3 x 10^4)

D. Belowground stem

$y = 4.61\text{E-03} + 0.40\text{E-07}x$
$r^2 = 0.940^{***}$

Belowground stem (kg) vs Biomass Index (mm^3 x 10^4)

E. Coarse roots

$y = 0.011 + 2.070\text{E-08}x$
$r^2 = 0.810^{***}$

Coarse roots (kg) vs Biomass Index (mm^3 x 10^6)

F.   Fine roots

G.   Belowground biomass

$y = 0.017 + 7.48E\text{-}08x$
$r^2 = 0.835^{***}$

H.   Total biomass

$y = 0.019 + 5.15E\text{-}07x$
$r^2 = 0.944^{***}$
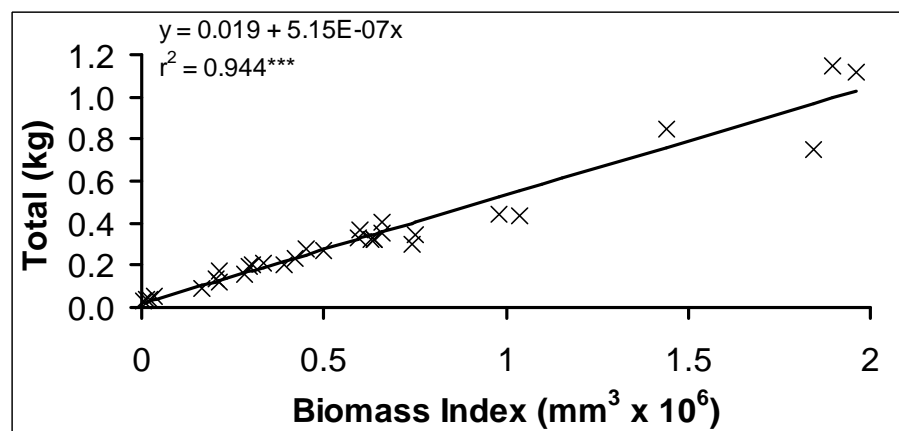
I. Major components
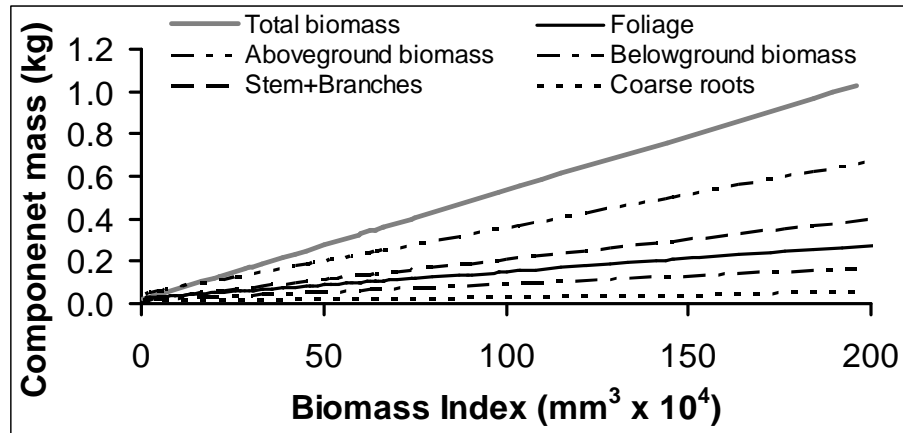
J. Standard error values of regression equations displayed in above figures of the relationship between biomass index and various biomass components of *E. grandis* trees 209 DAP at Rattray.

Component	Parameter	estimate	s.e.	t[a]	t pr.
Foliage	Constant	0.025	0.003	8.28	<0.001
	x	1.25E-07	3.61E-09	34.52	<0.001
Stem+Branches	Constant	0.019	0.003	6.74	<0.001
	x	1.90E-07	3.33E-09	57.04	<0.001
Aboveground biomass	Constant	0.044	0.006	7.91	<0.001
	x	3.15E-07	6.62E-09	47.55	<0.001
Belowground stem	Constant	0.005	0.002	2.04	0.05
	x	3.96E-08	1.74E-09	22.74	<0.001
Coarse roots	Constant	0.011	0.002	4.80	<0.001
	x	2.07E-08	1.71E-09	12.08	<0.001
Belowground biomass	Constant	0.017	0.005	3.54	0.001
	x	7.48E-08	5.86E-09	12.75	<0.001
Total biomass	Constant	0.019	0.018	1.02	0.315
	x	5.10E-07	2.27E-08	22.51	<0.001

[a] the residual degrees of freedom were 130 for foliage, stem+branches and aboveground biomass, while for the remaining components it was 31.

Appendix 7.2. Relationship between biomass index and various biomass components of *E. grandis* trees 211 DAP at Shafton.

A. Foliage
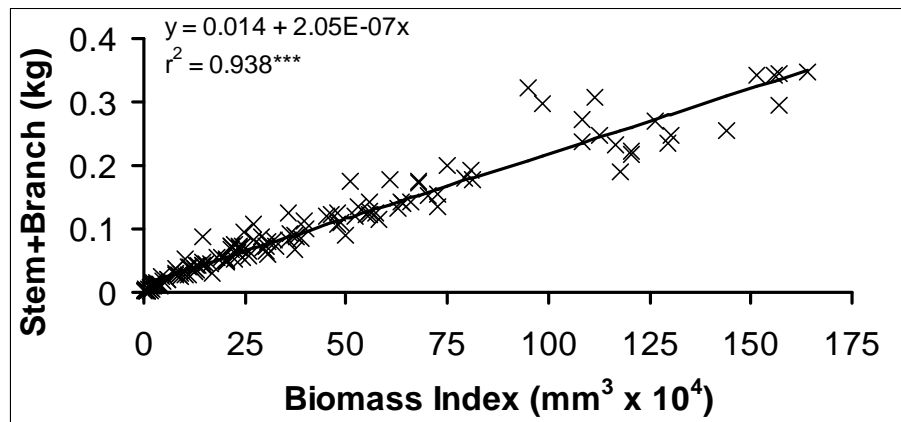
$y = 0.019 + 1.71E\text{-}07x$
$r^2 = 0.891***$

B. Stem + Branches

$y = 0.014 + 2.05E\text{-}07x$
$r^2 = 0.938***$

C.   Aboveground biomass

$y = 0.034 + 3.74E\text{-}07x$
$r^2 = 0.915^{***}$

Aboveground (kg)

Biomass Index (mm^3 x 10^4)

D.   Belowground stem

$y = 4.35E\text{-}03 + 3.81E\text{-}08x$
$r^2 = 0.825^{***}$

Belowground stem (kg)

Biomass Index (mm^3 x 10^4)

E.   Coarse roots

$y = 7.95E\text{-}03 - 3.05E\text{-}08x$
$r^2 = 0.610^{***}$

Coarse roots (kg)

Biomass Index (mm^3 x 10^4)

312
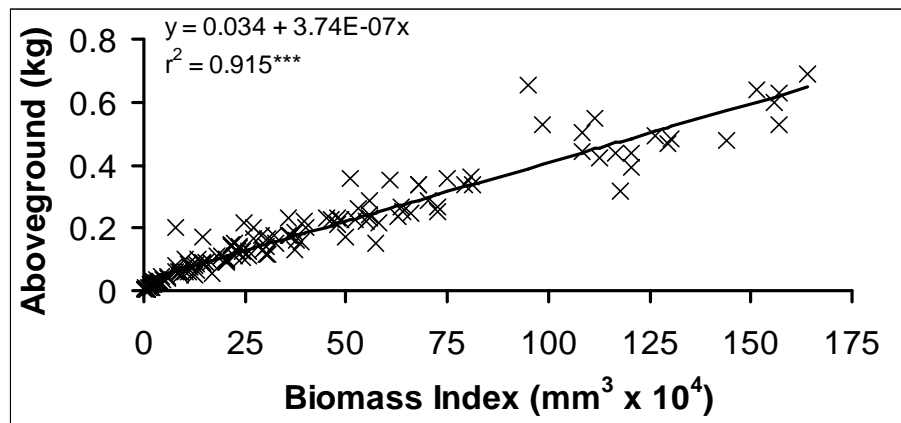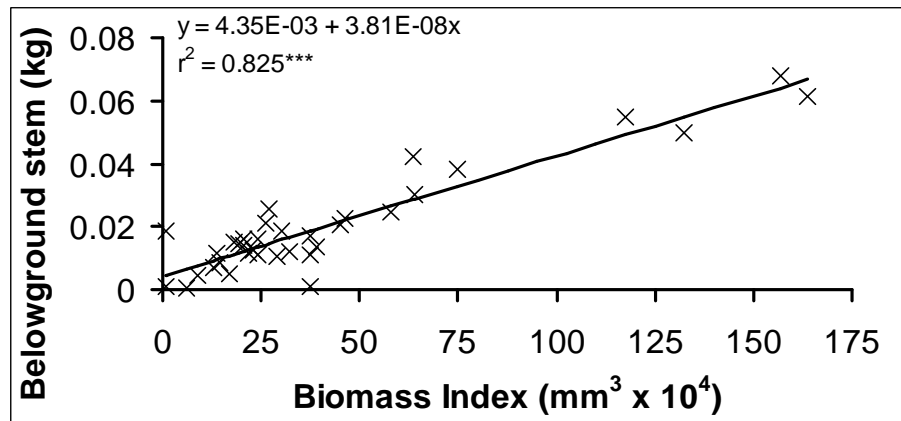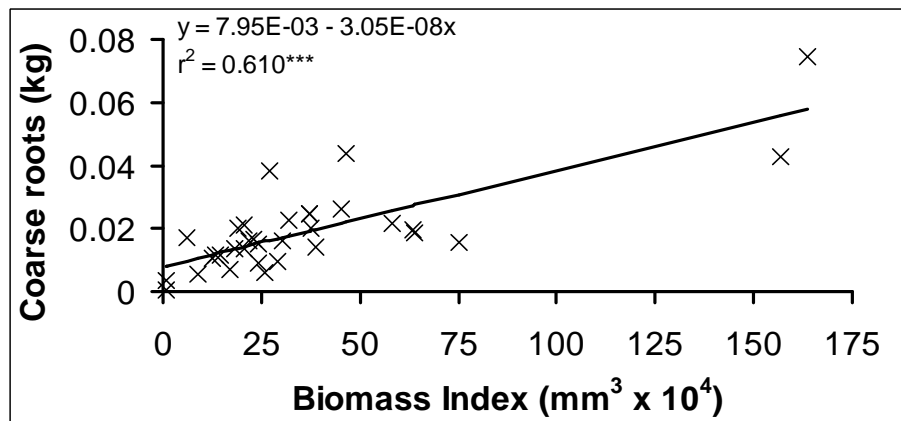
F.   Fine roots
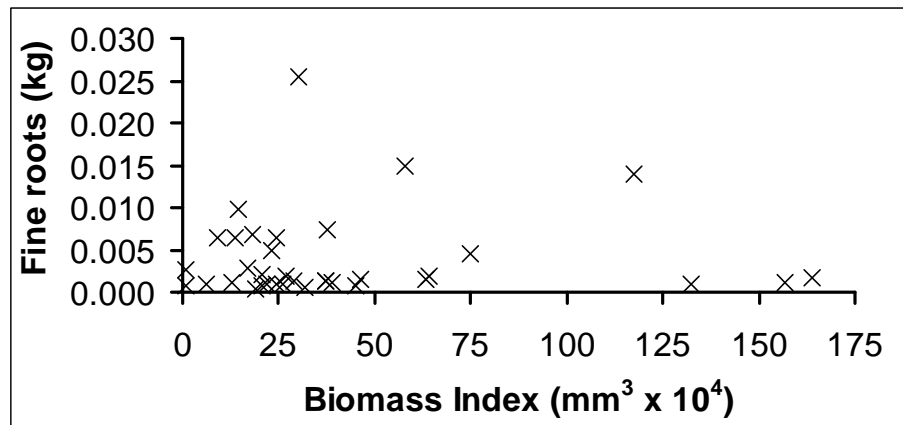
G.   Belowground biomass
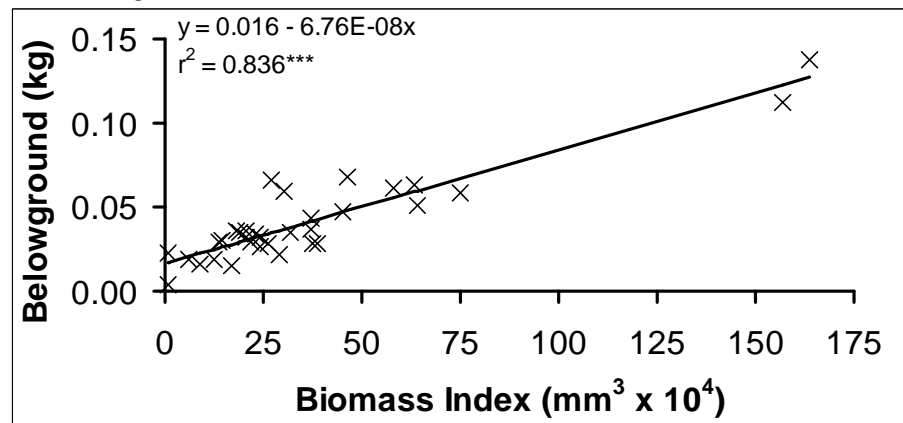
H.   Total biomass
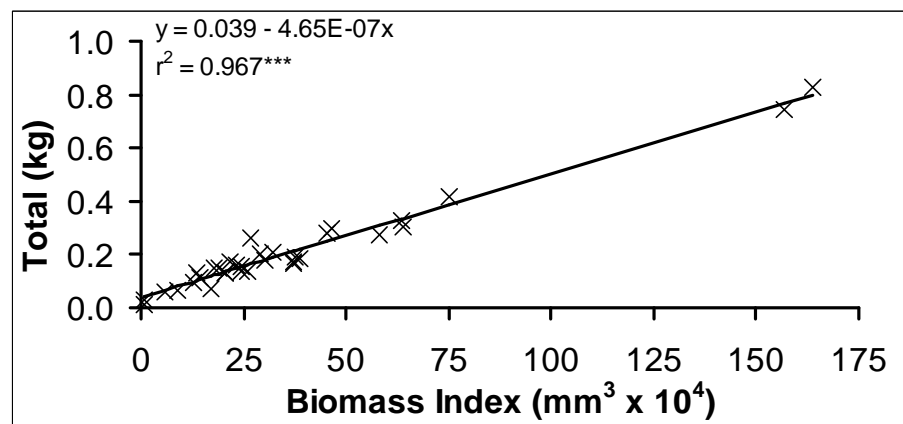
I. Major components
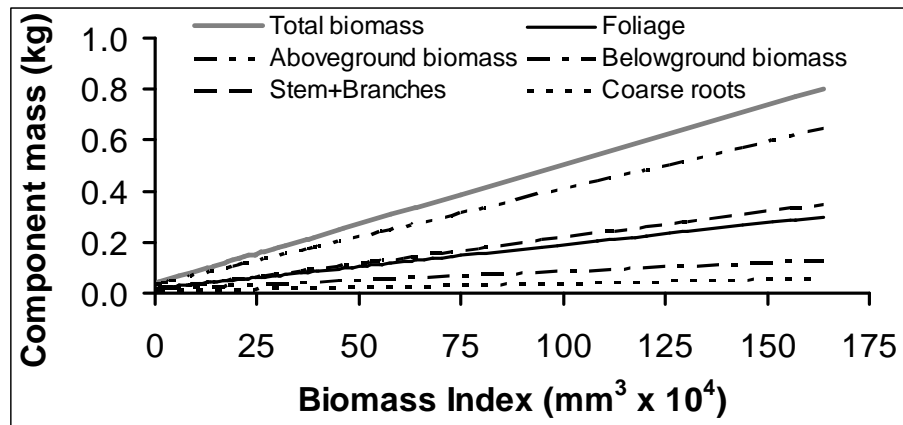
J. Standard error values of regression equations displayed in above figures of the relationship between biomass index and various biomass components of *E. grandis* trees 211 DAP at Shafton.

Component	Parameter	estimate	s.e.	t[a]	t pr.
Foliage	Constant	0.019	0.00302	6.21	<0.001
	x	1.71E-07	5.17E-09	33.12	<0.001
Stem+Branches	Constant	0.014	0.003	5.20	<0.001
	x	2.05E-07	4.54E-09	45.14	<0.001
Aboveground biomass	Constant	0.034	0.006	5.90	<0.001
	x	3.74E-07	9.86E-09	37.91	<0.001
Belowground stem	Constant	0.004	0.002	2.74	0.010
	x	3.81E-08	3.09E-09	12.34	<0.001
Coarse roots	Constant	0.008	0.002	3.62	<0.001
	x	3.05E-08	4.27E-09	7.14	0.001
Belowground biomass	Constant	0.016	0.003	6.04	0.001
	x	6.76E-08	5.27E-09	12.83	<0.001
Total biomass	Constant	0.039	0.008	4.96	0.315
	x	4.65E-07	1.53E-08	30.43	<0.001

[a] the residual degrees of freedom were 133 for foliage, stem+branches and aboveground biomass, while for the remaining components it was 31.

Appendix 7.3. Relationship between various biomass components of *E. grandis* trees at Rattray (209 DAP) and Shafton (211 DAP).

A. Belowground (BG) biomass and aboveground (AG) biomass[a].
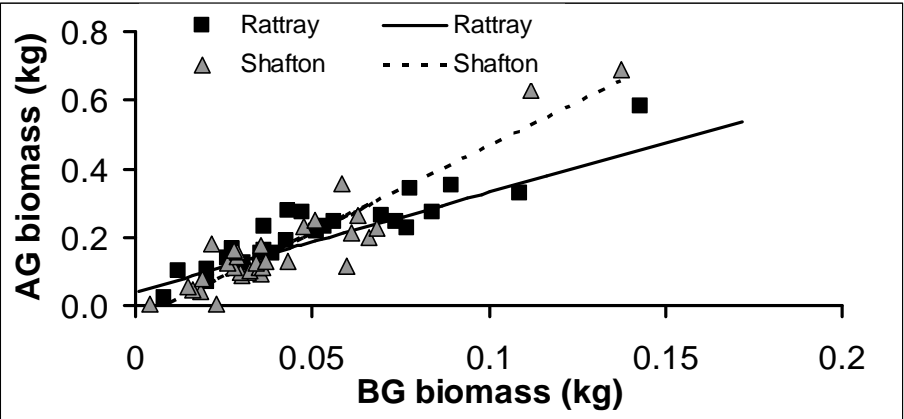
[a] Regression equations, percentage variance accounted for and levels of significance are given in **Table 7.2**.

B. Foliage biomass and stem plus branch (St+br)[a].
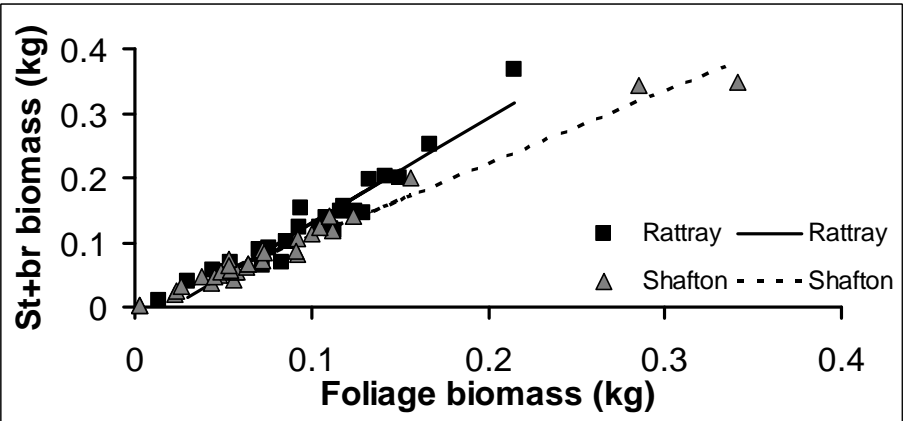
[a] Regression equations, percentage variance accounted for and levels of significance are given in **Table 7.2**.

C. Relationships between coarse root biomass and stem plus branch (St+br) biomass[a].
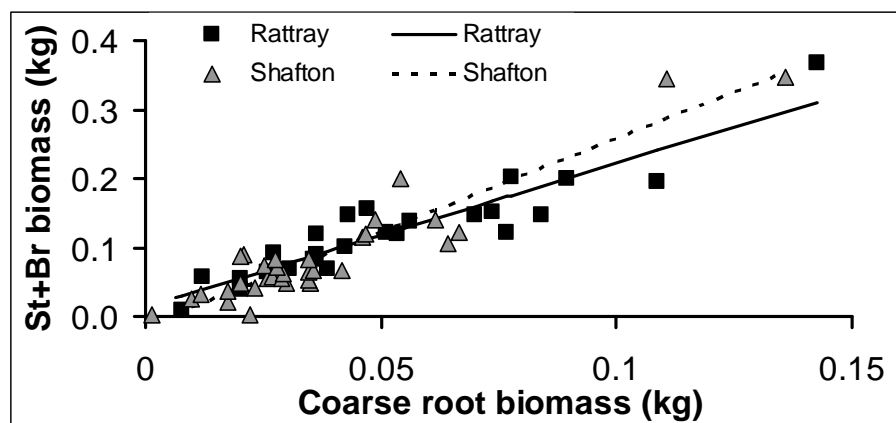
Regression equations, percentage variance accounted for and levels of significance are given in **Table 7.2**.

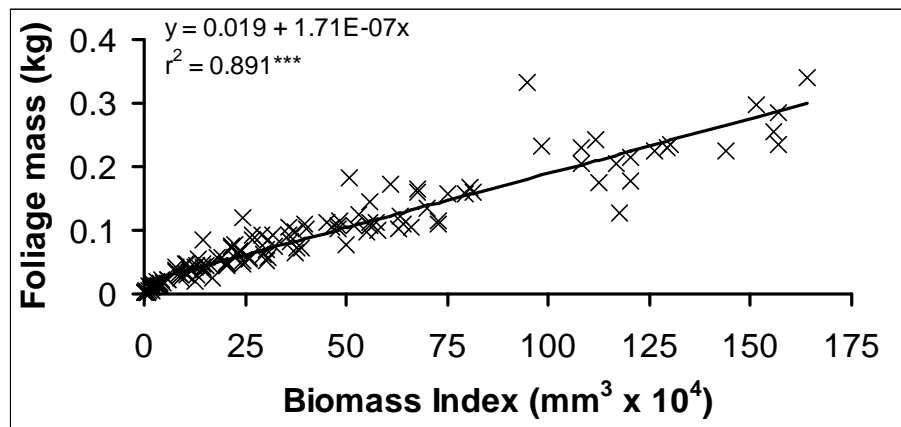**D.** Standard error values of regression equations displayed in above figures of the relationship between various biomass components of *E. grandis* trees at 209 and 211 DAP at Rattray and Shafton, respectively.

Relationship	Parameter	estimate	s.e.	t-d.f.[a]	t	t pr.
		Rattray				
Aboveground vs	Constant	0.041	0.018	23	2.20	0.038
belowground	x	2.902	0.260		11.15	<0.001
Stem+Branches	Constant	-0.033	0.003	130	-3.67	<0.001
vs foliage	x	1.624	0.025		58.22	<0.001
Stem+Branches	Constant	0.014	0.011	23	1.27	0.215
vs coarse roots	x	2.086	0.177		11.80	<0.001
		Shafton				
Aboveground vs	Constant	-0.040	0.018	31	-2.19	0.036
belowground	x	5.059	0.374		13.55	<0.001
Stem+Branches	Constant	-0.002	0.002	133	-2.21	0.029
vs foliage	x	1.117	0.017		66.81	<0.001
Stem+Branches	Constant	-0.013	0.009	31	-1.57	0.125
vs coarse roots	x	2.709	0.185		14.66	<0.001

[a] the residual degrees of freedom.

Appendix 7.4. **Estimates of parameters of regression equations displayed in Figure 7.1 between total biomass and tree leaf area of individual trees at Rattray (209 DAP) and Shafton (211 DAP).**

	Parameter	estimate	s.e.	t(23)	t pr.
Rattray	Constant	-0.012	0.024	-0.52	0.609
	x	0.207	0.015	13.58	<0.001
	Parameter	**estimate**	**s.e.**	**t(31)**	**t pr.**
Shafton	Constant	0.024	0.018	1.37	0.180
	x	0.102	0.007	13.86	<0.001

Appendix 7.5. Effect of compaction and residue management on the average foliar N and P concentrations of sub-plot trees at Shafton.

A. ANOVA of treatment effects on foliar N concentrations in sub-plot trees (211 DAP) at Shafton.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.299	0.150	9.56	0.001
Residue	2	0.341	0.171	10.91	<0.001
Compaction x residue	4	0.057	0.014	0.91	0.479
Residual	18	0.282	0.016		
Total	26	0.970			

B. ANOVA of treatment effects on foliar P concentrations in sub-plot trees (211 DAP) at Shafton. Data was power transformed (x^2) to prevent violation of normality assumptions

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	3.378E-05	1.689E-05	16.22	<0.001
Residue	2	1.143E-05	5.716E-06	5.49	0.014
Compaction x residue	4	2.036E-05	5.091E-06	4.89	0.008
Residual	18	1.874E-05	1.041E-06		
Total	26	8.432E-05			

C. The combined effect of compaction treatments and residue management on foliar P (g kg^{-1}) of sub-plot trees.

Compaction	Residue Management	Mean PSS$_1$ (kPa)
Low	Broadcast	0.115[a]
Low	Windrowed	0.098[b]
Low	Removed	0.096[bc]
Moderate	Broadcast	0.094[bc]
High	Removed	0.093[bc]
Moderate	Windrowed	0.092[bc]
Moderate	Removed	0.092[bc]
High	Broadcast	0.090[bc]
High	Windrowed	0.088[c]

[a] Treatments with different letters are significantly different ($p < 0.05$).

Appendix 7.6. Effect of compaction and residue management on root:shoot ratios of *E. grandis* trees 209 DAP at Rattray.

A. ANOVA of the effect of compaction treatments on root:shoot ratios of *E. grandis* trees 209 DAP at Rattray. Note: data was log transformed to prevent violation of normality and error assumptions.

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.637	0.319	5.39	0.015
Residue	2	0.064	0.032	0.54	0.593
Compaction x residue	4	0.126	0.032	0.53	0.713
Residual	18	1.065	0.059		
Total	26	1.892			

Appendix 7.7. ANOVA of the effect of compaction and residue management on the average GLD of sub-plot trees at Rattray.

70 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.796	0.898	6.66	0.007
Residue	2	0.327	0.163	1.21	0.321
Compaction x residue	4	1.281	0.320	2.38	0.090
Residual	18	2.426	0.135		
Total	26	5.829			

133 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	30.835	15.417	4.90	0.020
Residue	2	13.150	6.575	2.09	0.152
Compaction x residue	4	15.526	3.881	1.23	0.331
Residual	18	56.582	3.143		
Total	26	116.092			

167 DAP[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.364	0.182	5.03	0.018
Residue	2	0.102	0.051	1.41	0.270
Compaction x residue	4	0.211	0.053	1.46	0.256
Residual	18	0.652	0.036		
Total	26	1.330			

[a] Data transformed by the natural logarithm (ln) to prevent violation of normality assumptions.

209 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	94.12	47.06	3.05	0.072
Residue	2	27.78	13.89	0.90	0.424
Compaction x residue	4	40.98	10.24	0.66	0.625
Residual	18	277.41	15.41		
Total	26	440.29			

Appendix 7.8. ANOVA of the effect of compaction and residue management on the average height of sub-plot trees at Rattray.

70 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	57.356	28.678	3.90	0.039
Residue	2	23.729	11.864	1.61	0.227
Compaction x residue	4	37.051	9.263	1.26	0.322
Residual	18	132.288	7.349		
Total	26	250.424			

133 DAP[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	30761950	15380975	5.71	0.012
Residue	2	7684716	3842358	1.43	0.266
Compaction x residue	4	8464527	2116132	0.79	0.549
Residual	18	48493295	2694072		
Total	26	95404488			

[a] Data power transformed (x^2) to prevent violation of normality assumptions.

167 DAP[b]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.349E+08	6.747E+07	5.82	0.011
Residue	2	1.388E+07	6.939E+06	0.60	0.560
Compaction x residue	4	8.863E+07	2.216E+07	1.91	0.152
Residual	18	2.087E+08	1.160E+07		
Total	26	4.462E+08			

[b] Data power transformed to prevent violation of normality assumptions.

209 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	7429.2	3714.6	4.96	0.019
Residue	2	640.3	320.2	0.43	0.658
Compaction x residue	4	5144.8	1286.2	1.72	0.190
Residual	18	13474.1	748.6		
Total	26	26688.5			

Appendix 7.9. ANOVA of the effect of compaction and residue management on the average biomass index of sub-plot trees at Rattray.

70 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	37.180	18.590	7.38	0.005
Residue	2	7.683	3.841	1.52	0.245
Compaction x residue	4	26.279	6.570	2.61	0.070
Residual	18	45.358	2.520		
Total	26	116.500			

133 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	21804	10902	4.94	0.019
Residue	2	7148	3574	1.62	0.226
Compaction x residue	4	10166	2541	1.15	0.365
Residual	18	39728	2207		
Total	26	78846			

167 DAP[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.5550	0.277	5.40	0.015
Residue	2	0.097	0.049	0.94	0.407
Compaction x residue	4	0.343	0.086	1.67	0.201
Residual	18	0.925	0.051		
Total	26	1.920			

[a] Data logarithmically transformed (log x) to prevent violation of normality assumptions.

209 DAP[b]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	311.90	155.95	3.55	0.050
Residue	2	47.62	23.81	0.54	0.591
Compaction x residue	4	197.23	49.31	1.12	0.377
Residual	18	790.62	43.92		
Total	26	1347.37			

[b] Data square root transformed ($\sqrt{x}$) to prevent violation of normality assumptions.

Appendix 7.10. ANOVA of the effect of compaction and residue management on the average crown diameter of sub-plot trees at Rattray.

70 DAP[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.353	0.176	1.09	0.358
Residue	2	0.170	0.085	0.53	0.600
Compaction x residue	4	0.901	0.225	1.39	0.277
Residual	18	2.917	0.162		
Total	26	4.342			

[a] Data square root transformed ($\sqrt{x}$) to prevent violation of normality assumptions.

133 DAP[b]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	16197268	8098634	4.04	0.036
Residue	2	8782107	4391054	2.19	0.141
Compaction x residue	4	6335696	1583924	0.79	0.547
Residual	18	36104010	2005778		
Total	26	67419081			

[b] Data power transformed (x^2) to prevent violation of normality assumptions.

167 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1871.6	935.8	6.63	0.007
Residue	2	314.1	157.0	1.11	0.350
Compaction x residue	4	711.6	177.9	1.26	0.322
Residual	18	2541.6	141.2		
Total	26	5438.9			

209 DAP[c]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.0408	0.020	2.43	0.116
Residue	2	0.010	0.005	0.61	0.552
Compaction x residue	4	0.079	0.020	2.36	0.092
Residual	18	0.151	0.008		
Total	26	0.281			

[c] Data logarithmically transformed (log x) to prevent violation of normality assumptions.

Appendix 7.11. ANOVA of the effect of compaction and residue management on the average GLD or DBH of main plot trees at Rattray.

6 months of age[a] (GLD):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.139	0.070	7.29	0.005
Residue	2	0.004	0.002	0.21	0.816
Compaction x residue	4	0.045	0.011	1.18	0.352
Residual	18	0.172	0.010		
Total	26	0.361			

[a] Data logarithmically (log x) transformed to prevent violation of normality assumptions.

13 months of age (GLD):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	437.08	218.54	3.83	0.041
Residue	2	4.02	2.01	0.04	0.965
Compaction x residue	4	175.67	43.92	0.77	0.559
Residual	18	1028.09	57.12		
Total	26	1644.87			

18 months of age (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	409.57	204.78	3.57	0.050
Residue	2	17.11	8.56	0.15	0.863
Compaction x residue	4	238.38	59.59	1.04	0.415
Residual	18	1033.43	57.41		
Total	26	1698.48			

23.5 months of age[b] (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.526	0.763	2.28	0.131
Residue	2	0.189	0.094	0.28	0.757
Compaction x residue	4	0.748	0.187	0.56	0.695
Residual	18	6.015	0.334		
Total	26	8.477			

[b] Data square root transformed ($\sqrt{x}$) to prevent violation of normality assumptions.

31.5 months of age (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.703	0.851	1.94	0.173
Residue	2	0.304	0.152	0.35	0.712
Compaction x residue	4	2.153	0.538	1.22	0.335
Residual	18	7.911	0.440		
Total	26	12.071			

41.5 months of age (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.656	0.343	0.82	0.445
Residue	2	0080	0.040	0.10	0.909
Compaction x residue	4	3.214	0.804	1.93	0.149
Residual	18	7.493	0.416		
Total	26	11.473			

Appendix 7.12. ANOVA of the effect of compaction and residue management on the average height of main plot trees at Rattray.

6 months of age[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	23.319	11.660	8.47	0.003
Residue	2	0.067	0.033	0.02	0.976
Compaction x residue	4	9.193	2.298	1.67	0.201
Residual	18	24.767	1.376		
Total	26	57.346			

[a] Data transformed (square root) to prevent violation of normality assumptions.

13 months of age:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	26609	13305	5.55	0.013
Residue	2	1637	818	0.34	0.715
Compaction x residue	4	12269	3067	1.28	0.314
Residual	18	43127	2396		
Total	26	83642			

18 months of age[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	16.223	8.111	3.38	0.057
Residue	2	1.364	0.682	0.28	0.756
Compaction x residue	4	6.593	1.648	0.69	0.611
Residual	18	43.215	2.401		
Total	26	67.395			

[a] Data transformed (square root) to prevent violation of normality assumptions.

23.5 months of age:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	38818	19409	2.75	0.091
Residue	2	5938	2969	0.42	0.663
Compaction x residue	4	17115	4279	0.61	0.664
Residual	18	127185	7066		
Total	26	189056			

Tree height at 31.5 and 41.5 months determined from regressions in **Appendix 3.4**, and therefore not analysed as results will mirror those of DBH (**Appendix 7.8**).

Appendix 7.13.ANOVA of the effect of compaction and residue management on the average GLD of sub-plot trees at Shafton.

70 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.449	0.225	1.12	0.348
Residue	2	5.015	2.507	12.52	<0.001
Compaction x residue	4	0.520	0.130	0.65	0.635
Residual	18	3.604	0.200		
Total	26	9.588			

120 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	3.015	1.508	1.51	0.248
Residue	2	15.083	7.542	7.55	0.004
Compaction x residue	4	6.914	1.728	1.73	0.187
Residual	18	17.968	0.998		
Total	26	42.980			

211 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	5.219	2.610	1.16	0.335
Residue	2	8.873	4.437	1.98	0.168
Compaction x residue	4	7.261	1.815	0.81	0.536
Residual	18	40.416	2.245		
Total	26	61.770			

Appendix 7.14. ANOVA of the effect of compaction and residue management on the average height of sub-plot trees at Shafton.

70 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	6.540	3.270	0.48	0.626
Residue	2	26.780	13.390	1.97	0.169
Compaction x residue	4	19.573	4.893	0.72	0.590
Residual	18	122.475	6.804		
Total	26	175.369			

120 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	37.90	18.95	0.75	0.486
Residue	2	225.79	112.90	4.47	0.026
Compaction x residue	4	163.58	40.90	1.62	0.212
Residual	18	454.22	25.23		
Total	26	881.50			

211 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	525.8	262.9	1.56	0.236
Residue	2	449.3	224.6	1.34	0.288
Compaction x residue	4	789.3	197.3	1.17	0.355
Residual	18	3026.2	168.1		
Total	26	4790.6			

Appendix 7.15.ANOVA of the effect of compaction and residue management on the average biomass index of sub-plot trees at Shafton.

70 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	2.147	1.074	0.41	0.670
Residue	2	51.201	25.600	9.75	0.001
Compaction x residue	4	9.740	2.435	0.93	0.470
Residual	18	47.239	2.624		
Total	26	110.327			

120 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	820.8	410.4	1.34	0.288
Residue	2	2456.5	1228.2	4.00	0.037
Compaction x residue	4	2397.0	599.2	1.95	0.146
Residual	18	5532.4	307.4		
Total	26	11206.6			

211 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	28952	14476	1.83	0.188
Residue	2	29182	14591	1.85	0.186
Compaction x residue	4	39751	9938	1.26	0.322
Residual	18	142067	7893		
Total	26	239953			

Appendix 7.16. ANOVA of the effect of compaction and residue management on the average crown diameter of sub-plot trees at Shafton.

70 DAP[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.009	0.004	1.23	0.317
Residue	2	0.142	0.071	19.93	<0.001
Compaction x residue	4	0.022	0.005	1.53	0.236
Residual	18	0.064	0.004		
Total	26	0.237			

[a] Data logarithmically (log x) transformed to prevent violation of normality assumptions.

120 DAP[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1072188	536094	1.54	0.241
Residue	2	5355271	2677636	7.70	0.004
Compaction x residue	4	1744213	436053	1.25	0.324
Residual	18	6255941	347552		
Total	26	14427613			

[a] Data power (x^2) transformed to prevent violation of normality assumptions.

211 DAP:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	44.92	22.46	0.37	0.693
Residue	2	19.29	9.64	0.16	0.853
Compaction x residue	4	124.53	31.13	0.52	0.722
Residual	18	1078.47	59.91		
Total	26	1267.20			

Appendix 7.17. ANOVA of the effect of compaction and residue management on the average GLD or DBH of main plot trees at Shafton.

6 months of age (GLD):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.866	0.933	0.15	0.862
Residue	2	28.433	14.217	2.28	0.131
Compaction x residue	4	13.393	3.348	0.54	0.711
Residual	18	112.314	6.240		
Total	26	156.007			

12 months of age (GLD)[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.040	0.020	7.49	0.004
Residue	2	0.018	0.009	3.42	0.050
Compaction x residue	4	0.024	0.006	2.27	0.101
Residual	18	0.048	0.003		
Total	26	0.131			

[a] Data transformed (natural log; ln) to prevent violation of normality assumptions.

18 months of age (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.310	0.655	4.78	0.022
Residue	2	0.982	0.491	3.58	0.049
Compaction x residue	4	0.100	0.025	0.18	0.945
Residual	18	2.468	0.137		
Total	26	4.859			

25.5 months of age (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.333	0.666	6.65	0.007
Residue	2	1.783	0.892	8.90	0.002
Compaction x residue	4	0.008	0.002	0.02	0.999
Residual	18	1.803	0.100		
Total	26	4.926			

30.5 months of age (DBH):

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	1.351	0.676	4.63	0.024
Residue	2	2.356	1.178	8.08	0.003
Compaction x residue	4	0.091	0.023	0.16	0.957
Residual	18	2.624	0.146		
Total	26	6.423			

Appendix 7.18. ANOVA of the effect of compaction and residue management on the average height of main plot trees at Shafton.

6 months of age:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	764.4	382.2	1.20	0.325
Residue	2	819.7	409.9	1.28	0.301
Compaction x residue	4	660.1	165.0	0.52	0.724
Residual	18	5744.1	319.1		
Total	26	7988.4			

12 months of age[a]:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	3.830	1.915	5.61	0.013
Residue	2	2.528	1.264	3.70	0.045
Compaction x residue	4	2.243	0.561	1.64	0.207
Residual	18	6.145	0.341		
Total	26	14.746			

[a] Data transformed (square root) to prevent violation of normality assumptions.

18 months of age:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.976	0.488	2.47	0.113
Residue	2	0.238	0.119	0.60	0.558
Compaction x residue	4	0.097	0.024	0.12	0.972
Residual	18	3.559	0.198		
Total	26	4.871			

25.5 months of age:

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Compaction	2	0.698	0.349	0.61	0.553
Residue	2	1.366	0.683	1.20	0.325
Compaction x residue	4	0.182	0.046	0.08	0.988
Residual	18	10.261	0.570		
Total	26	12.507			

Tree height at 30.5 months was determined from a regression in **Appendix 3.4**, and therefore not analysed as results will mirror those of DBH (**Appendix 7.14**).