Integration of *Eucalyptus* coppice regeneration with mechanical harvesting in South Africa

by

Kylle Schwegman

Submitted in fulfilment of the requirements for the degree Magister Scientae in the Faculty of Science at the Nelson Mandela Metropolitan University, George, South Africa

March 2017

Supervisor: Dr K.M. Little
Co-supervisors: A. McEwan and S.A. Ackerman

Declaration

I, KYLLE SCHWEGMAN (211150207), hereby indicate that the dissertation for Magister Scientae in the Faculty of Science is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

________________ _______________

KYLLE SCHWEGMAN DATE

Official use:

In accordance with Rule G4.6.3,

4.6.3 A treatise/dissertation/thesis must be accompanied by a written declaration on the part of the candidate to the effect that it is his/her own work and that it has not previously been submitted for assessment to another University or for another qualification. However, material from publications by the candidate may be embodied in a treatise/dissertation/thesis.

Abstract

In South Africa, ca. 530 000 ha of the plantation area is planted to *Eucalyptus spp.* which are native to Australia. Commercially grown hardwoods account for 40.5% of the total area planted to trees, yet contribute more than 70% of the timber to the pulpwood market. This is largely attributed to the superior quality of fibre and pulping properties associated with eucalypt plantations, increases in global short-fibre pulp demands. This as well as the ability to reduce the temporary unplanted period and associated re-establishment costs when choosing to regenerate a stand through coppice management. With the unlikelihood of additional eucalypts being introduced into South Africa, and a reduction in genetic gains from 3rd-4th generation tree breading programmes, most of the eucalypts currently planted will be managed for at least one coppice rotation before replanting with improved genetic material if available. This together with the increased use of mechanised silvicultural and harvesting operations, concerns have been raised as to whether the integration of *Eucalyptus* coppice regeneration and mechanical harvesting in South Africa is both possible and financially viable for the forest industry to practise. The need for integration becomes more important as often mechanised systems have smaller tolerance levels when compared to manual systems.

The first trial was situated in Zululand and was implemented to determine the type and severity of stump damage, coppicing potential and coppice growth over the rotation, associated with four types of harvesting and extraction systems on coppice regeneration. Results obtained from these four treatments (harvesting systems that ranged from manual to fully mechanised cut-to-length systems), found that irrespective of the harvesting system used, more damage occurred to the top than bottom half of the stump, with a significant decrease in coppice regrowth with increasing stump damage. Most damage and least coppice regrowth occurred in the extraction rows where the damage recorded could be attributed to vehicle movement, tear-outs and/or log stripping. There was no significant difference between the harvesting systems in terms of stump mortality, final stem stocking and rotation-end volume. Although this trial indicates that the harvesting systems tested had no impact on tree production the severity of damage and/or difference may have been masked by the excellent coppice potential of the species used for this trial (*E. grandis* x *E. urophylla*).

Based on the results obtained in the first trial, and using five existing data sets, each data set consisted of four treatment sub-sets (4m_8m_s; 2m_8m_s; 4m_8m_BOP; 2m_8m_Or) where possible to determine the cost benefits associated with each treatment at various levels of stocking over a full rotation period. BOP (best operating practice) and Or (original stocking) refers to treatments with two stems stump^{-1}, and s (single stem) refers to one stem stump^{-1}. Within each of the four treatment sub-sets, treatments with three levels of stump survival were sought (60%; 80%; 100%), in order to assess financial viability of harvesting different coppice regimes (one coppice stem and two coppiced stems stump^{-1}) using a fully mechanised cut-to-length harvesting system was tested. No differences were found between one coppice stem and two coppiced stems stump^{-1} in terms of financial returns (internal rate of return). Of the four treatment sub-sets (4m_8m_s; 2m_8m_s; 4m_8m_BOP; 2m_8m_Or), treatments which had two coppice stems stump^{-1} lead to increased harvesting cost, while coppice stumps with one stem favours mechanised harvesting and reduced harvesting costs.

The final trial, which was also implemented in Zululand, tested the timing of reduction of one coppice stem stump^{-1} at various stump and stem densities in order to develop an appropriate coppice regime that could favour fully mechanised CTL harvesting systems. Although significant differences were detected at 23 months between the additional control (current recommendation) and the various Reduction_ht (3.5 m, 4.5 m, and 6.5 m) treatments for *Dbh, Ba, and Stocking*. It is likely that these differences may become less with time due to the decrease in absolute and relative differences between the various treatments with time.

This thesis indicates that it is possible to successfully integrate eucalypt coppice regeneration and fully mechanised CTL harvesting. As the results obtained showed that despite the harvesting-associated damage found, no significant difference occurred between the harvesting systems tested in terms of stump mortality, stem stocking (after the final reduction) and rotation-end volume.

With regards to the financial implications (using internal rates of return - IRR) associated with harvesting coppice stands of one or two stems stump^{-1}, no clear cost-benefits were found between either of these two treatment scenarios. As those factors that contribute to increased volumes per hectare (increased stem numbers and the retention of two stems stump^{-1}), tend to become normalised across a treatment sub-

set**,** this results in increased harvesting costs with a reduction in the IRR. Coppice management regimes need to be investigated that favour fully mechanised CTL harvesting systems (fewer stems to harvest, but with increased volumes per stem). This includes a reduction to one stem stump^{-1}, as opposed to the current recommendations where some stumps have two stems, such as was tested in the final trial. Although initial results were promising, rotation-end data would be needed to determine any longer term impacts from carrying out an early thinning of coppice shoots to one stem stump^{-1}.

Future research needs to be carried out to:

- determine the influence of mechanised harvesting and extraction for difference species of eucalypts, especially for those that do not coppice as well as the species tested in these trials (*Eucalyptus grandis* x *Eucalyptus urophylla*),
- develop harvesting productivity and/or volume models for coppiced stands of one and two stems stump^{-1} for different *Eucalyptus* spp.,
- determine financial returns using specifically designed coppice management regimes which optimise the integration of both mechanical harvesting and silvicultural operations.

Publications and presentations related to this research

Details of publications that form part of the research presented in this thesis.

Published reports and papers

Chapter 2: Schwegman K, Little KM, McEwan A, Ackerman SA. 2017. Harvesting and extraction impacts on *Eucalyptus grandis* x *E. urophylla* coppicing potential and rotation-end volume in Zululand, South Africa. *Southern Forests*. In press

Papers submitted for publication

Chapter 3: Schwegman K, Little KM, McEwan A, Ackerman SA. Mechanised harvesting costs for eucalypt coppice stands of varying stump and stem densities, South Africa. Submitted to *Southern Forests* for potential publication.

Chapter 4: Schwegman K, Little KM, McEwan A, Ackerman SA. The influence of *Eucalyptus grandis* x *E. urophylla* stump stocking and timing of stem reductions straight to one stem stump^{-1} to favour mechanised harvesting in Zululand, South Africa. Submitted to the Institute for Commercial Forestry Research for potential publication as peer reviewed *ICFR Technical Note*.

Presentations

ICFR Annual Research Meeting (showcasing current forestry research in South Africa). John Fischer Auditorium, Cedara Agricultural College, 2nd-3rd March, 2016. Oral presentation: "*Harvesting and extraction impacts on* Eucalyptus grandis *x* E. urophylla *coppicing potential and rotation-end volume in Zululand*" by Schwegman K, Little KM, McEwan A and Ackerman SA.

ICFR Zululand Field Day (research findings presented to forest companies). Mtubatuba, Zululand, 19th November, 2015. Oral presentation: "*The impacts of four harvesting systems on rotation-end* Eucalyptus grandis *x* E. urophylla *coppice growth in Zululand, South Africa*" by Schwegman K, Little KM, McEwan A and Ackerman SA.

Table of Contents

Page

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

List of Figures

List of Tables

Acknowledgements

There are many people who have helped to complete the research carried out in this thesis. However, I would like to say thank you to a few people who have been invaluable.

Dr Keith Little for his continued scientific guidance and mentorship over the period that this research was conducted (2015-2016). Without his enthusiasm, encouragement, and criticism this research would not have been possible.

Andrew McEwan for supporting this research and providing the academic guidance and critique required to complete the thesis, despite having to complete his own PhD thesis. Simon Ackerman for his reassurances, and valued input while conducting this research.

The South African forestry industry for providing the land and funding to enable the research trials to be conducted as well as their assistance in the implementation and maintenance of the trials. Andrew King and Mark Hitchings from Sappi Forests, Piet Rheeder of Melann Forestry and Samson Mbokazi of Mondi Mtunzini (SQF) were instrumental in terms of making these trials happen.

Numerous Institute for Commercial Forestry Research (ICFR) staff who were involved in the assessments, including Denis Oscroft, Musa Mkhwanazi, Carol Rolando, Paul Viero and Greg Fuller. Sally Upfold is also thanked for her constructive comments and Xolani Colvelle for sharing his experience and knowledge in data collection. All of the people both at the Institute for Commercial Forestry Research and in the forestry industry who reviewed the manuscripts prior to publication. Their comments were critical to improving the scientific content of the papers as well as the presentation of the results.

A special thanks to the Roberts family for being my home away from home and Jonathan Roberts for facing the trials and tribulations of research with me.

The Pannifers for the continued support and understanding. Especially to Paul Pannifer for his guidance and willingness to share industry experiences. My fiancé Kaylynne Pannifer for her motivation, understanding and high tolerance levels.

And last, but not least, to my parents and sister for instilling the foundation on which my current success is built.

CHAPTER 1

General introduction to mechanised harvesting in forestry, South Africa

1.1 Introduction

Until recently in South Africa, motor-manual harvesting was frequently applied to fell forest stands (Ackerman et al. 2011). This makes use of manually operated chainsaws for the felling, de-branching and cross-cutting of the trees (motor-manual), manual labour for de-barking and stacking of cut-to-length logs, and various combinations of mechanised equipment for extraction and loading (McEwan et al. 2013). Although these labour-intensive systems are still utilised by some growers, from the early 2000s there has been a general shift to the use of semi- or fully-mechanised systems (Längin and Ackerman 2007; Ackerman and Längin 2010).

Various factors have been identified which have contributed to the mechanisation of silvicultural and harvesting operations in the forest industry (Roothman 2014). These factors include:

- Market globalisation and increased global trade: South Africa joined the World Trade Organisation (WTO) in 1994 which lead to increased global trade (Faulker and Loewald 2008). With 164 member states (WTO 2016), export markets opened and competition for forestry and forest products increased. To remain competitive, the South African forest industry has had to become more efficient, which has included the mechanisation of silvicultural and harvesting operations (Baines 2004; SA Forestry 2015). The value of the export market from forest products increased by R 3.9 billion over nine years from 2001 to 2010 (FSA 2014).
- Occupational Health and Safety Act of 1993/1994: Forestry is a high risk occupation, as tasks are carried out infield using hazardous equipment such as chainsaws (DAFF 1997). The Occupational Health and Safety Act aims to ensure a working environment that is safe by facilitating the management of risks (Whiteside and Sunter 2000). Harvesting related incidents account

for up to 70% of all accidents in the forestry environment (Längin et al. 2010). Activities with the highest rates of accidents include motor-manual felling and cross cutting, with chainsaws being the most dangerous implement used (Längin et al. 2010). Studies have recorded a noteworthy reduction in accidents in forest harvesting operations that were mechanised (Reisinger et al. 1994; Axelsson 1998), indicating that fully mechanised operations are safer than motor-manual operations.

- Increase in minimum wage of forestry labourers in 2013: The minimum wage increased from R 58.95 in 2011-2012 to R 102.90 per day for a nine-hour shift in 2013 (RSA 2013). This increase resulted in forest companies reducing their large manual labour forces for those silvicultural and harvesting systems that were as a consequence not as productive as mechanised operations. This was evident in the “2010-2012 State of the Forests” report, where direct employment from forest timber growers decreased from 77 000 to 62 700 employees (DAFF 2015a).
- A diminishing and weakening labour force: Due to the physical nature of work required within the forest industry, educated labourers do not deem the physical working conditions associated with forestry as a preferred means of employment, leading to decreased manual labour forces (Spinelli 2001; Steenkamp 2008; McEwan and Steenkamp 2015). Also HIV/Aids has contributed to a weaker labour force which has led to lowered productivity, ultimately increasing overall costs (Topouzis 2007; Steenkamp 2008; McEwan and Steenkamp 2015).

Therefore, the mechanisation of harvesting operations has, amongst other reasons, occurred so as to capitalize on timber recovery, reduce costs of timber supply, and more importantly to increase operator safety (Gellerstedt and Dahlin 1999; Baines 2004; Spinelli 2001; SA Forestry 2015). Concerns have been raised as to the impacts of mechanised harvesting operations on site productivity and/or environment. Whereas manual-based harvesting systems have a lowered impact, studies have shown that the long term productivity of a site may be impacted by increasingly mechanised harvesting operations through nutrient removal, soil compaction, and soil disturbance (soil displacement) (Boyle et al. 1973; Dyck and Cole 1994; Worrell and Hampson 1997; Bertault and Sist 1997; Smith 1998; du Toit et al. 2004; Rietz 2013).

However, according to Bertault and Sist (1997), these negative impacts may be reduced by careful planning and execution of harvesting operations (for example during wet/dry conditions, soil compaction and/ displacement, and specific selection of extraction routes) and through reduced-impact logging techniques for harvesting and extraction operations (Bertault and Sist 1997; Pulkki 2003; Sist et al. 2003; Pokorny et al. 2005; Putz et al. 2008; Lattimore et al. 2009).

Sist et al. (2003) also discusses the need to develop new silvicultural prescriptions which assist in reducing the impacts of harvesting. This was evident in a trial carried out by Ackerman (2013) which tested the effect of irregular stand structures on growth, wood quality and its mitigation in operational harvest planning of *Pinus patula* Schiede ex Schltdl. & Cham. stands. The study indicated that by changing planting geometry (and hence also planting density) from 2.7 m x 2.7 m to 2.4 m x 3.0 m and 2.3 m x 3.1 m, harvesting trail lengths were reduced from 599.4 m ha^{-1} (2.7 m x 2.7 m), to 506.0 m ha^{-1} (2.4 m x 3.0 m) and 504.0 m ha^{-1} (2.3 m x 3.1 m) respectfully. When comparing 2.3 m x 3.1 m and 2.7 m x 2.7 m planting geometries, a trail reduction of 15.9 % is achieved, which means less movement is required reducing soil damage. Based on studies implemented by Warkotsch et al. (1994) and Bettinger et al. (1998), one can assume that fewer harvesting trails will result in reduced soil damage (soil compaction and soil disturbance) (Ackerman 2013).

The forestry sector, which includes forestry and forest products, provides direct employment for 62 000 people and approximately 30 000 indirect jobs (DAFF 2015a). Many people that are employed by forest companies are local inhabitants from rural areas that rely on forests for food, shelter, wood energy, and fibre (DAFF 2015b). According to DAFF (2013) and FSA (2014), in 2012 the forestry sector contributed 1.2% to the Gross Domestic Product of South Africa. Only 1.9% of the total land area (122. 3 million ha) is occupied by both exotic and indigenous forests, with ca. 1.1% (1.275 million ha) planted to exotic plantation forests (DAFF 2013; FSA 2014). Plantation forestry is aimed at producing commercial timber products of sawlogs, veneer logs, pulpwood, mining timber, poles, matchwood, charcoal and firewood which supply local and export markets (FSA 2014).

The South African commercial forest industry is based entirely on tree species that are native to other countries (Zwolinski and Bayley 2001). Exotic tree species such as *Pinus* (51%), *Eucalyptus* (42%) and *Acacia mearnsii* De Wild (7%), are planted commercially, with a few other tree species planted for niche products (FSA 2014). In the eastern parts of South Africa, selected species of eucalypts and wattle are favoured by commercial forest companies. This is due to their significant pulping yields within short rotations (8-10 years) and the inherent coppicing ability associated with certain *Eucalyptus* spp., which reduces the temporarily unplanted period, maintenance and re-establishment costs (Whittock et al. 2004; Crous and Burger 2015; de Souza et al. 2016).

1.2 Regeneration of *Eucalyptus* species through coppice management

In South Africa, commercial plantations make use of an even-aged stand and clearfelling system. This clearfelling system is a reliable and effective way to achieve uniform regeneration in plantation forestry, as the entire stand is clearfelled in one operation (Nyland 1996; du Toit and Norris 2011). Regeneration within plantation forestry may be carried out in different ways. These include replanting with seedlings or cuttings, direct sowing of seeds, or the management of stump coppice shoots following felling (Stubbings and Schönau 1980; Schönau 1980, 1984, 1991; Nyland 1996; Zbonak et al. 2007). According to Sims et al. (1999), coppice systems are restricted to hardwood genera such as *Eucalyptus* and *Populus* species. South Africa has ca. 530 000 ha of plantation area planted to *Eucalyptus spp.* which are native to Australia (Rockwood et al. 2008; FSA 2014). These tree species are of importance commercially, not only to South Africa, but also China, India and Brazil. Rockwood et al. (2008), state that this is largely attributed to the superior quality of fibre and pulping properties associated with eucalypt plantations, as well as increased global demands for short-fibre pulp.

1.2.1 Re-establishment (Replanting versus Coppicing)

Prior to the 1980s, the range of eucalypts planted was limited in South Africa due to a lack of species choice (Swain and Gardner 2003). From the early 1980s, the need to source and grow alternative *Eucalyptus* spp. was influenced by the South African forestry industry through a shift in focus from mining timber to pulp and paper production (Little and Gardner 2003). Up till this stage, the choice of species planted was primarily based on risk mitigation. For example, in the sub-tropical regions of

South Africa, the ability of a tree to withstand drought or heat damage was considered a more important factor than potential volume or the desirability of the wood for pulp properties and ability to coppice (Gardner et al. 2007).

With improved site-species matching and tree breeding, larger volume gains were obtained through replanting, than through coppice regeneration (Vou 1990; Whittock et al. 2004). Whittock et al. (2004) indicates that the productivity of a coppiced stand may become insufficient through genetic tree improvement, as the actual gains realised by genetically improved trees from parent seed stock may outperform a coppiced stand. However, to be profitable, the genetic gain needs to be more than 15% of the original seed stock (Whittock et al. 2004). Although coppiced stands grow faster than planted seedlings in the early stages, this advantage may not be maintained over longer rotations (Smith et al. 1997).

1.2.2 Coppice regeneration

Coppice stands are vegetatively regenerated by means of re-sprouting shoots on the original parent stump (Smith et al. 1997). The term coppice means a stand arising primarily from sprouting shoots (Smith et al. 1997). Sprouting is triggered as a response to sudden death (or stress), which includes clearfelling the tree and damage caused by an abiotic and/or biotic factor (Smith et al. 1997). The process of sprouting is a result of an interruption of the flow of plant hormones known as auxins, which are produced in the growing tips (i.e. meristematic tissue in the apical regions) of the mature tree and which inhibit the growth of dormant epicormic buds strand (Florence 1996). These epicormic buds are situated in the live bark, or cambium, at the base of the tree (Florence 1996; Whittock et al. 2003).

These dormant buds grow laterally from the original stem, and can be located beneath the bark (Smith et al. 1997; Florence 1996; Whittock et al. 2003), and if at any stage during the growth of the tree the connection between the pith of the dormant bud and the original pith is severed, the dormant bud becomes incapable of developing into a new shoot (Smith et al. 1997). In a study to assess the coppicing potential of *Eucalyptus nitens* Deane and Maiden, Little et al. (2002) found a link between increased damage, from harvesting, to stumps and reduced coppice growth. Although not significant, de Souza et al. (2016), found that willow, eucalypt and cottonwood stumps, when cut with a shear-head (during harvesting), regenerate more sprouts than stumps cut with a chainsaw. This was attributed to the rougher cutting surface created by the shear-head resulting in a higher number of sprouts regenerated, similar to findings obtained by Hytönen (1994) on willow and birch.

This is of concern when considering mechanised harvesting operations, as various studies have recorded different types of stump damage during harvesting operations, namely barber chair, missing chunk(s), fibre pull, split stumps and shattered stumps (Spinelli et al. 2007; Schweier et al. 2014; de Souza et al. 2016). If harvesting machines damage the bark of the stump during harvesting and extraction, the connection of the bark from the stump may be severed, leading to poor coppice production (Little et al. 2002; Spinelli et al. 2014).

Little research is available on the type and severity of *Eucalyptus* stump damage for different levels of mechanised harvesting systems and the subsequent influence of stump damage on coppice ability. This is particularly important in South Africa so as to generate an understanding of the influence of increased mechanisation on the ability to regenerate through coppice.

1.2.3 Benefits of coppice regime/s in South Africa

Many eucalypts are capable of regenerating via coppice for several rotations, although this depends on environmental conditions, stand management, coppice ability, and the vigour of selected tree species (Florence 1996; Sims et al. 1999). According to Chattaway (1958) and Smith et al. (1997), the rapid early growth of coppice sprouts can be attributed to carbohydrate supplies remaining in the stumps/roots from the parent tree and the already well-established root system (Chattaway 1958; Carrodus and Blake 1970; Crombie 1997; Smith et al. 1997). Furthermore the root to shoot ratio of a coppiced stand is higher when compared to replanted seedlings and may contribute to improved survival (Crombie 1997). Studies have shown that vegetation management and fertilisation in coppice stands do not produce any benefits in terms of enhanced coppice growth (Crowther and Evans 1983; Sims et al. 1999; Little and du Toit 2003), and as such coppicing regimes do not require intensive tending operations when compared to planting regimes (Little and du Toit 2003).

Coppice regeneration is mainly used in short rotation stands (such as energy wood, and pulp and paper), and when correctly executed, rapid canopy closure as well as the productive growth of the trees can be achieved (Zbonak et al. 2007; Viero and du Toit 2011). If the productivity, yield and wood quality of coppiced trees are similar to those of the parent trees, regeneration via coppice is preferred over replanting as it reduces management costs, the temporary unplanted period, and re-establishment costs (Whittock et al. 2004; Zbonak et al. 2007; Crous and Burger 2015). Coppice systems also have the ability to improve yields compared to the original parent stand, especially in stands which had lower stump stocking due to poor survival, by leaving two stems stump^{-1} (Schönau 1991). Due to the shorter rotation times associated with coppice relative to replanting (for example 7.5 years as opposed to 8 years) multiple rotations over ca. 254 years will result in the return on investment for coppice regeneration being one additional rotation (Crous and Burger 2015). If correctly managed, coppice regimes can be considered a low cost: high return silvicultural system.

1.2.4 Problems associated with coppice menegement regimes in South Africa

Various problems may be associated with the use of coppice management regimes. For example, if there is an increase in stump mortality over successive rotations of coppice regeneration, this can lead to insufficient stocking, subsequently reducing coppice yields (Stubbings and Schönau 1980). Studies have indicated that an increase in stump mortality, decreases coppice yields (Schönau 1991; Stubbings and Schönau 1980; Sims et al. 1999). Therefore in coppiced stands, the number of stumps per unit area is one of the main contributing factors to yield (Schönau 1991; Crous and Burger 2015). To maintain productive capacity, it is recommended that, an equivalent number of stems as the original stocking be retained for the coppiced stand (Schönau 1991), which means that where stump mortality increases, so will the number stumps with two stems stump^{-1} (Stubbings and Schönau 1980; Schönau 1991). However, if the stump mortality is too high, adequate compensation for mortality is no longer possible, and the option to replant needs to be considered.

A study implemented by Pyttel et al. (2013), on the effect of harvesting on stump mortality and re-sprouting in oak coppice forests, indicated that although stump mortality increased within the stand after coppicing, no clear relationships were found between stump mortality and harvesting method (Pyttel et al. 2013). In addition, a concern for coppice regimes is that where two stems occur stump^{-1}, individual coppice stem volume is reduced (Stubbings and Schönau 1980). For this reason, poorly stocked stands that are coppiced have been associated with smaller stem volume, high stem variation and poor stem form (Stubbings and Schönau 1980; Mc Carthy et al. 2014).

Although not well document, another problem associated with deciding on whether to coppice or replant is the sub-optimal silviculture of the parent crop, sub-standard site preparation, planting techniques and tending. Each of these lead to increased mortality and/or stem variability, which if then coppiced will impact negatively on the ability of that stand to reach its potential productive capacity.

1.2.5 Factors to consider when choosing to regenerate via coppice

In South Africa, due to the decrease in genetic gains over successive generations, it is common practice to coppice rotations after clearfelling the original seedling stock (Viero and du Toit 2011). Although site x species matching is important to ensure that the selected species is matched to the correct site, different eucalypts, levels of genetic improvement and different provenances exhibit differences in terms of their coppicing potential (Little and Gardner 2003). According to Little and Gardner (2003) eucalypts that are planted commercially and that are known to have above 90% coppice regeneration potential include *Eucalyptus andrewsii* Maiden, *E. benthamii* Maiden & Cambage, *E. smithii* Baker, *E. macarthurii* Deane & Maiden, *E. quadrangulata* Deane & Maiden and *E. badjensis* de Beuz et Welch. *Eucalyptus smithii* and *E. macarthurii* also coppice well, as do the hybrids of *E. grandis* x *E. urophylla* and *E. grandis* x *E. camaldulensis* (Little 2000; Little and Gardner 2003).

Little (2000) listed a number of factors, which if correctly managed, would lead to limited stump mortality and improve the development of coppice shoots. The bark should remain firmly attached to the original stump during felling and extraction operations. The height of the cut on the stump should be 10-15 cm above ground, as this will ensure that an adequate number of buds are present on the stump. It is also important to ensure that no slash is left on the stump as it could delay initial sprouting, as well as influence the form of the coppiced stem (Little 2000).

If the bark is removed from the stump, the cambium is also exposed to infection which may contribute to stump mortality (Lückhoff 1955). A study implemented by de Souza et al. (2016) to determine the effects of felling method and season of year on the regeneration of short rotation coppice found that the method of felling had no influence on coppice regeneration for the eucalypts tested and cotton wood trees. Little additional literature could be found on the damage caused to eucalypt stumps by different harvesting machines on coppice productivity, and the long-term impact of such damage, at rotation-end.

1.2.6 Recommendations for managing coppice regimes

To maximise the yield of short rotation coppice stands of *Eucalyptus grandis,* a prerequisite is that the site needs to be suitable for the specific species planted (Stubbings and Schönau 1980). Only then will the optimum stocking and uniformity of the initial stand contribute to achieving maximum yields (Stubbings and Schönau 1980). Stubbings and Schönau (1980), state that the correct planting density should be chosen according to the sites capacity and the end objective at rotation end. Furthermore, uniform parent crop and hence stumps are essential for uniform coppice regeneration. A study on the growth, yield and timber density of short rotation coppice stands of *Eucalyptus grandis,* tested the effects of timing of the initial coppice reduction, number of reductions and the final number of shoots that should remain on the stumps when coppicing (Schönau 1991). For each treatment carried out, Schönau (1991) determined the effect on the diameter, basal area, height, bark thickness, stocking, timber volume, tree form, stump and kerf wastage, changes in productivity and timber density which supported the current recommendations used when copping.

The recommendations made by Stubbings and Schönau (1980) based on this research are still practiced in South Africa today, and can be found in most forest company silvicultural polices. The reduction (thinning) of coppice shoots is carried out in two operations. The first reduction is implemented when the dominant height of the coppice stems is 3-4 m, leaving two shoots stump^{-1}. The second reduction is implemented at 7-8 m, leaving only one or two stems stump^{-1}. Drastic reductions should be avoided as this will increase secondary coppice regrowth (incorrectly referred to as feathering in South Africa), leading to the need for control as competition from this secondary coppice regrowth can reduce the final yield (Stubbings and Schönau 1980).

Stubbings and Schönau (1980) suggested that if two shoots are to be left on a stump, the stump should be large enough to facilitate uniform growth of the two remaining stems. Schönau (1991) found that the performance of a coppice stand is not only influenced by the regime followed for the reduction of coppice shoots (number and timing of reduction operations), but also by factors such as weather, site conditions, stocking and uniformity of initial stand, all which was described in detail by Stubbings and Schönau (1980).

Coppice is an important management tool, which if correctly executed can lead to financial gains. However, a study carried by Ramantswana et al. (2013), on the productivity of an excavator-based Cut-to-length (CTL) harvester in well-stocked *Eucalyptus grandis* compartments, indicated that harvesting (machine) productivity decreased when felling planted stands to coppiced stands of single stems, with the lowest productivity recorded in stands that included a high percentage of two stems stump^{-1}. This means that although coppicing of stands can lead to financial gain, the harvesting costs associated with the mechanised CTL felling of coppiced stands could reduce the overall profits made. There is a lack of research on harvesting productivity in coppiced stands with either one stem stump^{-1}, two stems stump^{-1} or in coppiced stands with varying stump and stem densities (as opposed to well stocked coppice stands). In addition, very little literature could be found that incorporated both silvicultural and harvesting costs into any financial models.

1.3 Harvesting within South Africa

Harvesting, regeneration and tending follow each other sequentially as part of a silvicultural system. Harvesting is an important part of silviculture and is considered the initial stage in the rejuvenation or renewal of a forest (Ackerman et al. 2011). Timber harvesting involves the felling and processing of timber into the desired end product required by management (Ackerman and Längin 2010).

According to Ackerman and Längin (2010) harvesting methods are based on the form in which timber is delivered to roadside and depends on the amount of processing that the wood or raw material undergoes in field.

There are three main harvesting methods used in ground based harvesting within South Africa namely Full-tree (FT), Tree-length (TL) and Cut-to-length methods (Ackerman and Längin 2010). The FT method occurs when the tree is felled at an acceptable stump height, also a requirement for TL and CTL methods, and all biomass above the stump and a portion of the stump is transported to roadside. The TL method occurs when trees are felled, debranched, and topped infield, with only the bole being extracted to roadside. The CTL method is where the trees are felled, debranched, crosscut and topped infield. The log lengths are then extracted to roadside. Each of these harvesting methods apply to different harvesting systems ranging from manual, semi-mechanised to fully mechanised operations (Ackerman and Längin 2010).

Felling can be described as the cutting of trees using equipment such as axes, saws, chainsaws or mechanical harvesting heads (Nyland 1996). Processing in CTL systems consists of de-branching, de-barking and topping and cross-cutting the timber in order to transport logs to roadside or storage depots (Nyland 1996). Where trees have value, harvesting costs can be repaid by selling the timber to local consumers for at a profitable margin (Nyland 1996).

1.3.1 Cut-to-length harvesting in South Africa

According to Längin et al. (2010), slope, ground roughness and ground conditions are factors which limit the selection of the desired harvesting system. Until the late 1990’s, the most commonly used harvesting and extraction systems within South Africa consisted of various combinations of manual, motor-manual, semi- and fully-mechanised systems (Längin and Ackerman 2007; Längin et al. 2010; Krieg et al. 2010).

Various studies have indicated that full-tree and tree-length harvesting methods have higher site impacts (nutrient removal, soil compaction, and soil displacement) when compared to CTL harvesting methods (Boyle et al. 1973; Han et al. 2009; Ackerman and Längin 2010). For this reason, the CTL method is practised widely in Scandinavia countries and Europe as a means of reducing the site impacts which are associated to the use of tree-length and full-tree harvesting methods (Ackerman and Längin 2010).

Motor-manual CTL systems can consist of manually operated chainsaws for the felling, de-branching and cross-cutting of the trees, manual labour for de-barking and stacking of logs, with various combinations of mechanised equipment for extraction and loading (McEwan et al. 2013; Jourgholami et al. 2013; de Wet and McEwan 2011), whereas a semi-mechanised CTL system involves the use of manual labour and machines (Mack 2010, Längin et al. 2010). In South Africa an example of this operation would include that of a chainsaw operator felling, mechanical debranching and de-barking of the tree length and motor-manual cross-cutting infield (Längin et al. 2010; Mack 2010). Manual stacking of logs is carried out infield and extraction is carried out by a three wheeled Bell loader, loading a flatbed trailer which is pulled by a tractor (Längin et al. 2010; Mack 2010). A fully mechanised CTL system in South Africa would include that of a harvester and forwarder, similar to systems used in Europe (Gellerstedt and Dahlin 1999; Krieg et al. 2010; de Wet and McEwan 2011), where the harvester fells, debranches, de-barks and cross-cuts the tree infield, whilst the forwarder loads and extracts the logs to roadside (LeDoux 2010).

There are numerous CTL systems that can be applied in short rotation coppice stands. Although these systems are still utilised, from the early 2000's there has been a transition by the larger commercial companies to the use of semi- or fully-mechanised harvesting systems. The fully-mechanised cut-to-length (CTL) harvesting system is preferred due to reduced site impacts, high quality and adequate fibre recovery (Puttlock 2005; Han et al. 2009; Eggers et al. 2010; de Wet and McEwan 2011).

1.3.2 The influence of coppice on fully mechanised CTL harvesting operations

Previous research on coppice management focused primarily on timing of reduction operations in combination with stem stocking in order to optimise timber volumes at harvesting. From these results, coppice management recommendations were developed which are still currently used within South Africa (Schönau 1980; Stubbings and Schönau 1980; Schönau 1991; Bredenkamp 1991; Little 2007). As discussed the current recommendations include a stepwise reduction of coppice stems, the first to two stems stump^{-1} at a dominant stem height of 3-4 m, and the second to original stocking (one or two stems stump^{-1}) at 7-8 m. Two stems are left on those stumps adjacent to missing stumps in order to obtain full (original) stocking (Schönau 1991). According to Stubbings and Schönau (1980), poor stem form, butt sweep and high stem variation occur due to delayed thinning, or when multiple stems are left within close proximity of one another on one stump (Stubbings and Schönau 1980). Furthermore, Suchomel et al. (2012), Ramantswana et al. (2013) and McEwan et al. (2016), indicate that fully mechanised cut-to-length (CTL) harvesting operations are hindered due to the small stem size and poor stem form associated with the presence of two stems on one stump.

Questions have been raised as to whether the current coppice management recommendations can still be practiced when mechanical harvesting is used (Stubbings and Schönau 1980; Suchomel et al. 2012). Little literature could be found where various coppice reduction heights were reduced in a once-off thinning to one stem stump^{-1} in order to facilitate mechanised harvesting.

1.4 Costs associated with fully mechanised CTL harvesting and silvicultural coppice regime activities

Within South African forestry, investment decisions are regularly made over a seven to 30-year period (Ham and Jacobson 2011). Any costs associated with establishing and tending a stand will only be recovered at the end of this period, dependent on end product (Ham and Jacobson 2011). Forest managers continuously choose between alternative actions such as the choice of species for regeneration, various silvicultural treatments, rotation age and harvesting and transport methods (Ham and Jacobson 2011).

Successful businesses analyse potential projects before investments are made to determine whether the return on investment (interest) received, is superior to other projects that are available (Investopedia 2015). The use of Internal Rate of Return (IRR) for any investor is a key financial decision making tool, and can be used to calculate alternative investment options which ultimately guides management in making decisions (Investopedia 2015; Ham and Jacobson 2011). IRR is defined as the discount rate often used in capital budgeting that makes the net present value (NPV) of all cash flows from a particular project equal to zero (Investopedia 2015). The higher the projects IRR, the more desirable it is to undertake or invest in (Investopedia 2015).

An increase in mechanised harvesting operations together with coppice regeneration has raised concerns regarding the costs associated with mechanical CTL harvesting operations in coppiced stands. Little research has been carried out to determine the cost benefits of mechanically harvesting coppiced stands with a CTL system (excavator based harvester and forwarder). To understand this, the costs involved with harvesting and transport associated with different coppice management regimes need to be calculated, and combined with the costs of associated silvicultural activities over the rotation period.

The implementation of coppice regimes is carried out over an extended period and the associated costs include capital equipment purchased, machines, labour and tools. These operations include the removal of slash from stumps after harvesting has taken place, which means labour is employed to physically remove slash from the stumps. Once the dominant height of the coppice shoots reaches 3 to 4 m, the first reduction operation is needed to remove coppice shoots, leaving two or three dominant stems per stump (Stubbings and Schönau 1980). The second reduction is recommended at a dominant height of 8 m leaving one or two stems stump^{-1} in order to reach the original stocking of the stand. Weed control and secondary coppice regrowth management is also required, at least two times within a rotation period of seven to ten years, to secure high volume yields for the coppiced stand (Little 2007; Little and Oscraft 2010; Roberts et al. 2016).

The costs related to harvesting and transport constitute an estimated 60 to 80% of the mill-delivered cost and is usually carried out at the end of a rotation period (Ackerman and Längin 2010). It is therefore important to understand factors which contribute to increased costs associated with the operations implemented. Tree size is a factor associated with harvesting productivity and as tree size is reduced, costs increase (Spinelli et al. 2002; McEwan et al. 2016). This may be of concern as coppice systems are associated with high stem variation and poor stem form (Stubbings and Schönau 1980).

1.5 Rationale and aims of the study

Although silviculture and harvesting are integrated, both have largely been researched in isolation. Efficiencies in harvesting may have negative impacts in subsequent silvicultural activities (e.g. nutrient removal, soil compaction and soil displacement). Whereas some silvicultural practices may hinder harvesting practices (e.g. closer planting geometry, planting on steep slopes, and the presence of more than one stem stump^{-1}). With increased mechanisation of both silvicultural and harvesting operations, the need for integration becomes more important as often mechanised systems have smaller tolerance levels when compared to manual systems. For example, mechanical felling of stands that are densely planted (close planting geometries, e.g. 2.7 m x 2.7 m) has shown a reduction in harvesting productivity due to limited manoeuvrability, whereas motor-manual systems are less influenced by planting geometry. Coppice regeneration is no different and as such the impacts of mechanised harvesting on subsequent coppice management, as well as the coppice management regimes used on harvesting systems need to be well researched and understood.

Due to the lack of research in this regard a series of trials and/or data were used to quantify and hence provide insight as to the way forward. As the CTL system of harvesting is favoured within South Africa, the coppice management regimes and any interpretations of the data were based on this system. Therefore this thesis aims to support the successful integration of different coppice management regimes with a fully mechanised CTL harvesting system with the following three main objectives:

i. quantifying whether damage caused to stumps with varying levels of mechanised CTL systems influences the ability of eucalypt stumps to coppice;
ii. determining whether there is a financial benefit for the use of fully mechanised CTL harvesting systems in short rotation coppice regimes with either one and/or two coppice stems stump^{-1} at various levels of stump stocking; and
iii. developing a coppice management regime which favours a fully mechanised harvesting CTL harvesting system.

The use of mechanised harvesting and extraction operations can cause different types of stump damage. This is of concern as damage caused to the stumps during these operations may influence the ability of a eucalypt stump to coppice. Little literature is available on the type and severity of stump damage for various levels of mechanised CTL harvesting (motor-manual, semi- and fully mechanised harvesting systems), and the subsequent influence of damage caused to the stump on coppice ability.

Coppice regimes are a low cost, high return silvicultural system but may be associated with poor stem form and high stem variation. This is of concern as harvesting costs increase with smaller stem size. However no research has been implemented to determine the financial return at rotation-end on harvesting a coppice stand, using a fully mechanised CTL system, of one and/or two stems stump^{-1} with varying levels of stump and stem stocking.

Furthermore, research has shown that mechanised harvesting favours one coppice stem stump^{-1} over two coppice stems stump^{-1} due to improved stem form. If coppice shoots are reduced to one stem stump^{-1}, questions are raised as to the required minimum stump/stem morality threshold before replanting? As the CTL system has only been recently introduced (<10 years) in South Africa, research needs to be conducted to better understand how this system is currently being implemented in South Africa, and whether it is being used correctly in relation to silvicultural activities (including coppice management) preceding harvesting.

It is important for the forest industry to obtain this information, and make use of it with regards to improving the integration of mechanised harvesting and silviculture and to develop an appropriate silvicultural coppice management regime for mechanical harvesting systems.

1.5.1 Objective One: To determine the effects of increased levels of mechanisation on the ability of *Eucalyptus grandis* x *E. urophylla* stumps to coppice.

Four combinations of harvesting and extraction systems were used to clearfell a stand of *E. grandis* x *E. urophylla*. These included a motor-manual harvesting system(*Man*), a fully mechanised system (*Mech*), and two additional systems (*Man_Mech_3W* and *Man_Mech_Flexi*) that had increased levels of mechanisation over that of the *Man* treatment. Data collected from these four treatments were used to determine the effects of mechanised harvesting systems on type and severity of stump damage, coppicing potential and coppice growth over the rotation.

Null hypothesis (H_0): No damage will be caused to the stumps by the various harvesting systems with no impact on coppice potential and/or rotation-end volume.

Alternative hypothesis (H_a): That the harvesting systems tested will cause variable amount of damage to the stumps, and hence coppicing potential and/or rotation-end volume.

1.5.2 Objective Two: Determine the cost benefits associated with mechanised harvesting of single and double stems stump^{-1} at various stocking levels.

Rotation-end data sets from five coppice trials were selected to fulfil this objective. Coppice regimes were selected that varied in either the timing (2 or 4 m) and number of reduction operations (one or two), in combination with stem (one or two) stocking (60; 80; 100%). This resulted in a range of treatments (coppice management regimes), against which the regeneration and tending costs and harvesting costs could be compared.

Null hypothesis (H_0): There will be no difference in terms of the return on investments for each of the financial scenarios created. There will be no difference with mechanically harvested coppice stands of one stem stump^{-1} and/or two stems stump^{-1} and various levels of stump stocking.

Alternative (H_a): That the return on investments, for each of the financial scenarios created will differ for mechanically harvested coppice stands of one stem stump^{-1} and/or two stems stump^{-1} and various levels of stump stocking.

1.5.3 Objective Three: Develop an appropriate coppice management regime best suited for mechanised harvesting

A trial was implemented in Zululand on *Eucalyptus grandis* x *Eucalyptus urophylla* to test coppice management regimes that would facilitate mechanised harvesting without loss of productivity. Coppice stems were reduced to a single stem stump^{-1} (3.5 m; 4.5 m; 6.5 m) in combination with varying stump stocking levels (75%; 85%; 100%). These nine treatment combinations were compared to current best operating practice.

Null hypothesis (H_0): No differences will be observed for the timing of thinning coppice shoots in one reduction operation to one stem stump^{-1} at various levels of stocking, and when compared to the current recommended best operation practices.

Alternative (H_a): That differences will be observed for the timing of thinning coppice shoots in one reduction operation to one stem per stump at various levels of stocking, and when compared to the current recommended best operation practices.

NOTE: The research chapters (Chapters 2, 3 and 4) contained within this thesis were prepared as separate research outputs (papers), with their original format retained. As the contents of these chapters dealt with subject matter around a common theme (coppice management and harvesting), some duplication of contents is inevitable, particularly with respect to the introduction and literature review sections. Data to fulfil Objectives One and Two were obtained from the Institute of Commercial Forestry Research.

CHAPTER 2

Harvesting and extraction impacts on *Eucalyptus grandis* x *E. urophylla* coppicing potential and rotation-end volume in Zululand, South Africa

Abstract

From the early 2000s there has been a general shift in South Africa in harvesting and extraction systems from the use of semi- to fully-mechanised systems. Any increase in mechanization, as is occurring in Zululand, will need to take into consideration damage to stumps and the subsequent ability to regenerate by coppice. In 2002, four types of harvesting and extraction systems, arranged in a randomised complete block design (RCBD), were used to clearfell a stand of *E. grandis* x *E. urophylla*. A motor-manual harvesting system was used to carry out the manual harvesting system (*Man*). The fully mechanised system (*Mech*) consisted of a single-grip harvesting head used with a tracked excavator to carry out all felling and processing operations. Two additional systems (*Man_Mech_3W* and *Man_Mech_Flexi*) had increased levels of mechanisation over that of the *Man* treatment. Both these harvesting systems made use of a Bell de-barker, with loading carried out by a Bell 3-wheeled loader in the *Man_Mech_3W,* and by a Flexiloader in the *Man_Mech_Flexi.* Data collected from these four treatments were used to determine the effects of mechanised harvesting systems on type and severity of stump damage, coppicing potential and coppice growth over the rotation. Irrespective of harvesting system, more damage occurred to the top than bottom half of the stump, with a significant decrease in coppice regrowth with increasing stump damage. Most damage and least coppice regrowth occurred in the extraction rows where the damage recorded could be attributed to vehicle movement, tear-outs and/or log stripping. There was no significant difference between the harvesting systems in terms of stump mortality, final stem stocking and rotation-end volume. Thus individual components within each harvesting system can have a larger impact than the overall harvesting system used. Future research should focus on these components, and where associated damage occurs for a specific component,

this should be lessened through management intervention, training or technological improvements.

2.1 Introduction

A harvesting system refers to the equipment and machines used to harvest and extract timber from an area (Ackerman and Längin 2010). Until the late 1990's, the most commonly used harvesting systems within South Africa consisted of various combinations of manual, motor-manual and mechanical operations (Ackerman and Längin 2010), for example the use of manually operated chainsaws for the felling, de-branching and cross-cutting of the trees (motor-manual), manual labour for de-barking and stacking of cut-to-length logs, and various combinations of mechanised equipment for extraction and loading (McEwan et al. 2013). Although these labour-intensive systems are still utilised by some growers, from the early 2000s there has been a general shift to the use of semi- or fully-mechanised systems (Ackerman and Längin 2010). The mechanisation of harvesting operations has, amongst other reasons, occurred so as to capitalize on timber recovery, reduce costs of timber supply, and to increase operator safety (Gellerstedt and Dahlin 1999). Although motor-manual harvesting techniques may be more cost-effective in certain circumstances, for example in difficult terrain and stands with lower stocking, concerns regarding operator safety have also contributed to an increase in mechanised operations (Spinelli et al. 2002). In addition, manual harvesting-related operations are likely to decrease with time due to a decline in the availability of manual labour (Spinelli et al. 2002).

In Zululand in particular, harvesting includes the use of semi- and fully-mechanised systems: chainsaw operators in combination with cable skidders extracting to road side; single grip tracked or wheeled harvesters for a cut-to-length system, where the logs are extracted to road side with various forwarders; the use of a wheeled/tracked feller-buncher together with a grapple skidder for extraction (McEwan et al. 2013); and specific machines used for targeted operations, for example a three-wheeled logger for processing, stacking and in-field loading of timber.

In South Africa, most eucalypts are regenerated through re-planting of seedlings or management of stump coppice shoots following felling. Both methods of regeneration are used in Zululand, although in well-stocked and uniform stands, coppice regeneration may be preferred due to associated reduced re-establishment costs (Whittock et al. 2004). Coppice regeneration makes use of the management of the re-sprouting shoots on the original parent stump following felling (Smith et al.

1997). The current recommendation requires two operations that reduce coppice shoot numbers, the first at a dominant height of 3-4 m leaving two stems $stump^{-1}$, and a second to the original stocking at a dominant height of 7-8 m (Stubbings and Schönau 1980). Damage to stumps during harvesting operations has been shown to have a negative impact on coppicing potential. In a study to assess the coppicing potential of *Eucalyptus nitens* Deane and Maiden, Little et al. (2002) found a link between increased damage from harvesting to stumps and reduced coppice growth.

Any increase in mechanisation, together with associated across-site impacts, will need to take into consideration damage to stumps and the subsequent ability to regenerate by coppice. Although not significant, de Souza et al. (2016), found that willow, eucalypt and cottonwood stumps when cut with a shear-head, regenerate more sprouts than stumps cut with a chainsaw. This was attributed to the rougher cutting surface created by the shear-head resulting in a higher number of sprouts regenerated, similar to findings obtained by Hytönen (1994) on willow and birch. Damage caused to coppice stumps by different harvesting machines on coppice productivity and the long-term impact of these at rotation-end is poorly represented in the literature. In 2002, four levels of harvesting (from manual, through semi-mechanised to fully mechanised) were used to fell a stand of *E. grandis* x *E. urophylla*. Data collected from these four treatments were to used determine the effects of mechanised harvesting systems on type and severity of stump damage, coppicing potential and coppice growth over the rotation.

2.2 Materials and methods

2.2.1 Trial location, design and layout

The trial was located at Trust Plantation, Sappi Forests Central Area in Zululand, South Africa (28° 31.960’ S and 32° 9.970’ E). The climate is sub-tropical, with a mean annual precipitation of 1 033 mm and mean annual temperature of 21.8 °C. The site was situated at an altitude of 39 m above sea level on deep yellow Fernwood soils (Soil Classification Working Group 1991) (FAO and USDA equivalents: arenic lixisol and arenic kandiustult, respectively). The growing conditions are considered optimum for *E. grandis* x *E. urophylla* with a Site index (SI_5) of 21 m, and an estimated maximum mean annual increment of 42 m^3 ha^{-1} (Smith et al. 2005a, 2005b). The site was originally planted to *E. grandis* followed by multiple rotations of coppice before being replanted to a *E. grandis* x *E. urophylla* hybrid clone (GU A380) in September 1994. The trees were planted at a square spacing of 2.74 m x 2.74 m, which results in a planting density of 1 332 stems ha^{-1}.

Four contrasting harvesting treatments/systems (Table 2.1) were imposed within the 8 ha stand when the trees were felled at age eight years (September - October 2002). The harvesting systems were selected to cover the then current harvesting practices occurring in the Zululand region at the time of trial implementation. Each treatment combination was selected to cover a range from manual, through semi-mechanised to fully-mechanised in terms of felling, de-barking, cross-cutting, stacking, loading and extraction (Table 2.1).

The manual treatment (*Man*), with the lowest degree of mechanisation, utilised manual labour to carry out all the felling operations together with a Bell three-wheeler (Bell 3-wheeler) and Bell tractor and trailer for loading and extraction (Bell Equipment 2015a). The fully mechanised treatment (*Mech*) consisted of a standard Hitachi 20-t tracked excavator (FH 200), equipped with a purpose built Waratah harvesting boom and Waratah 616 harvester head to carry out all felling operations (Hitachi 2015, Waratah 2015). A modified Bell front-end loader and Bell articulated dump truck (T17D) was used for loading and extraction. Two additional harvesting systems (Table 2.1: *Man_Mech_3W* and *Man_Mech_Flex*) were also included which had increased levels of mechanisation over that of the *Man* treatment. Both these harvesting systems made use of a 225A Bell de-barker with a 4-wheeled configuration to de-bark the trees (Bell Equipment 2015b). The main difference between *Man_Mech_3W* and the *Man_Mech_Flex* was that the loading was carried out by a Bell 3-wheeler for the *Man_Mech_3W* and a modified Bell front-end loader for the *Man_Mech_Flex* (Table 2.1).

Table 2.1: The four harvesting systems used to fell a stand of *Eucalyptus grandis* x *E. urophylla* in Zululand, South Africa. The harvesting systems were selected to include a transition from manual, through semi-mechanised to fully mechanised.

Harvesting systems	Felling	Debarking	Cross-cutting	Stacking	Loading and Extraction
Manual (Man)	motor-manual (chainsaw)	manual (axe)	motor-manual (chainsaw)	manual (labour)	Bell 3W onto Bell tractor and trailer
Man_Mech_3W	motor-manual (chainsaw)	mechanical (Bell de-barker)	motor-manual (chainsaw)	manual (labour)	Bell 3W onto Bell tractor and trailer
Man_Mech_Flex	motor-manual (chainsaw)	mechanical (Bell de-barker)	motor-manual (chainsaw)	manual (labour)	Flexiloader onto Bell tractor and trailer
Mechanised (Mech)	mechanical (harvester)	mechanical (harvester)	mechanical (harvester)	mechanical (harvester)	Flexiloader onto Bell forwarder (T17)

As the 8 ha stand was rectangular with service roads along the longitudinal axes, all harvesting operations were carried out in swathes across the stand from road to road. Each harvesting swathe consisted of 5 tree rows, with the extraction route (ex) in the centre, and 2 rows on either side. To simulate commercial harvesting operations, the stand was partitioned into 16 large blocks (plots), within which the harvesting systems were imposed. The four harvesting systems were examined in a randomised complete block design (RCBD) with four replications (16 harvesting system plots of 0.5 ha each). Three sub-plots were included within each harvesting system plot to account for some of the variability that may have occurred within each treatment swathe. These three sub-plots were systematically located within all treatment plots (harvesting swathe), with each sub-plot consisting of 3 rows of 20 stumps. The 3 sub-plot rows were always located such that they included an extraction row (ex), with 2 rows on either side (1st and 2nd row). This would allow for the detection of differences (if any) due to location within a swathe.

2.2.2 Measurements

Changes in stump mortality were determined relative to the original planted stocking. Stump height (m) and diameters (m) were measured, the latter in two planes, through the widest cross-section and at 90° to this section. These measures were used as co-variates in terms of their possible influence on coppice growth, with stump height providing information on either the height above ground at which stumps were cut (or as an indication of soil movement against the stumps) for the different harvesting systems.

To determine differences in the type and severity of stump damage caused during harvesting and extraction, each stump within the sub-plots were assessed for: vehicle damage (evidence of vehicle movement over stump);

- movement of slash and/or soil from around stump (exposed roots or stumps covered);
- damage caused during log stripping/cross-cutting;
- damage caused during felling (tear-outs where a section of bark and wood was removed during felling), splinters (section of wood remaining on the stump after felling); and
- stumps that were undercut (two incomplete cuts at different heights).

Viewed from above, each stump was divided into quarters within which all of the above assessments were carried out. To further determine if there were differences relative to the stump height at which damage occurred, the stumps were sub-divided into top and bottom halves. This equated to 2 lots of quarters (n = 8 sections in total) that were assessed per stump for every measurement. Within these 8 sections, the assessments were further graded in terms of damage severity (0 for none, 1 for partial, and 2 for total). The presence or absence of coppice shoots (sprouts) was assessed within each of the 8 sections.

2.2.3 Stand management and assessments

Current recommendations for the commercial management of coppiced stands were applied to the whole compartment. This involved the reduction of coppice shoots to 2-3 stems stump^{-1} at 3-4 m in height, followed by a second and final reduction to original stocking (1 332 stems ha^{-1}) at a height of 7-8 m. To compensate for missing stumps, two stems were left on adjacent stumps. Any vegetation or secondary coppice regrowth was chemically controlled with glyphosate so as to exclude competition (Little 2007). Stump survival and the number of coppice stems were assessed at the time of the reduction operations.

Following the final reduction to the original stocking in January 2004, the diameters at breast height (*Dbh* in cm) for all the coppice stems in each sub-plot were measured annually until rotation-end (September 2010). Four coppice stem heights (*Ht* in m) were measured within each sub-plot on each measurement occasion. At rotation-end a regression equation was derived for those trees with both *Dbh* with *Ht* measurements, and this was used to estimate the *Ht* for all the trees in the trial. *Stump* and *Stem Stocking* were derived from stump and coppice stem survival data, and *Stem Stocking* was used with the *Dbh* measurements to calculate the basal area (*BA* in m^2 ha^{-1}) on a treatment plot basis. The estimated merchantable underbark volume for each treatment to a top-end underbark diameter of 5 cm was calculated using the following equation (Equation 2.1) (Growth and Yield data base – Institute for Commercial Forestry Research, Pietermaritzburg, South Africa) developed for *E. grandis* x *E. urophylla* coppice growing in the same region:

$$Vol = (10\text{^}(-4.56+(\mathrm{LOG10}(Dbh)*2.06272)+(\mathrm{LOG10}(Ht)\times 1.000736))) \qquad \text{Eq. 2.1}$$

The volume (*Vol* in m^3 ha^{-1}) for each treatment was calculated by combining the sum of the merchantable volume $plot^{-1}$ with the stocking $plot^{-1}$.

2.2.4 Analysis

For the variables of *Stump* and *Stem Stocking*, *Dbh, Ht, BA* and *Vol,* an analyses of variance (ANOVA) appropriate for a RCBD (with 3 sub-plots within each treatment plot) was used to test for treatment effects using GenStat for Windows (VSN International 2013). Only if the *F*-value was significant ($p < 0.05$) were treatment differences further investigated using the least significant difference statistic (*lsd*). Prior to all analyses, the assumptions appropriate for a valid ANOVA were checked.

As the presence of living trees prior to felling within the treatments was significant, the *Stump Stocking* was used as a covariate to account any changes following treatment implementation.

Mean plot data for the variates of stump damage and coppice presence were first partitioned into the three stump positions relative to the extraction route (ex; 1st;

2^{nd}). Within each of these, the sum for the top (n = 4) and bottom half (n = 4) were determined. Regression (linear and non-linear) with treatments as groups was carried out to determine if there was a relationship between stump damage and coppice regrowth prior to any reduction operations. A single line was found to account for most of the variability in the data set, with a significant decrease in coppice regrowth (irrespective of harvesting treatments) with increasing stump damage (*F*-prob < 0.01; r = 0.89; RMSE = 3.04).

To further explore the type and severity of damage to the stumps relative to the four systems, the means, 95% confidence intervals and the standard deviation were calculated for the stump damage variates, and displayed as a box and whisker plot.

2.3 Results and discussion

Just before harvesting, the mean stocking was 1 223 stems ha^{-1}. There were no significant treatment differences in stump height ($\bar{x}$ = 11.6 cm) and diameter ($\bar{x}$ = 18.6 cm) following felling. This indicates a degree of uniformity of the standing trees prior to felling, as well as consistency in terms of the stump height at which felling occurred for the different systems which was within the accepted industry practice of 10 - 15 cm (Little 2000; Turnbull and Booth 2002; Crous and Burger 2015). Stump mortality was negligible, with a mean mortality for the whole trial of 2.13 % at rotation-end (1 197 stumps ha^{-1}) (Table 2.2). The mean stocking of the coppice stems at rotation-end was 98% of the original stocking (1 308 stems ha^{-1}) with no significant differences between harvesting systems.

Table 2.2: Summary analysis of variance showing mean square values for selected variates in a trial to determine the impact of four harvesting systems on *Eucalyptus grandis* x *E. urophylla* coppicing potential in Zululand, South Africa.

Source of variation	**d.f.**	***Dbh*** **(cm)**	***BA*** **(m^2 ha^{-1})**	***Vol*** **(m^3 ha^{-1})**	***Stump stocking*** **(stumps ha^{-1})**	***Stem stocking*** **(stems ha^{-1})**
Rep Stratum						
Covariate	1	0.017**	0.248^{ns}	15.620^{ns}	$4\,932.5^{ns}$	1.1^{ns}
Residual	2	0.138	0.910	66.550	43.1	877.4
Main Plot Stratum						
Harvesting systems	3	0.121^{ns}	1.309^{ns}	54.360^{ns}	$1\,100.1^{ns}$	944.4^{ns}
Covariate	1	0.027**	0.581^{ns}	50.460^{ns}	$52\,751.9^{ns}$	$1\,633.4^{ns}$
Residual	8	0.105	0.642	48.120	401.2	557.0
Main Plot_Sub-plot Stratum						
Covariate	1	0.006**	1.286^{ns}	51.990^{ns}	$96\,987.8^{ns}$	$6\,137.7^{ns}$
Residual	31	0.085	0.584	36.740	822.1	915.0
Total	47					
Summary of data						
Grand mean		13.7	19.6	130.6	1 196.7	1 308.4
Standard error of difference of means		0.203	0.501	4.335	12.520	14.750
Coefficient of variation % (units)		2.1	3.9	4.6	2.4	2.3

Note: ** indicates significance at *F*-prob < 0.01 and ^{ns}, non-significance.

Although there were no significant treatment differences in stump diameter and stump height with harvesting system, stump height varied with position in the felling swathe. For all four harvesting systems the stumps in the extraction route were the lowest, with an increase in height the further the stump row away (ex-row, $\bar{x} = 10.7$ < 1st row, $\bar{x} = 11.9$ < 2nd row, $\bar{x} = 13.0$). This difference in stump height did not indicate that the stumps were cut at different heights, but rather that the differences detected were a function of the movement of soil up against the stumps from vehicle movement. In a study of harvesting impacts on site, Grey and Jacobs (1987) found that vehicle movement during extraction could impact on soil in terms of soil movement up to half a wheel width from the vehicle tracks. The greatest soil movement occurred within the extraction row, as both sides of the vehicles wheels/tracks straddled the stumps, whereas only one wheel/track resulted in soil movement against the 1st row, and no vehicle movement for the 2nd row. A comparison of two harvesting systems in the central interior of British Columbia by Han and Renzie (2005) on subalpine fir, white spruce, lodgepole pine and Douglas-fir, recorded that manually felled stump heights were 5.5 cm higher than those that were mechanically felled. Slope, species and stump diameter influenced the two harvesting systems significantly and it was found that the feller-buncher, which used a cutting disk, was able to cut diameters of between 30-70 cm lower on slopes < 30%. As the slopes increased above 45%, the stump heights that were manually felled were lower than where mechanically felled. Possible reasons for this could be a combination of terrain difficulty associated with manual felling and the use of a felling disc for mechanical felling, which is able to cut lower down due to being more impervious to damage associated with low cuts.

The severity of damage was greatest within the extraction row for all systems (n = 4.28), followed by the 1st and 2nd rows (n = 3.26 and 2.99 respectively) (Figure 2.1). More traffic in the extraction rows is the most likely reason for this, with a corresponding decrease in traffic and hence damage in the 1st and 2nd rows. In contrast to the three manual and semi-mechanised systems (*Man, Man_Mech_3W, Man_Mech_Flex*), there was an increase in stump damage in the 2nd row for the fully mechanised treatment (*Mech*). This damage is possibly due to log processing (de-branching, stripping and cross-cutting) being carried out with a boom which lifted the tree above that of the 1st row. This resulted in the butt end of the log hitting the stumps in the 2nd row.

More damage occurred in the top than the bottom half of each stump (1.94 versus 1.15 quarters damaged stump^{-1}), irrespective of treatment (Figure 2.2). This is to be expected as the top half of each stump is more exposed during harvesting operations. Overall damage was lowest in the *Man* system and highest in *Man_Mech_3W* and *Man_Mech_Flex* systems. This could be explained by the increased vehicle movement within the harvesting swathes.

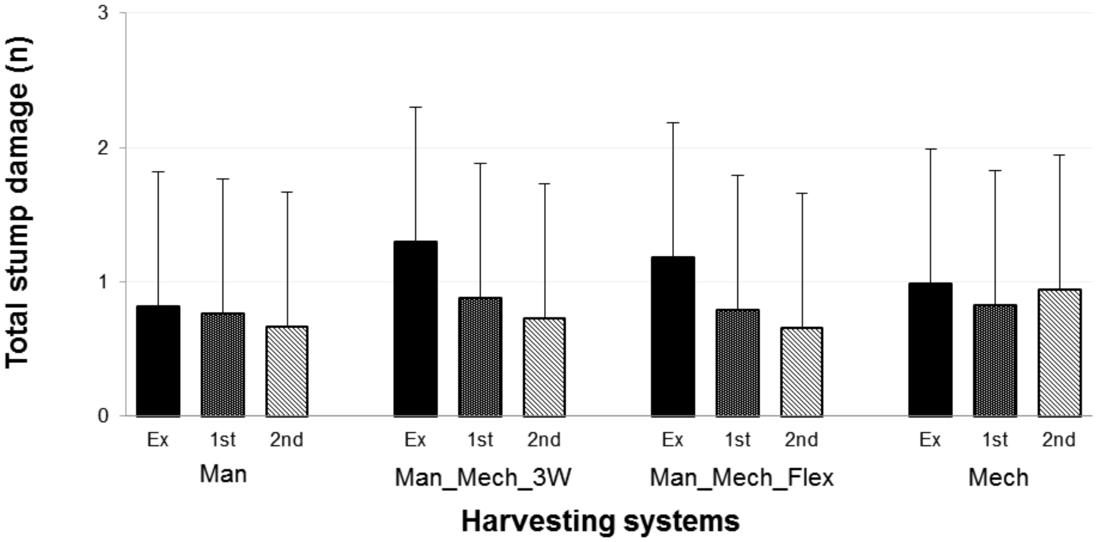

Figure 2.1: Stump damage (n = mean per treatment) relative to harvesting swathe position in a trial to determine the impact of four harvesting systems on *Eucalyptus grandis* x *E. urophylla* coppicing potential in Zululand, South Africa. Standard deviation is shown by bars.

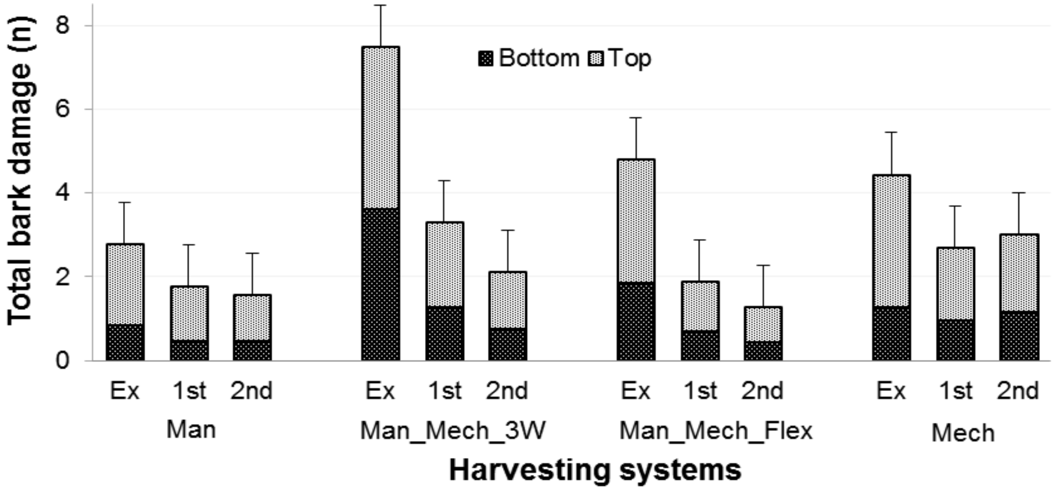

Figure 2.2: Bark damage (n = mean per treatment) relative to the top/bottom half of stumps and harvesting swathe position in a trial to determine the impact of four harvesting systems on *Eucalyptus grandis* x *E. urophylla* coppicing potential in Zululand, South Africa. Standard deviation of the total (top and bottom halves) shown by bars.

Of the variates that were assessed to explain harvesting and/or extraction damage, vehicle damage (which includes tyre and track damage), stump tear-out and log stripping accounted for most of the damage (39, 22 and 12 % respectively) (Figures 2.3a-c). V*ehicle damage* was highest for all four systems within the extraction row, followed by the 1st and then 2nd rows (Figure 2.3a-c) and most severe in *Man_Mech_3W and Man_Mech_Flex.* This could be explained by increased vehicle movement over the whole plot associated with the use of a Bell 3-wheeler to de-bark the trees. The lowest vehicle damage was recorded in the *Man* system, where vehicle movement was confined to the extraction row.

Although *Stump tear-outs* (removal of bark and fiber) accounted for 22% of the overall damage recorded, no clear trends occurred within, or between systems, other than the extraction row having lower damage. Damage from *Log stripping* was lowest in the *Man* treatment with no differences occurring between the 3 rows assessed. For the other three harvesting systems where logs were mechanically processed, there was an increase in log stripping damage, with the *Mech* treatment having the highest overall damage associated with *Log stripping*. This is due to the use of the harvester boom lifting the stem while de-barking the tree with the stem butt striking the stumps in the 1st and 2nd rows.

The influence of the harvesting system on coppicing potential was assessed by scoring the presence of coppice shoots prior to any reduction operations in the same 8 segments where damage was scored (Figure 2.4).

Coppicing potential could be related to the severity of damage caused to the bark of stumps by the various systems. Irrespective of harvesting system, an increase in bark damage resulted in a significant decrease in coppice potential, with more damage and less coppice on the upper half of the stumps (Figures 2.2 and 2.4). If the connection between the pith of the dormant epicormic bud and the original pith is severed, the dormant bud becomes incapable of developing into a new shoot (Smith et al. 1997).

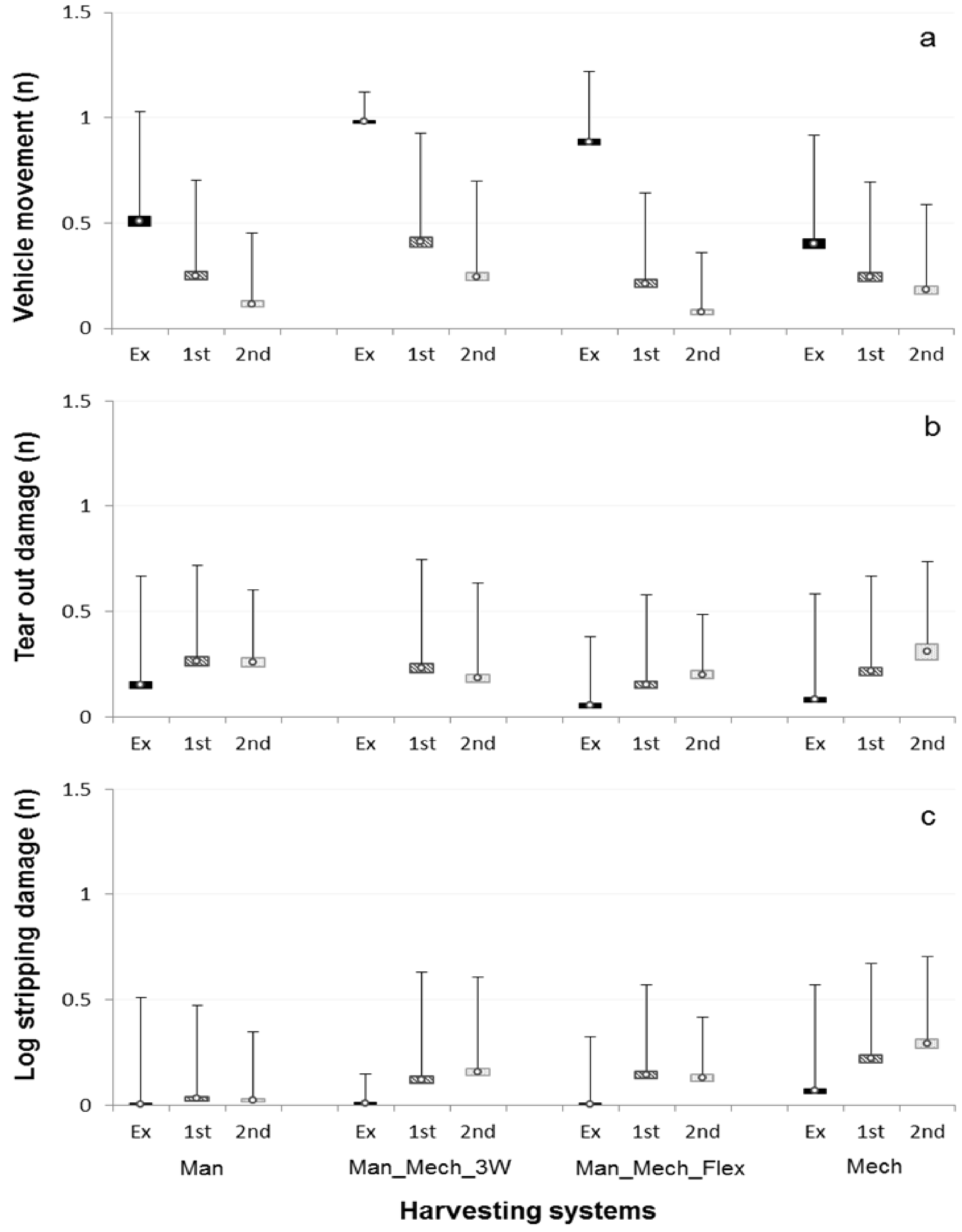

Figure 2.3: Stump damage (n = mean per treatment) caused by vehicle movement (a), tear-out (b), and log stripping (c) relative to harvesting swathe position in a trial to determine the impact of four harvesting systems on *Eucalyptus grandis* x *E. urophylla* coppicing potential in Zululand, South Africa. Harvesting system means are shown as hollow circles, the 95% confidence levels by the boxes, and the standard deviation by the bar.

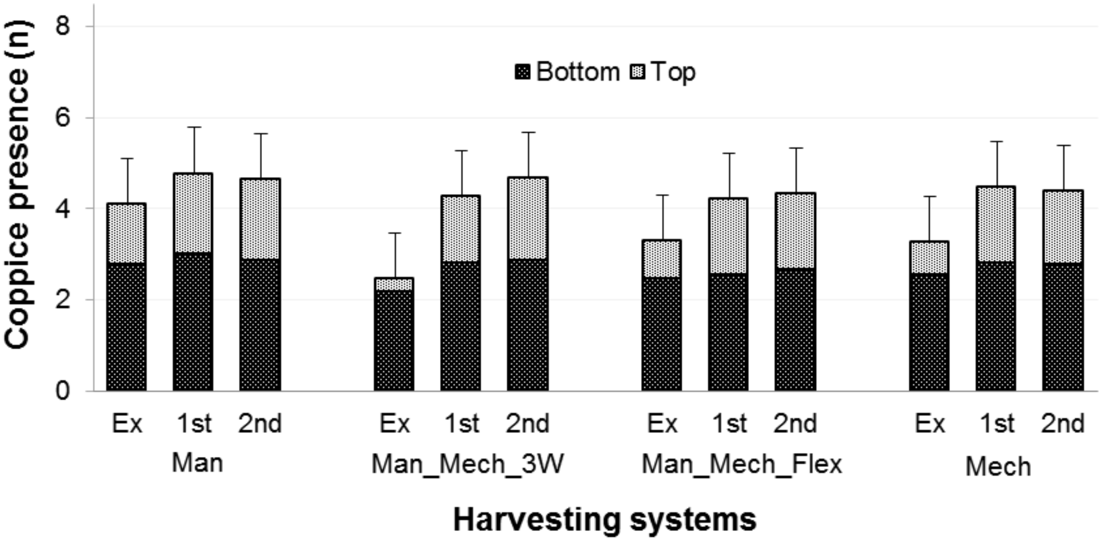

Figure 2.4: Presence of coppice (n = mean per treatment) relative to top/bottom half of the stump and harvesting swathe position in a trial to determine the impact of four harvesting systems on *Eucalyptus grandis* x *E. urophylla* coppicing potential in Zululand, South Africa**.** Standard deviation of the total (top and bottom halves) shown by bars.

Following the reduction operations, there was no significant impact of the damage recorded on stocking, with a non-significant mean trial stocking of 1 196.7 stem ha^{-1} achieved after the final reduction. This indicates that although increased damage resulted in reduced coppicing potential, enough coppice growth occurred such that adequate stocking was still obtained after the final reduction operation. Little and Gardner (2003), showed in a trial comparing the coppicing ability of 20 *Eucalyptus* species grown at two high-altitude sites in South Africa, that different eucalypts vary in their ability to coppice. If harvesting damage were to occur on weakly coppicing eucalypts, it is likely that there will be a reduction in coppicing potential and hence yield. A study carried out by Little et al. (2002) on the coppicing potential of *Eucalyptus nitens* (a weakly coppicing eucalypt) following felling, found that an increase in stump damage caused a significant reduction in the ability of that stump to produce coppice sprouts.

In contrast to *E. nitens*, the clonal hybrid used in this trial, *E. grandis* x *E. urophylla* is regarded as fairly resilient in terms of recovery following harvesting and/or fire. There were no treatment-related significant differences for any of the tree growth variates (*Ht*, *Dbh*, *BA* and *Vol*) at rotation-end. This indicates that although varying degrees of damage and coppicing potential were recorded, *E. grandis* x *E. urophylla* is still capable of recovering and producing a standing crop. Whether eucalypts with lower coppicing potential would be able to produce a similar crop following the same levels of damage would need to be tested in future studies.

2.4 Conclusions

Of the four harvesting systems tested, there were no significant differences in terms of the heights at which the stumps were felled, although differences were observed within each harvesting system, with lower stumps in the extraction row than in adjacent stumps rows. This could be attributed to soil movement against the stumps in the extraction row. Damage to the stumps was more severe, and coppice regrowth less, on the top half of the stumps due to the top half being more exposed. Likewise coppice regrowth was less in the extraction row due to increased damage from vehicle movement. This damage could be attributed to a combination of three main harvesting associated factors, vehicle movement, tear-outs (during felling) and log stripping. An increase in the use of vehicles for the various harvesting operations, for example a 225A Bell de-barker with a 4-wheeled configuration (*Man_Mech_3W* and *Man_Mech_Flex*) resulted in greater damage to stumps. Of interest, log stripping damage to the 2nd row of stumps was higher than the 1st row and extraction row in the fully mechanised harvesting system (*Mech*) due to the boom which lifted the tree above that of the 1st row. This resulted in the butt end of the log hitting the stumps in the 2nd row. Of the three main types of damage detected, future damage could be reduced through operator awareness and training. For example, careful movement around stumps, ensuring a clean cut through the tree which would reduce tear-outs, and the lifting of the booms and/or movement of the booms rather than the logs during log stripping.

Despite this harvesting-associated damage, no significant difference occurred between the harvesting systems in terms of stump mortality, stem stocking (after the final reduction) and rotation-end volume. Although this trial indicates that the harvesting systems tested had no impact on tree production, the damage severity and/or difference may have been masked by the excellent coppice potential of the species used for this trial (*E. grandis* x *E. urophylla*).

From this trial, it is clear that it is the individual components within each harvesting system used (felling, manual chainsaw operator versus single grip harvesting head, manually stripping versus mechanical stripping, etc.), that can have a larger impact than the overall harvesting system used. As such, future research should rather focus on the individual components of a harvesting system, and where associated damage occurs for a specific component, then this should be lessened through management intervention, training or technological improvements.

CHAPTER 3

Mechanised harvesting costs for eucalypt coppice stands of varying stump and stem densities, South Africa

Abstract

Within South Africa, the current recommendation for regeneration via coppice includes two reduction (thinning) operations, the first reduction is carried out when the coppice stems are at a dominant height of 3-4 m leaving two stems stump^{-1}, and the second reduction to the original stocking at a dominant height of 7-8 m. This results in some stumps having two stems. However with increased mechanisation, studies indicate that two stems stump^{-1} influence the harvesting costs for fully mechanised cut-to-length harvesting systems (e.g. harvester and forwarder), as machine productivity decreases the more stumps there are that have two stems. Five existing rotation-end coppice trials were selected based on coppice reduction treatments implemented and stocking variation within each trial. Each of these were then grouped into four treatment sub-sets (4m_8m_s; 2m_8m_s; 4m_8m_BOP; 2m_8m_Or) to determine the cost benefits associated with each treatment at various levels of stocking over a full rotation period. BOP (best operating practice) and Or (original stocking) refers to treatments with two stems stump^{-1}, and s (single stem) refers to one stem stump^{-1}. Within each of the four treatment sub-sets, treatments with three levels of stump survival were sought (60%; 80%; 100%). Since each trial originally had different objectives, not all treatment sub-sets occurred within each trial. However where two or more treatment sub-sets did occur, comparisons were made. Regardless of site, there was a decrease in individual stem volume with increased stocking. Individual stem volume was also greater for those treatment sub-sets that were thinned to one stem (s), as opposed to where two stems remained on stumps. For those treatments where two stems occurred on selected stumps (BOP and Or treatments), the volume of stem B was always smaller than stem A. Harvesting costs were directly related to individual stem volumes, with higher machine productivity associated with smaller stem volumes. Within treatment sub-sets, there was an increase in harvesting costs with increased stem and stump stocking. Variation across sites for Internal Rate of

Return (IRR) were largely a function of volume and transport costs (distance to the mill). For sites with lower volumes, the lower stumpage price and higher harvesting costs resulted in a lower IRR. No clear trends were noticed between treatment sub-sets for IRR. Therefore coppice management regimes that favour fully mechanised CTL harvesting systems should be investigated, particularly those where the merchantable volume is not significantly different from the current best operation practice. It is recommended that future studies with dedicated treatments need to be designed and data generated that will address the short-comings mentioned within this paper, as well as the formalization of harvesting productivity models which focus on one coppice stem rather than two coppice stems stump^{-1} for various species of *Eucalyptus*.

3.1 Introduction

Due to variable site and market conditions within South Africa, a variety of species are grown for the commercial production of timber. The main species include pines, eucalypts and *Acacia mearnsii*, with the eucalypts becoming increasingly important as the global demand for wood fiber increases (FAO 2009). Up to 1980, *Eucalyptus grandis* Hill ex Maiden, *Eucalyptus nitens* Maiden*, Eucalyptus macarthurii* H. Deane & Maiden, *Eucalyptus fastigata* H. Deane & Maiden and *Eucalyptus elata* Dehnh were planted extensively within sub-tropical, and warm and cool temperate regions of South Africa (Swain and Gardner 2003).

From the early 1980's, the South African market focus shifted from mining timber to pulp and paper. This was particularly important in terms of the global pulpwood market due the preference for various *Eucalyptus* spp. and their associated good timber properties (Swain and Gardner 2003). With the aim of increasing the cost-effective production per unit area (Jones et al. 2000; Little and Gardner 2003; Smith et al. 2005a). This led to the introduction of alternative *Eucalyptus* spp. namely *E. dunnii* Maiden, *E. benthamii* Maiden & Cambage and *E. smithii* R.T. Baker in South Africa, in combination with site-species matching and improved genotype (genetic improvement). It is unlikely that additional eucalypts will be introduced into South Africa, and this together with a reduction in genetic gains from the 3-4th generation tree breading programmes, will mean that most of the eucalypts currently planted will be managed for at least one coppice rotation before replanting with improved genetic material (Whittock et al. 2004; Viero and du Toit 2011).

Most of the *Eucalyptus* species have the ability to produce coppice shoots when felled, and are regenerated via coppice as opposed to replanting (Little and Gardner 2003). Within South Africa, the current recommendation for regeneration via coppice includes two reduction (thinning) operations, the first reduction is carried out when the coppice stems are at a dominant height of 3-4 m leaving two stems stump^{-1}, and the second reduction to the original stocking at a dominant height of 7-8 m (Stubbings and Schönau 1980; Little 2007). Although the selective removal of these stems during reduction operations is costly and may result in damage to the remaining stems, any stems that do remain will be the best on that stump (Little et al. 2002). Other important aspects to consider during the reduction operations are that the stems are firmly attached to the stump, and where two stems remain per stump, they should be evenly spaced, and if preferable on opposite sides for uniform stem form and volume (Stubbings and Schönau 1980; Little et al. 2002). Poor stem form, butt sweep and high stem variation occur due to delayed thinning, or when multiple stems are left within close proximity of one another on one stump (Stubbings and Schönau 1980). It is also recommended that two stems are left stump^{-1} on border or boundary rows when coppicing a stand to act as a buffer, and to compensate for wind-associated damage such as wind-throw. These recommended coppice management techniques will optimise the productive potential of that site (Evans and Turnbull 2004).

The number of stumps which have two stems stump^{-1} within any stand can vary dependent on a combination of original planting density and stocking when felled. Although a 20-25 % mortality of the original planting density may be considered acceptable for regeneration via coppicing, the higher the stump mortality, the more double stems (two stems stump^{-1}) that will be left within the stand following the final reduction. For example, within South Africa a stand will be replanted if the stocking at felling is less than 1 000 stems ha^{-1}, which if coppiced would mean that more than 333 stumps would have two stems stump^{-1} for an original stocking of 1 333 stems ha^{-1}, and more than 666 stumps would have two stems stump^{-1} for an original stocking of 1666 stems ha^{-1} (Stubbings and Schönau 1980). When compared to replanting, the costs associated with regeneration via coppice are reduced, as coppicing does not require intensive site preparation, nor the costs associated with planting and/or tending. In addition, growth may commence immediately after felling, due to a live and fully developed root system (Whittock et al. 2004; Zbonak et al. 2007).

Until the late 1990’s, the most commonly used harvesting and extraction systems within South Africa consisted of various combinations of manual, motor-manual and mechanical operations (Längin and Ackerman 2007). Although these systems are still utilised, from the early 2000’s there has been a general shift among the larger commercial companies to the use of semi- or fully-mechanised harvesting systems. The fully-mechanised cut-to-length (CTL) harvesting system is preferred due to its reduced site impacts, quality and adequate fibre recovery (Puttlock 2005; Han et al. 2009; Eggers et al. 2010; de Wet and McEwan 2011). An example of a fully mechanised CTL harvesting system includes the use of an excavator based harvesting machine with a felling and processing head and a forwarder for extraction (Längin et al. 2010). However, the presence of stands that have stumps with two stems stump^{-1} poses felling difficulties when a harvester head is used. This is due to poor stem form, high stem size variability and the extended handling times associated with felling two stems in close proximity on one stump that ultimately reduce the harvesting productivity (Spinelli et al. 2002; Suchomel et al. 2012; Ramantswana et al. 2013; McEwan et al. 2016). Also the average stem volumes for both individual stems (for stumps with two stems) is less than when compared to average volume of an individual stem (for stumps with one coppice stem). According to Morley et al. (2008) the reason for this difference is due to competition for light where two stems occur on one stump, which means lowered photosynthesis resulting in reduced growth. A study carried out by Morley and Little (2011), on the comparison of taper functions between two planted and coppiced eucalypt clonal hybrids in South Africa, indicated that where two stems occur on one stump, volumes were over-predicted by approximately 6% and where one stem occurred stump^{-1} the volumes were under-predicted by approximately 4%.

A study carried by Ramantswana et al. (2013), on the productivity of an excavator-based harvester in well-stocked *Eucalyptus grandis* compartments (that had either been planted or coppiced), indicated that harvesting productivity was highest in planted stands than in coppiced stands of single stems, with the lowest productivity recorded in stands that included a high percentage of two stems stump^{-1}. This decrease in productivity was attributed to the variation in stem size and poor stem form that can be associated with coppiced stands (Ramantswana et al. 2013). Similar results have been obtained for coppice and/or replanted stands by Stubbings and Schönau (1980), Spinelli et al. (2002), Suchomel et al. (2012) and McEwan et al. (2016). With the presence of two stems on the same stump, concerns over the efficiency of mechanised harvesting within coppiced stands have been raised (Suchomel et al. 2012).

Little literature could be found related to harvester productivity within coppiced stands of various stump and stem densities (as opposed to well stocked coppiced stands), or the total costs that take silviculture and harvesting in to consideration. As such, treatment data were selected from five completed *Eucalyptus* coppice management trials in South Africa to determine the:

- cost:benefits associated with the establishment and felling of stands managed under different coppice regimes;

- influence of stump mortality and stem stocking on profit;
- contribution made by the smaller of the two stems on one stump, to the final volume (where two stems have been left) and its influence on overall profit if mechanically harvested;
- influence of site, species and productivity on rotation-end volume and thus the income based on the Internal Rate of Return (IRR); and
- the optimum coppice management regime/s if a fully mechanised CTL system (harvester-forwarder combination) is used.

3.2 Materials and methods

3.2.1 Trial description

From the mid-1990's, a series of coppice-related trials were implemented within South Africa to test a range of coppice management regimes for optimum volume production. Five trials were selected that had different coppice reduction treatments implemented, together with a variation in stocking (stump and stem) that occurred within each trial. Although each trial was implemented with different objectives, and hence treatments that differed to those of this study, where possible similar coppice management treatments were sought that would allow treatment comparisons, both within and between trials. These treatments could be grouped into four main coppice management regimes (or treatment sub-sets) based upon the timing of coppice reduction operations (2m; 4m; 8m), number of reduction operations (one or two), and the number of stems remaining after the final reduction operation (1 or 2 stems stump^{-1}) (Table 3.1). Where possible the current recommendation, referred to as the "best operating practice" (BOP) was included for comparison, and consisted of two reduction operations, the first to 2-3 stems stump^{-1} at 4m, and the second to the original stocking (1-2 stems stump^{-1}) at 8m. For this treatment 2 stems are left on stumps adjacent to missing stumps to ensure the coppice stem stocking approximates that of the original stand density. Within each of the four treatment sub-sets, treatments with three levels of stump survival were sought (60%; 80% 100%). All five trials consisted of a eucalypt matched to that site, with original planting densities prior to coppicing that ranged from 1 333 to 1 666 stems ha^{-1} (Table 3.2).

Table 3.1: *Eucalyptus* coppice management regimes selected in terms of varying stump and stand densities for the determination of mechanised harvesting costs, South Africa.

Treat. No.	**Treat description**	**Number of coppice stems remaining after reduction (thinning)**			**Stump stocking (%)**	**Justification**
		Reduction at 2 m	**Reduction at 4 m**	**Reduction at 8 m**		
1	**2m_100_s**	1	-	-	100	- Early reduction to 1 stem stump^{-1} - 100% stump and stem stocking
2	**2m_80_s**	1	-	-	80	- Early reduction to 1 stem stump^{-1} - 80% stump and stem stocking
3	**2m_8m_100_Or**	2-3	-	1-2	100	- Final reduction to 1-2 stem stump^{-1} - 100% stump and stem stocking
4	**2m_8m_80_Or**	2-3	-	1-2	80	- Final reduction to 1-2 stems stump^{-1} - 80% stump stocking - 100% stem stocking
5	**2m_8m_60_Or**	2-3	-	1-2	60	- Final reduction to 1-2 stems stump^{-1} - 60% stump stocking - 100% stem stocking
6	**2m_8m_100_s**	2-3	-	1	100	- Final reduction to 1 stem stump^{-1} - 100% stump and stem stocking
7	**2m_8m_80_s**	2-3	-	1	80	- Final reduction to 1 stem stump^{-1} - 80% stump - 100% stem stocking
8	**2m_8m_60_s**	2-3	-	1	60	- Final reduction to 1 stem stump^{-1} - 60% stump stocking - 100% stem stocking
9	**4m_8m_100_s**	-	2-3	1	100	- Final reduction to 1 stem stump^{-1} - 100% stump and stem stocking
10	**4m_8m_80_s**	-	2-3	1	80	- Final reduction to 1 stem stump^{-1} - 80% stump stocking - 100% stem stocking
11	**4m_8m_100_BOP**	-	2-3	1-2	100	- Final reduction to 1-2 stems stump^{-1} - 100% stump and stem stocking
12	**4m_8m_80_BOP**	-	2-3	1-2	80	- Final reduction to 1-2 stems stump^{-1} - 80% stump stocking - 100% stem stocking

Table 3.2: Site characteristics for five *Eucalyptus* coppice management trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa.

Region	**Forest zone**	**KwaZulu-Natal - Midlands**	**KwaZulu-Natal - Zululand**	**KwaZulu-Natal - Zululand**	**KwaZulu-Natal - Zululand**	**Mpumalanga**
	Magisterial district, Plantation	**Greytown, Umvoti**	**Lower Umfolozi, Mavuya**	**Enseleni, Teza A**	**Enseleni, Teza B**	**Piet Retief, Vroegeveld Wes**
Latitude and Longitude		29° 14.207' S 30° 25.280' E	28° 31.756" S 32° 11.316" E	28° 30.688" S 32° 10.248" E	28° 28.438" S 32° 08.088" E	26° 58' S 30° 44' E
Altitude (m a.s.l.)		1197	30	55	75	1 291
Mean annual temperature (°C)		16	21.8	21.8	21.8	17.1
Mean annual rainfall (mm)		1173	990	916	897	858
Climate zone*		WT3 (warm temperate)	ST8 (sub-tropical)	ST7 (sub-tropical)	ST7 (sub-tropical)	WT4 (warm temperate)
Selected topsoil physical properties	**Taxonomy (SA)[1]**	Clovelly (2100)	Yellow Fernwood (1210)	Yellow Fernwood (1210)	Yellow Fernwood (1210)	Hutton
	Taxonomy (FAO)	-	Harplic Arenosol	Harplic Arenosol	Harplic Arenosol	-
	Depth (m)	+1.1	+1.5	+1.5	+1.5	0.59
	Texture	SiCLLm	sand	sand	sand	SaCLLm
	OC (WB)	6.76	0.30	0.35	0.31	-
Spacing (stems per hectare – sph)		3 x 2.16 m (1 544 sph)	3 x 2.5 m (1 333 sph)	3 x 2.5 m (1 333 sph)	3 x 2.5 m (1 333 sph)	3 x 2 m (1 666 sph)
Species planted		*E. smithii*	*E. grandis* x *E. urophylla*	*E. grandis* x *E. camaldulensis*	*E. grandis* x *E. camaldulensis*	*E. dunnii*
Drought Risk	**>850 mm**	81%	79%	68%	58%	11%
	<650 mm	1%	6%	6%	19%	55%
Potential productivity	**Growing conditions***	Optimum	Optimum	Optimum	Risk of drought	Optimum
	Estimated mean annual increment	38-40 $m^3\ ha^{-1}\ yr^{-1}$	38-42 $m^3\ ha^{-1}\ yr^{-1}$	18 $m^3\ ha^{-1}\ yr^{-1}$	17-18 $m^3\ ha^{-1}\ yr^{-1}$	19-22 $m^3\ ha^{-1}\ yr^{-1}$

*Data obtained from Smith *et al.*, 2005a and ICFR Trial Research database.

3.2.2 Overall silvicultural management of the coppice

For all trials, once felled any slash was removed off the stumps so as not to delay sprouting, or to impact negatively on subsequent coppice development. When the coppiced shoots reached a dominant height as specified for each treatment (2 or 4 m), the first coppice reduction was carried out so as to leave 2 to 3 stems stump^{-1}. At Piet Retief, one treatment also included the leaving of 1 stem stump^{-1} at a dominant height of 2 m (Table 3.3). A second reduction operation was carried out when the remaining coppice shoots reached a dominant height of ca. 8 m, and dependent on the specific treatment, leaving only 1 or 2 stems stump^{-1} (to achieve either the original planted stocking, or a single stem stump^{-1}). Regular weed control was carried out and the secondary coppice regrowth controlled so as not to impact negatively on the remaining coppice stems.

3.2.3 Measurements

Following the felling of the originally planted trees, treatment plots were superimposed on each stand at each site using the existing stump positions for the location of the plots. The presence or absence of living stumps was scored per plot and used to determine the overall stocking prior to felling, as well as for the determination of which treatment would be allocated to which plots. In all trials, the height of the coppice shoots was measured regularly during the first 9 - 22 months after felling, so as to schedule the timing of the reduction operations as determined by that specific treatment (Table 3.3).

Table 3.3: The timing and sequence of events for selected coppice management regimes in five *Eucalyptus* trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa.

Trial (species)	**Treatment scenario**	**Time of coppice reduction operation after felling (months)**		**Date trees planted**	**Date trees felled and managed for coppice**	**Date coppiced trees felled**	**Age when felled**	
		1st	**2nd**				**Year + month**	**Days**
Umvoti (*E. smithii*)	2m_8m_100_Or	9 m	22 m	01/1992	01/2002	01/07/2012	10 y 6 m	3 833 d
	2m_8m_80_Or	9 m	22 m					
	2m_8m_60_Or	9 m	22 m					
	2m_8m_100_s	9 m	22 m					
	2m_8m_80_s	9 m	22 m					
	2m_8m_60_s	9 m	22 m					
Mavuya (*E. grandis x E. urophylla*)	2m_8m_100_Or	8 m	13 m	10/1992	02/02/2000	18/02/2008	8 y 1 m	2 938 d
	2m_8m_80_Or	8 m	13 m					
	2m_8m_60_Or	8 m	13 m					
	2m_8m_100_s	8 m	13 m					
	2m_8m_80_s	8 m	13 m					
	2m_8m_60_s	8 m	13 m					
Teza A (*E. grandis x E. camaldulensis*)	4m_8m_100_BOP	6 m	15 m	Date unknown	09/1996	28/11/2003	7 y 2 m	2 617 d
	2m_8m_100_Or	4 m	15 m					
	4m_8m_100_s	6 m	15 m					
	2m_8m_100_s	4 m	15 m					
Teza B (*E. grandis x E. camaldulensis*)	2m_8m_100_Or	6 m	14 m	6/1991	14/06/2000	19/02/2008	7 y 8 m	2 806 d
	2m_8m_80_Or	6 m	14 m					
	2m_8m_60_Or	6 m	14 m					
	2m_8m_100_s	6 m	14 m					
	2m_8m_80_s	6 m	14 m					
	2m_8m_60_s	6 m	14 m					
Vroegeveld (*E. dunnii*)	2m_100_s	9 m	-	Date unknown	02/1995	18/05/2002	7 y 3 m	2 646 d
	2m_70_s	9 m	-					
	2m_8m_100_Or	9 m	22 m					
	2m_8m_80_Or	9 m	22 m					
	4m_8m_100_BOP	16 m	22 m					
	4m_8m_80_BOP	16 m	22 m					

Following the final coppice reduction (treatment specific), the diameters at breast height (*Dbh* in cm) and stem height (*Ht* in m) for all the coppice stems were measured annually until rotation-end. Stump and stem stocking were derived from survival data, and these together with *Dbh* measurements were used to calculate the basal area (*BA* in m^2 ha^{-1}) on a treatment plot basis. To allow for a comparison between harvesting productivity and harvesting costs at rotation-end, the estimated merchantable volume for each tree was calculated (underbark volume to a top-end underbark diameter of 5 cm - *Vol* in m^3). Volume equations, based on coppice stands, were used for *E. grandis* x *E. urophylla* and *E. grandis* x *E. camaldulensis* with generic tree equations applied to *E. smithii* and *E. dunnii* (Equations 3.1 – 3.4) (Growth and Yield data base – Institute for Commercial Forestry Research, Pietermaritzburg, South Africa):

$$\text{Merch } Vol\ (E.\ smithii) = (10^\wedge(-5.712+(\text{LOG10}(Dbh)*1.443)+(\text{LOG10}(Ht)\times 2.345))) \qquad \text{Eq. 3.1}$$

$$\text{Merch } Vol\ (GxU) = (10^\wedge(-0.986+(\text{LOG10}(Dbh)*1.7839)+(\text{LOG10}(Ht)\times 1.248))) \qquad \text{Eq. 3.2}$$

$$\text{Merch } Vol\ (GxC)= (10^\wedge(-4.5696+(\text{LOG10}(Dbh)*2.0845)+(\text{LOG10}(Ht)\times 0.9896))) \qquad \text{Eq. 3.3}$$

$$\text{Merch } Vol\ (E.\ dunnii)= (10^\wedge(-4.5084+(\text{LOG10}(Dbh)*2.1209)+(\text{LOG10}(Ht)\times 0.8414))) \qquad \text{Eq. 3.4}$$

The volume ha^{-1} for each treatment was then calculated by combining the sum of the merchantable volume $plot^{-1}$ with the stocking $plot^{-1}$.

3.2.4 Harvesting machine productivity

For the purpose of determining harvesting productivity, a model (Equations 3.5 and 3.6) based on a CTL mechanised harvesting system within South Africa was used (Ramantswana et al. 2013). The values obtained within the model were based on the felling of *E. grandis* coppiced stand by means of a tracked Hitachi Zaxis 200-3 excavator (equipped with an Isuzu four-cylinder turbo engine) as the carrier for a Waratah HTH616 harvester head (Ramantswana et al. 2013). Separate equations were used to calculate harvesting productivity for the first and second stems (Stem A - Equation 3.5; Stem B - Equation 3.6).

Harvesting productivity for stem A

$$\left(m^3\ PMH_0{}^{-1}\right)=2.494+61.9498*(Vol\ A)-26.5277*(Vol\ A)^2 \qquad \text{Eq. 3.5}$$

Harvesting productivity for stem B

$$(m^3\ PMH_0^{-1})=2.3016+39.2977*(\mathit{Vol}\ A)+31.1302*(\mathit{Vol}\ B)$$
$$-22.5507*(\mathit{Vol}\ A)^2-33.9884*(\mathit{Vol}\ B)^2+4.3548*(\mathit{Vol}\ A) \qquad \text{Eq. 3.6}$$

The mean stem volume for coppiced stands with one stem and two stems stump^{-1} was calculated for each treatment scenario. These means were then substituted into the harvesting productivity model along with the appropriate coefficients, which then calculated the cubic meters per Productive Machine Hour ($m^3\ PMH_0^{-1}$). Productive Machine Hours (PMH) refers to the portion of scheduled machine hours (actual working hours minus breakdowns, repairs, maintenance, fuelling and greasing) during which the machine is actually productive (Hogg et al. 2010).

To calculate the harvesting costs, the productivity model was used to determine harvesting machine productivity ($m^3\ PMH_0^{-1}$). Once this was determined the estimated volume ($m^3\ ha^{-1}$) was divided by the modelled machine productivity ($m^3\ PMH_0^{-1}$) to provide the expected $PMH\ ha^{-1}$. The harvesting costs were determined by multiplying the harvesting cost per hour (R 1 450 hr^{-1}) to operate the machine with the $PMH\ ha^{-1}$. The $R\ PMH^{-1}\ ha^{-1}$ was converted to dry volume ha^{-1} to determine the harvesting cost tonne^{-1}.

3.2.5 Cost assumptions

3.2.5.1 Silviculture

As these values (costs) differ from company to company due to company polices and/or practices, all cost assumptions made use of industry averages (FES 2016). Cost calculations were based on the assumption that the stand was managed for coppice regeneration according to company best operating practises. The activities in terms of labour units used ha^{-1}, include the clearing of slash from the stumps following harvesting, the carrying out of a 1st and 2nd reduction operation, and the management of secondary coppice regrowth following the reduction operations and up until canopy closure. Although competition from weeds has been shown not to impact on coppice growth (Little and du Toit 2003), targeted the control of woody weeds (in particular exotic invasive weeds) does occur at least every two years following canopy closure until felling, and these costs were also included. As the costs associated with each silvicultural activity differ between companies, an average cost based on data obtained from four commercial companies was used (Table 3.4). An overhead cost of R 900 ha^{-1} associated with tree protection, insurance and administration was also included.

Table 3.4: Silvicultural cost assumptions used for costing calculations based on a daily rate of R135 unit^{-1}.

Cost activities for the management of coppiced stands	No. of labour units (Unit's ha^{-1})	Cost (R unit^{-1})
Stump clearing	5	675
1st coppice reduction	10	1 350
2nd coppice reduction	6	810
Secondary coppice regrowth control	3.5	**472.5
Noxious weed control	0.8	*215.2

Note:* Costs include herbicide, ** Manually removed using bush knife.

Transport costs included primary transport (short-haul), loading and secondary transport (long-haul, delivery to mill). Although transport costs will vary depending on distance to mills, for example from Umvoti to the mill is approximately 100 km whereas Vroegeveld to the mill is approximately 250 km. To enable a direct comparison between sites that excluded exogenous factors, such as transport costs, an average value of R 236.63 tonne^{-1} was used.

3.2.5.2 Gross and Nett Income

Within South Africa, the cost of timber delivered to the mill is based on tonnes (R 850 tonne^{-1} for *Eucalyptus smithii* and R 775 tonne^{-1} for all other *Eucalyptus* spp. Using eucalypt-specific conversion factors, the volumes associated with each treatment were converted to tonnes ha^{-1}: *E. grandis* x *E. camaldulensis* = 0.75; *E. grandis* x *E. urophylla* = 0.70; *E. smithii* = 0.81; and *E. dunnii* = 0.88.

From this the gross income per hectare (*R ha^{-1}*) could be determined for each treatment, and the nett income could be calculated by subtracting the harvesting and transport cost hectare^{-1}.

3.2.5.3 Net Present Value (NPV) and Internal Rate of Return (IRR)

Using the total costs for the silvicultural activities hectare^{-1}, the NPV discounted at 6% over a standard 7-10 year period was calculated. The final year includes the nett income ha^{-1}. The IRR was calculated from the NPV and is defined as "*the* *discount rate used in capital budgeting that makes the net present value (NPV) of all cash flows from a particular project equal to zero*" (Investopedia 2015a). The higher the treatment IRR, the more desirable it is to undertake or invest in (Investopedia 2015a).

The data used within this study were obtained to test key questions associated with mechanised harvesting of coppiced stands. As such, cognisance needs to be taken of the following: data were obtained from five trials, whose original objectives differed from those of this study; measured treatment plots were small (12 - 16 measured trees excluding border rows), which meant that minor treatment differences could become masked and/or magnified; due to multiple possible arrangements of missing stumps (gaps within a plot), there could be variability in those plots with lowered stocking; generic regeneration costs were used, as were generic equations that were not always eucalypt- or site-specific, and; there was the backwards selection of treatments based on rotation-end stump and stem stocking. Nevertheless, care was taken in the selection of appropriate data sets so as to minimize the influence of the above aspects, allowing for the valid testing of principles as described in the objectives

3.3 Results and discussion

3.3.1 Tree growth

As each site consisted of different species, site productivities, planting densities and rotation lengths, tree performance varied according to site (Table 3.2). To allow for a more direct comparison across sites in terms of merchantable volume, the 2m_8m_100_Or treatment was selected as it was the only treatment common to all trials (Table 3.5). *E. smithii* at Umvoti had the highest volume per hectare (250 m^3 ha^{-1}) followed by *E. grandis* x *E. urophylla* at Mavuya (208 m^3 ha^{-1}), with *E. dunnii* at Vroegeveld the lowest (109 m^3 ha^{-1}). This is largely a function of age at felling with *E. smithii* felled at 10 years and *E. dunnii* at 7 years, whereas the maximum volume production for *E. dunnii* is achieved at 8 - 9 years (Kotze et al. 2011).

Table 3.5: Rotation-end stem and stand data for selected *Eucalptus* coppice management regimes obtained from five trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa (sph = Stems ha^{-1}).

Trial (species)	Treatment scenario	Original stump stocking (sph)	Coppiced stem stocking (sph)		Final stocking (sph)	Mean volume per coppiced stem (m^3)		Mean volume per ha (m^3 ha^{-1})		Total volume per hectare (m^3 ha^{-1})	Mean annual increment (m^3 ha^{-1} yr^{-1})
			Coppiced stem A	Coppiced stem B		Coppiced stem A	Coppiced stem B	Coppiced stem A	Coppiced stem B		Adjusted for coppice rotation
Umvoti **(*E. smithii*)** **1666 sph**	2m_8m_100_Or	1 429	1 429	250	1 679	0.149	0.147	213	37	250	23.8
	2m_8m_80_Or	1 236	1 158	309	1 467	0.176	0.160	204	49	253	24.1
	2m_8m_60_Or	1 081	1 043	463	1 506	0.189	0.158	197	73	270	25.7
	2m_8m_100_s	1 390	1 390	-	1 390	0.155	-	215	-	215	20.5
	2m_8m_80_s	1 236	1 158	-	1 158	0.174	-	201	-	201	19.2
	2m_8m_60_s	1 004	985	-	985	0.220	-	217	-	217	20.6
Mavuya **(*E. grandis x E. urophylla*)** **1333 sph**	2m_8m_100_Or	1 144	1 133	100	1 233	0.174	0.105	197	11	208	25.7
	2m_8m_80_Or	1000	988	166	1 154	0.192	0.137	190	23	212	26.3
	2m_8m_60_Or	944	922	267	1 189	0.169	0.116	156	31	187	23.1
	2m_8m_100_s	1 167	1 156	-	1 156	0.171	-	198	-	198	24.5
	2m_8m_80_s	1 067	1 067	-	1 067	0.188	-	201	-	201	24.8
	2m_8m_60_s	1 000	989	-	989	0.184	-	182	-	182	22.5
Teza A **(*E. grandis x E. camaldulensis*)** **1333 sph**	2m_8m_100_Or	1 259	1 148	185	1 333	0.138	0.052	158	10	168	23.5
	2m_8m_100_s	1 333	1 321	-	1 321	0.126	-	166	-	166	23.2
	4m_8m_100_BOP	1 272	1 222	111	1 333	0.129	0.035	158	4	162	22.6
	4m_8m_100_s	1 333	1 333	-	1 333	0.125	-	167	-	167	23.3
Teza B **(*E. grandis x E. camaldulensis*)** **1333 sph**	2m_8m_100_Or	1 230	1 126	222	1 348	0.109	0.056	123	12	135	17.6
	2m_8m_80_Or	1 259	993	267	1 260	0.117	0.051	116	14	130	16.9
	2m_8m_60_Or	1 274	859	430	1 289	0.123	0.071	106	31	136	17.8
	2m_8m_100_s	1 156	1 156	-	1 156	0.114	-	132	-	132	17.2
	2m_8m_80_s	1 022	1 022	-	1 022	0.126	-	129	-	129	16.8
	2m_8m_60_s	889	889	-	889	0.138	-	123	-	123	16.0
Vroegeveld **(*E. dunnii*)** **1666 sph**	2m_100_s	1 510	1 493	-	1 493	0.062	-	93	-	93	12.8
	2m_70_s	1 250	1 204	-	1 204	0.082	-	99	-	99	13.6
	2m_8m_100_Or	1 512	1 466	108	1 574	0.071	0.044	104	5	109	15.0
	2m_8m_80_Or	1 111	1 111	208	1 319	0.083	0.021	92	4	97	13.3
	4m_8m_100_BOP	1 528	1 481	31	1 512	0.068	0.039	101	1	102	14.1
	4m_8m_80_BOP	1 250	1 157	139	1 296	0.075	0.059	87	8	95	13.1

In addition, the Piet Retief region (within which Vroegeveld was located) experienced a drought during the early stages of establishment (1992-1995). During this period a mean annual average of 735.1 mm annum^{-1} was recorded in contrast to the long term average of 858 mm annum^{-1} (Weather SA 2016). However when the growth over the rotation is normalised through the use of the Mean Annual Increment (MAI) (average across all treatments for each site), Mavuya was the highest (24.5 m^{3} ha^{-1} yr^{-1}), Umvoti the second highest and Vroegeveld the lowest (13.7 m^{3} ha^{-1} yr^{-1}) (Table 3.5).

On sites with similar soil and climatic conditions, but planted to different trees, such as Mavuya and Teza A, *E. grandis* x *E. urophylla* outperformed *E. grandis* x *E. camaldulensis* (by 5.5%). As these trials were conducted prior to the recent occurrence of insect pests (for example *Thaumastocoris peregrinus* Carpintero and Dellapé from 2003; *Gonipterus scutellatus* Gyllenhal introduced from 1916 under biological control from the early 2000s; *Glycaspis brimblecombei* Moore from 2012; *Coryphodema tristis* Drury from 2004; and *Leptocybe invasa* Fisher & LaSalle from 2007 (Wingfield et al. 2008)), the growth differences are more likely a function of hybrid combination. When planted on the same site and without the incidence of drought, *E. grandis* x *E. urophylla* will generally outperform *E. grandis* x *E. camaldulensis* which is more tolerant to drought (Gardner et al. 2007). When comparing the same clone (hybrid combination) on different site productivities, for example *E. grandis* x *E. camaldulensis* at Teza A and B, the improved MAP, reduced variability in rainfall and risk of drought (MAP<650 mm = 6% for Teza A versus 19% for Teza B), and marginally better soil nutrient status (data not shown), resulted in a 21 % improvement in growth for Teza A than at Teza B.

Although all four treatment sub-sets (4m_8m_s; 2m_8m_s; 4m_8m_BOP; 2m_8m_Or) did not occur within each of the selected trials, comparisons within each site, and/or between sites could still be made where two or more treatments or sub-sets occurred. Regardless of site, there was a decrease in individual stem volume with increased stocking (Table 3.5 and Figure 3.1a-e). This is largely a function of available growing space (Morley et al. 2008). Individual stem volume was also greater for those treatment sub-sets that were thinned to a single stem (s), as opposed to where some stumps with two stems remained stump^{-1} (Figure 3.1a-e). As with stump stocking, an increase in the number of stems stump^{-1} will result in existing resources shared by more stems.

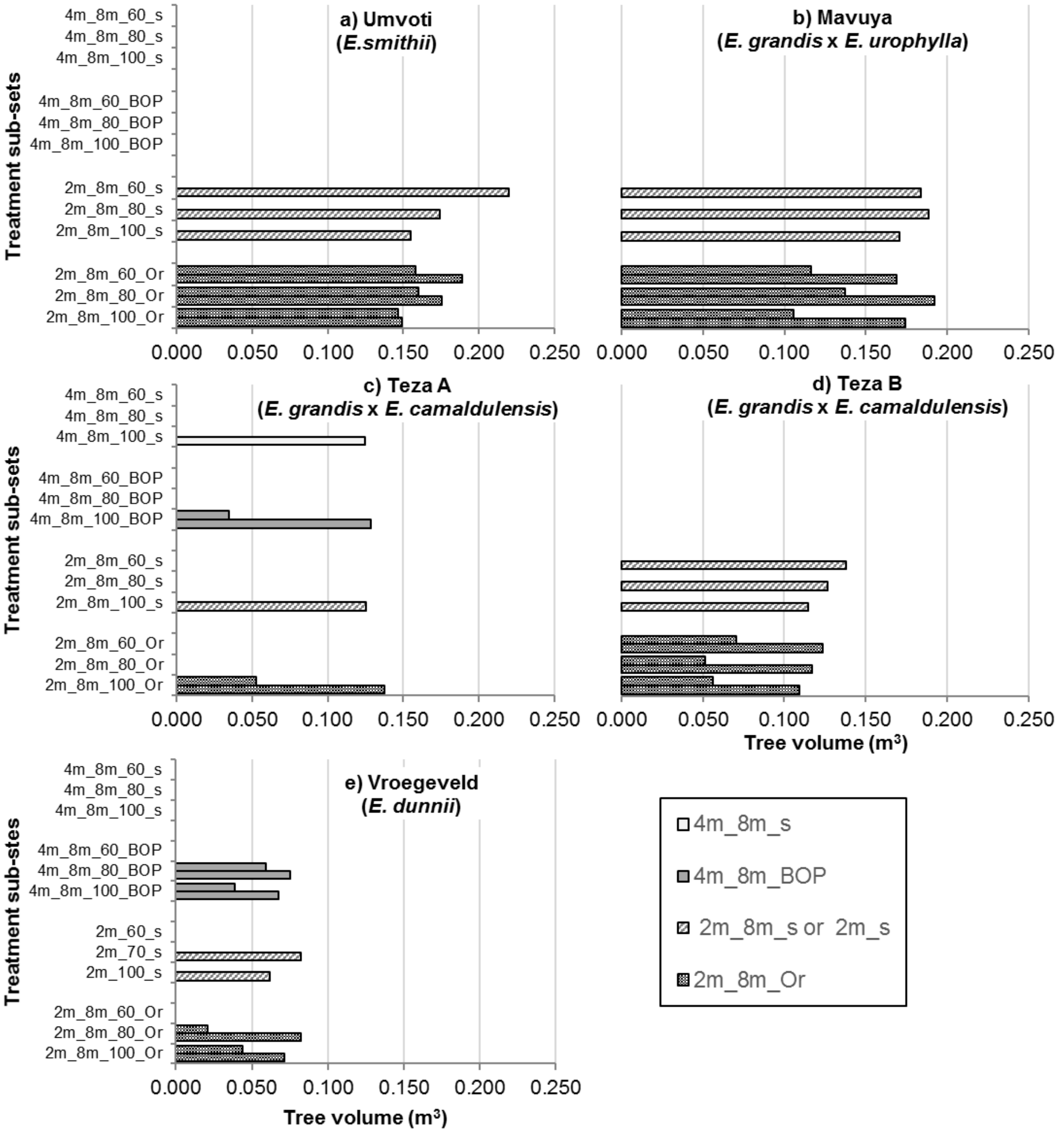

Figure 3.1a-e: Mean tree volume for for selected *Eucalptus* coppice management regimes obtained from five trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa.

For those treatments where two stems occurred on selected stumps (BOP and Or treatments), the volumes of Stem B were always smaller than Stem A. This despite the recommendation for the selection of evenly matched stems at the time of the reduction (Stubbings and Schönau 1980; Schönau 1991).

In contrast to individual volume, there was a general increase in volume ha^{-1} within each treatment sub-set with increased stocking (Figure 3.2a-e). In addition, and within each site, the treatment sub-sets that had some stumps with two stems stump^{-1} (BOP and Or) also had higher volumes ha^{-1} than the treatment sub-sets that were thinned to a single stem stump^{-1} (s). This was expected as the second stem on those stumps with two stems compensated for any loss in volume (Stubbings and Schönau 1980).

At Teza A, where there was only a single treatment within each of the four treatment sub-sets, the differences between these four treatments was small (6 m^3 ha^{-1} between highest,168 m^3 ha^{-1} and lowest, 162 m^3 ha^{-1}) (Table 3.5). Although the second stem (Stem B) contributed to an increase in the volume ha^{-1} within any specific treatment, the percentage contribution of stem B was always less than that of stem A (regardless of treatment) (Figure 3.3a-e). Not only was there a disproportionately lager contribution of stem A relative to stem B for any given stocking, this difference became more pronounced the lower the stump stocking (and hence the higher the number of stumps with two stems stump^{-1}). For example, at Mavuya in the treatment scenario 2m_8m_Or, at 100%, Stem A contributed 92% of the overall stocking and 95% of the volume ha^{-1} (Figure 3.3a-e). However at 60 % stump stocking, even with an increased number of B stems, Stem A contributed 83% to the overall volume, despite only contributing 78% of the stem stocking.

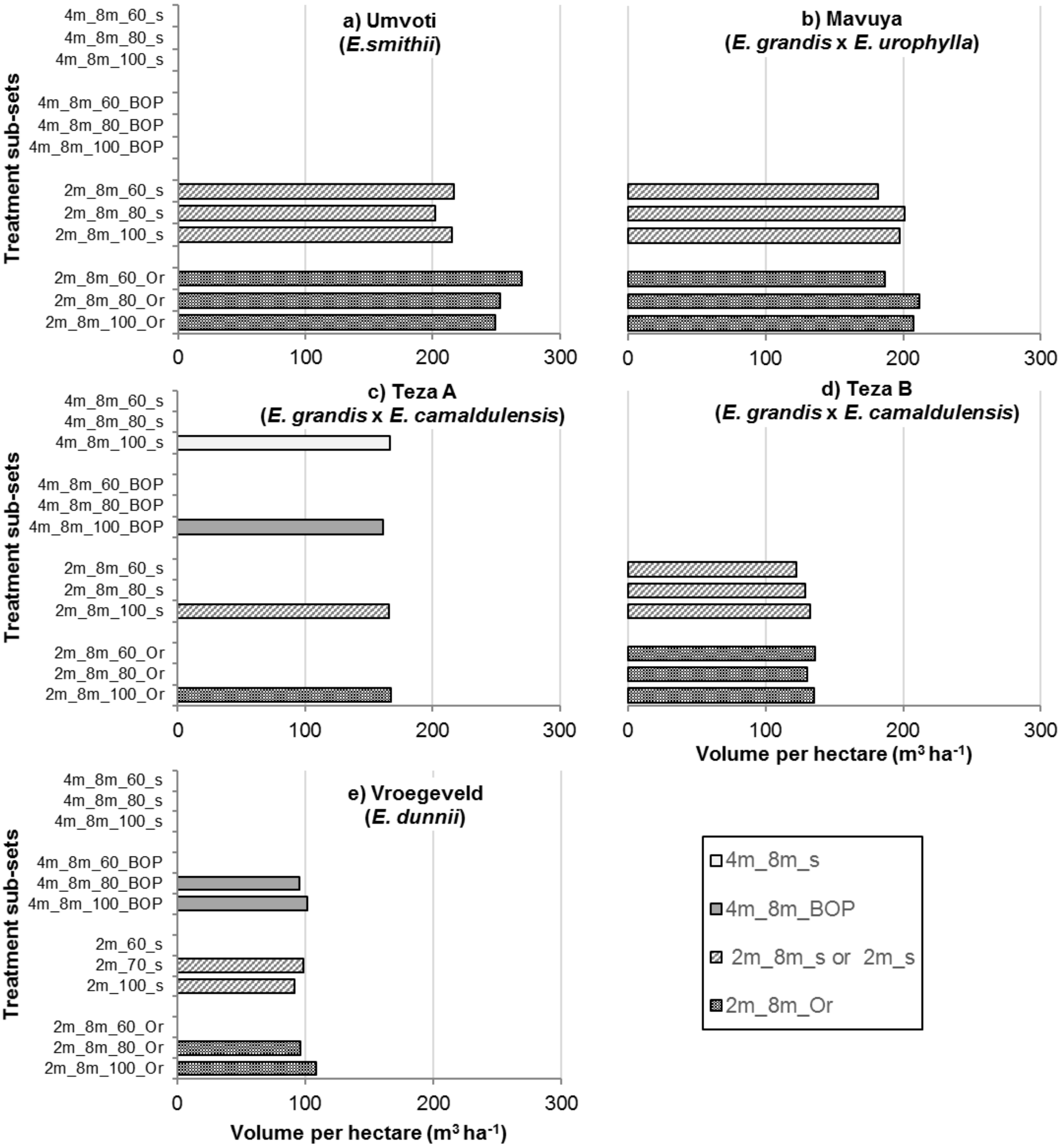

Figure 3.2a-e: Merchantable volume for selected *Eucalyptus* coppice management regimes obtained from five trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa.

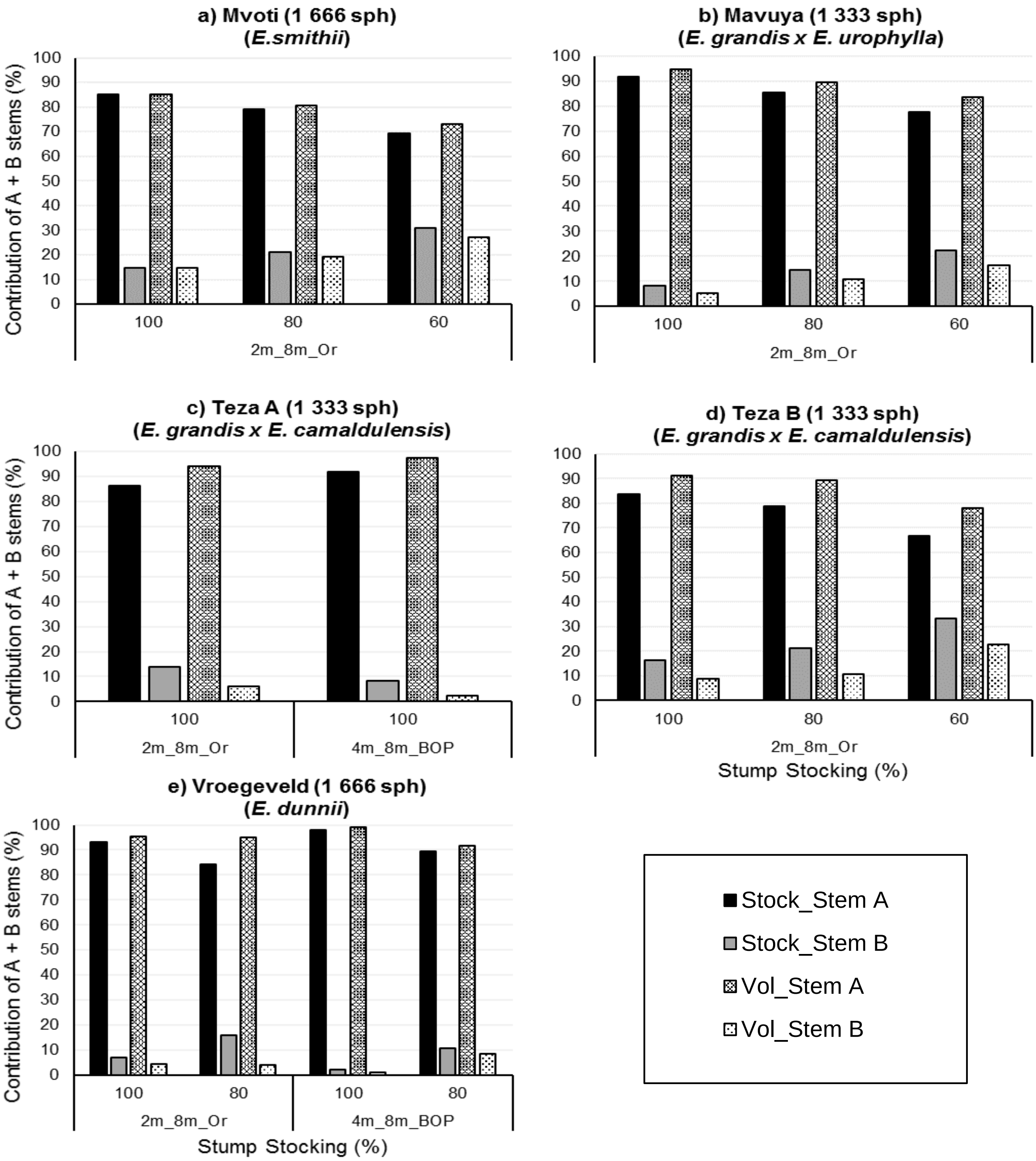

Figure 3.3a-e: Contribution of A and B Stems (as a percentage of overall stocking and volume) for *Eucalytptus* species, associated with treatment sub-sets (BOP and Or) located at five sites in South Africa.

3.3.2 Costs

Harvesting costs differed both between sites and within treatment sub-sets for each site and were highest at Vroegeveld (2m_8m_Or = R 238.8 tonne^{-1}) and Teza B (2m_8m_Or = R 201.6 tonne^{-1}), and lowest at Mavuya (2m_8m_Or = R 162.1 tonne^{-1}) and Umvoti (2m_8m_Or = R 140.4 tonne^{-1}). This can be directly related to individual stem volumes, with higher machine harvesting costs associated with smaller stem volumes (Tables 3.5 and 3.6; Figure 3.4a-e). Within treatment sub-sets, regardless of site, there was an increase in harvesting costs with increased stem and stump stocking (Figure 3.4a-e). This was largely a function of an increase in the number of stems processed, as well as a decrease in stem size (and volume) the higher the stocking. Also where reduction operations were carried out to Or or BOP (original stocking), compared to s (single stem treatments), more stumps with two stems occurred with correspondingly smaller stem volumes (Stubbings and Schönau 1980). For example, at Teza B the harvesting costs were 5.4% higher in the treatment sub-set with two stems (Or: R 207.2 tonne^{-1}) than with single stems (s: R 196.1 tonne^{-1}). Although few coppice studies have shown that an increase in the number of double stems (and hence stocking) result in an increase in the number of smaller stems within the stand (Stubbings and Schönau 1980; Ramantswana et al. 2013; McEwan et al. 2016), numerous studies have shown that harvesting cost increases when harvesting smaller stems (Spinelli et al. 2002; Adebayo et al. 2007; Jylhä et al. 2010; Suchomel et al. 2011, McEwan et al. 2016).

When all the costs over the rotation were taken into consideration, the costs associated with coppice regeneration varied slightly, with differences largely a function of the number of reduction operations (one versus two). The average regeneration costs were small relative to stumpage price and harvesting costs (10.2% of stumpage price; 20.7% of harvesting costs). The Internal Rate of Return (IRR based on NPV discounted at 6%), which included all silvicultural activities was calculated over the respective rotations (Table 3.6 and Figure 3.5a-e).

Table 3.6: Rotation-end harvesting, transport and stumpage costs for selected eucalpt coppice management regimes obtained from five trials, South Africa.

Trial (species)	Treatment scenario	Merchantable volume (m^3 ha^{-1})	Machine Productivity (hrs ha^{-1})	Harvester cost @ R 1 450 hr^{-1} (R ha^{-1})	Associated harvesting and transport costs (R ha^{-1})	Total harvesting cost (R ha^{-1})	Field wet tonnes (converted according to spp.) (tonnes ha^{-1})	Income (R ha^{-1})	Harvesting cost per tonne (R tonne^{-1})	Nett income (R ha^{-1})
Umvoti (*E. smithii*)	2m_8m_100_Or	250	22	32 082	47 781	79 863	201.9	171 636	158.9	91 773
	2m_8m_80_Or	253	20	28 912	48 514	77 426	205.0	174 268	141.0	96 842
	2m_8m_60_Or	270	20	29 231	51 790	81 021	218.9	186 035	133.6	105 014
	2m_8m_100_s	215	19	27 250	41 233	68 484	174.3	148 115	156.4	79 631
	2m_8m_80_s	201	15	21 977	38 670	60 647	163.4	138 907	134.5	78 260
	2m_8m_60_s	217	14	20 759	41 518	62 278	175.5	149 137	118.3	86 860
Mavuya (*E. grandis* x *E. urophylla*)	2m_8m_100_Or	208	17	24 207	34 417	58 624	145.4	112 722	166.4	54 098
	2m_8m_80_Or	212	16	22 946	35 117	58 063	148.4	115 013	154.6	56 950
	2m_8m_60_Or	187	15	22 202	30 929	53 131	130.7	101 299	169.9	48 168
	2m_8m_100_s	198	16	23 034	32 653	55 687	138.0	106 944	166.9	51 257
	2m_8m_80_s	201	15	22 034	33 290	55 324	140.7	109 031	156.6	53 707
	2m_8m_60_s	182	14	20 063	30 071	50 134	127.1	98 487	157.9	48 354
Teza A (*E. grandis* x *E. camaldulensis*)	4m_8m_100_BOP	162	16	23 471	28 645	52 115	121.1	93 816	193.9	41 700
	2m_8m_100_Or	168	16	23 256	29 755	53 011	125.7	97 453	184.9	44 442
	4m_8m_100_s	167	17	24 600	29 573	54 173	125.0	96 856	196.8	42 684
	2m_8m_100_s	166	17	24 184	29 450	53 634	124.5	96 454	194.3	42 820
Teza B (*E. grandis* x *E. camaldulensis*)	2m_8m_100_Or	135	15	22 078	24 061	46 139	101.7	78 805	217.1	32 666
	2m_8m_80_Or	130	14	20 078	23 082	43 160	97.5	75 598	205.8	32 438
	2m_8m_60_Or	136	14	20 314	24 194	44 508	102.2	79 240	198.7	34 731
	2m_8m_100_s	132	14	20 764	23 480	44 243	99.2	76 900	209.3	32 656
	2m_8m_80_s	129	13	18 922	22 925	41 847	96.9	75 083	195.3	33 236
	2m_8m_60_s	123	12	16 872	21 744	38 616	91.9	71 215	183.6	32 599
Vroegeveld (*E. dunnii*)	4m_8m_100_BOP	102	15	22 422	21 181	43 603	89.5	69 371	250.5	25 768
	4m_8m_80_BOP	95	14	19 719	19 857	39 576	83.9	65 036	235.0	25 460
	2m_100_s	93	15	21 231	19 154	40 385	80.9	62 733	262.3	22 348
	2m_70_s	99	13	18 648	20 592	39 240	87.0	67 441	214.3	28 201
	2m_8m_100_Or	109	16	23 383	22 699	46 082	95.9	74 343	243.8	28 261
	2m_8m_80_Or	97	13	19 178	20 005	39 183	84.5	65 520	226.8	26 336

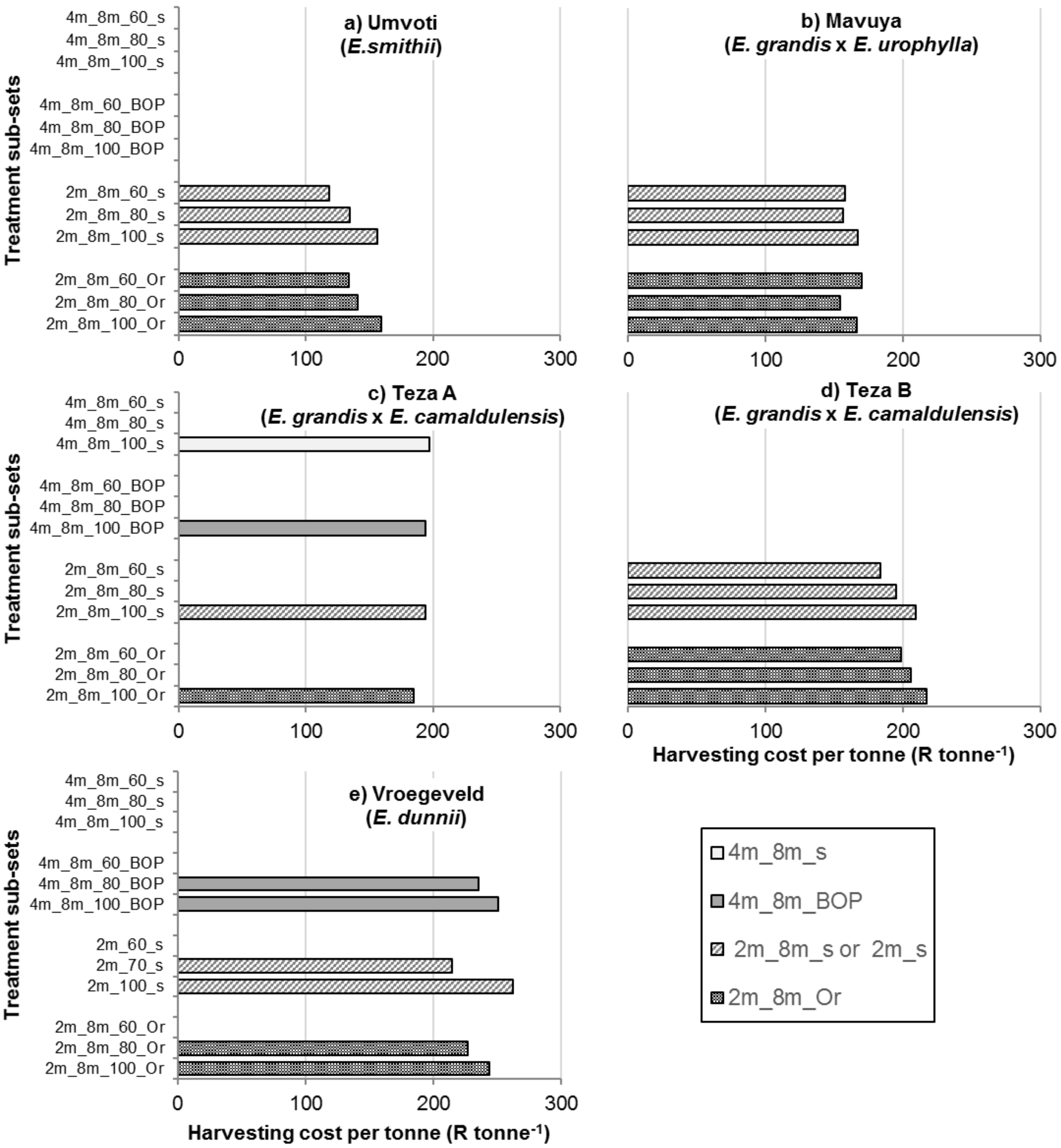

Figure 3.4 a-e: Harvesting costs for selected *Eucalptus* coppice management regimes obtained from five trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa.

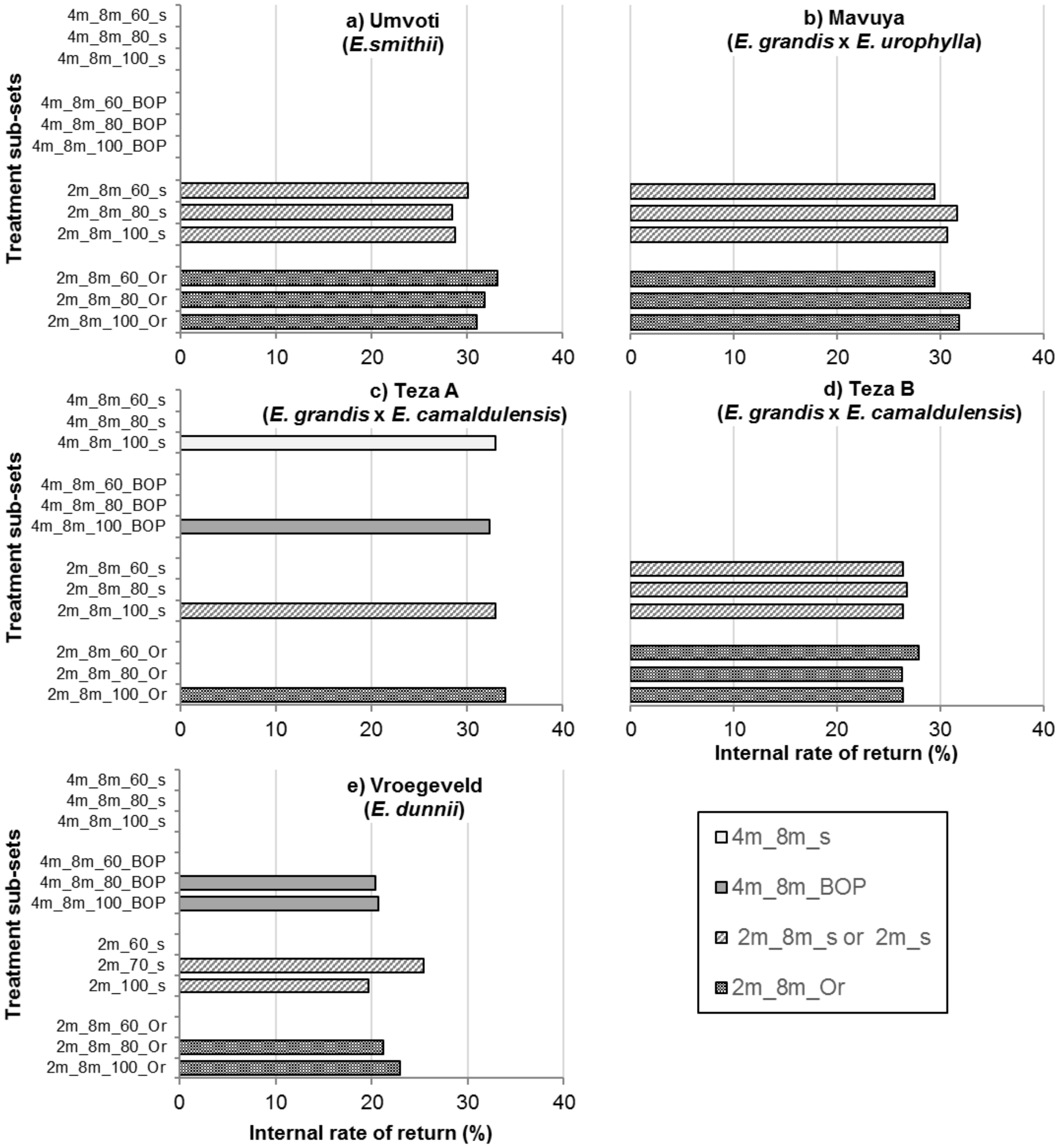

Figure 3.5 a-e: Internal rate of return (discounted to 6%), for selected eucalpt coppice management regimes obtained from five trials to determine the impact of varying stump and stand densities on mechanised harvesting costs, South Africa.

In terms of the IRR, there were large differences between sites, but not between the treatment sub-sets. At Vroegeveld and Teza B, the variation was largely a function of smaller volumes, lower stumpage prices and increased harvesting costs, resulting in lowered IRR when compared to Mavuya and Teza A. Whereas this trend was opposite for Mavuya and Teza A, which had higher volumes leading to higher stumpage prices and reduced harvesting costs resulting in highest IRR. Transport costs (distance to mill) also influenced the IRR, where Umvoti had a lower IRR when compared to Mavuya, despite lowered harvesting costs and higher volume. Similarly, for Teza B and Vroegeveld, Teza B had slightly better volumes, but higher harvesting costs compared to Vroegeveld with lower harvesting costs. However the IRR of Teza B was 10% greater than at Vroegeveld, with this large disparity mainly associated with the increased transport costs.

No clear trends between the treatment sub-sets (one stem stump^{-1} and two stems stump^{-1}) in terms of IRR were observed.

3.4 Conclusions

Although there was greater variability between treatments within treatment sub-sets, the overall trends between treatment sub-sets and these sub-sets across sites was more consistent. Coppice productivity was a function of site, species, rotation-age and management regime. The best growth occurred at Mavuya which had optiminum growing conditions for *E. grandis* x *E. urophylla*, and the worst growth at Vroegeveld (*E. dunnii*) which experienced a drought, together with the premature felling of the trees at 7 years and 3 months. Irrespective of site, those treatments which had two stems stump^{-1} (BOP and Or) resulted in higher volumes at rotation-end when compared to those with only one stem stump^{-1}. This despite the smaller contribution of stem B to merchantable volume. Individual coppice stems were larger the lower the stump and stem stocking, with the inverse in terms of volume.

Harvesting costs were lower in treatments that had one stem stump^{-1} when compared to treatments with two stems stump^{-1} due to the increased stocking and costs associated with processing smaller stems, especially where two stems occur per stump.

As there were no clear financial differences between the different coppice management regimes (one and/two stems stump^{-1}), the results obtained indicate alternative possibilities for coppice management which could favour fully mechanised harvesting operations. For companies that require maximum volume from their land-holdings (those that own their own mills), treatments that produced the highest merchantable volume may be preferred, even though costs of harvesting may be higher for those specific treatments. For those growers where overall costs are of concern, treatments with the lowest harvesting costs will be favoured as these will maximize their overall profit margins.

Future research should be focused on the development of coppice management regimes that favour mechanical harvesting (one stem stump^{-1}), but without loss in final yield.

CHAPTER 4

The influence of *Eucalyptus grandis* x *E. urophylla* stump stocking and timing of stem reductions to a single stem to favour mechanised harvesting in Zululand, South Africa.

Abstract

Current coppice recommendations are focussed on optimising volume production, which means that the higher the mortality of the parent crop, the higher the number of stumps with two stems stump^{-1} in the coppiced stand. However studies have shown that harvesting costs increase by up to 10% for fully mechanised cut-to-length harvesting systems, as the number of stumps with two stems stump^{-1} increases. A trial was implemented in Zululand on *Eucalyptus grandis* x *Eucalyptus urophylla* to test coppice management regimes that would favour mechanised harvesting (single stem stump^{-1} vs. current recommendation) without loss of productivity. The main factors included the height of the stem at which the coppice stems were reduced to a single stem stump^{-1} (Reduction_ht: 3.5 m; 4.5 m; 6.5 m), and stump stocking where stems were reduced to pre-determined stocking levels (Stocking: 75%; 85%; 100%). An additional control was included based on current coppice reduction recommendations where the first coppice reduction was implemented to two stems stump^{-1} at a dominant stem height of 3-4 m and the second to original stocking (one to two stems stump^{-1}) at 7-8 m. Significant differences were detected at 23 months between the additional control and the various Reduction_ht treatments for *Dbh, Ba, and Stocking*. Larger diameters in the Reduction_ht treatments were obtained when compared to the additional control. However, the trend for *Ba* was opposite to *Dbh*, with the additional control being significantly larger than the Reduction_ht treatments. This response was expected as the second stem could compensate for any loss of stems caused by either windthrow or damage caused during the reduction operations.

The lack of treatment differences for volume (within the Reduction_ht and/or between Reduction_ht and additional control), indicates the potential for alternative coppice management that would favour mechanised harvesting (one stem stump^{-1}). However, the timing of reduction operations needs to be tested further so as to limit

the consequences of windthrow. A stepwise reduction, but with only one stem remaining stump^{-1} at final reduction, or delaying final reduction to 7-8m as the stems will be more firmly attached could possibly limit windthrow.

4.1 Introduction

In South Africa, commercially grown hardwoods account for ca. 40.5% of the total area planted to trees, yet contribute more than 70% of the timber to the pulpwood market (FSA 2014). Commercial forestry is concentrated along the eastern seaboard of South Africa, where different *Eucalyptus* spp. or *Acacia mearnsii* De Wild. are managed over short rotations of 8-10 years (du Toit and Norris 2011). Different site productivities occur within this region, mainly associated with climate, soil characteristic and physiography, with the sub-tropical region of Zululand being the most productive (Smith et al. 2005a; 2005b). Within the forestry growing areas in Zululand, the topography is relatively flat, and although the rainfall is seasonal, rain does occur throughout the year (Schulze 2008).

As opposed to the replanting of seedlings, most eucalypts have the ability to regenerate though the development of coppice shoots (coppice regeneration) following felling, with both methods of regeneration used within South Africa. In planted stands which are well-stocked and uniform prior to felling, coppice regeneration is preferred due to a reduction in the temporary unplanted period and associated re-establishment costs (Whittock et al. 2004; Crous and Burger 2015). Previous research on coppice management focused primarily on timing of reduction operations in combination with stem stocking in order to optimise timber volumes at harvesting. From these results, coppice management recommendations were developed which are still currently used within South Africa (Schönau 1980; Stubbings and Schönau 1980; Schönau 1991; Bredenkamp 1991; Little 2007). The current recommendation includes a stepwise reduction of coppice stems, the first to two stems stump^{-1} at a dominant stem height of 3-4 m and the second to original stocking (one or two stems stump^{-1}) at 7-8 m. Two stems are left on those stumps adjacent to missing stumps in order to reach original stocking (Schönau 1991).

In the past ten years in South Africa there has been a shift towards increased mechanisation of harvesting operations (Längin et al. 2010). Due to the small stem size and poor stem form associated with the presence of two stems on one stump, fully mechanised Cut-to-Length (CTL) harvesting operations are hindered (Stubbings and Schönau 1980; Suchomel et al. 2012; Ramantswana et al. 2013). For example, Ramantswana et al. (2013) found that machine harvesting productivity decreased when coppiced stands were felled compared to planted stands of *E. grandis.* In addition, they found that machine productivity was further increased when felling stands that had two stems stump^{-1} as opposed a single stem stump^{-1}. These differences in machine harvesting productivity were attributed to stem form, with replanted stands having the best, followed by one and then two coppice stems.

To further explore the impact of different coppice management regimes on harvester productivity, Schwegman et al. (2016) carried out a study on five coppice management trials. Treatments were selected that contained varying numbers of one and/or two stems stump^{-1} at rotation-end. Based on this data, the harvester productivity and costs were calculated to determine the potential for coppice management regimes that would favour machine harvesting. These costs were combined with those over the whole rotation (establishment, tending, transport and stumpage prices) for the determination of the return on investment (Internal Rate of Return). From this data no noticeable differences could be determined in terms of coppice management regime, harvesting costs and that of the IRR. McEwan et al. (2016) found that costs of harvesting stumps with two stems stump^{-1} were higher than harvesting one stem stump^{-1}. This highlights the potential for a coppice management regime to favour mechanised harvesting, where one stem stump^{-1} is left without a loss in overall profit. Little literature could be found where various coppice reduction heights were reduced in a single thinning to one stem stump^{-1}.

To further explore coppice management regimes that would facilitate mechanised harvesting, a trial was implemented in 2015 in Zululand, South Africa, on a stand of *Eucalyptus grandis* × *Eucalyptus urophylla*, the objectives of which were to determine:

- difference in growth between the current recommended coppice management regime (two stems stump^{-1} at 3-4m; one to two stems stump^{-1} at 7-8m) and a single reduction to one stem stump^{-1};
- the optimum height (age) at which the reduction to one stem stump^{-1} should occur; and
- the influence of stump stocking on stand productivity.

4.2 Materials and methods

4.2.1 Trial location, design and layout

The trial was located at Mtunzini, Mondi Fairbreeze plantation in Zululand, South Africa (28° 59' 59″ S and 31° 41' 34″ E). The climate was sub-tropical, with a mean annual precipitation of 1 170 mm and mean annual temperature of 21 °C. The trial was situated at an altitude of 63 m above sea level on deep sandy loam soils. The growing conditions are considered optimum for *E. grandis* x *E. urophylla* with a Site index ($SI_{5\ years}$) of 24 m (Smith et al. 2005a; 2005b) The site was originally planted to *E. grandis* x *E. urophylla* hybrid clone (GU 007) followed by two rotations of coppice (currently on the third rotation of coppice). The trees were planted at a spacing of 3 m x 2 m resulting in a planting density of 1 667 stems ha^{-1}.

The trial consisted of a 3 x 3 factorial with 1 additional control treatment replicated three times, arranged in split plots and laid out as a randomised complete blocks design (RCBD). The additional control treatment was repeated three times within each replicate. The main factors included the height at which the coppice stems were reduced to a single stem stump^{-1} (Reduction_ht: 3.5 m; 4.5 m; 6.5 m), and stump stocking where stems were reduced to pre-determined stocking levels (Stocking: 75%; 85%; 100%) (Table 4.1). The additional control treatment was based on current coppice reduction recommendations (Stubbings and Schönau 1980; Schönau 1991), where the first coppice reduction is implemented to two stems stump^{-1} at a dominant stem height of 3-4 m and the second to original stocking (one to two stems stump^{-1}) at 7-8 m. It would be against the additional control treatment that the 9 Reduction_ht x Stocking treatment combinations could be compared. Reduction_ht formed the whole plots, whilst the sub-plots consisted of the stocking treatments. Each sub-plot consisted of seven rows, with six stumps row^{-1}. Only the inner four by five stumps/coppiced stems were measured (20 stems plot^{-1}) (Table 4.1).

Table 4.1: Treatment combinations (stump stocking and timing of stem reductions to a single stem stump^{-1}) tested in a *Eucalyptus grandis* x *E. urophylla* trial in Zululand, South Africa.

Treat. No.	**Treat description**	**Reduction height, with number of stems remaining stump^{-1}**			**Stump stocking (%)**	**Treatment justification**
		Reduction at 3.5 m	**Reduction at 4.5 m**	**Reduction at 6.5 m**		
1	3.5m_100_s	1	-	-	100	- Early reduction to 1 stem stump^{-1} - 100% stump and stem stocking
2	3.5m_85_s	1	-	-	85	- Early reduction to 1 stem stump^{-1} - 85% stump and stem stocking
3	3.5m_75_s	1	-	-	75	- Early reduction to 1 stem stump^{-1} - 75% stump and stem stocking
4	4.5m_100_s	-	1	-	100	- Early reduction to 1 stem stump^{-1} - 100% stump and stem stocking
5	4.5m_85_s	-	1	-	85	- Early reduction to 1 stem stump^{-1} - 85% stump and stem stocking
6	4.5m_75_s	-	1	-	75	- Early reduction to 1 stem stump^{-1} - 75% stump and stem stocking
7	6.5m_100_s	-	-	1	100	- Early reduction to 1 stem stump^{-1} - 100% stump and stem stocking
8	6.5m_85_s	-	-	1	85	- Early reduction to 1 stem stump^{-1} - 85% stump and stem stocking
9	6.5m_75_s	-	-	1	75	- Early reduction to 1 stem stump^{-1} - 75% stump and stem stocking
10	3.5m_6.5m_100_Control	2-3	-	1-2	100	- Final reduction to 1-2 stems stump^{-1} - 100% stump stocking -100% stem stocking

4.2.2 Measurements

The previous stand was felled in June 2014 and left to coppice. Stump height (m) and cut-surface diameters (cm) were measured for use as co-variates to determine if coppice growth were influenced by stump size. The reduction heights (3.5 m, 4.5 m, and 6.5 m) were implemented at 10, 13, and 18 months after clearfelling. The diameter at breast height for all coppice stems (*Dbh*; in cm) and first five coppice stem heights (*Ht* in m) were measured when treatments were imposed. A regression of the Dbh:Ht pairs was used to estimate the heights of the unmeasured coppice stems (*F*-prob < 0.01; r = 0.69; RSME = 0.43). *Stocking* was derived from stump and coppice stem survival, and this together with the *Dbh* measurements were used to determine the basal area (*Ba* in m^2 ha^{-1}) on a treatment plot basis. The estimated merchantable volume to a top-end underbark diameter of 5 cm was calculated for each stem using an equation (Equation 4.1) developed for *E. grandis* x *E. urophylla* coppice growing in the same region:

$$Vol = (10\text{\^{}}(-4.56+(\mathrm{LOG10}(Dbh)*2.06272)+(\mathrm{LOG10}(Ht)\times 1.000736))) \qquad \text{Eq. 4.1}$$

The volume ha^{-1} (*Vol* in m^3 ha^{-1}) for each treatment plot was then calculated by combining the sum of the merchantable volume $plot^{-1}$ with the stocking $plot^{-1}$.

All vegetation or secondary coppice regrowth was controlled with glyphosate so as to eliminate competition from these sources. Where the desired stocking was higher than that required by the treatment, additional stumps were killed. Final measurements were carried out in June 2016 (23 months after felling).

4.2.3 Data analysis

An analyses of variance (ANOVA) appropriate for a Randomised Complete Block Design was used to test for treatment effects using GenStat 18th edition for Windows (VSN International, Hemel Hempstead, UK, 2013). Only if the *F*-value significant (p < 0.05) will treatment differences further investigated using the Student's t-tests (*lsd's*). Prior to all analyses, the assumptions appropriate for a valid ANOVA were checked. Stump dimensions were used as covariates for the coppice stem variates, but as they were not significant they were not included within the final analysis.

4.3 Results and discussion

Significant differences were detected between the additional control and the various Reduction_ht treatments for *Dbh* (*F* prob < 0.001), *Ba* (*F* prob = 0.018), and *Stocking* (*F* prob < 0.001) (Table 4.2 and Figure 4.1a-c). No significant differences were detected for variates of *Ht* and *Vol,* with *Vol* only significant at the 10% level (*F* prob = 0.054).

Table 4.2: Summary analysis of variance showing mean squares of selected variates at 23 months in a trial to determine the influence of *Eucalyptus grandis* x *E. urophylla* stump stocking and timing of stem reductions to a single stem in Zululand, South Africa.

Source of variation	d.f.	***Dbh*** (cm)	***Stocking*** (sph)	***Ht*** (m)	***Ba*** (m^2 ha^{-1})	***Vol*** (m^3 ha^{-1})
Reps	2	1.395	15625	2.161	1.882	43.02
Additional_Control	1	4.378**	1296553**	0.799^{ns}	6.724*	49.29$^{\$}$
Additional_Control*Reduction_ht	2	0.318^{ns}	57356^{ns}	0.195^{ns}	0.848^{ns}	8.60^{ns}
Additional_Control*Stocking	2	0.088^{ns}	12603^{ns}	0.116^{ns}	0.284^{ns}	3.59^{ns}
Additional_Control*Reduction_ht* Stocking	4	0.227^{ns}	71631^{ns}	0.253^{ns}	1.723^{ns}	17.16^{ns}
Residual	24	0.173^{ns}	54511^{ns}	0.232^{ns}	1.043^{ns}	11.97^{ns}
Total	35					
Summary of data						
Grand mean		7.955	1208	7.69	6.02	18.89
Standard error of difference of means (Additional_Control*Reduction_ht* Stocking)		0.277	155.7	0.321	0.681	2.306
Coefficient of variation % (units)		5.2	19.3	6.3	17.0	18.3
Shapiro-Wilk test for Normality		0.984^{ns}	0.971^{ns}	0.985^{ns}	0.9577^{ns}	0.990^{ns}

Note: **, * and $^{\$}$ indicates significance at *F*-prob < 0.01, <0.05 and <0.10 respectively, ^{ns} indicates non-significance.

Stocking was highly significant (*F* prob < 0.001) for the interaction between the additional control x Reduction_ht. This was expected due to the various levels of Stocking within each of the Reduction_ht treatments (each with only a single stem stump^{-1}), in comparison to the control treatments where the leaving of 2 stems on selected stumps resulted in a higher stocking. (Figure 4.1a-c). Of interest, within the Reduction_ht treatments (3.5 m, 4.5 m, and 6.5 m), no significant differences were detected for any of the tree growth variates as well as for *Stocking*, most likely due to the high incidence of windthrow across all treatments which were reduced to a single stem. This highlights the risks associated with carrying out a single reduction to 1 stem stump^{-1}.

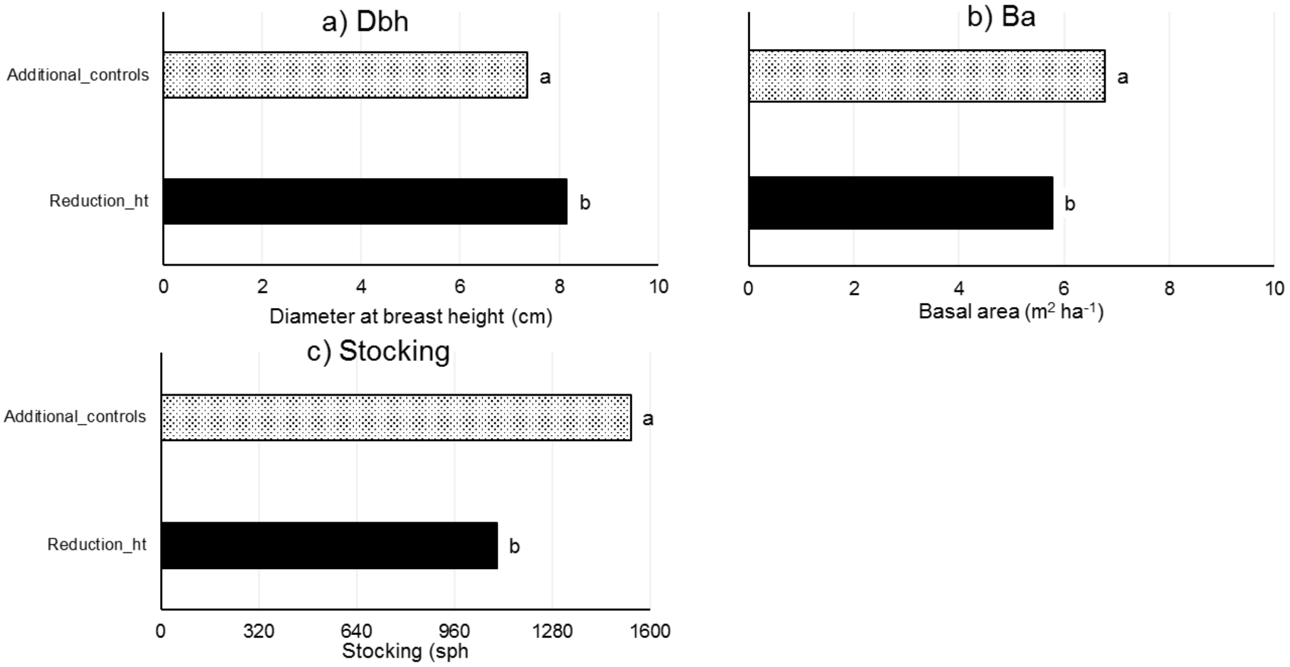

Figure 4.1a-c: The influence of *Eucalyptus grandis* x *E. urophylla* stump stocking and timing of stem reductions to a single stem on *Dbh*, *Ba* and *Stocking* at 23 months after felling in Zululand, South Africa.

The *Dbh* of the Reduction_ht treatments (coppice shoots reduced to one stem stump^{-1}) was significantly greater (*F* prob < 0.001) to the additional control, where coppice stems were reduced to match the original stocking (Figure 4.1a-c). Similar results were obtained by Stubbings and Schönau (1980) where *E. grandis* coppice shoots were reduced to one stem stump^{-1} at different ages, with the largest diameter being achieved when the earliest coppice reduction was implemented. A possible reason for larger diameters in the Reduction_ht treatments compared to additional controls could be the channelling of resources to the selected stem, resulting in a growth benefit (Little and du Toit 2003).

The opposite trend occurred for *Ba*, with the Reduction_ht treatments being significantly smaller (*F* prob = 0.018) than the additional controls (Figure 4.1a-c). This response was expected as the second stem on those stumps with two stems compensated for any loss of stems caused by either wind throw or damage from bushknives during the reduction operations (Stubbings and Schönau 1980; Schönau 1991; Little and du Toit 2003; Little 2007; Little and Oscraft 2010).

The lack of treatment differences for volume (within the reduction_ht and/or between reduction_ht and additional control) indicates the potential for alternative coppice management regimes that would favour mechanised harvesting (one stem stump^{-1}), but the timing of reduction operations needs to be tested further so as to limit the consequences of windthrow. Possibly a stepwise reduction, but with only one stem stump^{-1} at the final reduction, or delaying the final reduction to 7-8m as the stems will be more firmly attached.

It is important to note that these are early results (23 months after felling), and although there were differences in BA, these were not large. It is likely that these differences may become less with time due to the decrease in absolute and relative differences between the various treatments with time. Similar trends were detected in trials implemented by Stubbings and Schönau (1980) and Schönau (1991) with there being no differences in diameters when one stem was left stump^{-1} or when the number of stems equalled the original stocking at felling.

4.4 Conclusion

Significant differences were detected at 23 months for Dbh, Ba and Stocking between the Reduction_ht as a factor and the additional control. The lack of treatment differences (within the reduction_ht and/or between reduction_ht and the additional control) indicates the potential for alternative coppice management that would favour mechanised harvesting (one stem stump^{-1}), but the timing of reduction operations needs to be tested further so as to limit the consequences of windthrow. Possibly a stepwise reduction, but with only one stem stump^{-1} at final reduction, or delaying final reduction to 7-8m as the stems will be more firmly attached. It is also important that rotation-end data be collected from trials established on different sites and with different eucalypts.

CHAPTER 5

Synthesis and conclusion

5.1 Summary of major findings and future research possibilities

Although the disciplines of silviculture and harvesting are integrated, most of the research conducted has been carried out independently of each other. Coppice regimes in particular have been based more on maximising volume production irrespective of harvesting system used. This was possible as manually-based harvesting systems are flexible and could adapt to the range in stem numbers and sizes that result from varying coppice management regimes. However with the increase in mechanisation (over the last 10 years), specifically within harvesting, the need to understand the influences of coppice silviculture activities on harvesting systems and visa-versa is required. This thesis used data obtained from research trials to answer specific questions related to the successful integration of coppice management regimes with mechanised harvesting systems.

5.1.1 Influence of increased levels of mechanised harvesting on eucalypt stump damage and coppice ability.

Although no significant differences were found between the four harvesting systems for rotation-end volume, there were components (vehicle movement, tyre damage and log stripping) within the four different levels of harvesting that led to increased severity of stump damage and subsequently less coppice on the top half of the stump as opposed to the bottom. However the damage severity and/or differences may have been masked by the excellent coppicing potential of the species used for this trial (*Eucalyptus grandis* x *E. urophylla*). Whether similar results would be obtained for those eucalypts that coppice less vigorously would still need to be tested in future.

Future research should focus on the individual components of a harvesting system which are associated with the severity of stump damage, rather than on the whole harvesting system. In this manner the damage associated with individual components can be dealt with through management intervention, training or technological improvements.

5.1.2 Mechanised harvesting costs for eucalypt coppice stands of varying stump and stem densities.

Although variation did occur for individual stem volume, volume ha^{-1} and harvesting costs between sites and coppice management regimes, the results indicated that there were no clear differences (with regards to IRR) between treatment sub-sets with either one stem stump^{-1} and two stems stump^{-1}. This is due to those factors that contribute to increased volumes hectare^{-1} (increased stem numbers and the retention of two stems per stump) tend to become normalised across a treatment sub-set. Therefore it is possible that the management of coppice regimes that favour mechanised harvesting (one stem stump^{-1}) could be further investigated.

Future research should focus on developing harvesting productivity models that are specifically designed for alternative species of eucalypt coppice stands with one and/or two stems stump^{-1}.

5.1.3 The influence of *Eucalyptus grandis* x *E. urophylla* stump stocking and timing of stem reductions to a single stem to favour mechanised harvesting.

Significant differences were detected for the different coppice management regimes at 23 months for the variates of Dbh, Ba, and Stocking. When compared to the current recommend practice (1-2 stems stump^{-1} after final reduction), the reduction of to one stem stump^{-1} is a viable option, provided windthrow does not have a major impact on stocking. Delaying the timing of thinning to ensure firmer attachment, or carrying out a stepwise reduction, but with a final reduction to 1 stem needs to be investigated further. As the results from this trial were of shorter duration, longer term data would need to be generated.

Future studies should focus on collecting more data with regards to silvicultural systems that favour mechanised harvesting systems.

Overall the results from this research are promising, not only as they have provided insight into the possibilities for alternative coppice management regimes that may favour mechanised harvesting, but they have also enabled a greater understanding of the factors that need to be dealt with for the successful integration of coppice regeneration and harvesting.

References

Ackerman P, Längin D. 2010. Introduction. In: Längin DW, Ackerman PA, Krieg B, Immelman A, van Rooyen J, Upfold S (eds), *South African Ground based harvesting handbook*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Ackerman P, Längin D, Olsen G. 2011. Timber harvesting and transport. In: Brendenkamp BV, Upfold S (eds), *South African Forest Handbook* (5th edn). Pretoria: South African Institute for Forestry. pp. 359-373.

Ackerman SA. 2013. The effect of irregular stand structures on growth, wood quality and its mitigation in operational harvest planning of *Pinus patula* stands, Stellenbosch: *Published MSc Thesis* Stellenbosch University, Stellenbosch.

Adebayo AB, Han HS, Johnson L. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *Forest Products Journal* 57: 59-69.

Axelsson S. 1998. The mechanisation of logging operations in Sweden and its effect on occupational safety and health. *Journal of Forest Engineering* 9(2): 25-31.

Baines C. 2004. Forest Research Crossing Borders – A Foreword. Forest Research Crossing Borders, in: *EFI Proceedings* No. 50. Available at http://fefr.org/files/attachments/publications/proc50_net.pdf [accessed 23rd of September 2016].

Bell Equipment. 2015a. *Logger*. Available at http://www.bellequipment.com/en/products/loggers [accessed 22nd of September 2015].

Bell Equipment. 2015b. *225A Bell Debarker*. Available at http://en.minosucra.com/images/upload/1343-8610501.pdf [accessed 15 October 2015 2015].

Bertault J-G, Sist P. 1997. An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. *Forest Ecology and Management* 94: 209-218.

Bettinger P, Bettinger KA, Boston K. 1998. Correlation among spatial and non-spatial variables describing a cut-to-length thinning site in the Pacific Northwest, USA. *Forest Ecology and Management* 104(1-3): 139–149.

Boyle JR, Phillips JJ, Ek AR. 1973. "Whole tree" harvesting: Nutrient budget evaluation. *Journal of Forestry* 71: 760-762.

Bredenkamp BV. 1991. Results of a *Eucalyptus grandis* coppice reduction trial in Zululand. *CSIR Report No. 38*. Pretoria, Council for Scientific and Industrial Research.

Carrodus B, Blake T. 1970. Studies on the lignotubers of *Eucalyptus obliqua* L'Heri. *New Phytologist* 69: 1069-1072.

Chattaway MM. 1958. Bud development and lignotuber formation in eucalypts. *Australian Journal of Botany* 6: 103-115.

Crombie D. 1997. Water relations of jarrah (*Eucalyptus marginata*) regeneration from the seedling to the mature tree and of stump coppice. *Forest Ecology and Management* 97: 293-303.

Crous JW, Burger L. 2015. A comparison of planting and coppice regeneration of *Eucalyptus grandis* x *Eucalyptus urophylla* clones in South Africa. *Southern Forests* 9: 1-9.

Crowther RE, Evans J. 1986. Coppice. *Forestry Commission Leaflet 83.* HMSO, London.

Department of Agriculture, Forests and Fisheries (DAFF). 1997. *Sustainable forest development in South Africa.* Available at www.daff.gov.za/doaDev/sideMenu/ForestryWeb/dwaf/cmsdocs/25___Forestry%20White%20Paper.htm [accessed 25 October 2016].

Department of Agriculture Forest and Fisheries (DAFF). 2013. *Pocket Guide to South Africa 2011/12*. Department of Agriculture Forest and Fisheries, Pretoria.

Department of Agriculture Forest and Fisheries (DAFF). 2015a. *State of the forests report 2010-2012*. Available at http://www.nda.agric.za/doaDev/sideMenu/ForestryWeb/webapp/Documents/State%20of%20the%20forests%20report%202010-2012.pdf [accessed 5th of October 2016].

Department of Agriculture Forest and Fisheries (DAFF). 2015b. *Congress outcome process*. Available at http://www.daff.gov.za/wfc2015final/English/outcomes.html [accessed 5th of October 2016].

de Souza DPL, Gallagher T, Mitchell D, McDonald T, Smidt M. 2016: Determining the effects of felling method and season of year on the regeneration of short rotation coppice. *International Journal of Forest Engineering* 27: 53-65.

de Wet P, McEwan A. 2011. Timber harvesting and extraction In: Längin DW, Ackerman PA, Krieg B, Immelman A, van Rooyen J, Upfold S (eds), *South African Ground Based Harvesting Handbook*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. pp 391-415.

du Toit B, Dovey SB, Fuller GM, Job RA. 2004. Effects of harvesting and site management on nutrient pools and stand growth in a South African eucalypt plantation. In: Nambiar EKS, Ranger J, Tiarks A,Toma T (eds), *Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003*, Center for International Forestry Research, Bogor, Indonesia. pp 31-44.

du Toit B, Norris C. 2011. Elements of silvicultural systems and regimes used in southern African plantations. In: Brendenkamp BV, Upfold S (eds), *South African Forest Handbook* (5th edn). Pretoria: South African Institute for Forestry. pp. 29-34.

Dyck WJ, Cole DW. 1994. Strategies for determining consequences of harvesting and associated practices on long-term productivity. In: Dyck WJ, Cole DW, Comerford NB, (eds). *Impacts of Forest Harvesting on Long-Term Site Productivity*. Dordrecht: Springer Netherlands. pp 13-40.

Eggers J, McEwan A, Conradie B. 2010. *Pinus* saw timber tree optimisation in South Africa: a comparison of mechanised tree optimisation (harvester/processor) versus current manual methods. *Southern Forests* 72(1): 23–30

Evans J, Turnbull J. 2004. *Plantation forestry in the tropics*. 3rd ed. New York, Oxford University Press. pp 467.

Faulkner D, Leowald C. 2008. Policy change and economic growth: a case study of South Africa. *Policy Paper No. 14*. Pretoria: National Treasury of South Africa.

Florence R. 1996. *Ecology and silviculture of eucalypt forests*. CSIR publishing. Collonwood, p 154

Food and Agricultural Organisation (FAO). 2009. *Responsible management of planted forests: voluntary guidelines – preparation for action – the country level methodology*. FAO, Rome, Planted Forests and Tree Working Paper 45/E. Available at Available at http://www.forec.co.za/index.php?option=com_content&view=article&id=50&Itemid=59 [accessed 23rd of March 2015]

Forest Economic Services (FES). 2016. Available at http://www.forec.co.za/index.php?option=com_content&view=article&id=50&Itemid=59 [accessed 23rd of March 2015]

Forest South Africa (FSA). 2014. *The South African forestry industry’s perspective on forestry & forest products statistics*. Available at www.forestry.co.za/statistical-data [accessed 25 July 2016].

Gardner RAW, Little KM, Arbuthnot A. 2007. Wood and fibre productivity of promising new eucalypt species for coastal Zululand, South Africa. *Australian Forestry* 70: 37–47.

Gellerstedt S, Dahlin B. 1999. Cut-to-length: The next decade. *Journal of Forest Engineering* 10: 17-24.

Grey D, Jacobs E. 1987. The impact of harvesting on forest site quality. *South African Forestry Journal* 140: 60-66.

Han S-K, Han H-S, Page-Dumroese DS, Johnson LR. 2009. Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. *Canadian Journal of Forest Research* 39: 976-989.

Han H-S, Renzie C. 2005. Effect of ground slope, stump diameter, and species on stump height for feller-buncher and chainsaw felling. *International Journal of Forest Engineering* 16: 81-88.

Ham C, Jacobson M. 2011. Financial decision making in the forestry projects. In: Brendenkamp BV, Upfold S (eds), *South African Forest Handbook* (5th edn). Pretoria: South African Institute for Forestry. pp 497-507

Hitachi. 2015. *Products*. Available at https://www.hitachicm.com/global/ourbusiness/products/ [accessed 21 October 2015].

Hogg G, Krieg B, Ackerman P, Längin D. 2010. Harvesting system and equipment costing. In: Längin DW, Ackerman PA, Krieg B, Immelman A, van Rooyen J, Upfold S (eds), *South African Ground Based Harvesting Handbook*. Pietermaritzburg, Institute for Commercial Forestry Research.

Hytönen J. 1994. Effect of cutting season, stump height and harvest damage on coppicing and biomass production of willow and birch. *Biomass and Bioenergy* 6(5): 349-357.

Investopedia. 2015. *Internal Rate of Return*. Available at http://www.investopedia.com/terms/i/irr.asp [accessed 22nd of March 2015].

Jourgholami M, Majnounian B, Zargham N. 2013. Performance, capability and costs of motor-manual tree felling in Hyrcanian hardwood forest. *Croatian Journal of Forest Engineering* 34: 283-293.

Jones WR, Clarke CRE, van Staden J. 2000. Understanding the breeding system of cold tolerant *Eucalyptus* species and its impact on seed production. In: *Proceedings of the IUFRO Working Party 2.08.01 Tropical Species Breeding and Genetic Resources*: Forest Genetics for the Next Millennium, 8–13 Oct. 2000, Durban, South Africa. Institute for Commercial Forestry Research, Scottsville, South Africa. pp. 146–150.

Jylhä P, Dahl O, Laitila J, Kärhä K. 2010. The effect of supply system on the wood paying capability of a kraft pulp mill using Scots pine harvested from first thinnings. *Silva Fennica* 44: 695-714.

Krieg B, de Wet P, Olsen G, McEwan A. 2010. Ground based harvesting equipement. In: Längin DW, Ackerman PA, Krieg B, Immelman A, van Rooyen J, Upfold S (eds), *South African Ground Based Harvesting Handbook*. Pietermaritzburg, Institute for Commercial Forestry Research.

Kotze H, Kassier HW, Fletcher Y. 2011. 3.1 Growth modelling and yield tables. In: Bredenkamp BV, Upfold SJ (eds.). *South African Forestry Handbook* (5th edn). Pretoria: Southern African Institute of Forestry. pp 167–174.

Längin D. Ackerman P. 2007. South Africa forest engineering survey 2006/2007. *Final report to the South African Forest Industry*, Stellenbosch University and Institute for Commercial Forestry Research. November 2007.

Längin D, Ackerman P, Olsen G. 2010. Introduction to ground based harvesting systems and methods. In: Längin DW, Ackerman PA, Krieg B, Immelman A, van Rooyen J, Upfold S (eds), *South African Ground Based Harvesting Handbook*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Lattimore B, Smith C, Titus B, Stupak I, Egnell G. 2009. Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. *Biomass and Bioenergy* 33: 1321-1342.

LeDoux CB. 2010. Mechanised systems for harvesting eastern hardwoods. *General Technical Report NRS-69*. Broomall, US Department of Agriculture.

Little K. 2000. Eucalypt coppice management. *ICFR Technical Innovations 1/2000*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Little KM, van den Berg G, Fuller G. 2002. Coppicing potential of *Eucalyptus nitens*: Results from a field survey. *Southern African Forestry Journal* 193: 31-38.

Little KM, du Toit B. 2003. Management of *Eucalyptus grandis* coppice regeneration parent stock in Zululand, South Africa. *Austrailian Forestry* 66: 108-112.

Little KM, Gardner RAW. 2003. Coppicing ability of 20 *Eucalyptus* species grown at two high-altitude sites in South Africa. *Canadian Journal of Forest Research* 33: 181-189.

Little KM. 2007. Final results from a *Eucalyptus grandis* x *E. camaldulensis* coppice trial. *Scientia Forestalis* 76: 85-90.

Little K, Oscroft D. 2010. Coppice growth as influenced by damage occurring during reduction operations and control of secondary coppice regrowth. *ICFR Technical Note No.02/2010*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Lückhoff H. 1955. The establishment and regeneration of *Eucalyptus saligna* plantations in the coastal belt of Zululand. *Journal of the South African Forestry Association* 25: 1-20.

Mack R. 2010. Semi-mechanised harvesting systems: best of both worlds. *SA Forestry Magazine*, October pp. 17. Available at http://saforestryonline.co.za/articles/harvesting_silviculture/semi_mechanised_harvesting_systems_best_of_both/ [accessed 20 May 2016].

Mc Carthy R, Ekö PM, Rytter L. 2014. Reliability of stump sprouting as a regeneration method for poplars: clonal behaviour in survival, sprout straightness and growth. *Silva Fennica* 48(3): 9.

McEwan A, Brink M, van Zyl S. 2013. Guidelines for difficult terrain ground-based harvesting operations in South Africa. In: Talbot B, Berkett H (eds), *Proceedings of the IUFRO unit 3.06 Conference on Forest Operations in Mountainous Conditions*; June 2–5; Honne, Norway; 27–28.

McEwan A, Steenkamp J. 2015. *Silviculture modernization in the South African forestry industry*. In: Proceedings of the Second International Congress of Silviculture. Designing the future of the forestry sector. Florence, 26.29 November, 2014. Firenze: Accademia Italiana di Scienze Forestali. Vol. 2, p. 822-826. ISBN 978-88-87553-21-5. http://dx.doi.org/10.4129/2cis-ame-sil.

McEwan A, Magagnotti N, Spinelli R. 2016. The effects of number of stems per stool on cutting productivity in coppiced *Eucalyptus* plantations. *Silva Fennica* 50: 2 article id 1448. http://dx.doi.org/10.14214/sf.1448.

Morley TA, Little KM, Rolando CA. 2008. Enhancing the benefits of stand management: Background to improved understanding of individual tree growth. *ICFR Bulletin Series No. 11/2008.* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Morley T, Little K. 2011. Comparison of taper functions between two planted and coppiced eucalypt clonal hybrids, South Africa. *New Forests* 43(1): 1-13.

Nyland RD. 1996. *Silviculture: Concepts and applications*. New York: McGraw-Hill.

Pokorny B, Sabogal C, Silva J, Bernardo P, Souza J, Zweede J. 2005. Compliance with reduced-impact harvesting guidelines by timber enterprises in terra firme forests of the Brazilian Amazon. *International Forestry Review* 7: 9-20.

Puttock D, Spinelli R, Hartsough BR. 2005. Operational trials of cut-to-length harvesting of poplar in a mixed wood stand. *International Journal of Forest Engineering* 16(1): 39-49.

Pulkki R. 2003. Minimizing negative environmental impacts of forest harvesting operations. In: Burton PJ, Messier C, Smith DW, Adamowicz WL, (eds), *Towards Sustainable Management of the Boreal Forest*. Ottawa: National Research Council of Canada. pp. 581–628.

Putz F, Sist P, Fredericksen T, Dykstra D. 2008. Reduced-impact logging: challenges and opportunities. *Forest Ecology and Management* 256: 1427-1433.

Pyttel PL, Fischer UF, Suchomel C, Gärtner SM, Bauhus J. 2013. The effect of harvesting on stump mortality and re-sprouting in aged oak coppice forests. *Forest Ecology and Management* 289: 18–27.

Ramantswana M, McEwan A, Steenkamp J. 2013. A comparison between excavator-based harvester productivity in coppiced and planted *Eucalyptus grandis* compartments in KwaZulu-Natal, South Africa. *Southern Forests* 75: 239-246.

Reisinger TW, Sluss RG, Shaffer RM. 1994. Managerial and operational characteristics of "safety successful" logging contractors. *Forest Products Journal* 44: 72.

Republic of South Africa (RSA). 2013. Basic conditions of employment act (Act No. 75 of 1997). *Government Gazette, South Africa* 573(36224). Pretoria.

Rietz D. 2013. The effect of compaction and residue management on soil properties and early *Eucalyptus* growth on a granite-derived soil. *ICFR Bulletin Series No.03/2005.* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Roberts JC, Little KM, Light ME. 2016a. The use of glyphosate for the management of secondary coppice regrowth in a*Eucalyptus grandis* × *E. urophylla* coppice stand in Zululand, South Africa. *Southern Forests* 78: 217- 223.

Rockwood DL, Rudie AW, Ralph SA, Zhu J, Winandy JE. 2008. Energy product options for Eucalyptus species grown as short rotation woody crops. *International Journal of Molecular Sciences* 9: 1361-1378.

Roothman D. 2014. Demands and requirements for mechanised operations. *Wood and Timber Times Southern Africa December* 2014: 14-15.

SA Forestry. 2015. *Mechanisation changing the face of forestry*. Available at http://saforestryonline.co.za/articles/harvesting_silviculture/mechanisation-changing-the-face-of-forestry/ [accessed 25 October 2016].

Schönau APG. 1980. Timber density of planted parent trees and first generation coppice of *Eucalyptus grandis*. *Wattle Research Institute Report for 1979- 1980*. Institute for Commercial Forestry Research, Pietermaritzburg. South Africa, pp. 107-110.

Schönau APG. 1984. Silvicultural considerations for high productivity of *Eucalyptus grandis*. *Forest Ecology and Management* 9: 295-314.

Schönau APG. 1991. Growth, yield and timber density of short rotation coppice stands of *Eucalyptus grandis*. *South African Forestry Journal* 156: 12-22.

Schulze R. 2008. *South African Atlas of Climatology and Agrohydrology.* Water Research Commission. Pretoria, South Africa.

Schwegman K, Little KM, McEwan A, Ackerman SA. 2016. Mechanised harvesting costs for eucalypt coppice stands of varying stump and stem densities, South Africa. *Unpublished MSc Thesis.* Nelson Mandela Metropolitan University. George, South Africa.

Schweier J, Spinelli R, Maganotti N, Becker G. 2014. Mechanized coppice harvesting with new small-scale feller-bunchers: results from harvesting trials with newly manufactured felling heads in Italy. *Biomass Bioenergy* 72: 85–94.

Sims RE, Senelwa K, Maiava T, Bullock BT. 1999. *Eucalyptus* species for biomass energy in New Zealand—Part II: Coppice performance. *Biomass and Bioenergy* 17: 333-343.

Sist P, Sheil D, Kartawinata K, Priyadi H. 2003. Reduced-impact logging in Indonesian Borneo: some results confirming the need for new silvicultural prescriptions. *Forest Ecology and Management* 179: 415-427.

Smith DM, Larson B, Kelty M, Ashton P 1997. *The practice of silviculture*: Applied forest ecology (9th edn). John Wiley and Sons, New York, NY.

Smith C. 1998. Site damage and long-term site productivity of forest plantations in South Africa: Impacts of harvesting operations and suggested management strategies. *ICFR Bulletin Series No. 14/1998.* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Smith CW, Pallett R, Kunz R, Gardner R, Du Plessis M. 2005a. A strategic forestry site classification for the summer rainfall region of southern Africa based on climate, geology and soils. *ICFR Bulletin Series No. 03/2005.* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Smith CW, Gardner R, Pallett R, Swain T, du Plessis M, Kunz R. 2005b. A Site Evaluation for Site: Species Matching in the Summer Rainfall Regions of South Africa. *ICFR Bulletin Series No. 04/2005.* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Soil Classification Working Group. 1991. *Soil Classification: A Taxonomic System for South Africa: a Report on a Research Project Conducted Under the Auspices of the Soil and Irrigation Research Institute*. Department of Agricultural Development.

Spinelli R, Hartsough B. 2001. A survey of Italian chipping operations. *Biomass and Bioenergy* 21(6): 433–444.

Spinelli R, Owende PM, Ward SM. 2002. Productivity and cost of CTL harvesting of *Eucalyptus globulus* stands using excavator-based harvesters. *Forest Products Journal* 52: 67-77.

Spinelli R, Cuchet E, Roux P. 2007. A new feller-buncher for harvesting energy wood: results from a European test programme. *Biomass Bioenergy* 31: 205–210.

Spinelli R, Brown M, Giles R, Huxtable D, Relaño RL, Magagnotti N. 2014. Harvesting alternatives for mallee agroforestry plantations in Western Australia. *Agroforestry Systems* 88: 479–487.

Steenkamp JC. 2008. The effect of HIV and AIDS on the viability and management of forestry contracting businesses in South Africa. *PhD Thesis*, Nelson Mandela Metropolitan University, South Africa.

Stubbings J, Schönau A. 1980. Management of short rotation coppice crops of *Eucalyptus grandis* Hill ex Maiden. *South African Forestry Journal* 115: 38-46.

Suchomel C, Becker G, Pyttel P. 2011. Fully mechanized harvesting in aged oak coppice stands. *Forest Products Journal* 61: 290-296.

Suchomel C, Spinelli R, Magagnotti N. 2012. Productivity of processing hardwoods from coppice forests. *Croatian Journal of Forest Engineering* 33: 39–47.

Swain TL, Gardner RAW. 2003. Use of site–species matching and genetic gain to maximise yield-a South African example. In: Wei RP, Xu D. (eds). *Proceedings of the International Symposium on Eucalyptus Plantations: Research, Management and Development*, Guangzhou, China, 1–6 September 2002. World Scientific, Singapore, pp. 167–185.

Topouzis D. 2007. HIV/AIDS: a risk to the social and economic sustainability of forestry in sub-Saharan Africa? *International Forestry Review* 9: 558-562.

Turnbull JW, Booth TH. 2002. Eucalypts in cultivation: an overview. In: Coppen JW (ed.) *Eucalyptus: the genus Eucalyptus*. London: Taylor and Francis. pp 52–73.

Viero PW, du Toit B. 2011. Establishment and regeneration of eucalypt, pine and wattle stands. In: Brendenkamp BV, Upfold S (eds), *South African Forest Handbook* (5th edn). Pretoria: South African Institute for Forestry, pp. 107-114.

Vou P. 1990. Genetic parameters and gains expected from selection in *Eucalyptus globulus* in Tasmania. *Silvae Genetica* 39 (1): 18-21.

Waratah. 2015. Harvesting and Processing Heads. Available at http://nz.waratah.net/harvesting-processing-heads/ [accessed 21 October 2015 2015].

Warkotsch PW, Van Huyssteen L, Olsen GJ. 1994. Identification and quantification of soil compaction due to various harvesting methods—A case study. *South African Forestry Journal* 170(1): 7–15.

Weather SA. 2016. Annual rainfall over the period of 1988-1998 for Emahlathini and Watervaldrift weather stations. South African Weather Service, Erasmusrand, South Africa.

Whiteside A, Sunter C.2000. *AIDS: the challenge of South Africa.* Cape Town, Tafelberg, pp.180.

Whittock SP, Apiolaza LA, Kelly C, Potts B. 2003. Genetic control of coppice and lignotuber development in *Eucalyptus globulus*. *Australian Journal of Botany* 51: 57-67.

Whittock SP, Greaves BL, Apiolaza LA. 2004. A cash flow model to compare coppice and genetically improved seedling options for *Eucalyptus globulus* pulpwood plantations. *Forest Ecology and Management* 191: 267-274.

Wingfield MJ, Slippers B, Hurley BP, Coutinho TA, Wingfield BD, Roux J. 2008. Eucalypt pest and diseases: growing threats to plantation productivity. *Southern Forests* 70: 139-144.

World Trade Organisation (WTO). 2016. Members and observers. Available at www.wto.org/english/thewto_e/whatis_e/tif_e/org6_e.html [accessed 23 October 2016].

Worrell R, Hampson A. 1997. The influence of some forest operations on the sustainable management of forest soils—a review. *Forestry* 70: 61-85.

Zbonak A, Bush T, Grzeskowiak V. 2007. Comparison of tree growth, wood density and anatomical properties between coppiced trees and parent crop of six *Eucalyptus* genotypes. *IUFRO-Improvement and Culture of Eucalyptus*: pp 1-10.

Zwolinski J, and Bayley AD. 2001. Research on planting stock and forest regeneration in South Africa. *New Forests* 22: 59–74.