SILVICULTURAL VALUE CHAIN ANALYSIS OF SHORT ROTATION *EUCALYPTUS GRANDIS X UROPHYLLA* STANDS IN COASTAL ZULULAND

by

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DECLARATION

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ABSTRACT

Intensive silivciultural management at establishment is part of commercial practises on short rotation *Eucalyptus* spp. plantations in South Africa. There is however some uncertainty within the industry whether or not particular activities at plantation level add higher value to the product than the initial investment cost. This study is divided into two sections. Firstly, a case study research method is performed to identify if historical operational data can be used to determine the effect of silvicultural activities on the early height growth and rotational performance of *Eucalyptus grandis x urophylla* stands in coastal Zululand. The relationship between silvicultural activities and the final tonnes harvested at end of rotation was determined by means of robust regression analysis. Secondly, Microsoft Excel Solver was used to build an optimization simulation model. The model is based on the results from the analysis in the first section. The optimization model provides the lowest cost, highest production and most profitable path through the silvicultural value chain for Zululand North and South respectively.

The results from the first section illustrated the important impact that site, climate and other external factors have on the growth and performance of stands, and that stands in Zululand South perform better than stands in Zululand North. Results also indicated that site specific silviculture is very important, with some silvicultural activities showing significantly positive effects on the final tonnes harvested in one region, while the same activities did not have a significant effect in the other region.

Results from the operational data analysis were compared to results from published trial research studies. Results related to the effect of pre-plant spray and planting with water on early survival, the effect of fertiliser on final volume growth in Zululand South and the effect of number of weedings on early height growth in Zululand South were contradictory to research studies. The effect of planting with water on early height growth in Zululand North, effect of planting season in both regions and the effect of blanking on final tonnes in Zululand South correlated to results from published research studies. It seems that operational data in the current format is not suitable to demonstrate cause and effect of silvicultural activities. Small changes to operational data collection protocols could enhance the research use of this data substantially.

The Excel Solver simulatution model is based on the results of the first section and is only used to illustrate the potential it can have in future management decisons. Results from the Excel Solver simulation illustrated that the highest production and most profitable path is the same path through the silvicultural value chain in Zululand North and in Zululand South. The activities included in these paths did however differ between the two regions. The most

profitable path through the silvicultural value chain in Zululand North illustrated a potential cost-benefit of R4716.62 ha^{-1}, while the most profitable path through the silvicultural value chain in Zululand South illustrated a potential cost-benefit of R159.31 ha^{-1}.

OPSOMMING

Intensiewe boskultuur bestuur tydens vestiging van kort-rotasie *Eucalyptus* plantasies word kommersiël toegepas in Suid-Afrika. Daar is egter 'n mate van onsekerheid in die bedryf of al die aktiwiteite op plantasievlak hoër waarde toevoeg by die finale produk as die aanvanklike beleggingskoste. Die studie is in twee afdelings verdeel. Eerstens word 'n gevallestudie-navorsings metode uitgevoer om te identifiseer of historiese operasionele data gebruik kan word om die effek van boskultuur aktiwiteite op die korttermyn hoogte groei en die rotasie produktiwiteit van vakke te bepaal. Die verhouding tussen die effek van boskultuur aktiwiteite en die finale tonne geoes aan die einde van rotasie is bepaal deur middel van robuuste regressie-analise. Tweedens word Microsoft Excel Solver gebruik om 'n optimaliserings simulasie model te bou. Die model is gebaseer op die resultate van die analise in die eerste afdeling. Die optimaliseringsmodel bied die laagste koste, hoogste produksie en mees winsgewende pad deur die boskultuur waardeketting vir Zululand Noord en Suid onderskeidelik.

Die resultate van die eerste afdeling illustreer die belangrike impak wat die terrein, klimaat en ander eksterne faktore het op die groei en prestasie van vakke, en dat vakke in Zululand Suid beter presteer as vakke in Zululand Noord. Resultate het ook aangedui dat terrein spesifieke boskultuur baie belangrik is, aangesien sommige boskultuur aktiwiteite betekenisvolle positiewe effekte toon op die finale tonne geoes in een streek, terwyl dieselfde aktiwiteite nie in die ander streek betekenisvolle effekte gehad het nie.

Resultate van die operasionele data-analise is vergelyk met die resultate van gepubliseerde proefnavorsingstudies. Die effek van voorplantspuit en plant met water op vroeë oorlewing, die effek van kunsmis op die finale volume groei in Zululand Suid en die uitwerking van die aantal onkruidbeheer aktiwiteite op vroeë hoogtegroei in Zoeloeland Suid is teenstrydig met wat gevind is navorsingstudies. Die effek van plant met water op vroeë hoogtegroei in Zululland Noord, die effek van plantseisoen in albei streke en die effek van inboeting op finale tonne in Zululand Suid, korreleer met resultate van gepubliseerde navorsingstudies. Dit blyk dat operasionele data in die huidige formaat nie geskik is om oorsaak en gevolg van boskultuur aktiwiteite te toon nie. Klein veranderinge aan operasionele data-insamelingsprotokolle kan die navorsingsgebruik van hierdie data substansieel verbeter.

Die Excel Solver simulasie is gebaseer op die resultate van die eerste afdeling en word slegs gebruik om die toekomstige potensiaal vir bestuursbesluite te illustreer. Resultate van die Excel Solver simulasie model het getoon dat die hoogste produksie- en mees winsgewende roete dieselfde roete is deur die boskultuur waardeketting in Zululand Noord en in Zululand

Suid, onderskeidelik. Hierdie roetes het egter tussen die twee streke verskil. Die mees winsgewende roete deur die boskultuur waardeketting in Zululand Noord het 'n potensiële kostevoordeel van R4716.62 /ha geïllustreer, terwyl die mees winsgewende roete deur die boskultuur waardeketting in Zululand Suid 'n potensiële koste-voordeel van R159.31 /ha geïllustreer het.

ACRONYMS

SI	Site Index
SQ	Site Quality
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
MAI	Mean Annual Increment
TUP	Temporarily unplanted
DBH	Diameter at Breast Height
LAI	Leaf Area Index
N	Nitrogen
S	Sulfur
ASN	Ammonium Sulphate Nitrate
VCA	Value Chain Analysis
TCS MAI	Timber Control System Mean Annual Increment
MHPR	Median Height Pro Rata
Anova	Analysis of Variance
rlm	robust linear models
glm	generalized linear models
lm	linear models
H_0	Null Hypotheses
H_1	Alternative Hypotheses

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Chapter 1

INTRODUCTION TO THE RESEARCH STUDY

1.1 GENERAL INTRODUCTION

Commercial forestry in South Africa makes use of fast-growing, even-aged plantations with simplified economic, silviculture and harvesting systems (Pallett 2005). The increase in demand for wood products and the limited forest area has forced the forestry industry to increase the productivity of existing plantations in order to meet the demand for wood products and reduce the cost of timber (Boreham and Pallett 2009; Dovey 2012). According to Boreham and Pallett (2009), genetic tree improvement, site-species matching, improved silviculture and harvesting practices, along with rotation length and stand density optimisation, are essential for increasing the productivity of existing short rotation plantations.

Intensive silvicultural management includes the following main phases in the life cycle of plantation forests: site-species-market matching, tree improvement and propagation, land clearing, land preparation, planting, fertilising, vegetation management, post-establishment silviculture and other continuous activities. Each of these phases consists of different activities, which are believed to add value to the timber yield harvested at rotation age. These activities are affected by site type and by previous harvesting systems used on the site (du Toit and Norris 2012).

There have been numerous research trials on the effect of silvicultural activities on tree growth, tree survival, stand productivity and stand uniformity. Results from these studies illustrate both significant and non-significant responses to silvicultural activities dependent on site conditions, with the majority indicating tree growth benefits from the silvicultural activities (du Toit and Oscroft 2003; Smith and Du Toit 2005; Germishuizen and Smith 2007; Little *et al*. 2007; Viero and Button 2007). Ackerman and Reitz (2014) suggest, however, that there is uncertainty within the commercial forestry industry as to whether or not silvicultural activities at plantation level add higher value to the product than the initial investment cost of these activities.

A value chain study could be used to test the suggestion of Ackerman and Reitz (2014). A value chain can be defined as a linked set of value-adding activities all the way from basic raw material, through to product delivered to the consumer (Chivaka 2007). Carlsson and Rönnqvist (2005) indicated that value chain management and optimization in forestry is becoming increasingly important in order to improve its operations and ensure its economic sustainability. Such management and optimization would allow for integration between activities and potential improvements in the forestry value chain. According to Bullinger *et al*.

(2002) a value chain analysis is required to quantify the status quo of a business in order to identify potential improvements within the value chain and to keep track of the current improvement objectives.

It is however necessary to determine if operational historical data can be used to determine cause and effect of silvicultural activities performed at re-establishement, and to link the cost of activities to the monetary value added by the respective silvicultural activities. Such a value chain study is not indendent to replace or downplay silviculture trials, but rather to determine if the results correlate with controlled scientific trials.

1.2 STUDY APPROACH

The study is divided into two sections. Firstly, a case study research method is performed in which an empirical investigation is done to identify if historical data can be used to determine the early height growth, survival and rotational growth effects silvicultural activities have on stands. This is done with the use of a value chain analysis. The value chain analysis deconstructs the whole value chain into relevant activities (Chivaka 2007). These activities are then analysed to determine if there is a relationship between the respective silvicultural activities, the short term tree height growth of trees and the final tonnes harvested at end of rotation. The investment cost of these activities are compared to the value created by the relevant activities to determine whether the benefits outweigh the initial investment cost of the activities.

Secondly, a shortest route network model in Microsoft Excel Solver is used to build an optimization simulation model (Winston *et al*. 2004). The model is based on the results from the value chain analysis in the first section. The optimization model provides the lowest cost, optimum production and most profitable path through the silvicultural value chain for Zululand North and South respectivly.

1.3 OBJECTIVES

The objectives of this study are to:

- Determine if historical operational data can be used to identify the effect silvicultural activities have on short term height growth and final volume growth.
- Investigate if a correlation between silvicultural activities, early survival and final volume growth can be determined from historical operational data.
- Identify potential financial and productivity improvements within the silvicultural value chain.

- Create a simulation model based on real historical values that can provide the lowest cost, highest production and most profitable activity path through the silvicultural value chain, in order to help with decision making at ground level.

1.4 LIMITATIONS

Monitoring the impact silvicultural activities have on plantation productivity using measures of tree growth and forest product output may be a poor indication when used alone. This is due to the impact that climatic variability, previous landuse, pest and disease outbreaks, genetic improvements and natural disturbances have on the productivity of a site. The limitation to this study is that data collected is spread over a range of different geographical locations and gathered from uncontrolled field conditions. Although all in the same district and sub-tropical silviculture zone, they may differ in soil type, soil depth, mean annual precipitation (MAP), mean annual tempereture (MAT) and different risks which can influence the tree growth, and therefore lead to misleading results. To minimise the impact of external factors, the data collected has been segmented into Zululand North and Zululand South regions.

1.5 OUTPUTS

The results from the value chain analysis will help to understand to what extend operational data can be used to model silvicultural activities in the value chain. It will also present an opportunity to recommend future data collection and aggregation protocols. The simulation model built in Microsoft Excel Solver is created in such a way that it provides the following three outputs for the two regions: (1) the highest production irrespective of cost, (2) the lowest cost path through value chain and (3) the optimum profitability when taking in to account timber production and total cost of activities. The simulator is aimed at being a decision making tool which foresters can use on a range of sites to implement site specific silviculture which is intact with the objectives of their organisation.

Chapter 2

LITERATURE REVIEW

2.1 CHARACTERISTICS OF SHORT ROTATION *EUCALYPTUS* STANDS

South Africa is heavily dependent on commercially grown short rotation plantation forest for timber (Forestry Economic Services 2003). According to Louw (2012), plantation forestry was initially established in 1876 and Godsmark (2017) indicated the forestry area currently covers more than 1 224 456 hectare (ha) of land, which is 1% of the land use in South Africa. According to Godsmark (2017) 41.8% of this area is planted to *Eucalyptus* species of which 86.7% are for pulpwood, 5.3% for mining timber and 2.9% for other uses. These plantation forests are widely distributed but prominently spread on the eastern seaboard and its adjacent escarpments of KwaZulu-Natal, as well as the adjoining Highveld and Lowveld of Mpumalanga (Smith *et al*. 2010; Dovey 2012; Herbert 2012). The distribution of plantations is responsible for the wide range of different growing conditions as result of their lithology, latitude, climate, altitude, topography and biotic factors (Louw 2012).

According to Pallett (2005), these are the main variables used to explain the variation in growth within species in different areas. These variables are used in site classification systems to classify land types. Land types are used to understand the productive potential of land (Pallett 2005). Site quality is a rating given to a site that refers to potential tree growth of that site and is based on the productivity in terms of volume production. The growth potential of a site (site index) can be estimated from historic enumerations by calculating the mean height of those 20% largest trees in terms of diameter at breast height (DBH) (du Toit and Dovey 2005) at a fixed reference age. Site index is a measure of growth potential and is used by Sappi to define five site quality classes, which rank sites from poorest to most productive (Pallett 2005).

2.2 VALUE CHAIN COMPONENTS OF SHORT ROTATION *EUCALYPTUS* STANDS

The South African plantation forestry value chain consists of the following main components: research, silviculture, harvesting and transport (Ackerman and Reitz 2014). Each component consists of a number of phases and activities, which are expected to add value to the product (Reitz *et al*. 2015). Plantation management is a cyclical process involving all the value chain components mentioned above.

According to Ackerman and Reitz (2014), plantation management is performed by a number of independent steps, with each step normally managed in isolation by different sections or individuals within the enterprise, or outsourced to contractors, each of which are not concerned with the activities that occur prior to or after their activities. This results in operational inefficiencies between the different elements of the forestry value chain. Instead of thinking of the forestry activities as disconnected from one another, the supply of timber from seedling to mill could be analysed with value chain typology. This provides the opportunity to improve and further optimise the efficiency of the entire process (Ackerman and Reitz 2014).

2.3 SHORT ROTATION PLANTATION MANAGEMENT

The increase in demand for wood products and the limited forest area has forced the forestry industry to increase the productivity of existing plantations in order to meet the demand for wood products and reduce the cost of timber (Boreham and Pallett 2009; Dovey 2012). Genetic tree improvement, site-species matching, improved silviculture and harvesting practices, along with rotation length and stand density optimisation, are essential for increasing the productivity of existing short rotation plantations (Boreham and Pallett 2009). Pallett (2005) also suggested that it is very important to integrate intensive silvicultural management and genetically improved material in order to optimise plantation productivity. The critical time in which the productivity of short rotation plantations can be influenced is from felling to canopy closure (Smith *et al.* 2010). This inter-rotation period can be used to correct previous mistakes and set the course for sustainable forest management (Gonçalves *et al.* 2008).

Activities in this phase include several site preparations and silvicultural practices, e.g. minimizing harvesting impacts, management of harvesting residue (land clearing), land preparation, planting practices, planting density, fertilization and vegetation management (Dovey 2012). These operations influence the early growth of the trees and often determine the productivity of the remainder of the rotation (Smith *et al.* 2010; Dovey 2012).

Silvicultural activities provide early improvement in nutrient availability, which results in accelerated canopy development, especially on sites with limited water availability (du Toit 2008). Smith *et al.* (2010) stated that there are several empirical experiments that indicate a decrease in time to canopy closure when growth resources are manipulated through these silviculture operations. These operations also reduce interspecific competition and improve stand homogeneity (Little and van Staden 2003) and according to the growth dominance theory by Binkley (2004), it can contribute to the productivity of a stand. The response that tree growth has to management practices varies across different sites and, according to Dovey

(2012), sites with rapid growth and high nutrient turnover will be more sensitive to management practices than dryer, cooler, more slow growing sites.

2.4 SILVICULTURAL MANAGEMENT

The effects of silvicultural operations across a wide range of sites in South Africa are well documented in academic literature and are discussed in depth in the following sub-sections.

2.4.1 Residue management

Plantation slash (residues) is an important asset on forestry sites as it stores valuable nutrients, can be used to enhance moisture content of a site and to protect soils in the long-term. Residue management has an impact on a site's productivity (Upfold 2000). Early growth rate of short rotation *Eucalyptus* plantations are dependent on available resources (nutrients, light and water) (du Toit *et al*. 2008). The effect on tree growth is different for different residue management treatments (Gonçalves *et al.* 2008). Results of a soil fertility trial in Brazil by Gonçalves *et al.* (2008) suggested that the fertility of the soil and the nutrient pool of the ecosystem are heavily affected by residue management, and that some treatments can have an effect on the sustainability of plantation productivity. Slash burning as residue management treatment has a short term benefit of up to one year after treatment. In that period it has the biggest increase in uptake and availability of nutrients of all the treatments (Smith *et al.* 2010). Gonçalves *et al*. (2008) suggested that slash burning results in a higher volume growth rate in the early years, as a result of high initial nutrient availability and mineralisation. Slash burning also intensifies the loss of nutrients and carbon which can cause site degradation (Deleporte *et al*. 2008). Deleporte *et al.* (2008) studied the effect of different slash and litter management practised on the growth of *Eucalyptus*. Slash burning was responsible for increased early growth as it had the highest height, DBH and above ground biomass after 11 months, however after two years the growth of the treatment slowed compared to other treatments. According to a case study by du Toit *et al.* (2008), slash burning increased the initial sum of base cations and increased the topsoil pH, however these changes were temporary as most treatments returned to their initial value after time (Mendham *et al.* 2008).

From above we can see that the burning of slash temporary releases a large amount of nutrients, which increases growth (Scheepers 2014). However, it has negative implications for the total ecosystem nutrient pool, can have a negative impact on long-term soil fertility and can reduce productivity over succeeding rotations, which may well outstrip the short term benefits from early growth (Deleporte *et al*. 2008; Gonçalves *et al.* 2008; Smith *et al.* 2010). In such situations, mild slash burning can be restricted to non-sensitive sites in order to see better survival and facilitate growth of seedlings (du Toit *et al.* 2008; Nambiar and Kallio 2008).

2.4.2 Land preparation

Early research by Schönau *et al*. (1981) illustrateded that there were benefits of rapid early growth in hardwoods from tillage, and that intensive land preparation techniques became common practice in South African plantation forest over three decades ago during afforestation of virgin grasslands. Smith *et al.* (2001) indicated there were, however, mixed results in early research worldwide regarding the impact land preparation has on growth and survival at re-establishment, with some achieving improved growth and survival from intensive land preparation (Berg 1975; Guild 1971; Burger and Pritchett 1988), while in others no improvement was shown (van Goor 1985; Madeira *et al*. 1989). South Africa had the same experience, and responses were likely to be site specific. Smith (1998) critically reviewed the early research done on the impact of land preparation on growth and survival and consequently re-analysed (Smith *et al*. 2000; Smith *et al*. 2001) and illustrated the impact that intensive land preparation has on re-establishment (Smith *et al.* 2010). Results of a study by Smith *et al.* (2001) illustrated that final survival generally lacked a significant response to land preparation treatments, with ripping showing improved tree growth on re-establishment sites where soil drainage is problematic. The general lack of significant response is interesting since field experience indicates land preparation has a large effect on survival (Smith *et al.* 2001). Smith *et al.* (2001) suggested the reason land preparation had little effect is as a result of the high standard of planting and weed control activities in the trials, which is not always the case in the field. Intensive land preparation treatments had no significant growth response in terms of volume or basal area when compared to a standard pitting control treatment.

Results from Smith *et al.* (2001) suggest that the physical condition of the soils in the summer rainfall area of South Africa is not growth limiting and that factors limiting growth are rather related to the climate. According to Madeira *et al.* (1989), the reason for non-significant responses to intensive land preparation can be due to a combination of mixing of subsoil and topsoil and top soil disturbance, which can lead to lower water capacity and decreased nutrient availability. According to Smith *et al.* (2001) forest management should focus on more cost effective land preparation treatments under re-establishment, unless a growth limiting factor exists. Upfold (2000) suggested that the best land preparation treatment for re-establishment is generally the simplest and thus the most cost-effective.

2.4.3 Planting density

Stand density is the surface area available for individual trees and is expressed as spacing, which is the inter and intra-row distance between trees. Stocking and stand density is mostly described as the number of stems per hectare (sph) (Schönau and Coetzee 1989).

Spacing has a large impact on short rotation stands in terms of time to canopy closure, competition for nutrients, end stocking, tree-growth rate, final volume and silvicultural operations. The appropriate spacing depends on climate, species, site quality, objectives, silvicultural treatments, harvesting methods and rotation length (Schönau and Coetzee 1989; Mead 2005). High stand densities in general produce higher volume growth per area, but this volume will consist of smaller individual trees, while wider spacing leads to lower total volume per area but higher volume per tree (Schönau and Coetzee 1989; Gonçalves *et al.* 2004; Smith *et al.* 2005; Smith *et al.* 2010; Crous *et al.* 2013). Gonçalves *et al.* (2004) stated that closer spacing at planting enables faster development of leaf area index (LAI), which leads to an increase in light interception and photosynthesis and, according to Smith *et al.* (2010), it promotes faster growth and minimizes the time taken to reach canopy closure, which can contribute to weed control cost savings.

Early research on stand density by Hamilton and Christie (1974) stated that mortality increased with closer spacing. Van Laar and Bredenkamp (1979) indicated that *E.grandis* had an increase in mortality for higher stand density on high-quality sites, but no increase in mortality was found for same species on low-quality site for stocking between 1200—1700 trees per hectare (Schönau 1974) . Schönau and Coetzee (1989) concluded that the relationship that exists between higher density and increased tree mortality is affected by age, species and site conditions. A study by Crous *et al.* (2013) found similar results for *E. grandis* and *E.dunnii*. However, Crous *et al.* (2013) also suggested that selecting a species that is water stress tolerant was more important in terms of mortality than the planting density on sites where soil drainage is sometimes problematic at certain times.

An interesting finding in the study by Crous *et al.* (2013) is that dominant height and mean height decrease with increasing planting density, similar to the study by Coetzee *et al.* (1996). Schönau and Coetzee (1989) stated that mean height increase, but dominant height does not increase, with decreasing stand density - this was also found in a spacing trial in Brazil (Bernardo *et al.* 1998). Crous *et al.* (2013) suggested that the loss in tree height with the increase in planting density is as a result of extreme competition for resources.

Planting density can have financial implications, due to the effect on tree size. Harvesting operation costs (R tonne^{-1}) generally increase as individual tree diameters and tree volumes decrease (Crous *et al.* 2013). However, where manual labour is used, the harvesting of smaller tree sizes is economically more attractive (Smith *et al.* 2010). According to Coetzee and McLennan (2000), *Eucalyptus* species planted for pulpwood should have a stand density between 1600—1800 stems per hectare to achieve optimum stocking at rotation age. However, Mead (2005) suggested that tree growth rate, mortality patterns, planting methods, weeding, rotation length and harvesting should be considered when decisions are made.

2.4.4 Planting

In South Africa re-establishment of short rotation plantations is constrained to climate. Because climate has an impact on the soil moisture content and evapotranspiration, the timing of planting operations (season) is critical (Viero and Button 2007). According to Viero and Little (2006), cool and warm temperate regions are mainly planted in months where higher rainfall events is expected. Viero and Button (2007) indicated that planting for these regions is mainly confined to spring and autumn months of the year, suggesting that excessive heat can lead to increased mortality in mid-summer (Viero *et al.* 2000; Schulze 1997) . Frost risk and the lack of rainfall in the winter months leads to high mortality in these regions. In contrast, the sup-tropical region of coastal Zululand experiences year-round rainfall and is characterised by very high temperatures in summer. This means that most *Eucalyptus* planting operations take place in the cooler winter months, when the evapotranspiration is lower (Little *et al.* 1996; Viero *et al.* 2000; Schulze 1997).

A typical planting operation in short rotation *Eucalyptus* plantations includes pit preparation, planting or planting with an application of either water or hydrogel, all of which can have an impact on the tree growth and survival of seedlings (Viero *et al.* 2000; Viero *et al.* 2008). These activities can be performed with different application methods and concentrations depending on the geographical location, soil type (water holding capacity), site quality, climate, season, company policy and individual preference. Some forestry companies have a no-water or hydrogel policy, while others only plant with water or hydrogel and others only use it when planting conditions are suboptimal (Viero *et al.* 2008). According to Rolando and Little (2008), the availability of adequate water plays a role in the success of a eucalypt planting operation and reduces the initial water stress for planting stock. Studies by Viero *et al.* (2000) and Viero and Little (2006) have shown that the inclusion of water and hydrogel into pits at planting can reduce the risk of early mortality, depending however on the region and season.

A study by Viero and Button (2007) indicated that planting with water and hydrogel had a significant impact on the growth and survival of seedlings when planted out of season in coastal Zululand, but when planted in commercially accepted planting season, the dry planting treatments also performed well when compared to water and hydrogel treatments at planting. These results indicate that planting in the optimum planting periods can reduce mortality and therefore save cost at re-establishment (Viero and Button 2007).

2.4.5 Fertilizing

The aim of silvicultural operations is to optimise the availability of growth resources for trees at re-establishment so as to maximise survival, growth and stand uniformity of short rotation eucalypt plantations (du Toit and Drew 2003). There have been a number of studies focused on fertilizer trials at time of re-establishment in South Africa over the past three decades, which covered a wide variety of site types, species and re-establishment conditions. Results from these studies show that the addition of fertilizer at re-establishment has the potential to improve productivity in terms of volume and wood density at the end of rotation in short rotation *Eucalyptus* stands (Schönau and Herbert 1989; du Toit *et al.* 2001; du Toit and Oscroft 2003). However, according to Smith *et al.* (2010), there are a number of trials that did not indicate a response to fertilizer applications, where the trials were abandoned and the lack of a response not recorded in literature. The lack of response in some of these cases was as a result of low rainfall conditions. The levels of fertilizer application are expressed on a per tree basis since fertilizer is locally applied approximately 10—20 cm from each transplant in either a ring around the plant, or in two bands on either side and is buried 5 cm below the soil surface, irrespective of the stocking (Schönau and Herbert 1989; Boreham and Pallett 2009; Smith *et al.* 2010).

The optimum fertilizer application level is dependent on site condition, soil type and harvesting residue management. The application should complement the current nutrient availability of the stand (Smith *et al.* 2010). Noble (1992) indicated that the organic carbon content of the topsoil has an effect on fertiliser requirements; for example increasing organic matter in topsoil increases the nitrogen (N) supply potential of soils and as such, the soil does not require large quantities of N in the form of fertilizer at establishment (Boreham and Pallett 2009; Smith *et al.* 2010). Residue management treatment also influences the requirements of fertilizer application. The incorporation of harvesting residue into top soil by disturbance or certain harvesting methods may increase mineralization and provide available nutrients, thus decreasing the need for fertilizer. Slash burning increases the availability and uptake of nutrients and may also decrease the need for fertilizer (du Toit and Dovey 2005; du Toit 2008; Smith *et al.* 2010). In order to achieve the best possible benefits, the timing, application rate and method of application must be optimised (Smith *et al.* 2010).

Research by du Toit and Oscroft (2003) tested the stand growth response of a *Eucalyptus grandis* x *urophylla* hybrid to fertiliser with nitrogen (N), phosphorus (P) and sulfur (S) across five different site types in coastal Zululand. Results of the trials indicate that the two trials on the lowest fertility sites had the greatest response, and the most fertile site had the weakest response to fertiliser treatment (du Toit and Oscroft 2003). The volume responses at clear-felling were similar for trials on intermediate and high fertility sites (du Toit and Oscroft 2003). If for some reason site specific treatment is not possible and a blanket application is therefore practised, du Toit and Oscroft (2003) recommend applying ammonium sulphate nitrate (ASN) at 50 g N per tree as it resulted in positive responses on all the different sites. However, there are several areas in the coastal Zululand, which were prevouisly intensively managed for agricultutre operations. Several of these areas have extremely infertile soils which supports poor tree growth (du Toit *et al*. 2001), A study by du Toit *et al.* (2001) suggests that the application of high levels of N with smaller amounts of P, K and other nutrients had a significant effect on stand growth up to rotation.

A critical review of literature on fertilisation at establishment in hardwoods in the summer rainfall area of South Africa was conducted by Germishuizen and Smith (2007). The review indicated that, at the time of writting, 72 trials had been completed, 47 of which showed a significant response to fertilisation at planting. Most of these responses were characterized by a Type 1 response, where fertilisation achieved early growth responses, with it declining after a few years. Only 17 out of the 72 trials were measured up until harvesting. Four out of the 17 trials indicated no significant increase in growth at time of harvest. The trials that did show positive responses at harvest yielded volume increases between 22.90 and 127.6 m^3 (Germishuizen and Smith 2007). However, Germishuizen and Smith (2007) suggested that the effect of fertilisation at establishment decreases with time and that the main benefits of fertilization are in the first few years of growth.

2.4.6 Vegetation management

In order for a tree in a newly planted short rotation stand to grow at the optimal rate, the growth resources of the stand must be solely available for the crop planted (Little *et al.* 1997). Any other vegetation present at re-establishment is competing with the crop for water, light, nutrients and growing space, which can result in sub-optimal tree growth and higher mortality (Little *et al.* 2003; Wagner *et al.* 2006). Vegetation management in short rotation plantations is an integral part of successful silviculture in South Africa and around the world (Wagner *et al.* 2006).

A study by Little and van Staden (2003) indicated different vegetation management treatments resulted in a difference in tree growth as soon as 60 days after planting took place. The degree of competition could be directly linked to the different types of vegetation and its distance from the planted trees. Initially, tree growth was most affected by treatments where vegetation was in immediate vicinity of the planted tree (no ring weeding, weedy control and inter-row weeding), but with time it changed and tree performance was better for treatments where the percentage area kept free of vegetation was higher (Little and van Staden 2003). There were significant differences in tree growth between all the treatment means which remained for the duration of the trial, with the weed free (manual) treatment producing the best growth and weedy control treatment, the worst (Little *et al.* 2003b).

Timing and planning of weeding operations is one of the greatest challenges in successful vegetation management, due to the diversity of sites in terms of abundance and growth of weeds, weed species composition, local climate and different site preparation methods (Jarvel and Pallett 2002; Small and McCarthy 2002; Taverna *et al.* 2005). Little *et al.* 2007 analysed 33 vegetation management eucalypt trials across South Africa in an attempt to link physiographic, climatic conditions and management treatments to the time taken for inter-specific competition to supress tree growth. Results indicated that site preparation (burning vs not burning), altitude, and the interaction between the two factors, was significant in the time taken for tree suppression to occur (Little *et al.* 2007). The abundance of weeds generally increased with decreasing altitude, which resulted in earlier growth suppression from inter-specific competition at lower altitude sites, regardless of the site preparation method used. Similar results were found in two separate studies for pine regions in South Africa (van Heerden and Masson 1991; Jarvel and Pallett 2002). At higher altitudes, where the vegetation is not as diverse and vigorous, burning as a site preparation method enhances the growth of competing vegetation and reduces the time for inter-specific competition to occur (Little *et al.* 2007).

Little and Rolando (2008) tested the operational and economic viability of regional vegetation management standards on a commercial basis. Results indicated that the level of vegetation management required to produce significant growth responses decreased with increasing altitude. At two high altitude sites, no level of vegetation management had a significant effect on tree growth. The moderate and high-intensity vegetation management treatments at the two mid-altitude sites and the lower altitude site illustrated a significant increase in growth. However, there was a lack of significant growth difference between the moderate-intensity and high-intensity vegetation management treatments for these sites (Little and Rolando 2008).

2.5 IMPORTANCE OF ANALYSING THE INTERACTIONS BETWEEN VALUE CHAIN ELEMENTS.

Ackerman and Reitz (2014) stated that there are operational inefficiencies within in the forestry value chain as a result of sub-optimisation and a lack of interaction between individual elements of the forestry value chain. Ackerman and Reitz (2014) suggested that if plantation management took a more holistic approach, the whole value chain and the efficiency of the entire process could be improved and further optimised. One area that has raised particular concern in the past is the operational inefficiencies that occur between the harvesting and silviculture interface. Ackerman and Reitz (2014) presented the challenges for silviculture from harvesting activities as being slash and utilisable timber waste left in the compartment after harvesting, compaction of soils on extraction routes from heavy machinery, and high stumps which limit or slow down mechanised silvicultural operations. For silvicultural operations, the orientation of planting lines and initial spacing have an important impact on harvesting operations (Ackerman and Reitz 2014). The component in the forestry value chain with the greatest opportunity for improved operational efficiency is that of silvicultural operations. It has been well documented in the sections above that extensive research has been done on silviculture to improve operations since plantations were established in South Africa. Much of this research remains relevant, but there is a continuous need to identify improvements that are aligned with changes in the industry (Reitz *et al.* 2015).

Donelan and Kaplan (1998) proposed that all activities in the value chain of an enterprise are interrelated in a way. No activity in the value chain may be performed independently without looking at the impact on all other activities. For example, cutting costs of upstream activities can have serious consequences on the production cost and product quality of downstream value chain activities (Chivaka 2007). With the forestry value chain, it is no different. Harvesting, which is the start of the forestry value chain, mainly impacts land clearing (harvesting residue management), depending on the harvesting system used (Upfold 2000; Ackerman and Reitz 2014). The type of land clearing operations effects the accessibility of the stand, which can have an influence on land preparation and planting methods used. It effects the soil nutrient availability of the stand, which have an impact on fertiliser operations (Deleporte *et al.* 2008; du Toit *et al.* 2008; Gonçalves *et al.* 2008; Mendham *et al.* 2008). Land preparation impacts the soil structure, friability, depth, form and nutrient availability, which in turn influences the planting method and whether fertiliser is needed (Norris 1995; du Toit and Dovey 2005; du Toit 2008). Fertiliser application provides needed nutrients to the soil for enhanced tree growth, but these added nutrients are also available for competing vegetation, thus resulting in increased vegetation management operations required (du Toit *et al.* 2001;

du Toit and Oscroft 2003). All of these activities have a collective impact on tree survival and therefore, blanking operations. The main aim of all these operations is to enhance tree growth, increase tree survival and increase volume production. It is however important to understand the impact each operation has on the following operations, in order to optimise the whole value chain from start to finish in terms of benefits versus cost as opposed to optimising single activities (Smith *et al.* 2010).

Recently the forestry supply chain has been examined to find ways to perform plantation management activities more efficiently and effectively, and to reduce the cost of producing timber. Reitz *et al.* (2015) indicated an improvement in efficiency was found through increased integration between the value chain elements. This included combining two activities into one operation, putting more emphasis and importance on certain elements of the value chain (e.g. more focus on seedling survival), which can result in reducing the need for other elements or activities (e.g. improved survival can reduce the need for blanking operations), and the mechanisation of certain activities to improve the efficiency (Reitz *et al.* 2015).

2.6 VALUE CHAIN ANALYSIS (VCA)

2.6.1 Background

In order to identify the effects, benefits and wastes of each activity, or interactions of activities in the silvicultural value chain, an extensive value chain analysis on the operational silvicultural value chain of the organisation is required (Smith *et al.* 2010).

According to Chivaka (2007), a value chain can be defined as a linked set of value-adding activities all the way from basic raw material, through to the end product delivered to the consumer. Carlsson and Rönnqvist (2005) indicated that supply chain management and optimization in forestry is increasingly important in order to improve its operations and to ensure economic sustainability. Such management and optimization allows for integration between activities and potential improvements in the forestry supply chain. It enables enterprises to identify the impact of one activity on the performance and costs of other activities in the chain, regardless of where in the chain activities are performed. When managing the entire value chain instead of different components, fixed cost supporting activities can be changeable with joint optimisation (Chivaka 2007).

Value chain analysis is a tool that organizations can use (Chivaka 2007) to quantify the status quo of their value chain and identify potential improvements within the value chain. The status quo enables the organization to keep track as to whether or not they are achieving their value chain improvement objectives (Bullinger *et al.* 2002). The value chain analysis process deconstructs the whole value chain into relevant activities in order to manage cost and, since all relevant activities contribute to cost, each activity along the value chain is expected to add value. After identifying the relevant activities, the investment cost must be compared to the value created by these activities. The aim of value chain analysis is to ensure that each activity along the value chain generates higher value than its investment cost. With the focus on the activities, value chain analysis identifies the importance of interdependencies and interrelationships between different activities, processes and business units throughout the value chain (Chivaka 2007). In the past, practitioners and researchers mainly investigated activities in the supply/value chain individually, however in recent years more attention has been placed on the design, analysis and performance of the supply/value chain as a whole (Beamon 1998).

Chivaka (2007) stated that value chain analysis has three characteristics that make it a valuable tool when performing strategic cost management: (1) identifying the strategy of the enterprise, (2) the focus on the key activities for competitive advantage, and (3) it emphasises that interrelationships and complex linkages are very important within a value chain.

There are a number of methodologies for different operational value chain analyses; these make use of different performance measurement and process mapping tools. The information needed for these can be collected through a variety of different research modelling approaches. The approaches include: case study approach, action research, operational research, value stream management, simulation and scenario-based approach (Taylor 2005; Shabani *et al.* 2013).

2.6.2 Methodologies

2.6.2.1 Value chain analysis with value stream and process mapping tools

A general framework proposed by Bullinger *et al.*, (2002) consists of three phases. Firstly, identification, during which the business objectives, processes and the partner relationships within the value chain of the company are identified with the aim to model the information and material flow within the value chain (Bullinger *et al.* 2002). Second is the measurement of process performance, the core operation within the analysis of the value chain. It aims to monitor, measure, control and direct activities. It is related to the strategic optimization decisions within the business. Last is the conclusion phase in which, if changes are in line with the objectives of the business and have significant improvement compared to the present state, the result with best improvement potential in terms of cost and “fit for purpose” will be interpreted for the purpose of a call for action (Taylor 2005).

Hines and Rich (1997) described a value chain mapping tool that identifes waste, inconsistencies and potential improvements through the value chain. The mapping tool uses a case study approach to: (1) study the flow of the processes, create a status quo of the current situation, analyse the relationships between activities and final product; (2) identify waste by identifying and analysing non-value adding, necessary but non-value adding and value adding operations within value chain; (3) a consideration of a better flow pattern and if everything done at each stage is really necessary within the value chain (Hines and Rich 1997).

Taylor (2005) developed a staged approach to value chain analysis, the methodology of this approach includes the following seven stages:

1. Create understanding of potential for the business from VCA.
2. Develop a supply chain structure map and select a target value stream.
3. Mapping of individual elements along the value chain.
4. Develop current state map of value chain.
5. Identify problems, issues and opportunities across value chain.
6. Develop future map state and recommendation.
7. Develop action plan.

According to Schmidtke *et al.* (2014), value stream mapping is a simple, straightforward method with which process performance can be analysed and improved. A typical value stream mapping method consists of four phases: (1) selection of product family – to avoid over-complication; (2) current state map – current process is analysed and visualised; (3) cuture state map – one or more lean production processes are developed; (4) develop work plan to reach future state map (Schmidtke *et al.* 2014).

2.6.3 Pitfalls of value chain analysis

McCutcheon and Meredith (1993) suggested that investigating ongoing business operations faces difficulties, as it does not allow for conditions to be controlled or treatments to be performed to affect outcomes. These limitations eliminate the use of controlled experimentation, along with proceses that form the basis of expiriments and mathematical simulations (McCutcheon and Meredith 1993). Therefore the researcher must study the occurance and severity of all conditions that might affect outcomes of a study.

Additionally, Meredith (1998) states that performing statisitical analysis of objective measures of the variables can result in data, which may be measurable, but are also likely to be of liitle value or importance. Other disadvantages or limitations from operational field research identified by Bonoma (1985) and Benbasat *et al.* (1987) include: the make up and character of key variables within an analysis, the failure in achieving predictive validity, the lack of comparability between studies, the distribution restrictions such as normality often influences statistical methods or value, the large sample sizes required and difficulty in interpreting and implementing the results of these studies.

2.6.4 Value chain simulation

The Discrete Event Simulation (DES) proposed by Schmidtke *et al.* (2014) is a promising add-on to value chain mapping and analyses. This method enables the modelling of complex processes with great detail (Schmidtke *et al.* 2014). The simulation should only be applied after potential improvements to the value chain are identified. The aim is to integrate value chain analysis with simulation in order to provide feasible improvements (Solding and Gullander 2009). Schmidtke *et al.* (2014) suggest the DES be used to simulate the proposed changes/improvements in order to do:

- Feasibility analysis – to determine if the improvements are feasible, if they result in better performance, is it in line with company objectives, etc.

- Trade-off analysis – to determine if the proposed changes bring more financial benefits than the current situation when all the cost factors are considered, what changes produce most financial benefits, etc.

The simulation may reduce the possibility of implementing changes to the value chain, which could lead to increased cost of processes without the desired benefit. In cases where results of simulation are non-beneficial it must be recorded and should serve as a basis for redevelopment, thus ensuring the future changes to value chain are feasible. It will also optimise the process before an action plan is implemented (Schmidtke *et al.* 2014).

2.6.5 Benefits of value chain analysis and simulation

According to Taylor (2005), the main benefits of a value chain analysis is to understand the current state of the whole value chain and to understand the flow of the process and the effect each activity within the process has on the final product. This enables one to: identify key problems, wastes and opportunities within each element of the value chain or, when analysing the value chain as a whole, identify the importance of interdependencies and interrelationships between different activities in the value chain (Chivaka 2007). It also allows for the identification of potential improvements within the value chain and the creation of a future state vision which will optimise the value chain and allow for the development of an action plan to achieve this future state (Taylor 2005).

The action plans to achieve a future state identified in value chain analyses are assessed with a feasibility and trade-off analysis through simulation. All future states will thus be simulated to ensure it is feasible. Schmidtke *et al.* (2014) suggested that there is a number of benefits with the method of value chain analysis with simulation. These include: knowledge as to whether or not the future state will fulfil the customer demand before implementation, the financial benefits of future state can be determined before implementation, results from simulation can be used to gain management acceptance as it provides hard figures and the company's objectives can be aligned with the proposed future state (Schmidtke *et al.* 2014).

Chapter 3
METHODOLOGY

3.1 INTRODUCTION

A case study research approach and process has been used in this study. The purpose of a case study may be to describe a situation or to understand how and why events occur. The methodology is an empirical approach that aims to develop an understanding of "real world" events (McCutcheon and Meredith 1993). A case study approach is an objective, in-depth examination of historical records or the current situation where the investigator has little control over conditions or events (Yin 1984). Within the research process, actual historical records were used to gather data for the analyses. Investigating historical data does not allow the conditions to be controlled or variables to be manipulated by the researcher to effect outcomes of the study (McCutcheon and Meredith 1993). Case study research is used to develop new theories, investigate unfamiliar situations, support, or raise doubts, about existing theories (Taylor 2005).

The study is based on actual historical compartment information, with the aim to link silvicultural activities and cost of activities performed on a compartment to seedling mortality, early tree growth and final tonnes produced at end of rotation. The data used to perform the study included all the silvicultural activities performed on a compartment, operational gain data which provided tree growth (median height *pro rata*) one year after planting, and actual tonnes harvested at end of rotation. The research process is ilustated in Figure 3.1 below:

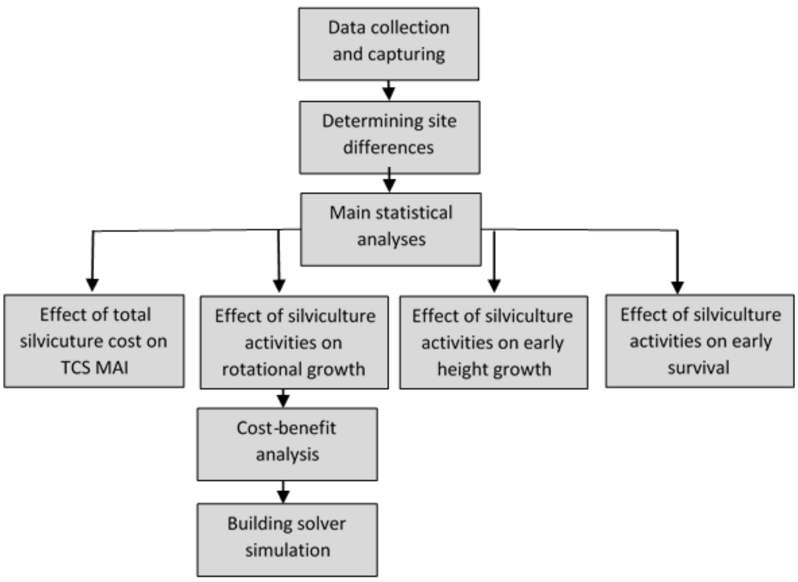


Figure 3.1 Flow diagramme showing the steps followed in the research process.

3.2 STUDY SITE

The study is based on Sappi Forests plantations in the coastal Zululand plains of Kwa-Zulu Natal in South Africa. The area falls in the Zululand region, with the plantations situated approximately 25—50 km North of Richards Bay (Figure 3.2). The majority of Sappi plantations in the region are planted to *E. grandis x E. urophylla* clones. The Zululand district is internally divided into the Zululand North and Zululand South regions. An internal report by Wise and Kassier (2016) indicated that Zululand South historically performed considerably better in terms of tree growth than Zululand North. They also suggested that the difference in tree growth is directly related to rainfall, with productivity of stands decreasing with decreasing rainfall.

The case study is based on all the Sappi plantations in the Zululand district and therefore, the distribution of plantations is exposed to a range of different growing conditions. According to Pallett (2005) these growing conditions are responsible for variation in growth within species in different areas. The Sappi plantations investigated in the study are planted with *E. grandis x urophylla* on a pulp timber working circle, ranging from approximately 0—120 m above sea level.

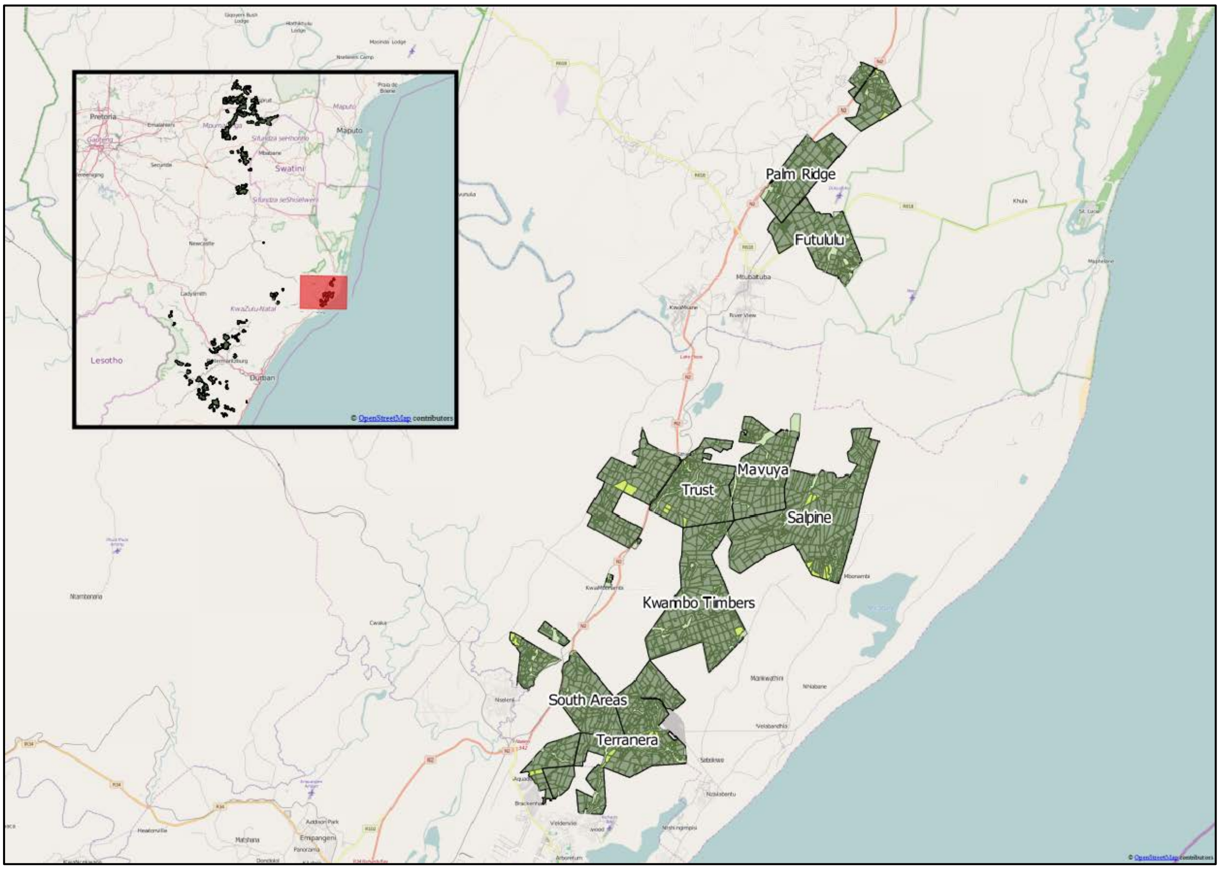


Figure 3.2: Map showing all the Sappi plantations in the Zululand District (source:Sappi planning offices).

3.2.1 Climate, natural vegetation and soils

The weather stations used to best represent weather conditions of the Sappi plantations in the two regions are Mtubatuba (28°26'21" S, 32°11'5" E) 46 m above sea level and Kwambonambi (28°38'0" S, 32°5'0" E) 30 m above sea level for Zululand North and South respectively (SASRI 2017). Rainfall recorded from 2003—2016 from the two weather stations revealed a mean monthly and mean annual rainfall of 78 mm and 940 mm respectively for Zululand South, and 64 mm and 765 mm for Zululand North (SASRI 2017). These climatic figures are similar to rainfall figures presented in studies by Morley (2008) and Reitz and Little (2014). It is important to note that the Zululand district experienced a drought in 2014 and 2015 with the MAP being significantly lower than the norm (Figure 3.3). The Zululand region falls within the sub-tropical climatic zone, characterised with very high temperatures in summer, and although the majority of rainfall occurs in summer months, rainfall also occurs during the cooler months (Fuller and Little 2007; Viero and Button 2007).

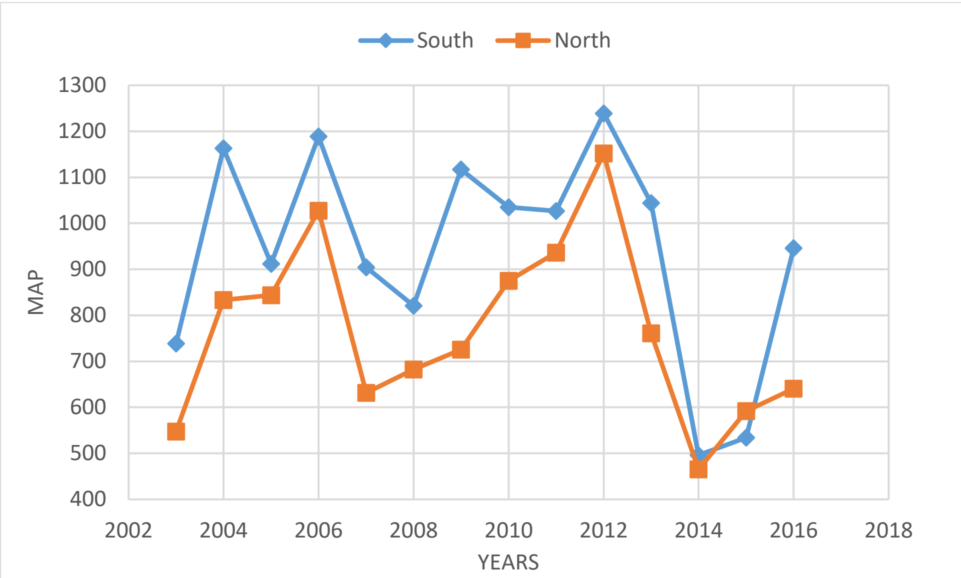


Figure 3.3: Mean annual precipitation of Zululand North and Zululand South (SASRI 2017).

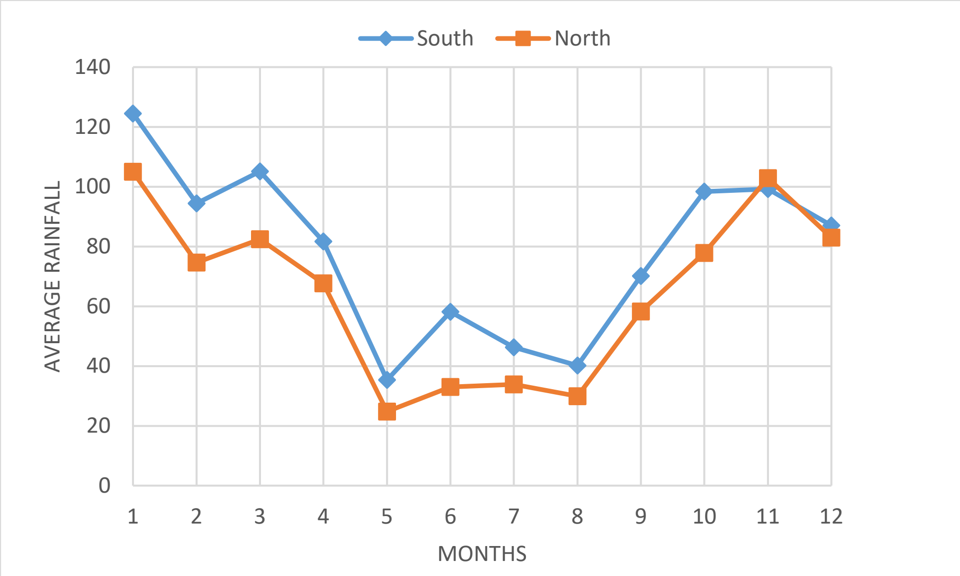


Figure 3.4: Mean monthly rainfall in Zululand North and Zululand South (SASRI 2017).

The soils of coastal Zululand are often referred to as the Zululand sands, characterized by light coloured A horizons and grey or yellow E horizons (du Plessis and Zwolinski 2003). These sandy soils consist almost entirely of arenosols derived from recent Aeolian sands with low clay percentage. The majority of soils are deep sands belonging to the Fernwood soil form (Smith and du Toit 2005; Fuller and Little 2007). Soils in the region are generally characterized by low (<0.5%) organic carbon content (Viero *et al.* 2000; Smith and du Toit 2005; Reitz and Little 2014). However, according to du Toit and Oscroft (2003), the soils of the Zululand coastal plain differ widely in terms of nutrient supplying potential.

3.3 DATA COLLECTION

The data used in the statistical analyses is operational historical data. This historical data includes silviculture information, actual harvesting information, operational gain data and compartment attribute information. The following historical data were received from Sappi Forests:

3.3.1 Silvicultural activities

Record of all silvicultural activities that have taken place on each compartment in Zululand district from 2002—2016. This also included compartment ID, silviculture activity (job description), job date and area notes.

3.3.2 Site attributes and damaged events

Compartment attributes for every compartment in the Zululand district that included: mean altitude, site quality (SQ), site index (SI), soil type and land type. This also included a record of compartments where damaged had occurred (fire, insects, etc.), along with damaged area and percentage area damaged.

Record of total rainfall of each compartment, extracted from local weather stations with the plant date and harvest or measurement date. This provided the total rainfall in mm from planting to either harvesting, or measure date for every compartment.

3.3.3 Operational gain data

The operational gain data is a data set that was obtained from a measurement within one year after planting. Trees per hectare (TPH) and median height were calculated at measurement. The median height was normalised to one year, giving the predicted median height *pro rata* (MHPR) for each compartment at one year after planting. The data set included measurement age, TPH at planting (TPH0), TPH at measurement (TPH1), median height and median height pro rata for all the compartments.

3.3.4 Harvesting APO

A record of all compartments harvested between 2005 and 2016. This record contained the species, area, plant date, fell date, actual tonnes harvested, planned tonnes and planned volume for each compartment.

3.4 DATA CAPTURING

The study is based on stands that were planted to *Eucalyptus grandis x E. urophylla*. These stands needed to have a record of all the silvicultural activities that took place from establishment. Data was captured in Microsoft Excel and summarized by means of pivot tables that linked the various activities per compartment. The silvicultural activities of a compartment are represented by numbers. Pre-Plant spray, planting, fertilising and blanking are represented by binary numbers because it either took place or it did not; if it took place that cell is represented with a 1, if it did not take place it is 0. All of these activities were multiplied with the cost of that activity and were then summed together to obtain a total silviculture cost for each compartment.

Three data sets were created: Data set 1 for the actual harvested data, obtaining the final tonnes harvested along with all the silvicultural activities, Data set 2 for the operational gain data, obtaining the MHPR along with all the silvicultural activities and Data set 3 was created by combining the information of Data set 1 and 2. These data sets were imported into R studio (R) (RStudio Team 2015). All the silvicultural activities in all the data sets that are categorical were then transformed to factor with the "as.factor" function in R. The original data set had three columns for planting: "plant wet", "plant dry" and "plant stock". A new column was created replacing all three columns in R studio called "plant status". With the values of plant status being plant wet or plant dry.

3.4.1 Variables

In the statistical analysis different response variables and different independent/explanatory variables were used for the different analyses, below are all the variables with a short description.

Independent/explanatory variables
Site Related

- **MAPstand** – Mean annual precipitation of a compartment. It is the total rainfall from planting to felling divided by the felling age of the specific compartment.
- **Rotrain** – The total amount of rainfall from planting to measurement in Data set 2.
- **M1R** – The amount of rainfall in the first month after planting.
- **SI** – Site index of the compartment (tree height at reference age 5 years).

Silviculture activities

- **Pre-plant** – It is a pre-plant spray. It is represented by either 0 or 1. 1 indicating the activity took place and 0 it did not take place.
- **Plant status** – Planting took place either with water (planting wet) or without water (planting dry).
- **Fert** – Fertiliser operation. It is represented by a binary number 0 or 1. 1 indicating the activity took place and 0 it did not take place.
- **Blank** – Blanking operation (re-planting trees that died shortly after planting). It is represented by either 0 or 1. 1 indicating the activity took place and 0 it did not take place.
- **Num weedings** – It is the amount of weedings that took place on a compartment. It is represented by a numerical number. The number is the amount of weeding operations that took place on the compartment.
- **Plant firstweed** – Time in days from planting to first weeding operation.
- **Season** – The season in which the compartment was planted.
- **Silvtot cost** – It is the total silviculture cost spent on that compartment. It is the sum of the cost of all the silvicultural activities that took place on that compartment.
- **TPH0** – Trees p/ha at planting. Planting density.
- **TPH1** – Trees p/ha at measurement.

Response/Dependent variables

- **TCS MAI** – Timber Control System (TCS) is the system where the final harvested tonnes were extracted from. The final tonnes harvested at end of rotation for a compartment were divided by the area of that compartment and then with the felling age. Giving the mean annual increment m^3 ha^{-1} a^{-1} of the compartment.
- **Median height pro rata (MHPR)** – Standardised height to one year after planting.
- **Blank** – Blanking is also an independent variable in the other analyses, but it is also a good indication of early survival.

3.5 Site differences based on statistical analyses

In order to determine the impact the silvicultural activities have on the performance of stands, the variations in growth as result of different growing conditions have to be minimised. The performance of a stand refers to the rate of volume growth of trees on a stand. In an attempt to minimize these external effects on growth and performance, stands with similar growing conditions had to be grouped together.

The plantations are internally subdivided into different site quality classes. Site quality is a rating of the tree growth potential of a site and is a based on the productivity of a site in terms of round wood production. Historical enumerations and historical compartment productivity information was used to classify site index, which is used to define five site quality classes from poorest to most productive (Pallett 2005). Table 3.1 indicates the number of compartments within each site quality class.

Table 3.1: Number of compartments within each Site Quality class of Data set 1

Site Quality		
SQ1	**SQ2**	**SQ3&4**
200	82	28

From Table 3.1 it can be seen that the majority of compartments in the Zululand district are in SQ1, and then SQ2. SQ3 and SQ4 were grouped together because there were very few compartments in both the classes. Even when grouped together, there were not enough compartments to group the data according to site quality classes for the analyses.

3.5.1 *Regional Differences*

In Section 3.1 it was shown that the study is based on plantations in the Zululand district which is geographically divided into two regions, namely Zululand North and Zululand South. The Zululand North and South regions were compared with regards to SI, final tree volume and rainfall to identify if there are significant differences between them. This helped to group compartments together to minimise the impact of external factors based on the results of the analyses. The results can be seen in Section 4.1.

3.5.1.1 TCS MAI

TCS MAI was used throughout the study as a measure of the performance of stands over the entire rotation. The higher the TCS MAI, the better the growth and performance of a stand. TCS MAI was used in this analysis as the response variable in a descriptive statistic for the regions combined and then for Zululand North and South respectively. This was done to identify if there is a significant difference in the mean TCS MAI for the two regions, and by how much they differed from the mean of the regions combined. Descriptive statistics highlighted a difference in the mean TCS MAI between the regions (Table 4.2) . Consequently, a linear regression model was created with TCS MAI as the response variable and region as independent variable to identify significant differences in performance between regions (Table 4.3).

3.5.1.2 Effect of rainfall between regions

In order to test the statements mentioned in Section 3.5.1 made by Wise and Kassier (2016), it was necessary to determine if rainfall does have an effect on the performance of stands in Zululand with regards to tonnes harvested at end of rotation. A linear regression model was created with TCS MAI as the response variable and MAPstand (total rainfall a stand received in the rotation period divided by the felling age of that stand) as the independent variable to test if the mean annual rainfall of a stand received, significantly impacted the performance of stands. According to Quinn and Keough (2002), a simple linear regression can be used to describe the relationship between a single numerical response variable and a single numerical predictor variable.

Descriptive statistics were also used to illustrate the mean MAPstand for the two regions respectively, and then combined.

3.6 MAIN STATISTICAL ANALYSES

Four different sets of analyses were conducted with R software to test the following:

- If the total silviculture cost has an effect on the rotational performance of stands.
- If the silvicultural activities performed have a rotational effect on the performance of stands.
- If silvicultural activities performed have an effect on initial height growth of young trees.
- If silvicultural activities performed at establishment have an effect on initial seedling survival.

The Zululand North and South regions were analysed separately to reduce the effect of external factors on the performance of the stand.

3.6.1 Total Silviculture Cost effect on TCS MAI at end of rotation

The goal of this analysis was to identify if there is a relationship between money spent on silviculture, and the final tonnes harvested. In order to determine if there is a linear relationship between total silviculture cost and the growth of a stand, a simple linear regression model was created with TCS MAI as the response variable and total silviculture cost as the independent variable. According to Kaps and Lamberson (2004), a simple linear regression can be used to model a single numerical dependent variable and a single numerical independent variable as a straight line. According to Quinn and Keough (2002), the purpose of a linear regression model is to: (1) describe the linear relationship between dependent and independent variable; (2) to determine how much of the variation of the dependent variable can be explained by the relationship with the independent variable; (3) and to predict new values of the dependent variable from new independent variable values.

The null hypothesis (H_0) tested in the linear regression analysis is that the slope of the population regression model equals zero and that there is no linear relationship between the dependent and independent variable, which is most commonly tested with an analysis of variance (ANOVA) table (Table 4.8) (Quinn and Keough 2002). If the independent variable had a $p<0.05$, the H_0 was rejected and was reported as having a straight line relationship between the independent variable and response variable. If $p>0.05$, the H_0 could not be rejected, meaning there was no straight-line relationship between the independent variable and response variable. A scatter plot (Figure 4.2) was created in R with the function “ggplots2” showing the total silviculture cost against the TCS MAI.

Hypothesis testing:

H_0: $\beta j = 0$ (No straight-line relationship between Total Silviculture Cost and TCS MAI)

H_1: $\beta j \neq 0$ (Straight-line relationship between Total Silviculture Cost and TCS MAI)

3.6.2 Effect silvicultural activities have on the final yield harvested

3.6.2.1 Robust linear regression with TCS MAI as response

The aim of this analysis was to determine if it is possible to identify from operation data the effect silvicultural activities, performed at establishment, have on the rotational growth and performance of stands in both Zululand North and South. First, a multiple linear regression was used as the statistical technique to determine the relationship between a singular numerical response variable and multiple numerical and categorical explanatory variables. However, the normality assumption on which a multiple linear regression is based did not hold. There were also some influential outliers and leverage points identified. According to Quinn and Keough (2002), the assumption is not required for linear regression models but it is necessary for reliable hypotheses testing and estimation. The normality assumption check is based on the residuals of the fitted model. According to Quinn and Keough (2002), there are at least two options if the normality assumption is not met. First, a transformation of the response variable may be appropriate. Second, a linear model can be fitted that is not as vulnerable as the least squares to unusual data (Fox and Weisberg 2002). A statistical procedure is robust if it provides useful information even when some of the assumptions are not met.

Robust regression is an alternative to linear regression when data is not normally distributed, or when the data is contaminated with outliers, high leverage points or influential observations (Fox and Weisberg 2002). Robust regression can be used as a statistical method in any situation where the least squares regression are used. Robust regression gives each observation a different weight based on how well behaved these observations are (UCLA 2017). The most common robust regression method is Huber *M-estimation* (Huber 1964). In Huber weighting, observations with small residuals get a weight of 1 and the larger the residual, the smaller the weight. In other words, the outliers and high leverage points with large residuals will be down-weighted (UCLA 2017).

The effectiveness of most silvicultural activities is dependent on the climatic and soil conditions of the site. The effect of interactions between silvicultural activities on the growth and performance of stands is also very important. A robust regression was created with TCS MAI as the response variable. The explanatory variables included; SI, MAPstand, planting season, silvicultural activities along with interactions between these variables. In Zululand North, fertiliser was included in the model as a variable, however no interactions with fertiliser were tested because not enough stands were not fertilised. In Zululand South, plant status was not included as a result of insufficient stands being planted wet. The results from the analyses are illustrated in Tables 4.10—4.13. Based on the results in Section 4.2.2, it was decided not to include any interactions in the analyses of this study.

As a result of the above mentioned, a robust regression was performed to determine the relationship between the response variable and the independent variables in this analysis. Data set 1 was used in this analysis with TCS MAI as the response variable in the robust regression model created. The robust regression model was created using a (rlm) function in R, the model included the SI, MAPstand, planting season and time to first weeding, along with all the silvicultural activities, as explanatory variables and the TCS MAI as the response variable. The effects of the explanatory variables were analysed using an analysis of deviance table. For treatments with $p<0.05$, the H_0 was rejected, and therefore that treatment was reported as having a statistically significant contribution to the explanation of the response variable. In treatments with $p>0.05$, the H_0 could not be rejected, and the treatments were reported as not having a significant contribution to the explanation of the response variable.

Plant status was removed from the analysis in Zululand South, because not enough compartments in Zululand South were planted with water and therefore, no accurate comparisons could be made

Hypothesis testing:

H_0: $\beta j = 0$ (Do not contribute to the explanation of Y)

H_1: $\beta j \neq 0$ (Do contribute to the explanation of Y)

3.6.2.2 Testing assumptions

The robust regression method provided an alternative to least squares linear regression by requiring less restrictive assumptions. Robust regression is not limited to the normality assumption of the residuals (Fox and Weisberg 2002). It must, however, come from the same single distribution, i.e. have the same variability across the range of fitted values (homoscedasticity assumption).

The homoscedasticity assumption can be tested by Bartlett's or Levene's tests, or by inspecting the residual vs fitted plot of the model (Quinn and Keough 2002). Bartlett's test is sensitive to deviations from normality. In this thesis homoscedasticity is tested by inspecting the Residuals vs Fitted plot for any obvious patterns. If there is no pattern visible, a subjective interpretation can be made that the residuals are homoscedastic. If there is a pattern visible, the residuals are not homoscedastic.

3.6.2.3 Cost-benefit analysis

The aim of the cost benefit analysis is to determine if it is possible to use operational data to determine if the silvicultural activities performed created more value in terms of monetary returns than the initial investment cost of these activities. The cost-benefit analysis is based on the results from the analysis mentioned above, and the results of the cost-benefit analysis are used in Microsoft Excel Solver to create a simulation model. The average cost of each silviculture activity (R ha^{-1}), cost of mechanised harvesting system (R $tonne^{-1}$), extraction cost (R $tonne^{-1}$), rail transport cost (R $tonne^{-1}$) and the selling price (R $tonne^{-1}$) was used in the analysis. The harvesting and transport costs were subtracted from the timber selling price to obtain a Net Standing Value (R $tonne^{-1}$) on which the silviculture cost-benefit analysis was performed. The robust linear regression analysis performed in Section 3.6 calculated the impact of each activity on TCS MAI for both Zululand North and South, respectively. The coefficients in Table 4.15 indicated the effect each variable had on the TCS MAI for that model. These coefficients indicated whether the TCS MAI increased or decreased on sites where the activity took place. These coefficients were multiplied by eight years to obtain the impact it had in terms of final tonnes at the end of rotation (potential improvement tonne ha^{-1} over a rotation of eight years). The potential improvement (tonne ha^{-1}) value was then multiplied with the standing value (R $tonne^{-1}$) in order to obtain the monetary value in R ha^{-1} that the particular activity produced. The cost in R ha^{-1} of the silviculture activity was then subtracted to obtain the cost-benefit of that activity. If positive, the activity produced greater returns than the investment cost but if negative, the activity cost more than the benefit produced. The cost-benefit was calculated for both Zululand North and South respectively.

3.6.3 Effect silvicultural activities have on short term height growth of stands

3.6.3.1 Robust regression with Median height pro rata as response variable

In the analyses mentioned above the rotational effects of the silvicultural activities were investigated, based on operational data. In this analysis the aim was to investigate if it is possible to determine the short term effect and benefits of the different silvicultural activities within the two regions from operational gains data from Data set 2. The performance measurement of early growth was investigated with the median height of a stand. All the heights were measured within the first year after planting. However, all the compartments were not measured on exactly the same age, therefore a standardised height was calculated. The median height pro rata (MHPR) in the operational gain data was obtained from standardising the initial median height of the compartment to one year from its measurement age. The MHPR value was used as the response variable in a robust regression model for the analysis in this section. The analysis was done to determine if operational gain data can be used to identify a relationship between silvicultural activities at establishment and early height growth of stands. Robust regression was used as the statistical method because the normality assumption on which least squares linear regressions are based on, did not hold and a number of influential outlier and leverage points were identified. Robust regression was discussed in Section 3.6.2.1.

Robust linear regression models were created using (rlm) function in R for the analysis, the model included the SI, MAPstand, season and time to first weeding, along with all the silvicultural activities as explanatory variables and the MHPR as the response variable.

In order to identify if the explanatory variables had a significant effect on the height growth of a stand, the probability value in the analysis of the deviance table was investigated. For treatments with $p<0.05$, the H_0 was rejected and therefore, that treatment was reported as having a statistically significant contribution to the explanation of the response variable. In the treatments with $p>0.05$, the H_0 could not be rejected and the treatments were reported as not having a significant contribution to the explanation of the response variable. The assumption was tested the same as mentioned in 3.6.2.2.

Hypothesis testing;

H_0: βj = 0 (Do not contribute to the explanation of Y)

H_1: βj ≠ 0 (Do contribute to the explanation of Y)

3.6.4 Impact Silvicultural activities have on early survival

Data set 3, with all the compartments, was used to perform these analyses. The first analysis in this section was a logistic regression with blanking as response. The analyses were performed to determine if operational data can be used to identify if activities prior to blanking had an effect on whether or not blanking took place.

3.6.4.1 Logistic regression with blanking as response

The dependent variable in these analyses were binary and therefore categorical, which meant classical regression or analysis of variance was not appropriate, because assumptions such as normality and homogeneity were often not satisfied. Because of the binary nature of the response variable, a technique called logistic regression, a type of generalised linear model (glm), was used. This model can explain the effects of the independent variables on the binary dependent variable. Generalized linear models are models in which the independent variables explain a function of the mean of the dependent variable (Kaps and Lamberson 2004). The independent variables can either be continuous and/or categorical. If the independent variables are categorical, they need to be converted to dummy variables, which the R software does automatically for any variable specified as factor type variables (Quinn and Keough 2002).

A logistic regression model was created to test the correlation between silvicultural activities prior to blanking and blanking, using glm function in R. The model included SI, M1R and season, along with the silvicultural activities prior to blanking as independent variables. and blanking as the dependent variable.

In order to identify if the explanatory variables had a significant effect on the early survival of a stand, the probability value in the analysis of the deviance table was investigated. In treatments with $p<0.05$, the H_0 was rejected, and were reported as a having statistically significant association between the independent variable and dependent variable. In logistic regression models, interpreting the effect variables have on the dependent variable is performed using the coefficients from the summary function in R, if the coefficient value is positive, the probability of the dependent variable taking place increases with the additional unit of the explanatory variable and if it is negative, it decreases the probability of the dependent variable taking place.

Hypothesis testing:

H_0: No significant association between the independent variable and dependent variable.

H_1: Significant association between the independent variable and dependent variable.

3.6.4.2 Contingency tables with blanking as response

In the logistic regression above, all the independent variables were included in a model, which was used to determine if an individual independent variable had association with the dependent variable. In the following analyses, contingency tables were used to summarise count data of the different silvicultural activities and test for association between that specific activity and blanking, with no regard of the impact of any of the other variables.

Contingency tables (two rows x two columns) were created with the “xtabs” function in R for pre-plant, plant status and fertiliser with blanking and a 3x2 contingency table for planting season with blanking. From the 2x2 contingency tables, Fisher’s exact test was performed to test whether there was an association between the variables, and to calculate the odds ratio. According to Quinn and Keough (2002), Fisher’s exact test was designed for 2X2 tables with fixed marginal totals.

Hypothesis testing:

H_0: No association between variables.

H_1: An association between variables exists.

3.6.5 Testing association between Season and Plant Status

In order to determine if planting season had an effect on the type of planting operation, testing needed to be done to see if there was an association between the variables. Viero *et al.* (2008) indicated that planting season is very important for the survival and growth of stands and that it can influence the methods of the activities that follow. Contingency tables were created in the same way as mentioned in Section 3.6.4.2, but with variables plant status and season. The Fisher's exact test could not be performed, therefore it was tested with Pearsons's chi-square test for association between the variables (Quinn and Keough 2002).

Hypothesis testing:

H_0: No association between variables.

H_1: An association between variables exist.

3.7 SOLVER SIMULATION

In this study, the results of the analyses in Section 3.6 were used to create a shortest path network model in Microsoft Excel solver to illustrate how the lowest cost, maximum productivity and optimum profitable path through the silvicultural value chain in both Zululand North and South could be calculated.

Network models can be used to determine the shortest route through large, complex projects that consist of many activities (Winston *et al.* 2004). The network model consists of arcs and nodes; arcs in the network represent the activity and nodes are used to specify event times (Figure 3.5) . Therefore, the end node of an arc (the node the arc enters) represents the end of that specific silviculture activity.

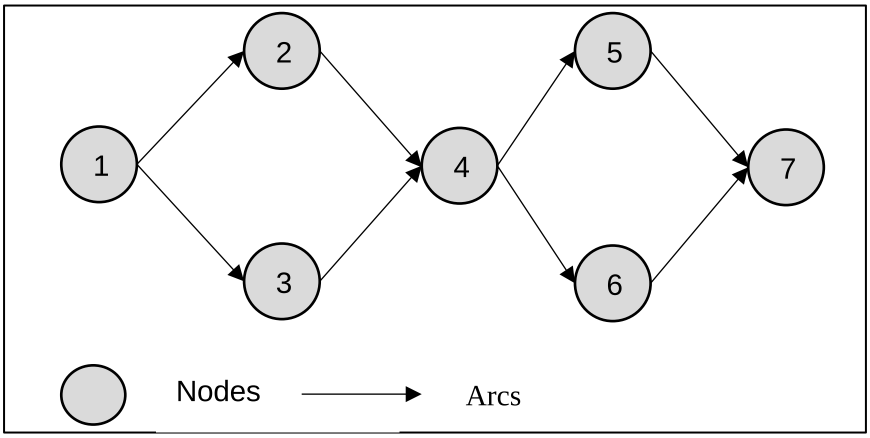


Figure 3.5: Illustration of a network model, presenting the nodes and arcs of the model.

The silvicultural value chain starts at node one and finishes at the last node; all nodes are numbered from one to the last node. In order to perform a network model, node one must have an outflow equal to 1 and the last node must have inflow equal to 1. All other nodes are transhipment nodes, which means the net outflow must equal 0 – that means that if an arc (silviculture activity) goes into a node, there must be an arc going out of that node. The flow of each arc will be either 0 or 1, with 0 indicating that the arc is not included in the objective cells shortest path, and 1 meaning it is. The model also enables the user to manually enter constraints if certain activities need to take place. This is possible by simply adding the end node of an arc to the inflow constraint and adding it at the outflow constraint. Network models can be used to calculate the shortest path through the value chain in order to produce the minimum and maximum value of the objective cell. The objective cell is the sum product of the value of all the arcs involved on the path (Winston *et al.* 2004).

Building the solver model is complex and it involves many steps steps, in order to keep track with the methodology followed, a solver model of the simple network model illustrated above was created and illustrated in Table 3.2 below. Table 3.3 illustrates the constraints required for the model. Table 3.2 and 3.3 is only presented as an example, illustrating the lowest cost path:

Table 3.2: Illustration of a solver model, showing the lowest cost path

Start node	End node	Cost	Improvements	Cost-benefit	Flow
1	2	50	9	20	1
1	3	100	10	0	0
2	4	50	5	10	1
3	4	50	5	10	0
4	5	50	5	0	1
4	6	100	10	10	0
5	7	10	10	0	1
6	7	10	10	0	0
		Lowest cost	**Highest production**	**Cost-benefit**	
Objective cell's		160	29	30	

Table 3.3: Flow balance constraint of the solver model illustration

Flow balance constraints			
Node	**Outflow**		**Required**
1	1	=	1
Node	**NetOutflow**		**Required**
2	0	=	0
3	0	=	0
4	0	=	0
5	0	=	0
6	0	=	0
Node	**Inflow**		**Required**
7	1	=	1

The lowest cost path is the same for both Zululand North and South. The objective cell of this simulation was the sum product of the cost column and the flow column. The flow column represents the arcs, and whether the arcs are included in the path or not. The flow column is also the changing cell in the solver model. The solver model changes the flow column, in order to include activities on the path to achieve the objective cell aim. In order to get the lowest cost path through the value chain, the objective cell must be set to minimum in the solver model. The only constraints in the model is that the outflow of node 1 must be equal to 1 and the inflow of the final node must be equal to 1, and the flow of all other nodes must be equal to 0. If the solver model is run, the flow column will change, including the activities in the path wich will result in the minimum value of the objective cell, creating the lowest cost path through the silvicultural value chain.

The highest production path is the path through the silvicultural value chain that produced the best improvement in tonnes ha^{-1} irrespective of the cost. The results from the robust regression were used to obtain the impact silvicultural activities have on the TCS MAI. The coefficients in Table 4.15 show how much the TCS MAI increased or decreased with the silvicultural activities for Zululand North and South respectively. These coefficients were then multiplied to work out the impact the activity will have on the final tonnes at rotation end. Two solver models were created, one for Zululand North and one for Zululand South. The objective cell for these models were the sum product of the flow column with the North improve tonnes ha^{-1} and South improve tonnes ha^{-1} respectively. In the solver model building window, the objective cell was set at maximum in order to get the path through the silvicultural value chain that will maximise the improvement in final tonnes. If the solver model is run, the flow column column wil change, including the acitvities in the path that will yield the highest production.

The most profitable path is the path through the silvicultural value chain which will produce the highest profit for stands in Zululand North and South. The results from the robust regression were used to create a cost-benefit analysis mentioned in Section 3.6.2.3. The results from the cost benefit analysis was used to build the solver model for the highest profit path. The objective cell is the sum product of the values of the cost-benefit analysis and the flow column. The solver model was built the same as mentioned above, just with the objective cell changing to maximise the cost-benefit for Zululand North and South respectively.

Chapter 4
RESULTS

Chapter 4 will follow the same flow as that of Chapter 3. It will present the differences in site in terms of growth potential and rainfall in Zululand, followed by the results of the four main statistical analyses and concluding with the results of the solver simulation model.

4.1 SITE

4.1.1 TCS MAI

Through the use of descriptive statistics, Table 4.1 and 4.2 present the difference in performance of stands between regions. The results indicate the mean for Zululand South is about seven tonnes ha^{-1} per year more than Zululand North, and three tonnes ha^{-1} more than the combined average. These results indicate that the growing condition in Zululand South is better than the growing condition in Zululand North and therefore, TCS MAI cannot be used to measure the effect of silvicultural activities with Zululand North and South combined. This will lead to biased results.

Table 4.1: Descriptive statistic of SI in Data set 1 presenting the minimum, mean and maximum values of SI

SI						
	Min	**1st Qu.**	**Median**	**Mean**	**3rd Qu.**	**Max**
Combined	8.7	16.5	18.70	18.54	21.10	26.2
North	8.7	14.58	17.05	16.79	19.22	23.7
South	12.50	17.95	20.70	19.99	21.90	26.2

Table 4.2: Descriptive statistic of TCS MAI in Data set 1 presenting the minimum, mean and maximum values of TCS MAI

TCS MAI						
	Min	**1st Qu.**	**Median**	**Mean**	**3rd Qu.**	**Max**
Combined	5.6	15.85	21.92	22.20	28.40	43.91
North	5.6	12.57	17.59	18.45	23.79	37.52
South	10.33	19.34	25.76	25.28	30.36	43.91

In order to further investigate site differences between regions, a linear model with TCS MAI as the response variable and region as the independent variable, as mentioned in Section 3.5.1.1, was performed.

Table 4.3: Anova summary table with TCS as response variable and Region as independent variable

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	18.449	0.628	29.367	2.00e-16
RegionSouth	6.834	0.848	8.055	1.76e-14

Table 4.4: Global significant testing of the linear regression model

Residual Standard error	7.433 on 308 DF
R-Squared	0.174
F-Statistic	64.89 on 1 and 308
p-value	1.757e-14

The results of the linear regression analysis are similar to those found in the descriptive statistic mentioned above. The low p-value ($p<0.01$) indicates that the TCS MAI is significantly different between the two regions. The estimate column in Table 4.3 illustrates that for this model, Zululand South produces on average 6.8 TCS MAI more than Zululand North. The result from the linear regression analysis supports the conclusions made that Zululand South performs better in terms of final volume than Zululand North.

4.1.2 MAPstand

The amount of rainfall a stand receives throughout the rotation seems to correspond with the growth of trees in a stand, which significantly impact the final tonnes harvested at the end of rotation. Results from the linear regression indicate the that MAPstand significantly ($p<0.01$) impact TCS MAI at 99% confidence level, with TCS MAI increasing with increasing MAPstand (Table 4.5 and 4.6). These results are also presented graphically in Figure 4.1.

Table 4.5: Anova summary table with TCS MAI as response variable and MAPstand as independent variable

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-11.782	3.929	-2.999	0.00293
MAPstand	0.0378	0.00435	8.697	<2e-16

Table 4.6: Global significant testing of linear regression model

Residual Standard error	7.329 on 308DF
R-Squared	0.197
F-Statistic	75.63 on 1 and 308 DF
p-value	<2e-16

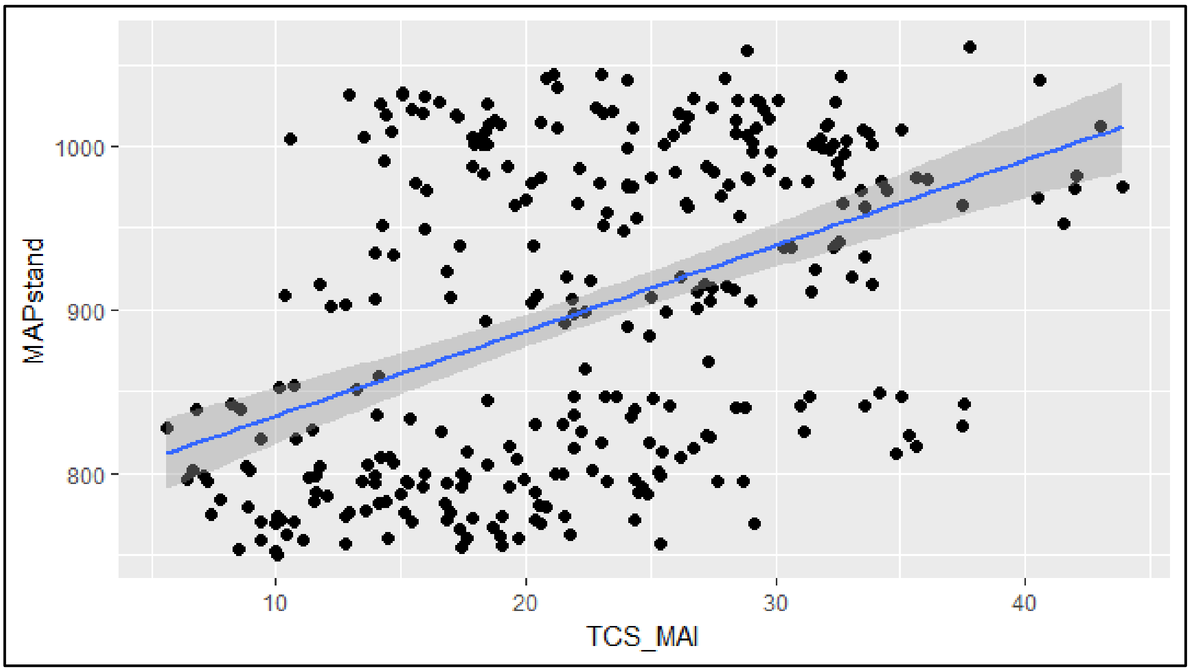


Figure 4.1: Scatter plot illustrates the relationship between TCS MAI and MAPstand.

Figure 4.1 illustrates that TCS MAI increases with increasing MAPstand. However, it is also clear that there are two congestions of points on the plot. The two congestions of points in Figure 4.1 led to further investigation and a descriptive statistic was done to identify the difference in MAPstand for both Zululand North and South – results can be seen in Table 4.7 below.

Table 4.7: Descriptive statistics of MAPstand in both Zululand North and South

MAPstand						
	Min	**1st Qu.**	**Median**	**Mean**	**3rd Qu.**	**Max**
Combined	750.7	801.5	907.3	898.6	989.3	1061
North	750.7	776	798.1	801.7	825.4	868.1
South	883.8	948.9	983.8	978.5	1013	1061

Results in Table 4.7 confirm that MAPstand in Zululand South is on average higher than the MAPstand in Zululand North. It can also be said that the two congestions of points in Figure 4.1 above are the two regions: Zululand North and Zululand South. Based on the results in Section 4.1.1 and 4.1.2, it was decided to divide the data set into region – Zululand North and Zululand South for the analyses in this study. This was done in an atempt to compare stands with similar growth rates and external factors, in order to test if it is possible to identify if the different silvicultural activities have an effect on the growth and performance of stands in both the regions.

4.2 MAIN STATISTICAL ANALYSIS

This section presents the results of the analyses performed in Section 3.6. The results of the statistical analyses are mostly presented in the form of tables and figures. The stars in the probability tables represent the level of significance of the independent variables as follows:

* Significant at 90% level

** Significant at 95% level

*** Significant at 99% level

4.2.1 Effect of Total Silviculture cost on TCS MAI

Total silviculture cost is the sum of the cost of all silviculture activities that took place on a stand. The first analysis (output in Table 4.8 and 4.9) in this section was performed in an attempt to identify if there is a relationship between the money spent at establishment and the return, in terms of final tonnes harvested.

Table 4.8: Summary of a linear regression Anova presenting the p-values of both Zululand North and South

Probability > F		
	North	South
Silvtot_Cost	0.0505 *	0.01532 **

Table 4.9: Global significant testing of the linear regression model

	North	South
Residual Standard error	7.109 on 133	6.905 on 161
R-Squared	0.02846	0.03597
F-Statistic	3.896 on 1 and 133	6.007 on 1 and 161
p-value	5.05E-02	0.01532

The results from the linear regression indicates that the effect of the total silviculture cost on TCS MAI in Zululand North was not significant (p>0.05). The results for Zululand South indicate total silviculture cost significantly effected (p<0.05) TCS MAI. The H_0 was rejected, meaning there is a straight-line relationship between total silviculture cost and TCS MAI in Zululand South. Table 4.8 presents p-values for corresponding effects and Table 4.9 presents the R-squared value for the models. The linear models for both Zululand North and South had very low R-squared values (<0.05), which means the model explained less than 5% of the variation of the TCS MAI. Figure 4.2 and 4.3 graphically illustrate the relationship between total silviculture cost, and TCS MAI for Zululand North and South respectively.

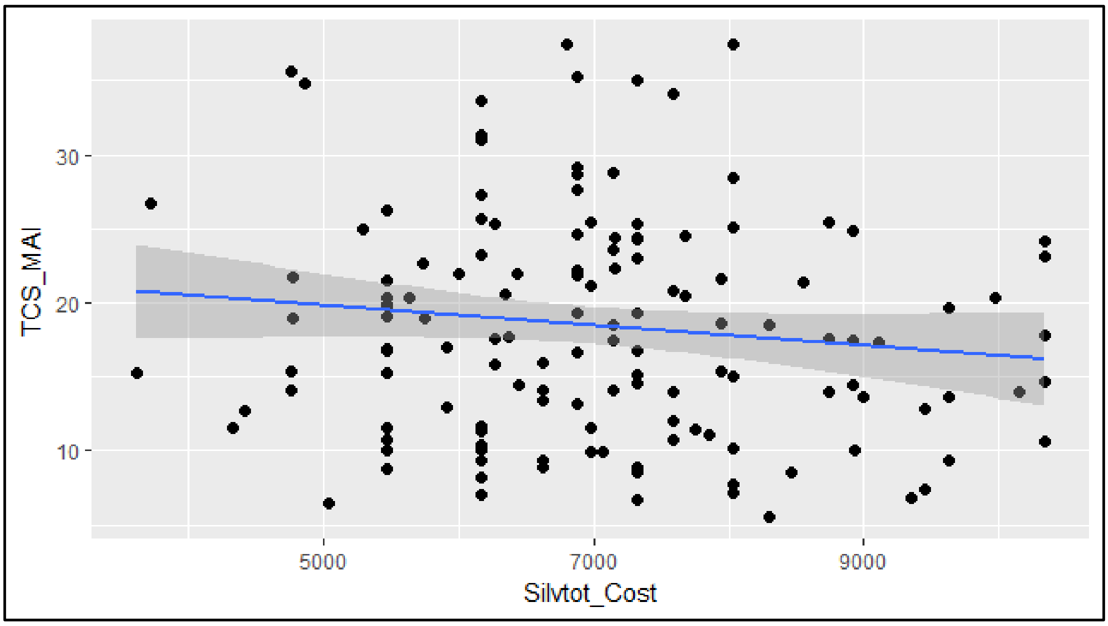


Figure 4.2: Scatter plot illustrates the relationship between total silviculture cost and TCS MAI in Zululand North.

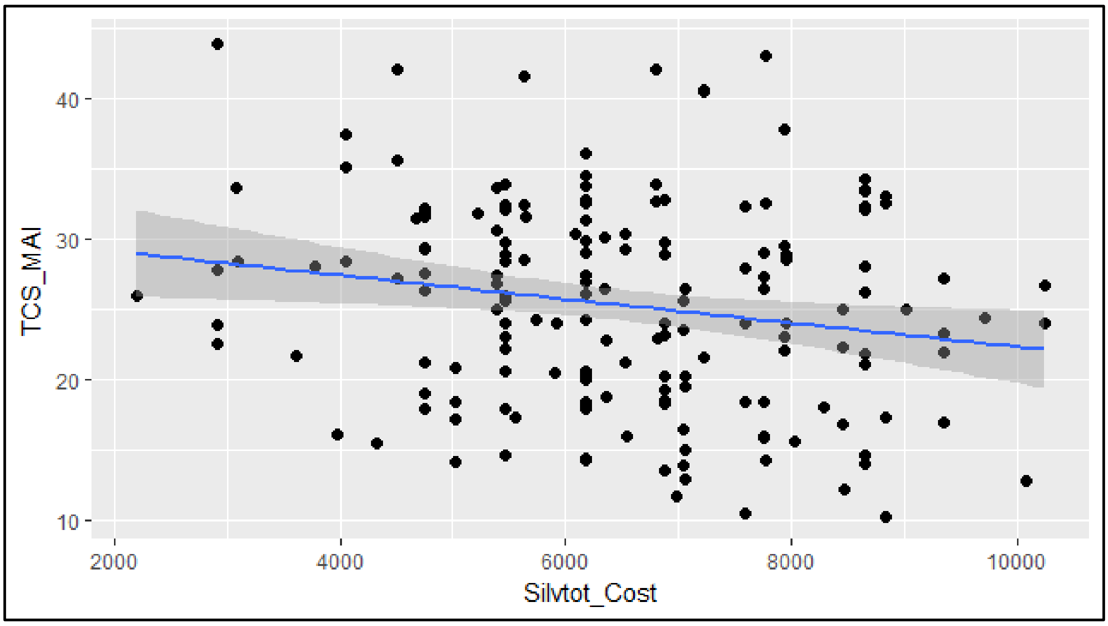


Figure 4.3: Scatter plot illustrates the relationship between total silviculture cost and TCS MAI in Zululand South.

In both Figure 4.2 and 4.3 it seems there is a slight negative slope, meaning the TCS MAI decreases with increasing silviculture cost. This is an unexpected result, which may be an outcome of the site and growing conditions of stands, with it being common practice that additional silviculture activities are applied to the poorer sites or stands under stress. It cannot be quantified if these additional activities had any benefit, but it can be concluded that they did not perform better than other sites with lower total silviculture cost.

4.2.2 Effect of interactions between silvicultural activities and site on TCS MAI at end of rotation

The results presented in Table 4.10 and 4.12 indicate that none of the interactions in Zululand North had a significant effect ($p>0.05$) on the final tonnes harvested at end of rotation. In Zululand South (Table 4.11) the interaction between SI and fertiliser application significantly ($p<0.05$) effected the TCS MAI. However, only 34 out of 170 stands were not fertilised, which is limiting and when analysing the interaction between fertiliser and another activity, it decreases even more, which may lead to biased and misleading results. The very high fertiliser coefficient in Table 4.13 also suggests that the output of the analyses are misleading and biased. From these results, there is little that indicates that interactions significantly effects the final tonnes harvested. The relationship between TCS MAI and SI of stands that were fertilised, and stands not fertilised in Zululand South are illustrated in Figure 4.4 below. The figure illustrates that there was no representation for no fertiliser below 16 SI. Thus, the fertiliser points below 16 SI had a high leverage on the regression. As a result of the small data set and the unbalanced representation of activities within the data set, it was decided not to include any interactions in the analyses.

Table 4.10**:** Summary of a robust linear regression with TCS MAI as response variable, presenting the p-values of all the independent variables for Zululand North

Propability > F		
Variables	**North**	
MAPstand	8.058e-06	***
SI	2.2e-16	***
Season	0.0491	**
Pre_Plant2	0.6677	
Plant_status	0.0623	*
Fert2	0.3584	
Blank2	0.6226	
Num_Weedings	0.3589	
Plant_Firstweed	0.4056	
SI:Season	0.6058	
SI:Pre_Plant	0.8783	
SI:Plant_Status	0.4123	
Season:Pre_Plant	0.1731	
Season:Plant_Status	0.1967	
Pre_Plant2:Plant_Status	0.2218	

Table 4.11: Summary of a robust linear regression with TCS MAI as response variable, presenting the coefficients of all the independent variables for Zululand North

Coeficients	
Variables	**North**
(Intercept)	68.7905
MAPstand	0.0652
SI	2.0551
SeasonSpring	4.7786
SeasonWinter	-1.0528
Pre_Plant21	-1.4280
Plant_statusWet	4.0858
Fert21	1.3013
Blank21	0.5057
Num_Weedings	-0.2536
Plant_Firstweed	0.0099
SI:SeasonSpring	-0.2955
SI:SeasonWinter	-0.0297
SI:Pre_Plant21	0.0512
SI:Plant_statusWet	-0.2950
SeasonSpring:Pre_Plant21	-3.1515
SeasonWinter:Pre_Plant21	-4.9661
SeasonSpring:Plant_statusWet	0.394
SeasonWinter:Plant_statusWet	4.5825
Pre_Plant21:Plant_statusWet	3.211

Table 4.12: Summary of a robust linear regression with TCS MAI as response variable, presenting the p-values off all the independent variables for Zululand South

Propability > F		
Variables	**South**	
MAPstand	0.0034	***
SI	1.14e-33	***
Season	0.0079	***
Pre_Plant2	0.0367	**
Fert2	0.0447	**
Blank2	0.2075	
Num_Weedings	0.1084	
Plant_Firstweed	0.1852	
SI:Season	0.6715	
SI:Pre_Plant2	0.7484	
SI:Fert2	0.0338	**
Season:Pre_Plant2	0.2924	
Season:Fert2	0.1503	
Pre_Plant2:Fert2	0.6146	

Table 4.13: Summary of a robust linear regression with TCS MAI as response variable, presenting the coefficients of all the independent variables for Zululand South

Coeficients	
Variables	**South**
(Intercept)	-47.367
MAPstand	0.0254
SI	2.6488
SeasonSpring	-6.838
SeasonWinter	-4.2007
Pre_Plant21	-3.2269
Fert21	15.695
Blank21	1.0205
Num_Weedings	-0.4789
Plant_Firstweed	-0.0186
SI:SeasonSpring	0.1975
SI:SeasonWinter	0.2739
SI:Pre_Plant21	0.0921
SI:Fert21	-0.8637
SeasonSpring:Pre_Plant21	-1.2742
SeasonWinter:Pre_Plant21	-2.8133
SeasonSpring:Fert21	1.2929
SeasonWinter:Fert21	-2.6032
Pre_Plant21:Fert21	1.0198

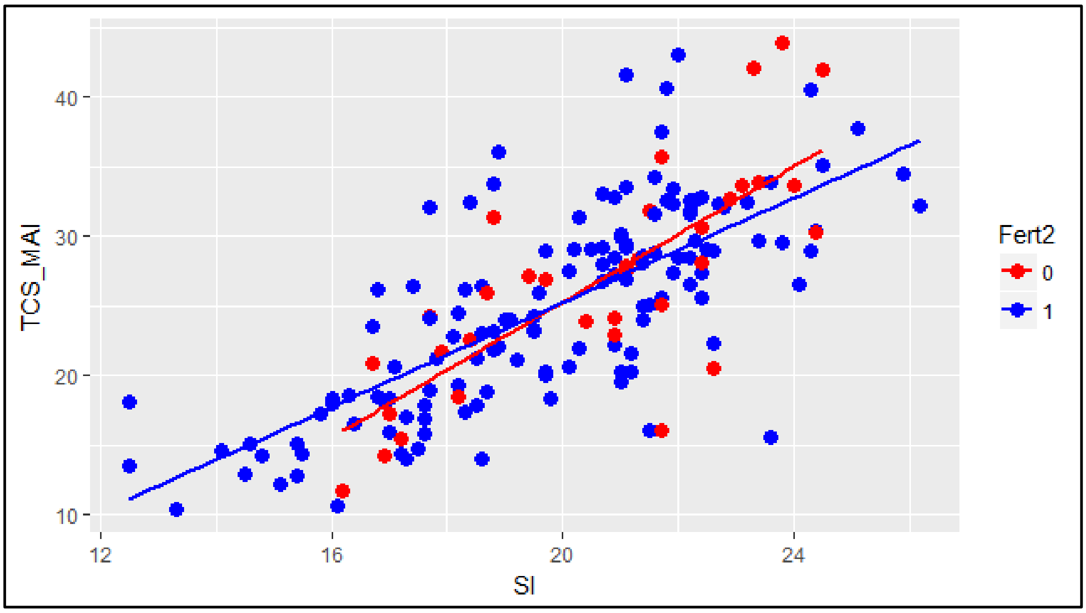


Figure 4.4: Scatter plot illustrating the relationship between SI and TCS MAI for stands that were fertilised and stands not fertilised respectively in Zululand South.

4.2.3 Effect silvicultural activities have on TCS MAI at end of rotation

In this analysis, a robust regression was performed in an attempt to identify if operational data can be used to determine if the silvicultural activities performed at establishment had an effect on the final tonnes harvested. The robust regression method was performed to reduce the influence of outliers and leverage points in order to provide a better fit for the majority of the data. The observations and the weights of the residuals are presented in Figures 4.5 and 4.6 below for Zululand North and South respectively.

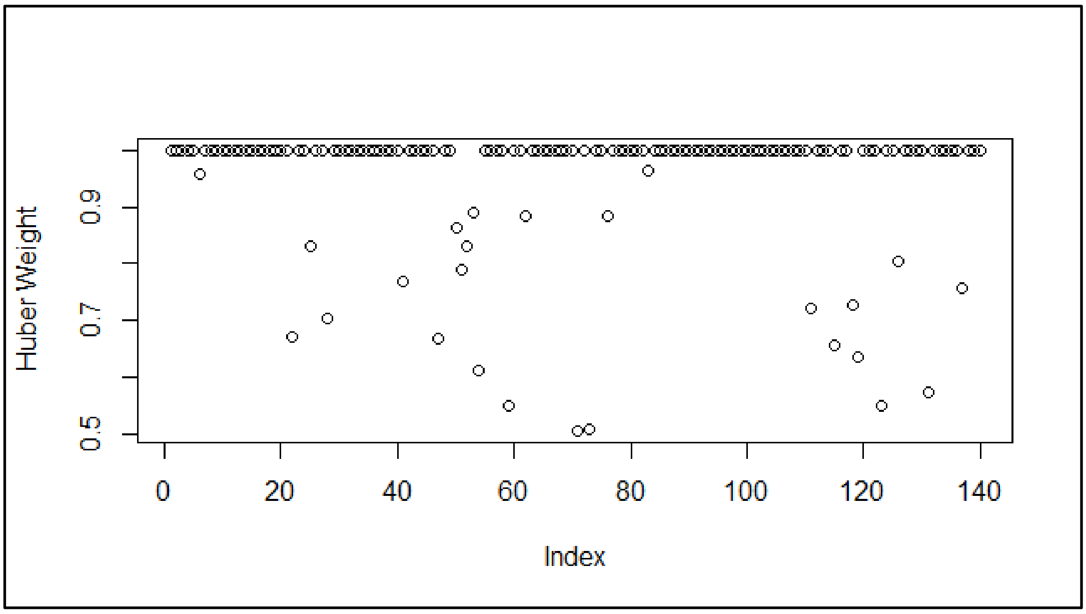


Figure 4.5: Influential observations weighted with Huber M-estimation for robust regression model in Zululand North.

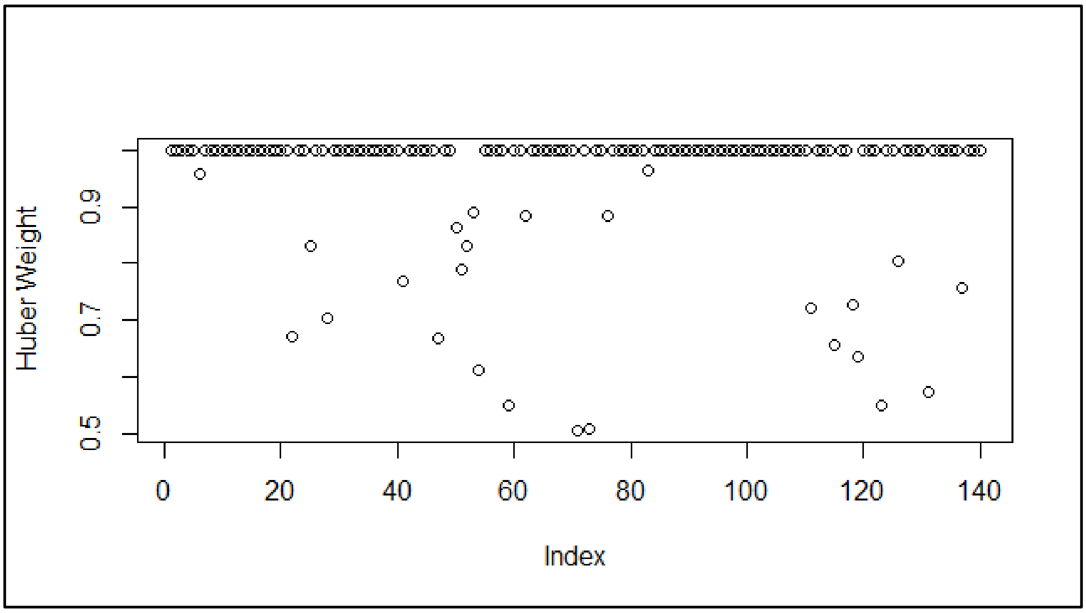


Figure 4.6: Influential observations weighted with Huber M-estimation for robust regression model in Zululand South.

The p–values of the robust linear regression models are presented in Table 4.14 below. The coefficients of the activities (Table 4.15) were used to determine if the activities had a positive or negative effect on the TCS MAI.

SI was included in the model as an independent variable. The results indicate that TCS MAI significantly increased ($p<0.05$) with increasing SI in both Zululand North and South. The total rainfall a stand received in its rotation had an influence on the growth of the stand. Results indicate that the TCS MAI increased with increasing MAPstand. The MAPstand significantly ($p<0.01$) effected TCS MAI.

The season in which trees are planted do not only affect early survival and the silvicultural activities that follow, results from Table 4.14 and 4.15 indicate that stands that were planted in autumn in both regions performed significantly ($p<0.05$) better in terms of TCS MAI when compared to stands planted in spring or winter.

In Zululand, stands were planted either with water (planting wet) or without water (planting dry). Planting with water in Zululand North had a positive influence on the growth of stands, and it significantly ($p<0.05$) impacted the tonnes harvested at the end of rotation. In Zululand South not enough compartments were planted with water to draw accurate conclusions, therefore plant status was not included in the model for Zululand South.

Fertiliser application indicated very different results for the two regions. Fertiliser application in Zululand North did not have a statistically significant ($p>0.05$) impact on TCS MAI. However, even though not significant, Table 4.15 indicates the coefficients for fertiliser application had a positive impact on TCS MAI. In Zululand South the application of fertiliser did not have a significant ($p>0.05$) effect on the TCS MAI. Although not significant the the fertiliser application did show a negative coefficient (Table 4.15), meaning that stands that were fertilised had a decrease in final tonnes harvested compared to stands not fertised..

Blanking was performed on stands where survival was below 90%, 4-6 weeks after planting, in an attempt to obtain maximum stocking on a stand. In Zululand South, blanking had a significantly positive ($p<0.05$) impact on the final TCS MAI. In Zululand North, blanking also increased the TCS MAI, but the impact was not significant ($p>0.05$) and the H_0 could not be rejected.

Weeding is performed from planting up until trees reach canopy closure. It is performed to remove weeds from the compartment that compete with the newly planted trees for the nutrients available in the soil. The analyses yielded an unexpected result with the TCS MAI decreasing with increasing number of weedings on stands in both Zululand North and South. The results for both regions were, however, not significant (p>0.05).

Table 4.14: Summary of a robust linear regression with TCS MAI as response variable, presenting the p-values off all the independent variables for both Zululand North and South

Probability > F				
Variables	North		South	
SI	2.20e-16	***	2.20e-16	***
MAPstand	3.03e-06	***	0.001103	***
Season	0.0275	**	0.0077	***
Pre_Plant2	0.5884		0.0661	*
Plant_status	0.0489	**		
Fert2	0.137		0.0722	*
Blank2	0.5756		0.0249	**
Num_Weedings	0.1746		0.2046	
Plant_Firstweed	0.7752		0.5199	

Table 4.15: Summary of a robust linear regression with TCS MAI as response variable, presenting the coefficients of all the independent variables for both Zululand North and South

Coefficients		
	North	South
(Intercept)	-59.9357	-38.8734
SI	1.8337	2.0744
MAPstand	0.059	0.0278
SeasonSpring	-2.6648	-2.896
SeasonWinter	-0.9456	-1.7419
Pre_Plant21	-0.5673	-1.4561
Plant_statusWet	1.9294	NA
Fert21	2.0312	-1.6913
Blank21	0.561	1.7669
Num_Weedings	-0.371	-0.3671
Plant_Firstweed	0.0031	-0.0086

4.2.3.1 Testing assumptions

The homoscedasticity of the data was tested by investigating the Residual vs Fitted plots (Figure 4.6—4.7) of the robust linear regression for Zululand North and South. Both plots illustrated no distinct pattern formed by the residuals. As such, a subjective interpretation was made that the residuals are homoscedastic for both Zululand North and South.

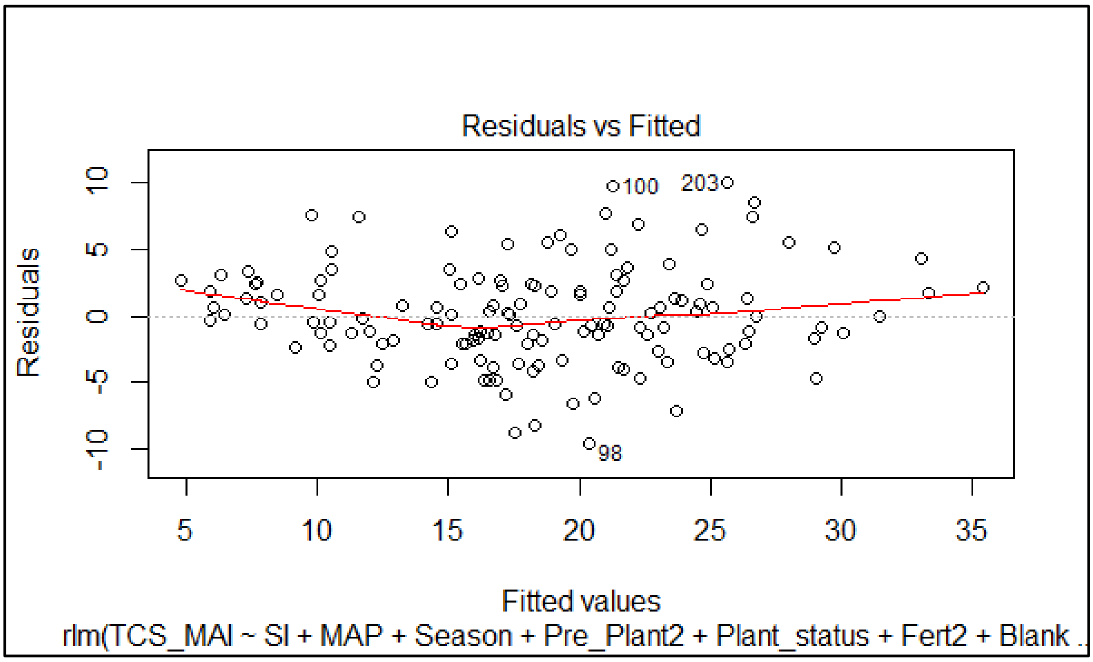


Figure 4.7: Residual vs fitted scatter plot for the robust regression model in Zululand North.

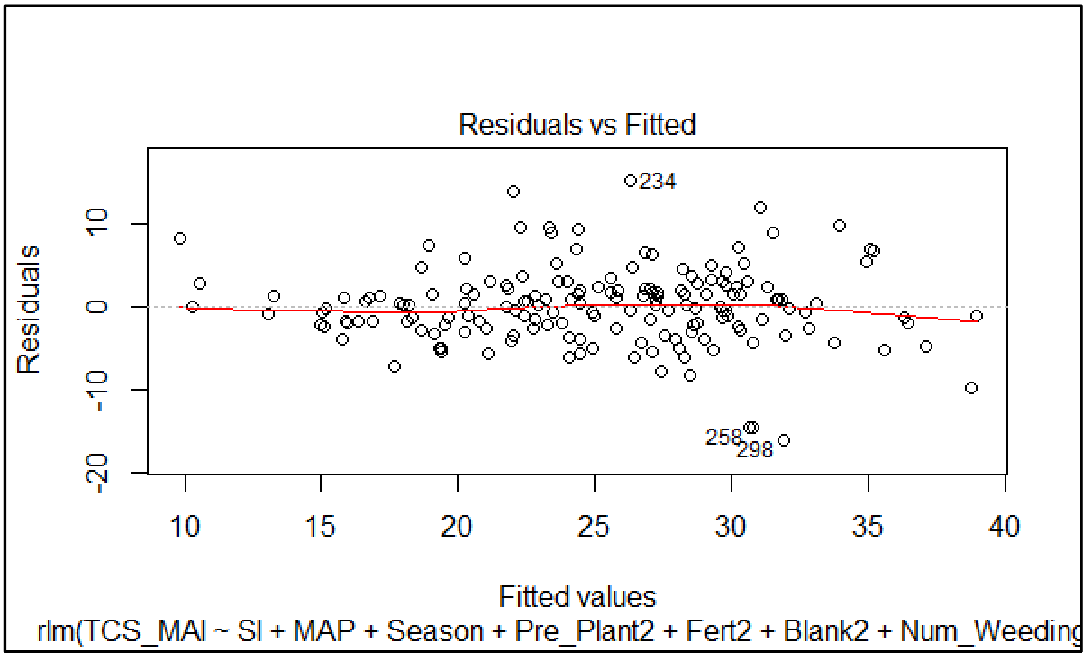


Figure 4.8 Residual vs fitted scatter plot for the robust regression model in Zululand South.

4.2.4 Effect silvicultural activities have on early height growth

The robust regression model was created in attempt to identify if operational data can be used to determine if silvicultural activities affect the early height growth of a stand. The robust regression use Huber *M*-estimation to down weigh the residuals of influential outliers or leverage points in order to have a better fit for the majority of the data. Figure 4.9 and 4.10 below illustrate the observation and Huber weight of the influential residuals for Zululand North and South respectively.

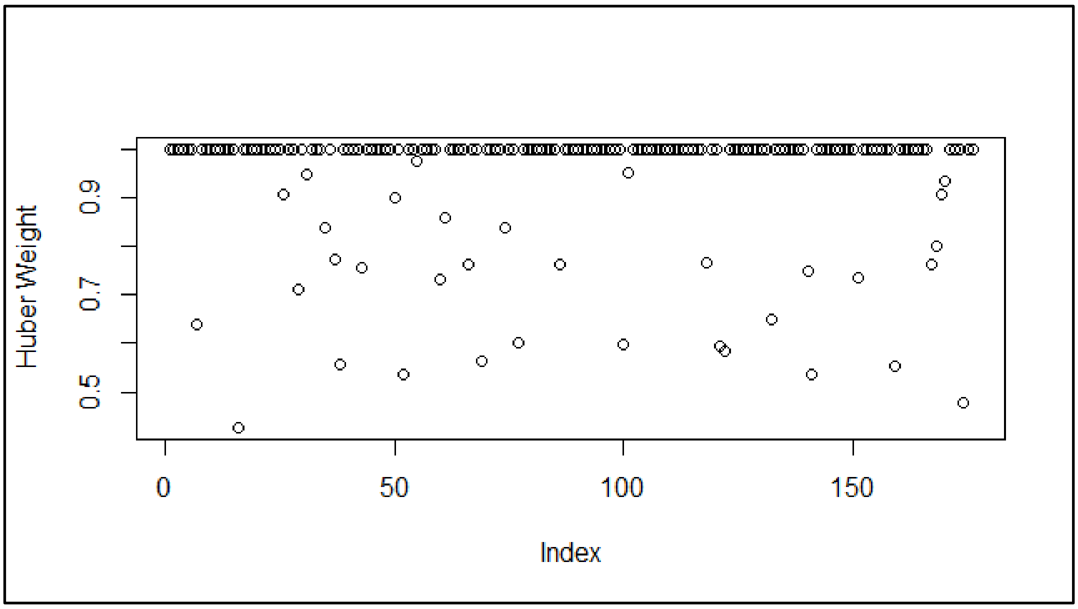


Figure 4.9: Influential observations down-weighted with Huber M-estimation for robust regression model in Zululand North.

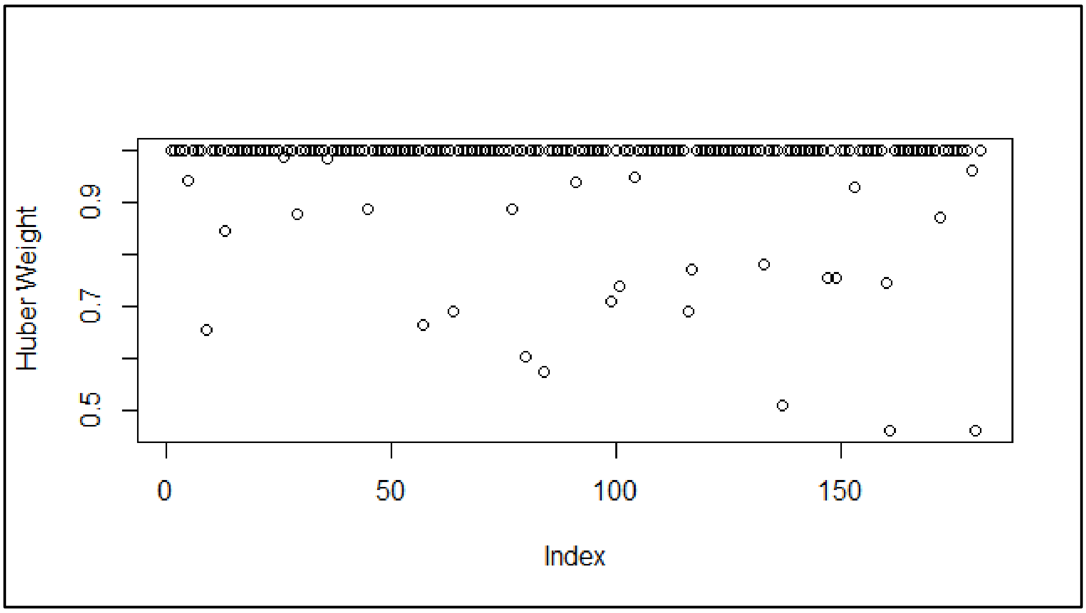


Figure 4.10: Influential observations down-weighted with Huber M-estimation for robust regression model in Zululand South.

The p-values of the independent variables in the robust linear regression model are presented in Table 4.16 with the coefficients of these variables presented in Table 4.17. Interestingly SI, which is a measure of height growth of a stand at a particular point in time, had no significant ($p>0.05$) impact on the MHPR of stands in both Zululand North and South. Rotrain is the amount of rainfall from planting up until measurement. Rotrain showed a significantly positive ($p<0.01$) effect on early height growth on stands in Zululand North, with the MHPR increasing with increasing rainfall. Rotrain also had a positive but non-significant ($p>0.05$) effect on MHPR in Zululand South.

In this data set there were enough stands planted with water in Zululand South to include plant status in the analysis. The results found for plant status indicated that planting with water significantly ($p<0.01$) improved the MHPR on stands in Zululand North, which are historically poorer sites and on average receive less rain than Zululand South. Planting with water in Zululand South did not have a significant effect ($p>0.05$) on the MHPR when compared to planting without water.

Neither fertiliser nor blanking had a significant effect ($p>0.05$) on the early height growth of stands in both Zululand North and South. However, even though not significant, blanking and fertiliser increased the MHPR in Zululand North and South.

Results indicate that the number of weedings did not have a significant ($p>0.05$) impact on the early height growth of stands in Zululand South. The impact of the number of weedings was however significant ($p<0.05$) on stands in Zululand North, with the MHPR decreasing with increasing number of weedings.

In Section 2.2 it is stated that the density to which stands are planted do impact the growth of stands in different geographical areas. The results in Table 4.16 and 4.17 indicate that stand density significantly ($p<0.01$) impact the early height growth of stands in Zululand North, with the MHPR increasing with increasing TPH0. The opposite was true for Zululand South – although not significant ($p>0.05$), MHPR decreased with increasing TPH0.

TPH1 is the trees per ha of stands at the time of measurement. The TPH1 can be affected by a number of factors. However, TPH1 signficantly ($p<0.01$) effected early growth on stands in Zululand North and South. In Zululand North the MHPR increases with increasing TPH1, and in Zululand South the MHPR decreases with increasing TPH1. The p-values and coefficients can be seen in Table 4.16 and 4.17.

Table 4.16: Summary of a robust linear regression with MHPR as response variable, presenting the p-values off all the independent variables for both Zululand North and South

Probability > F				
Variables	**North**		**South**	
SI	0.3778		0.412	
Rotrain	5.95e-08	***	0.2	
Season	0.8015		0.1495	
Pre_Plant2	0.4616		0.5719	
Plant_status	0.0069	***	0.5564	
Fert2	0.8948		0.7538	
Blank2	0.3961		0.3023	
Num_Weedings	0.0129	**	0.0938	*
Plant_Firstweed	0.0607	*	0.8106	
TPH1	0.00081	***	0.0023	***
TPH0	0.0085	***	0.208	

Table 4.17: Summary of a robust linear regression with MHPR as response variable, presenting the coefficients of all the independent variables for both Zululand North and South

Coeficients		
	North	**South**
(Intercept)	-34.494	57.5283
SI	0.0217	-0.0305
Rotrain	0.0026	0.0004
SeasonSpring	0.0332	0.0218
SeasonWinter	-0.0918	0.3552
Pre_Plant21	0.1259	-0.0888
Plant_statusWet	0.5166	-0.1208
Fert21	0.0407	0.0667
Blank21	0.1303	0.1733
Num_Weedings	-0.1639	0.1046
Plant_Firstweed	-0.0047	-0.0008
TPH1	0.0225	-0.036
TPH0	0.0025	0.0012

4.2.4.1 Testing assumptions

The homoscedasticity of the data was tested by investigating the Residual vs Fitted plots (Figure 4.11—4.12) of the robust regression for Zululand North and South. Both plots illustrate no distinct pattern formed by the residuals. As such, a subjective interpretation was made that the residuals are homoscedastic for both Zululand North and South.

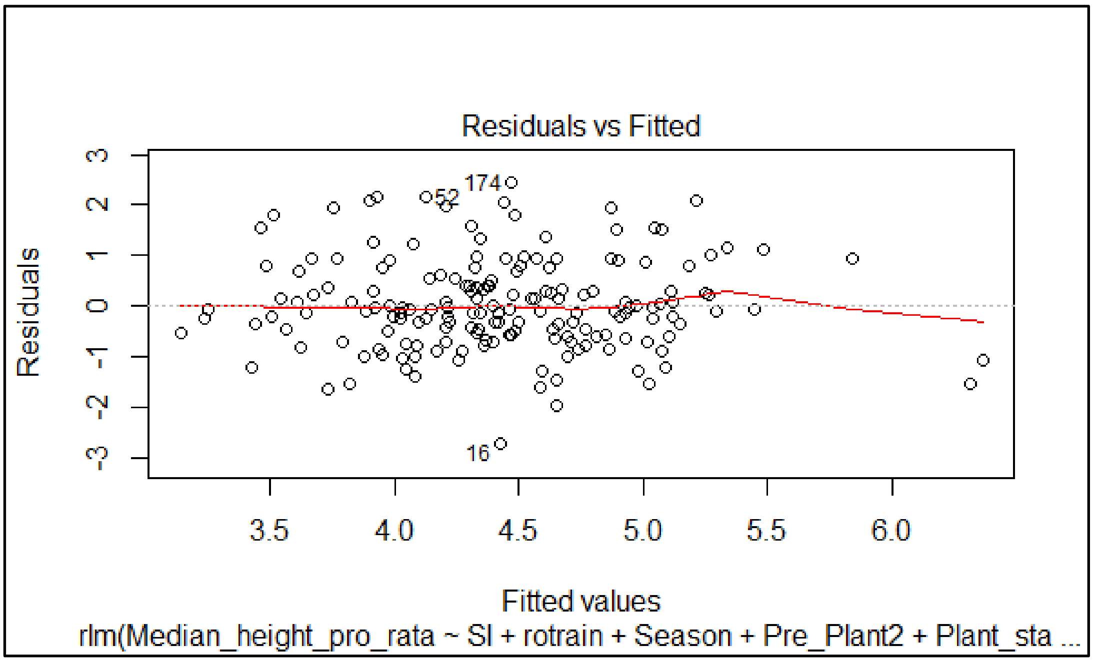


Figure 4.11: Residual vs fitted plot for the robust regression model in Zululand North.

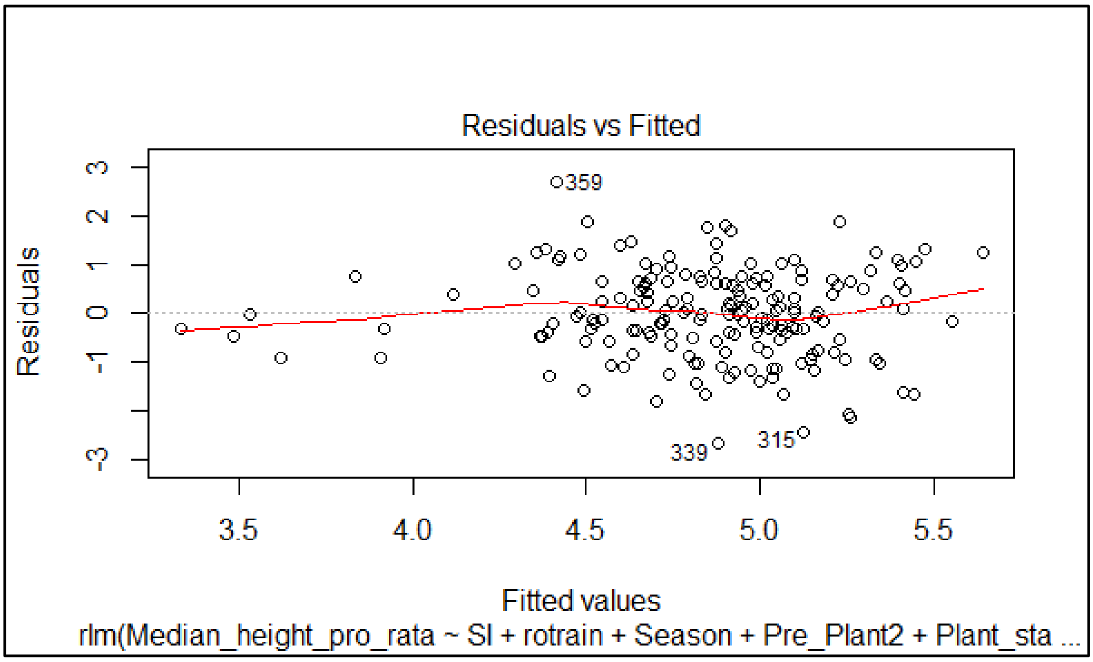


Figure 4.12: Residual vs fitted plot for the robust regression model in Zululand South**.**

4.2.5 Logistic Regression with blanking as response

The results from the logistical regression aim to illustrate if operational data can be used to demonstate whether or not the activities prior to blanking had an effect on the chances of blanking taking place. Table 4.18 below presents the p-values of the independent variables in the logistic regression model, with the coefficients being presented in Table 4.19 for both Zululand North and South. The results obtained were generally negative and not as expected, with the chances of blanking taking place increasing with silvicultural activities present.

SI did not have a significant (p>0.05) effect on whether or not blanking took place in Zululand North or Zululand South.

Table 4.18 indicate the season in which stands were planted were statistically significant (p<0.05) in both Zululand North and South. In Zululand North, stands that were planted in both spring and winter had positive coefficients compared to planting in autumn, which means chances of blanking taking place increased when planted in spring or winter compared to planting in autumn. In Zululand South, spring showed a positive coefficient and winter a negative coefficient, meaning when planted in spring, the chances of blanking taking place increased compared to planting in autumn, but when planted in winter, chances of blanking taking place decreased when compared to planting in autumn.

Results from the logistical regression indicate that plant status significantly (p<0.05) effected early survival in both Zululand North and South. Coefficients in Table 4.19 indicate that stands planted with water increased the chances of blanking taking place when compared to stands that were planted without water. Results can be seen in Tables 4.18 and 4.19.

Pre-plant spray significantly (p<0.01) effected early survival in both Zululand North and South, with the chances of blanking increasing where pre-plant spray was present, when compared to where pre-plant spray was absent (Table 4.18 and 4.19).

Table 4.18: Summary of logistic regression Anova with blanking as response variable, presenting the p-values of all the independent variables

	Probability > F			
	North		South	
SI	0.0739	*	0.4573	
Season	0.0543	*	0.00113	***
M1R	0.2418		0.2188	
Plant_status	0.0162	**	0.0134	**
Fert2	0.8571		0.6539	
Pre_Plant2	0.00053	***	2.2812e-06	***
AIC	388.04		444.49	

Table 4.19: Summary of logistic regression Anova with blanking as response variable, presenting the coefficients of all the independent variables

Coefficients		
	North	South
(Intercept)	-0.6178	-1.5467
SI	-0.0667	0.0341
SeasonSpring	0.7769	0.6810
SeasonWinter	0.1669	-0.5093
M1R	0.0038	0.0026
Plant_statusWet	0.6454	0.9315
Fert21	0.0900	0.1388
Pre_Plant21	0.9361	1.1106

4.2.6 Contingency tables with Blanking

The contingency tables in the sections below illustrate the number of stands where blanking was present and the number of stands where blanking was not present, along with whether the independent variables prior to blanking took place or not. With the count data, a Fisher's exact test was performed to determine if there is an association between the independent variable and blanking, and provided the odds ratios (Quinn and Keough 2002). This was done for all the stands in Zululand North and South.

4.2.6.1 Zululand North

Pre plant

The results from the Fisher's exact test, discussed in Section 3.6.5, indicate pre-plant had an influence on whether or not blanking took place. The P-value was 9.879e-06, which means the H_0 can be rejected, meaning there is a significant association between pre-plant and blanking. Table 4.20 below presents the number of stands that were blanked, versus not blanked, when pre-plant spray was present or absent.

Table 4.20: Contingency table between Blanking and Pre-plant in Zululand North

Pre Plant	Blank		Total
	0	1	
0	90	30	120
1	93	94	187
Total	183	124	307

Results from the Fisher's exact test indicate an odds ratio of 3.021. This is interpreted as follows: the odds of blanking taking place when pre-plant spray is present is 3.021 times the odds of blanking taking place when pre-plant spray is absent in Zululand North.

Plant status

The p-value was 3.835e-05, which means H_0 can be rejected, meaning there is a significant association between plant status and blanking. Table 4.21 below presents the number of stands that were blanked, versus not blanked, when planting wet or planting dry in Zululand North.

Table 4.21: Contingency table between Blanking and Plant status in Zululand North

Plant status	Blank		Total
	0	1	
Dry	134	62	196
Wet	49	62	111
Total	183	124	307

Results from the Fisher's exact test indicate the odds ratio of 2.73. The odds of blanking taking place when planting wet is 2.73 times the odds of blanking taking when planting dry.

Fertiliser

The p-value was 0.5832, which means the H_0 cannot be rejected. Therefore, there is no association between the variables. Table 4.22 below presents the number of stands that were blanked, versus not blanked, when fertiliser was present or absent in Zululand North.

Table 4.22**:** Contingency table between Blanking and Fertiliser in Zululand North

Fert	Blank		Total
	0	1	
0	11	9	20
1	172	115	287
Total	183	124	307

Season

Table 4.23 is a 3x2 contingency table, therefore the Fisher's exact test cannot be performed. Pearsons's chi-square test was performed to test if season had a significant influence on whether or not blanking took place. The P-value was 0.001384, which means the H_0 can be rejected. Consequently, this means that there is a significant association between the season and blanking. The table presents the number of stands that were blanked and the number of stands not blanked for all the planting seasons in Zululand North. Stands planted in autumn and winter indicated that more stands were not blanked, therefore the probability of blanking taking place is less than the probability of blanking not taking place. Stands planted in spring indicated more stands were blanked, therefore the probability of blanking taking place is more than blanking not taking place.

Table 4.23: Contingency table between Blanking and Season in Zululand North

Season	Blank		Total
	0	1	
Autumn	81	43	124
Spring	34	46	80
Winter	68	35	103
Total	183	124	307

4.2.6.2 Zululand South

Pre plant

The P-value was 3.86e-07, therefore the H_0 can be rejected, meaning there is a significant association between the pre-plant and blanking. Table 4.24 below presents the number of stands that were blanked, versus not blanked, when pre-plant spray was present or absent in Zululand South.

Table 4.24: Contingency table between Blanking and Pre-plant in Zululand South

Pre Plant	Blank		Total
	0	1	
0	103	64	167
1	62	119	181
Total	165	183	348

The odds of blanking taking place when pre-plant spray is present is 3.0783 times the odds of blanking taking place when pre-plant spray is absent.

Plant status

The p-value was 0.02814, which means H_0 can be rejected. There is a significant association between plant status and blanking. Table 4.25 below presents the number of stands that were blanked, versus not blanked, when planting wet or planting dry in Zululand South.

Table 4.25: Contingency table between Blanking and Plant status in Zululand South

Plant status	Blank		Total
	0	1	
Dry	153	156	309
Wet	12	27	39
Total	165	183	348

The odds of blanking taking place when planting wet is 2.202 times the odds of blanking taking place when planting dry.

Fertiliser

The p-value was 0.6433, which means the H_0 cannot be rejected. Therefore, there is no association between the variables. Table 4.26 below presents the number of stands that were blanked, versus not blanked, when fertiliser was present or absent in Zululand South.

Table 4.26: Contingency table between Blanking and Fertiliser in Zululand South

Fert	Blank		Total
	0	1	
0	33	32	65
1	132	151	283
Total	165	183	348

Season

Table 4.27 is a 3x2 contingency table and as such, Pearsons's chi-square test was performed to test if season had a significant influence on whether or not blanking took place. The P-value was 7.597e-05, which means the H_0 can be rejected. This means that there is a significant association between the season and blanking. The table presents the number of stands that were blanked and the number of stands not blanked for the planting seasons in Zululand South. Planting in winter indicated more stands were not blanked, meaning the probability of blanking taking place is less than the probability of blanking taking place when planted in winter. Planting in spring and autumn indicated more stands were blanked than not blanked, meaning the probability of blanking taking place is more than the probability of blanking not taking place when planted in these seasons.

Table 4.27: Contingency table between Blanking and Season in Zululand South

Season	Blank		Total
	0	1	
Autumn	65	77	142
Spring	26	59	85
Winter	74	47	121
Total	165	183	348

4.2.7 Testing association between Season and Plant Status

4.2.7.1 Zulaland North

Table 4.28 is a 3x2 contingency table, thus Pearsons's chi-square test was performed to test if season had a significant influence on planting method. The P-value was 0.02184, which means the H_0 can be rejected and consequently, that there is a significant association between the season and plant status. The table presents the number of stands that were planted with water, and the number of stands planted without water for the different planting seasons in Zululand North. Stands planted in autumn and winter indicated that more stands were planted dry than wet. The probability of planting dry is more than the probability of planting wet when planted in these seasons. Stands planted in spring illustrated a very similar distribution between planting dry and planting wet.

Table 4.28: 2x3 Contingency table between Season and Plant Status in Zululand North

Season	**Plant Status**		**Total**
	Dry	**Wet**	
Autumn	83	41	124
Spring	41	39	80
Winter	72	31	103
Total	196	111	307

4.2.7.2 Zululand South

Table 4.29 is a 3x2 contingency table and therefore Pearsons's chi square test was performed to test if season had a significant influence on planting method. The P-value was 0.9738, which means the H_0 cannot be rejected. This indicates that there is no significant association between the season and plant status The table illustrates that the majority of stands are planted dry in Zululand South, irrespective of planting season.

Table 4.29: 2x3 Contingency table between Season and Plant Status in Zululand South

Season	**Plant Status**		**Total**
	Wet	**Dry**	
Autumn	16	126	142
Spring	10	75	85
Winter	13	108	121
Total	39	309	348

4.3 SOLVER SIMULATION

The solver network model is based on the results obtained from the robust regression in Section 3.6. These results (Table 4.14 and 4.15) and the results from the cost-benefit analysis were used in a shortest path network model in Microsoft Excel Solver to illustrate a lowest cost, highest production and most profitable path through the silvicultural value chain in both Zululand North and South.

The coefficients in Table 4.15 indicate the effect each variable had on the TCS MAI for that model. These coefficients indicate whether the TCS MAI increased or decreased on sites where the activity took place. These coefficients were multiplied by eight years to obtain the impact it had in terms of final tonnes at the end of rotation (potential improvement tonne ha^{-1} over a rotation of eight years). This value obtained for every silviculture activity were associated with its represented arcs in the network model, meaning if the model included the arc in the path that tonnes ha^{-1} value were summed with the value of the other arcs involved in the path to obtain the highest production path.

The results from the cost-benefit analyses for each silviculture activity mentioned in Section 3.6.2.3 were also associated with its represented arc in the network model. The cost-benefit value of the arcs involved in the path tested were summed together to obtain the highest profitable path through the silvicultural value chain. Table 4.30 below presents the results of the different paths, and the impact that path has on the cost, productivity and profitability of the value chain.

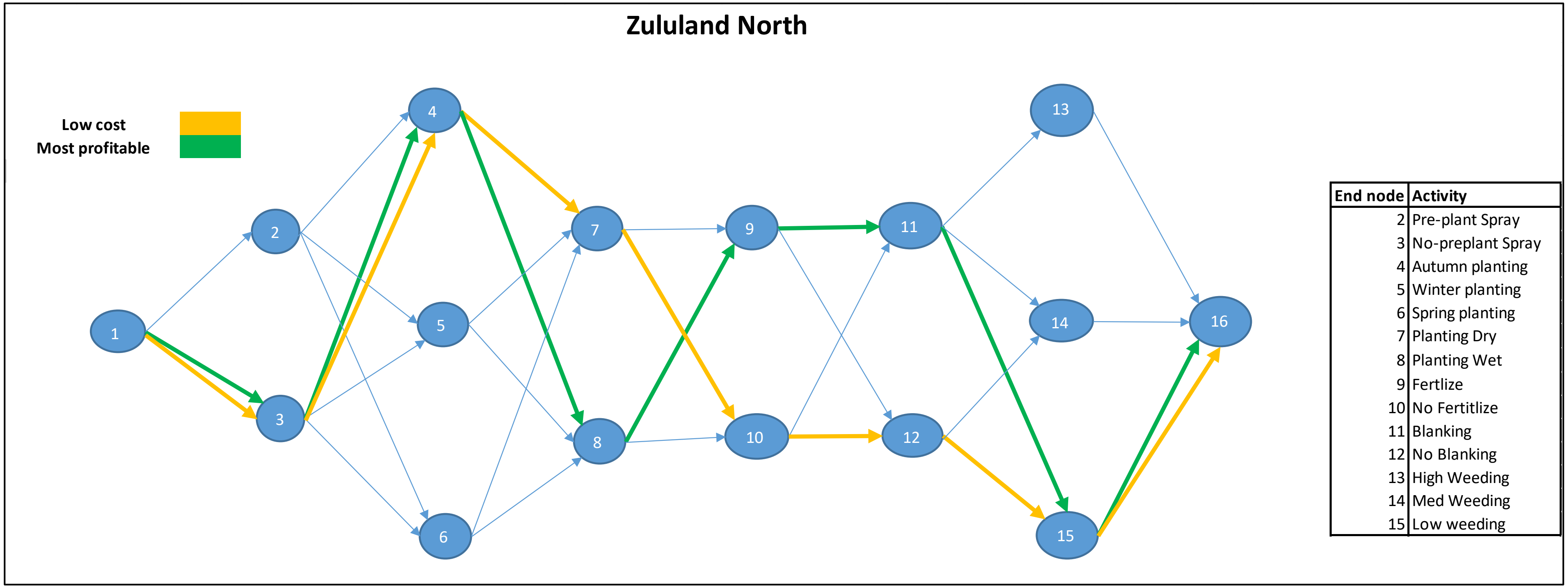
Table 4.30: The cost, productivity and cost-benefit of the different paths through the silvicultural value chain

Solver simulation			
	Lowest cost (R ha^{-1})	**North cost-benefit (R ha^{-1})**	**South cost-benefit (R ha^{-1})**
Cost (R/ha)	3120.67	5954.36	4010.57
North cost-benefit (R/ha)	-3120.67	4716,6	-2686.61
South cost-benefit (R/ha)	-3120.67	-5775.94	159.31
North improve (ton/ha)	0	36.17	4.49
South improve (ton/ha)	0	0.60	14.14

The lowest cost path through the silvicultural value chain for both regions illustrated a potential cost benefit of R-3120.67 ha^{-1} throughout the rotation, with the potential productivity improvement 0 tonnes ha^{-1}. The highest production path was also the most profitable path through the silvicultural value chain for both Zululand North and South. These paths did however differ between the two regions. In Zululand North, the highest production and most profitable path (Figure 4.13) included planting in autumn, applying water at planting, fertilization, blanking and low weeding. This path had a total silviculture cost of R5954.36 ha^{-1}, but delivered a cost benefit of R4716.62 ha^{-1}, with a productivity improvement of 36.17 tonnes ha^{-1}. In Zululand South, the highest production and most profitable path (Figure 4.14) included planting in autumn, dry planting, exclusion of fertilizer, included blanking and low weeding. This path had a cost of R4010.57 ha^{-1}, but delivered a cost benefit of R159.31 ha^{-1}, with a productivity improvement of 4.49 tonnes ha^{-1}. The cost-benefit value is not the total profit of stands, but rather the potential improvement in profit when the most profitable path is followed.

The network models created is aimed at being a decision making tool which foresters can use on a range of sites in both Zululand North and South to implement silvicultural activities on stands based on their historical performance, which is intact with the objectives of their organisation. Therefore the user should select his objective (lowest cost, highest production or highest profitibility) and the region then the model will simulate the path through the silvicultural value chain based on th results found in the study. The user is also able to manualy enter constraints into the model if a certain acitivity needs to take place, by simply adding the node of that activtity to the inflow and outflow constraints, which means the path are required to include the specific activity.

The lowest cost and most profitable paths for both Zululand North and South are illustrated in Figures 4.13 and 4.14 respectively. The silviculture activity associated with the end node is illustrated in the Table in Figure 4.13 and 4.14.



End node	Activity
2	Pre-plant Spray
3	No-preplant Spray
4	Autumn planting
5	Winter planting
6	Spring planting
7	Planting Dry
8	Planting Wet
9	Fertlize
10	No Fertitlize
11	Blanking
12	No Blanking
13	High Weeding
14	Med Weeding
15	Low weeding

Figure 4.13: Lowest cost, highest production and most profitable path’s through the silvicultural value chain in Zululand North.

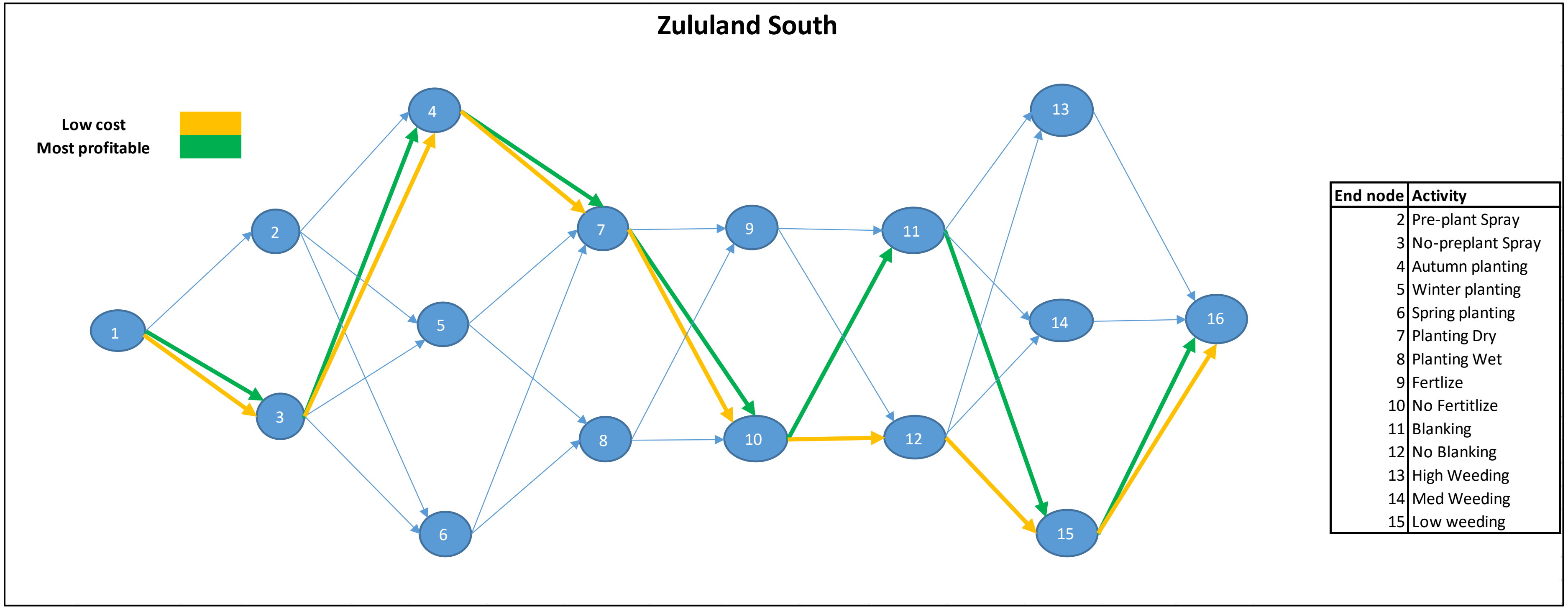


Figure 4.14: Lowest cost, highest production and most profitable path through the silvicultural value chain in Zululand South.

Chapter 5
DISCUSSION

The study was performed on real historical operational data. Stands included in the analyses were spread over a wide geographical area, which means they were exposed to different climatic and growing conditions. The case study research approach limits the researcher to having little to no control over the data used in the analyses. It is however also beneficial as it allows for an analysis of the situation without introducing experimenter bias (McCutcheon and Meredith 1993).

Due to the wide geographical range of the study, stands were divided into the Zululand North and South regions in an attempt to minimise the effect of climate and site factors. These factors, along with other external factors, did however have an influence on the results outcome of the study.

Nonetheless, it can be confirmed that the growing conditions for short rotation *Eucalyptus* stands are better in Zululand South than in Zululand North and that trees had better performance in these areas. These results are similar to those stated by Wise and Kassier (2016). It was also noted that some phases in the silvicultural value chain were performed differently between the two regions, meaning site specific silviculture to some extent.

The results from the anylses that showed the effect of the silvicultutre activities on the rotational performance, early height growth and the early survival of stands are discussed individually in subsections below. These results are then compared to results from scientific research trials.

5.1 SEASON

The season in which stands are planted is very important because the temperature, evapotranspiration and rainfall are different between seasons, which can affect the growth rate, survival and even silviculture activities of the stand (Veiro and Button 2007). The Zululand district is in the sub-tropical silviculture zone, which is characterised by very warm summer months. From the data received, no stands were planted in the summer months, which correlates with Viero and Button (2007) who suggested that excessive heat can lead to increased mortality in mid-summer (Viero *et al.* 2000; Schulze 1997). Viero and Button (2007) also created the following risk profile based on seasonal changes to estimate the potential success of survival in Zululand: summer = high risk, winter = low risk and spring = medium risk.

The effect of planting season on rotational gowth indicated that stands that were planted in autumn in both regions performed significantly ($p<0.05$) better in terms of TCS MAI when compared to stands planted in spring or winter. However, it must be noted that harvesting takes place all year round. Thus there is a cost associated by leaving areas Temporary unplanted (TUP) until autumn. Results from the analysis in Section 4.2.3 show that planting season did not have a significant effect ($p>0.05$) on the early height growth of stands. It did however have a significant effect ($p<0.05$) on the survival of newly planted stands in both Zululand North and South. In Zululand North stands planted in autumn and winter showed better survival than stands planted in spring. In Zululand South, stands planted in winter had better survival than stands planted in autumn or spring. However it is not nessearily the season in which it was planted that effected the survival, but it could be the site on which it was planted. Stands planted in spring in Zululand North also illustrated an increase in probability of planting with water, which means it also increased the probability of incurring extra cost. This can be an indication that planting conditions were not optimum in spring (Viero and Little 2006).

Most of the literature regarding the seasons to which seedlings are planted focused on tree survival in order to create acceptable planting windows for the area.The planting seasons to which stands were planted in both Zululnad North and South are in line with studies by Little *et al.* (1996), Viero *et al.* (2000) and Schulze (1997) which show that the sup-tropical region of coastal Zululand experiences all-year-round rainfall and is characterised by very high temperatures in summer, this means that most of *Eucalyptus* planting operations takes place in the cooler winter months; when the evapotranspiration is lower.

5.2 PRE-PLANT SPRAY

Stands on which pre-plant spray were performed did not show a significant effect ($p>0.05$) on rotational growth or early height growth in Zululand North or Zululand South. Little and van Staden (2003) states that long and short term growth of trees are negatively affected when the area planted is not weed free. Results from a study by Little *et al.* (1997) indicated that even when planting into a weed-free compartment, initial competition can occur as soon as one month after planting, and if planted into a compartment that is not weeded, tree suppression will occur much sooner. According to Little (2002), pre-plant spray is opperationally the most cost effective way to control weed growth during the establishment phase. Weed control after planting is less cost effective as young trees must be shielded or special care has to be taken not to damage the young trees when non-selective herbicides are used.

Results from the logistic regression and the contingency tables show that stands where pre-plant spray were performed showed significantly ($p<0.01$) lower survival than stands where pre-plant spray was absent, in both Zululand North and South. These results sit in opposition to the intended goal of the activity, which is to remove competing vegetation in order to decrease growth suppression and mortality (Little *et al.* 2003a). However, it is likely that foresters only applied pre-plant spray in situations where it was deemed necessary, e.g. stands with high initial weed growth, and stands with no weed growth were not sprayed. Therefore one reason for the poorer survival where pre-plant were present could likely be competition of weed infestation (which was kept at bay, but only to a limited degree), by the spraying. The negative effect on the early survival on stands where pre-plant spray were present compared to absent could not be quantified, because stands were never tested under the same conditions. In order to help/improve future operational value chain studies, it is recommended that an estimate of weed density or weed infestation be recorded when the spraying activity takes place. This can help to test the effect of the activity on stands with similar weed infestation.

5.3 STAND DENSITY

Only the operational gain data (Data set 2) had planting density information available. Therefore, only the short term effect of planting density on early height growth of stands could be analysed. The results show that stand density significantly ($p<0.01$) impacts the early height growth on stands in Zululand North, with the height growth of stands increasing with increasing density. Increased early competition (increased density) could result in taller, but more slender trees at a young age.

However, only two stand densities were present in this data set, which means this result only indicates that stands with higher stand density showed improved early height growth in Zululand North when compared to stands with lower stand density. The analysis only compared the two stand densities, no conclusions can be made for stand densities higher or lower than the ones present in the data set.

The stand density was also calculated at measurement and was included in the operational gain data. It was included in the model as an explanatory variable in Section 3.6.3.1. The stand density measured significantly ($p<0.01$) effected the early height growth of stands in both Zululand North and South. Coeficients of TPH1 in Zululand North were positive, meaning that stands with increasing density showed better height growth. In Zululand South coeficients were negative, meaning stands with lower density showed better height growth.

A study by Crous *et al.* (2013), shows that mean height at rotation end decreases with increasing planting density, similar to studies by other authors (Coetzee *et al.* 1996; Bernardo *et al.* 1998).Schönau and Coetzee (1989) stated that mean height increase, but dominant height does not increase, with decreasing stand density - this was also found in a spacing trial in Brazil (Bernardo *et al.* 1998). Crous *et al.* (2013) suggested that the loss in tree height with the increase in planting density is as a result of extreme competition for resources.

The effect stand density had on mortality or survival of stands could not be measured because Data set 1 did not have stand density information available. Althought a study by Van Laar and Bredenkamp (1979) indicated that *E.grandis* had an increase in mortality for higher stand density on high-quality sites, but no increase in mortality was found for same species on low-quality site for stocking between 1200—1700 trees ha^{-1} (Schönau1974).

5.4 PLANTING

A typical planting operation on short rotation *Eucalyptus* plantations includes pit preparation, planting without water, or planting with an application of either water or hydrogel, all of which can have an impact on the growth and survival at re-establishment (Viero *et al.* 2000; Viero 2008). There are different applications, methods and concentrations in which it can be applied. This is dependent on a number of factors, including geographical location, soil type (water holding capacity), site quality, climate, season in which it is planted, company policy and individual preference. Viero *et al.* (2008) suggest that some organizations only plant with water or hydrogel when planting conditions are suboptimal.

In the data received there were only two planting operations: planting without water (planting dry) and planting with water (planting wet. In Zululand South the majority of stands were planted dry with insufficient stands planted with water to have accurate results, consequently plant status was not included in the robust regression model for the analysis in Section 3.6.2. It was however included in the model that tested the effect silvicultural activities had on the early height growth of stands, but it did not show a significant effect ($p>0.05$). In Zululand North more stands were planted with water than in Zululand South, but within Zululand North more stands were planted without water than with water. There was however more than enough stands planted with water to include plant status in all the analyses. Planting with water significantly ($p<0.05$) effected the rotational performance of stands. Coeficients were positive, meaning stands that were planted with water, had higher TCS MAI when compared to stands planted without water. Planting with water also significantly effected ($p<0.01$) the early height growth of stands in Zululand North. Coeficients were positive, meaning stands planted with water showed better early height growth, compared to stands planted without water.

The Zululand district is in the sub-tropical silviculture zone, with very high temperatures in mid-summer. Zululand receives predominantly summer rainfall, but is characterized by some rainfall throughout the year. In Section 2.2 it can be seen that on average Zululand South receives more rain than Zululand North. In Zululand South only a few stands were planted with water, it is probably the case that only stands that experienced severe stress or suboptimal conditions were planted with water. In Zululand North more stands were planted with water. According to Rolando and Little (2008), the availability of adequate water plays a role in the success of a eucalypt planting operation and reduces the initial water stress for planting stock. An application of water and hydrogel illustrated some increase in initial tree growth for all three trials in Zululand, with larger increases on the trial which were planted outside of the commercially accepted planting season for Zululand (Viero and Button 2007).

Results from the logistical regression of Zululand North and South show the coeficients of planting with water were positive, which means stands planted with water, showed an increased chance of blanking taking place when compared to stands planted without water. These results are similar to Viero and Little (2006) who illustrated planting with water resulted in poorer survival on two of three trials. Similar results were found by Viero and Button (2007) who suggest that hydrogel and water planting had a significant effect on early survival when planted in summer months which is the high risk months. But trials planted in low-risk (winter) and medium-risk (autumn and spring) seasons, illustrated that dry planting treatments performed well when compared to the water and hydrogel treatments at planting, and no significant improvements were observed for these treatments, however it must be stated that the trial in which these results were observed did receive substantial rainfall two days after application (Viero and Button 2007).

Despite similar results observed in research experiments, one can speculate that this result might not necessarily relate planting with water to poorer survival but planting with water could be a result of planting under suboptimal conditions, and the water applied at planting was not effective to the point where blanking was not needed, relative to other sites. In order to obtain usable observations from operational value chain analyses, it is recomended that foresters record the site conditions and the actual date (and not only plant month) when planting operation took place. This will allow anlaysis of observations under conditions that are similar and to determine rainfall and temperature shortly before and after planting.

5.5 FERTILISER

Unfortunately, with case study research the researcher has little to no control over the application, quantities, concentrations or methods in which the different variables in the analysis are performed. In Zululand North, only 10 out of 140 stands in the actual harvesting data, and 12 out of 176 stands in the operational gain data were not fertilised. Fertiliser was included in both robust regression models for the two analyses, but it did not show a significant effect ($p>0.05$) on the final tonnes harvested at end of rotation, or the short term height growth. It was decided to retain fertiliser in the model because it did not have an impact or change the effect of other variables on the response variable. The small number of stands not fertilised do limit the study in such a way that no conclusions or recommendations can be made for fertilizer applications in Zululand North. It must also be said that the concentrations, type, quantity and method of the fertiliser application on the stands were not available. Smith *et al.* (2010) states that in order to achieve the best possible benefits, the timing, application rate and method of application must be optimised.

In Zululand South there were more stands not fertilised than in Zululand North, but the majority of stands were fertilised. Only 34 out of 170 stands in the actual harvesting data, and 30 out 181 stands in the operational gain data, were not fertilised. It was decided that there were enough stands that were not fertilised to include it in the analyses. The results from the robust regression model in Section 3.6.2 show that fertiliser did not have a significant ($p>0.05$) effect on the TCS MAI in Zululand South. However, although not significant the coefficient were negative, meaning that stands that were not fertilised performed better on average than stands that were fertilised. This was an unexpected result, which may have been caused by not enough stands left unfertilised or data not captured accurately (e.g. stands fertilised but not recored in the operational data system). A couple of the stands that were not fertilised performed extremely well and had a TCS MAI that was considerably higher than the mean of the region, and with the sample size so small it could have had a large effect causing biased results.

According to Germishuizen and Smith (2007), there were a number of trials that did not show a response to fertilizer applications, where the trials were abandoned and the non-response not recorded in literature. However Schönau and Herbert (1989) and du Toit *et al.* (2001) found positive responses to fertiliser at establishment in terms of volume and wood density. du Toit and Oscroft (2003) did a fertiliser study on five sites in Zululand and stated that volume responses to fertiliser treatments over that of the control were the greatest in the trials on the most infertile sites, and weakest on the trials with most fertile site.

All stands in the analysis were burned as land clearing activity and the majority of stands were fertilised. One reason for the lack of response to fertiliser in Zululand South might be that slash burning increases the availability and uptake of nutrients and thus, may also decrease the need for fertilizer (du Toit and Dovey 2005; du Toit 2008; Smith *et al.* 2010).

No conclusions can be made on the impact fertiliser application has on Zululand North and South. At an operational level it is very important to record the type, concentration and timing of fertiliser into the management system. This could enable future studies to analyse the impact different applications have on the performance of a stand, rather than a mere comparison of fertilised vs. not fertilised.

5.6 BLANKING

Blanking is an activity where the newly planted trees that died are replanted 4—6 weeks after planting (Viero and Button 2007) and is normally performed when the survival of a stand is below 90%. Blanking was used in this study as an explanatory variable in the robust regression models mentioned in Section 3.6.3 and 3.6.4 respectively. It was also used as the response variable in the logistic regression models and contingency tables mentioned in Section 3.6.5. It was used as the response variable in an attempt to determine if the activities prior to blanking had an effect on whether or not blanking took place. This ultimately attempted to test whether the activities had an effect on the early survival of stands in both Zululand North and South. The effect of the different activities on blanking are discussed with that particular activity.

In Zululand North, blanking did not have a significant effect ($p>0.05$) on the TCS MAI at harvesting or on the early height growth of stands, although not significant, stands that were blanked had better TCS MAI at harvesing than stands not blanked. In Zululand South, blanking significantly effected ($p<0.05$) the TCS MAI at harvesting. Coeficients were positive, meaning stands that were blanked, showed higher TCS MAI compared to the stands not blanked. However, it is not possible to deduct from the availbale data if blanking was responsible for the increase in TCS MAI, because stands were never tested under the same conditions. High stand densities in general produce higher volume growth per area, but this volume will consist of smaller individual trees, and wider spacing leads to lower total volume per area but higher volume per tree (Schönau and Coetzee 1989; Gonçalves *et al.* 2004; Smith *et al.* 2010).

5.7 VEGETATION MANAGEMENT

In this study, the number of times weeding took place on a stand was used without the type of weeding or timing of weeding being considered. The number of weedings was used as the explanatory variable in both robust regression models in Sections 3.6.3 and 3.6.4 respectively. In the data weeding operations took place from planting up until canopy closure had been reached. According to Gonçalves *et al.* (2008), young trees are more susceptible to competition from weeds. After planting, the competition for water and resources by weeds can be intense. However, once the trees are established they can take up water from deeper soil layers than most of the other weeds (Crous *et al.* 2017).

In Zululand North and South the number of weedings that took place on a stand did not have a significant effect ($p>0.05$) on the TCS MAI. It did however, although not significant, reveal that stands with high number of weedings showed lower TCS MAI than stands with lowering number of weedings. Little *et al.* (1993) and Little *et al.* (2003, 2007) presented contradictory results with superior growth and performance on weed free stands when compared to weedy controls.

These were unexpected results – it was assumed that the weeding activities would remove competing vegetation, which would then reduce the competition for growth resources and in all likelywood increase growth and performance of stands. However, Titshall (2016) mentioned that drift from non-selective herbicides can negatively affect tree growth. If it is assumed that the number of weedings are directely related to the presence and abundance of competing vegetation, one reason for the results may be that the competing vegetation affected the growth of the stand before the weeding activities took place, or the method of removing the vegetation was not effective. Due to a a lack of site descriptions this remain speculation and cannot be confirmed by the operational data. Little and van Staden (2003) suggested the degree of competition could be directly related to the type of vegetation and its distance from the planted trees. Initially, tree growth are most affected by treatments where vegetation is in the immediate vicinity of the planted tree (no ring weeding, weedy control or inter-row weeding). With time it changes, and tree performance is better in treatments where the percentage area kept free of vegetation is higher. Timing and planning of weeding operations is one of the greatest challenges in successful vegetation management, due to the diversity of sites utilised in terms of abundance and growth of weeds, weed species composition, local climate and different site preparations methods (Jarvel and Pallett 2002; Small and McCarthy 2002; Taverna *et al.* 2005).

In the operational gain data, only the number of weedings that took place between planting and the measurement date were extracted and used in the analyses. In Zululand South, number of weedings did not have a significant effect ($p>0.05$) on the early height growth of stands. Despite not being significant, the coeficients were positive, meaning that stands with a more intense weeding regime indicated better early height growth. However, it is not possible to deduct if it were the weedings that increased the early height growth. These results are similar to studies by Little *et al.* (2003) and Wagner *et al.* (2006) which suggest that competing vegetation can result in sub-optimal tree growth. Little *et al.* (2007) states the abundance of weeds generally increases with decreasing altitude, which results in earlier growth suppression from intra-specific competition at lower altitude sites.

The type of weeding operation, timing and the the total area weeded could not be taken into consideration due to a lack of accurate detai in the operational data. The weedings analysed could have been partial weeding, manual or chemical weeding, etc. To improve the value of the data more detail about the type of weeding operation should be included (manual – hoe, slash, handpull, etc,), and in the case of a chemical weeding operation the active ingredient, application rate and equipment used (manual knapsack or tractor sprayboom) must be recorded. The actual date of the weeding operation should also be recorded into the manament system.

5.8 LIMITATIONS OF THE VALUE CHAIN ANALYSES ON OPERATIONAL DATA

The analysis of operational data at times confirmed the results of scientific research trials, but at times also contradict scientific findings. The following effects of silviculture activities were contradictory to what was found in literature: the effect of pre-plant spray and planting with water on early survival, the effect of fertiliser on final volume growth in Zululand South and the effect of number of weedings on early height growth in Zululand South. Findings that were supported by research include: The effect of planting with water on early height growth in Zululand North, effect of planting season in both regions and the effect of blanking on final tonnes in Zululand South.

The main reason for the deviation from literature was the lack of information about site conditions during times of silvicultural treatments and in some cases a lack of information about the intensity or type of treatment. This makes it impossible to compare site with similar conditions or treatments at similar levels. Therefore attempting to for instance determine the effect the silvicultural activities had on early survival, early height growth and rotational volume growth of stand will most probably lead to biased and inaccurate results because the activities were never tested under the same conditions**.** This was evident in the number of unexpected results found in the analyses. The study showed that operational data in the format available were insuffiecient to be used to evaluate the impact/effectiveness of silvicultural operations. Meredith (1998) and Benbasat *et al.* (1987) warn that although operational data can be analysed the results might not be useful and provide little evidence for scientific generalisation (Zainal 2007).

5.9 OPERATIONAL DATA REQUIREMENTS TO IMPROVE RESULTS

In Section 5.8 above the shortcommings with the analysis performed in this study were outlined. In this section the gaps in data which made the analyses difficult will be discussed along with suggestions, which can potentially improve the accuracy and reliability of similar future operational value chain studies.

A record of all silvicultural activities performed on a stand were available, however some critical detail regarding these activities were not recorded. The date of a specific activity was available, but with some investigation it was evident that these dates were not accurate to when the actual activity was performed but rather the mid date of the month in which activity is performed was captured in the management system. It is recommended to accurately record the date the actual activity took place, if these dates are accurate, future studies could focus more on the timing of activities along with the interaction with site conditions at that stage (Rainfall figures and climate data for the region prior to and post planting can be obtained, to compare planting application, etc.).

Other shortcommings in data available, are that the type of application nor the concentration to which the activities were performed were recorded. It is suggested that these are recorded along with the activity. If this information is available the effect of different concentrations or applications can be analysed in the future instead of the activity being present or absent.

One of the biggest gaps limiting the use of the operational data, is that there was no site data available when activities were performed. It is recommended that along with each activity recorded, a set of site description/evaluation data must be recorded, which describes the site at that point in time, this will enable future researchers to compare the presence, absence, application or concentrations of different activities on sites with similar conditions (e.g. compare weeding intensity on sites with same weed infestation, planting with water on sites with similar soil moisture content, etc.).

These suggestions and recommendations can go a long way in ensuring better results from operational value chain studies, which can be used in the future to better determine the effect silvicultural activities on the performance of stands.

In the company's internal silviculture guidelines book (Sappi 2011), all the silvicultural activities along with when they should be apllied, what application and the concentration to which it should be applied are clearly prescribed. Meaning that if decsions are made based on these guidelines, the above mention information should be available. Therefore it can be concluded that the lack of information are as result of poor data recording at operational level (Sappi 2011).

5.10 SOLVER SIMULATION

The main aim of the solver simulation is to illustrate the potential it can have at operational level for site specific silviculture decision making. In order to illustrate the benefits of the simulation model the results from the robust regression analysis in Section 3.6.2 and cost-benefit analysis in Section 3.6.2.3 were used. The Microsoft Excel Solver simulation models were created for Zululand North and Zululand South respectively, these simulation models included all the activities in the silvicultural value chain. The results from these simulation models are not intended to make recommendations to change current operational regimes, but rather an illustration of the potential benefits it can have at operational level in the future.

The simulation models created can simulate the following three paths through the silvicultural value chain for both regions: lowest cost, highest production and most profitable path. This enables the decision maker to align the management of stands with their organization's objectives. The results from the simulation models show the highest production path in terms of tonnes ha^{-1} is also the most profitable path through the silvicultural value chain in both regions. This finding highlights the importance of aiming for, and achieving, maximum volume production per unit area in short rotation pulpwood plantations. It is also clear that the two most profitable paths differ between the two regions. These results suggest site specific silviculture is very important between the two regions. The site (climatic and soil conditions) have a sizeable influence on the type and effectiveness of silvicultural activities (Schönau and Coetzee 1989; Smith *et al.* 2000, 2010; du Plessis and Zwolinski 2003; du Toit and Oscroft 2003; Little and van Staden, 2003; Crous *et al.* 2013). The climatic conditions differ and there might be different external factors which have an effect on the optimum silviculture activity on the two regions (Wise and Kassier 2016).

The results indicate that site specific silviculture has a substantial effect on the cost and the potential cost-benefit of stands. The most profitable path in Zululand South delivered a potential cost-benefit of R159.39 ha^{-1}. The most profitable path in Zululand North delivered a potential cost-benefit of R4761.62 ha^{-1}. The cost-benefit value is not the total profit of stands, but rather the potential improvement in profit when the most profitable path is followed. These results are presented purely for illustration purposes and not to make any recommendations. The results does however emphasise the important impact site specific silviculture can have on the financial feasibility and profitability of stands in different geographical areas of coastal Zululand (Rolando and Little 2008).

The potential of the simulation model illustrated above can be useful in the forestry industry if the simulation models is built based on the results of replicated silviculture trials, where the different applications and concentrations of activities can be compared against a control under similar growing conditions. Under the mentioned conditions it will be possible to determine cause and effect of the silvicultural activities and therefore perform a more accurate cost-benefit analysis and ultimately a simulation model. Schmidtke *et al.* (2014) suggested that there are a number of benefits with the method of value chain analysis with simulation. These include: financial benefits or implications can be forecasted before implementation, knowledge on the potential productivity before implementation and results from simulation can be used to gain management acceptance as it provides hard figures and the company's objectives can be aligned with the proposed future state (Schmidtke *et al.* 2014).

Chapter 6

CONCLUSION AND RECOMMENDATIONS

The main focus of the study was to identify whether historircal operational data can be used to determine the effects of silvicultural activities on productivity and financial feasibility of *Eucalyptus* plantations in coastal Zululand. The first objective was to identify if the operational data can be used in the analyses to effectively determine the effect of silvicultural activities on early survival, early height growth and rotational productivity. To achieve this, the data collected was segmented into regions Zululand North and Zululand South, in an attempt to minimise the impact of site, climate and external factors on the productivity of stands. In order to analyse the effect of the silvicultuter activites, two robust regression models were created: one for the operational gain data, and one for the actual harvesting data for both Zululand North and South respectively.

The findings illustrated that climate, site conditions, operational intensities and/or application rates of agrochemical products (and even potentially unknown external factors) may have an overwhelming influence on the outcome of the study. Therefore attempting to determine the effect of silvicultural activities on early survival, early height growth and rotational volume growth of stands, will most probably lead to biased and inaccurate results because the activities were never tested under the the same conditions**.** This was evident in the number of unexpected results found in the analyses that contradicted replicated field experiments that included untreated controls. There is thus not enough evidence from the case study research results to make any suggestions or recommendations for silvicultural management decision making. It is thus concluded that operational data cannot be used to determine the effect of silvicultural activities when tested in the way it was performed in this thesis. However, operational data could most likely be used more effectivily if foresters documented the site conditions under which they made the decisions or document their reasons for decisions, in order to analyse silvicultural activities individually under the same conditions.

The third objective for the study is to identify any potential improvements in the silvicultural value chain for both Zululand North and South. We already discussed above that the results of this analyses cannot be used to determine cause and effect of silvicultural activities with the analyses performed. The analyses did however identify some key observations and benefits of the silvicultural activities, which provides useful information on the current silvicultural value chain, interactions between site and silvicultural activities, waste and potential improvements within the silvicultural value chain. It also confirmed that growing conditions for short rotation

Eucalyptus stands are better in Zululand South than in Zululand North and that trees illustrated better performance in this area.

The final objective of the study was to develop a simulation model in Microsoft Excel Solver to help forest operations with site specific silviculture decision making, based on their organization's objectives. In order to do this, the results from the robust regression analyses in Section 3.6.2 were used. These coefficients (Table 4.15) were used to perform cost-benefit analyses in order to determine if the benefit created in terms of monetary value outweighs the initial cost of the silviculture activity. These results were then used in the simulation model. The simulation model aimed to simulate the lowest cost, highest production and most profitable path through the silvicultural value chain for both regions. Results from the simulation illustrated that the highest production and most profitable path is the same path through the silvicultural value chain in Zululand North and in Zululand South. These paths did however differ between the two regions. The most profitable path through the silvicultural value chain in Zululand North illustrated a potential cost-benefit of R4716.62 ha^{-1}. The path included: no pre-plant spray, planting in autumn, planting wet, fertiliser application, blanking operation and Low weeding intensity. The most profitable path through the silvicultural value chain in Zululand South illustrated a potential cost-benefit of R159.314 ha^{-1}. The path included: no pre-plant spray, planting in autumn, planting dry, no fertiliser, a blanking operation and low weeding intensity.

The conclusion mentioned above which states that the analyses performed in this thesis can not not acurately determine cause and effect of silvicultural acitivites, meant the simulation model build in this thesis is only for illustration purposes, showing the potential benefits it can have at operational level. However, with some adjustments in the capturing of site information when activities are performed, can lead to more accurate analysis determininng cause and effect, which may, in turn, lead to better, more site specific simulation results.

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