THE EFFECT OF FERTILISING *PINUS RADIATA* STANDS AT MID ROTATION AGE IN THE WESTERN CAPE PROVINCE ON LEAF AREA, GROWTH EFFICIENCY AND STAND PRODUCTIVITY

by
Johannes Jurie Badenhorst

Thesis presented in partial fulfilment of the requirements for the degree Master of Science in Forestry at the University of Stellenbosch

Supervisor: Dr. Ben du Toit
Faculty of AgriSciences

March 2010

DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Signature   Date

ABSTRACT

Mid rotation fertiliser application is generally practised in forestry to enhance nutrient availability in areas were soils are impoverished and do not provide sufficient nutrients for high productivity. Generally speaking there is great potential for mid rotation fertiliser in pine plantations, but stand and site characteristics such as water availability, soil depth, stand density and available nutrients need to be considered before fertiliser treatments are implemented. Foliar nutrient analyses were used to estimate nutrient availability. These levels were measured throughout the study and were used to implement specific fertiliser treatments that would boost nutrient availability. Treatments consisted of an unfertilised control, a single fertiliser application (1F) and two fertiliser applications over two consecutive years (2F). Leaf area index (LAI) and stem volume increment were measured in order to evaluate its influence on growth efficiency. LAI was estimated using the gap fraction method with the use of a ceptometer. Volume increment was calculated with diameter and height measurements. Basal area was calculated by means of diameter measurements. These growth responses were used to determine the effect of increased nutrient availability and although increases were found in LAI, volume increment, basal area increment and growth efficiency, none were significant. The lack of significance may be due to relatively large variations in other factors such as stand density and initial volume of the experimental plots. The 18 month monitoring period apparently did not allow complete reaction time to increased nutrient availability and limited our understanding of the responses somewhat. Despite this, the magnitude of some growth responses was large as nutrient ratios in the foliage increased to levels within the norms range. Increases in current annual volume increment (CAI) of 3.48 m^3 ha^{-1} a^{-1} and 3.62 m^3 ha^{-1} a^{-1} in 1F plots at Grabouw and La Motte plantations indicated that it may be economically feasible to fertilise at mid rotation age as the NPV and IRR increased over a projected 25 year rotation. The Grabouw site had the most significant response with regards to CAI in 2F treatment with a mean volume increment of 5.43 m^3 ha^{-1} a^{-1}. The mechanism of the response was examined further by taking water availability and soil characteristics into account. The seasonal

climatic effect (length of the moisture growing season) had a significant influence on the response to fertilisation.

OPSOMMING (AFRIKAANS)

Die toediening van mid-rotasie bemesting word algemeen in bosbou toegepas om voedingstofbeskikbaarheid te verhoog in areas waar voedingstowwe onvoldoende is vir hoë produktiwiteit. Daar is oor die algemeen ruim potensiaal vir mid-rotasie bemesting in denne plantasies, maar eienskappe soos waterbeskikbaarheid, gronddiepte, opstanddigtheid en beskikbaarheid van voedingstowwe moet in ag geneem word voor optimum bemestingtoedienings bepaal kan word. Blaaranalise is gebruik om voedingstofbeskikbaarheid in plantasies te skat. Hierdie voedingstofvlakke is deurgans gemeet en is gebruik om spesifieke bemestingsbehandelings te implementeer wat voedingstofbeskikbaarheid kon opstoot. Behandelings het bestaan uit ‘n onbemeste kontrole, ‘n eenmalige kunsmistoediening (1F) en twee kunsmistoedienings in opeenvolgende jare (2F). Blaar oppervlak indeks en toename in stamvolume is gemeet om die invloed daarvan op die effektiwiteit van groei te bepaal. Blaaroppervlakindeks is bepaal deur middel van die gapingfraksie metode met behulp van ‘n stralingsmeter. Toename in volume is bereken met stamdeursnee en hoogte meetings. Basale oppervlakte is bereken deur middel van deursnee metings. Hierdie groeireaksies is gebruik om die effek van verbeterde voedingstofbeskikbaarheid te bepaal. Al die groeireaksies het toegeneem maar was nie statisties beduidend nie. Die gebrek aan beduidende toename kan toegeskryf word aan variasies in opstandsdigtheid en oorspronklike volume van die bome in die navorsingspersele. Die toetstydperk van 18 maande het moontlik nie genoeg tyd gegee vir die bome om op die toename in voedingstofbeskikbaarheid te reageer nie. ‘n Goeie groeirespons is wel waargeneem waar die voedingstofverhoudings in die naalde aanvaarbare norme bereik het. Die toename in volume aanwas van tussen 3.48m^3 ha^{-1} a^{-1} en 3.62 m^3 ha^{-1} a^{-1} in 1F persele by Grabouw en La Motte plantasies het aangedui dat dit ekonomies lewensvatbaar is om op mid-rotasie ouderdom bemesting toe te dien aangesien die netto teenswoordige waarde en die interne opbrengs koers toegeneem het op ‘n geprojekteerde 25 jaar rotasie. Die persele op Grabouw plantasie het die mees beduidende respons getoon met betrekking tot huidige jaarlikse aanwas (5.43 m^3 ha^{-1} a^{-1} in die 2F perseel). Die meganisme van die respons is verder nagevors met inagneming van

waterbeskikbaarheid en grondeienskappe. Die seisoenale klimaatseffek (lengte van die vog-groeiseisoen) het ‘n beduidende impak op die respons tot bemesting.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to the following people who made this thesis possible:

- MTO Forestry (PTY) Ltd for making their plantations and resources available. Furthermore also for funding the research project and allowing me to do further studies on a part time basis.

- Dr Ben du Toit who supervised this study, and for all the time and effort that he put in and for his family for the patience that they had with me.

- Lecturers at the Forestry and Wood Science department at Stellenbosch for assisting in any proof reading and guidance towards this study.

- Professor Daan Nel for his assistance with the statistical analyses of the data.

- All managers at MTO Forestry for assistance on any info required, and patience in allowing me to collect data, and spend time away from work during the time of the study.

- My family and friends for their prayers and support during the time of this study.

- My loving wife Danelle for her patience, prayers, support and strength that she has provided me during the study. Without you it would not have been possible.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABREVIATIONS

ANOVA	Analysis of variance
a	Annum
B	Boron
˚C	Degrees Celsius
C	Control (unfertilised) plots
Ca	Calcium
CAI	Current annual volume increment
cm	centimeter
Cu	Copper
DBH	Diameter at breast height
E_r	Reference potential evaporation
1F	Fertilised plots with a single application
2F	Repeatedly fertilised plots
Fe	Iron
G	Basal area of a population of trees
GE	Growth efficiency
Ha	Hectares
Ht	Tree Height
I_G	Basal area increment
I_V	Volume Increment
IRR	Internal rate of return
K	Potassium
LAI	Leaf area index
MAI	Mean annual volume increment
Mg	Magnesium
mg	Milligram
MGS	Moisture Growing Season
Mn	Manganese
MP	Monthly Precipitation

m	Meter
mm	Millimeter
N	Nitrogen
NPP	Net primary production
NPV	Net present value
P	Phosphorus
S/ha	Stems per hectare
Yr	Year

CHAPTER I GENERAL INTRODUCTION

Sustainability is a key objective in the forestry industry, and the ability of the industry to reach this objective financially and environmentally is vital for its longevity. Research globally and in South Africa in understanding plantation dynamics and its interaction with fluctuating climatic conditions has strengthened managers with knowledge and information to manage plantations sustainably.

In the Western Cape, forestry's sustainability or its shear existence is threatened by a lack of productivity which is mainly due to impoverished soils and climatic conditions (Donald, 1987). Large areas in the Western Cape were identified by the state to be phased out because of the poor economic performance of the business in 1998 (du Preez, personnel correspondence, 20 Nov 2009). The decision was taken to convert the unprofitable forestry areas to so called appropriate land uses which include agriculture, tourism and conservation. Most of these areas are situated on steep slopes that do not only provide challenges towards growth potential but also towards accessibility. It is a fact that fertility is a major problem in this area but by improving stand nutrition and productivity through fertilisation the viability of the forestry industry can be re-evaluated, instead of managing it to finality.

The study focuses on long rotation *P. radiata* stands which is managed to supply the saw timber market. MAI's average 10 m^3 ha^{-1} a^{-1}, and rotation ages range between 25-40 years according to site productivity. The majority of the annual precipitation occurs between May and August during which time temperatures do not encourage rapid growth. The growing season is very short, as summers are characterised by very hot, dry and windy conditions which can start as early as November and last until mid April. These conditions are not conducive for nutrient accretion and rapid growth. With due consideration to the growing conditions, good timing of a fertiliser application with regards to season, and silvicultural operations can allow the crop to make full use of the optimum window for growth. We set out to measure the growth responses that can be obtained under these conditions.

The outcomes of this project could thus serve as initial attack towards developing practical methods for the industry to identify areas with potential nutrient deficiencies, and the subsequent prerequisites to ensure sustainable responses after fertilisation with regards to volume growth. This study could also serve as building blocks for further research to ensure that a good understanding of mechanisms involved are known which will help to develop strategies that will enhance productivity in the future.

The main task of any Forester is to enhance growth through management activities to strive for an increasingly positive rate of return on the investment. In order to obtain satisfactory growth rates on such sites, fertilisation should be a prerequisite rather than a possible counteractive measure when the soil reserves run down. The Mediterranean climate however only allows for a short growing season and this, coupled with sandy, nutrient-poor soils, adds to the challenge of optimising management strategies in terms of fertilisation to improve productivity.

1. Study objectives

The objective of this study was to provide information that can be utilised by management to improve stand nutrition and productivity. Experimentally, it was achieved by applying fertilisers to mid rotation *Pinus radiata* plantations, and measuring growth responses that occurred as a product of the increased nutrient availability. The growth responses tested were limited to stem and leaf area index increases and supporting information was examined to propose possible explanations for responses. The economic feasibility of applying fertilisers to mid rotation stands was examined by means of net present value (NPV) and internal rate of return (IRR) calculations.

In order to establish how the *Pinus radiata* stands will react to mid rotation fertilisation in a Mediterranean climate, consideration has to be given to the timing of the availability of different resources.

2. Key concepts with respect to growth responses

To establish whether responses are evident seasonal measurements of specific growth indicators need to be done. In this study three main growth indicators were measured in order to establish whether fertilisation of mid rotation *P.radiata* could increase the needle growth in order to sustain an increased carbon allocation in the stem. These growth indicators included leaf area index (LAI), volume increment (I_V), and growth efficiency (GE). Foliar analyses were used in determining the nutrient content of the foliage in order to establish optimum fertiliser treatment.

- Leaf area index (LAI) is the projected leaf area (A_1) per unit land area, and could be defined as the radiation absorbing surface of a tree canopy.
- Growth efficiency (GE) is the stem volume growth per unit of LAI, and is thus related to the net primary production (NPP) and the partitioning of carbohydrates to stem wood.

3. Hypotheses (HP) and key questions (KQ)

HP 1 Increased nutrient availability in mid-rotation *P. radiata* stands will improve the foliar nutrient profile, and hence, increase both leaf area index and growth efficiency across a range of sites in the Boland region.

> KQ 1 How does the foliar nutrient profile of the trees in the fertilised plots change after application? Does it come closer to optimum norms?

KQ 2 Does the change in foliar nutrition improve both leaf area index and growth efficiency? Is the response mechanism dominated by any one of these response mechanisms?

HP 2 Mid-rotation fertiliser application in *P. radiata* stands can increase volume increment across a range of sites in the Boland region, thus making plantation forestry more profitable.

KQ 3 Can volume increment be improved with fertilisation across all experimental sites and what is the magnitude of this improvement?

KQ 4 Does the increase in yield justify the cost of fertiliser and its application in terms of net present value and internal rate of return?

CHAPTER II LITERATURE REVIEW

The productivity and growth efficiency of most forests is limited simultaneously by a variety of resources including light, water, and one or more nutrients (Fisher & Binkley, 2000; Turner *et al.*, 1995). The supply rates of nutrients are variable changing naturally across biomes, with changes in climate, vegetation and under management influences. These patterns and influences directly affect the ability of trees to uptake resources that determine growth efficiency and carbon allocation.

In conifers a clear decrease in mineral nutrient concentration occurs during the growing season as nutrients are re-translocated to the youngest foliage for further growth (Fife & Nambiar, 1982). This supports Miller's (1981) findings that growth prior to canopy closure depends primarily on nutrient uptake from the soil and after canopy closure nutrients continues to re-translocate within the crown and is withdrawn from the lower crown prior to leaf fall. Fluctuations do however occur seasonally, and may not necessarily be similar throughout the lifetime of coniferous species.

Forests tend to increase growth following fertiliser application, and it has been found that in many cases substantial profits are made (Donald, 1987; Fisher & Binkley, 2000). Fertiliser application has increased volume production in mid rotation pines by 3 to 10 m^3 ha^{-1} over periods of 5 to 10 years with largest increases on dominant trees (Fisher & Binkley, 2000).

It has been found that increases in stem growth following fertiliser application are ascribed to increases in leaf area and net primary production, thus leading to increases in foliar photosynthesis and shifts in allocation of photosynthates from root production to stem production (Colter Burkes *et al.,* 2003). Fertiliser application has also been found to directly influence stand characteristics by increased growth rates, dominance and self thinning of stands (Linder, 1985).

1. Characterisation of the nutritional status of stands by means of foliar analysis

Plant tissue analysis, particularly foliar analysis is a preferred method of evaluating plant nutritional status since it provides an integrated assessment of many factors that influence nutrition. Nutrient deficiencies are most widely expressed in terms of critical levels (Needham *et al.,* 1990). A critical level is defined as the nutrient concentration required in a plant tissue for optimum growth, yield, or quality, assuming that no other factor is limiting or suboptimal (Ulrich & Hills, 1967; Mead, 1984). Different methods exist to establish and evaluate critical levels or norms. One of these is the Diagnosis and Recommendation Intergrated System (DRIS) index and is used as a mechanism for defining optimum nutrient levels and balance (Beaufils, 1973). DRIS norms are developed for ratios of nutrients rather than individual nutrient concentrations. Other methods include vector analyses (Timmer & Morrow, 1984). This method graphically plots foliar concentration versus unit needle weight versus unit foliar content. In this study, foliar nutrient levels are interpreted and evaluated against critical ratios that were developed by Linder (1995). This methodology evaluates N using the critical level approach and then expresses all other nutrients as a ratio relative to N (e.g. P/N) which is then compared to a set of established norms.

2. The effect of management activities on the availability and uptake of nutrients

Carlyle (1995) studied the influence of fertilising *Pinus radiata* before a thinning operation. That study found that the soil mineral N content was increased rapidly with the application of fertiliser. Berg and associates (1987) further found the N release from the nutrient rich litter of fertilised trees to be greater and more rapid than that of the litter from unfertilised trees. These studies indicate that in a *P. radiata* stand available N could be increased with a fertiliser treatment whether it is directly following an application or by release from the nutrient rich biomass, but that this does not necessarily induce the uptake of mineral N. The N requirement of a rapidly developing canopy places a high demand on the soil as a source of N, but after canopy closure the canopy mass stabilises and net N requirement from soil reserves declines as internal cycling and N release from the litter resume dominance (Miller, 1981).

Carlyle (1995) indicated that the foliar N concentrations were significantly higher after fertilisation, but suggested that the majority of the N was stored in the upper canopy. According to that study, 51% of the N taken up following fertilisation was stored in the tree biomass. This accentuates the importance of timing of fertiliser application in relation to thinning. Fertiliser applications before thinning may increase N uptake and reduce leaching. Such a strategy may be particularly appropriate for soils that have a low capacity to retain applied N (Carlyle, 1995). This further motivates that nutrients lost from a thinning operation will be available at a later stage, while the tree retains the biomass with the greatest nutrient concentration. By avoiding fertiliser application directly after thinning as done in this study, the effect of leaching is likely to be minimal.

Turner *et al.* (1995) and Donald (1987) supports Carlyle's (1995) findings that significant productivity gains are achievable when applying fertilisers to *P. radiata* plantations after thinning. Turner *et al.* (1995) however, found that by combining NP treatments, the effects are generally more pronounced. It is evident that timing of fertiliser with regards to water availability is important, but the fact that an application of fertiliser in mid rotation trees could induce uptake is reassuring. It will thus be important to determine whether sufficient nutrients can be taken up to achieve optimum nutrient concentrations.

3. Effects of nutrition on biomass production and growth efficiency

3.1 Nutrient uptake and content in tree biomass

In older stands, re-translocation and mineralisation of litter are likely to be more important sources of nutrients for growth of new tissues than nutrients derived directly from the mineral soil pool (Turner *et al.,* 1995; Miller, 1981). Turner and Lambert (1983) found that the net annual removal of nitrogen from the soil in a 27-year-old stand of *Eucalyptus grandis* was 30 kg ha^{-1} compared to a total requirement of 100 kg ha^{-1}. This indicates that the total quantity of nutrients available for new growth includes the uptake from mineral soil, internal re-translocation and mineralisation of organic matter.

In younger stands, however, a significant portion of nutrients have to be taken up from the soil. Raison and associates (1989) estimated that a 10-year-old *Pinus radiata* stand would take up 166 kg ha^{-1} N during the first year of fertilisation. The estimation is very high considering that the annual uptake of N is 24-28 kg ha^{-1} in unfertilised temperate coniferous forests (Cole & Rapp, 1981). When fertility is high, accumulation of N by young forests stands with rapidly developing canopy components can be as high as 213 kg ha^{-1} a^{-1} by Poplar and 100 kg ha^{-1} a^{-1} by *radiata* pine (Anonymous, 1985). When irrigated with wastewater, accumulation of N has been found to increase up to 400 kg ha^{-1} a^{-1} by Poplar (Cole, 1981). When considering that direct measurements of 100 kg ha^{-1} N in the crown and 20 kg ha^{-1} N in the wood during the first year of fertilisation in *P. radiata*, (Raison *et al.*, 1989) together with litter transfer of 15 kg ha^{-1} N, totalling up to 135 kg ha^{-1}, a 166 kg ha^{-1} N uptake is not unrealistic.

According to Carlyle (1995), based on biomass relationships, 180 kg ha^{-1} N was present in the above ground biomass before fertilisation. Carlyle (1995) further found that an N uptake of 103 kg ha^{-1} occurred in the same compartment over a period of 24 months. On relatively infertile sites with low growth rates, where canopy closure is absent, responses to fertiliser are likely irrespective of stocking, while on better sites, thinning returns the canopy to an aggrading phase and may be a prerequisite for a fertiliser response (Miller, 1981; Woolons, 1985; Snowdon & Waring, 1990). This observation explains the change in the requirement of N and other nutrients after canopy closure (Carlyle, 1995). Carlyle (1995) and Raison *et al.* (1992) concluded that the high uptake was due to the existence of an established canopy, N deficiency, and the ideal conditions for N uptake and tree growth that was present during the first growing season. These findings give an indication that high levels of nitrogen application could be taken up by the trees, which further highlights the potential of substantial, even repeated fertiliser applications as tested in this study.

The time between first treatment and repeated treatment also needs to be taken into consideration, as the concentration of nutrients present in the tree also plays a role in determining additional quantities that may be taken up. Raison and associates (1992) observed that N uptake in a 10-year-old *Pinus radiata* plantation stopped between 72 and 118 days after application of 400 kg ha^{-1} N and uptake of 130 kg ha^{-1} N. This was despite a high concentration of mineral N in the soil and ideal conditions for growth and uptake. They concluded that there was an active discrimination against further N uptake because of high concentration of N in the tree.

Others (Jones *et al.,* 1991; Jensen & Petterson, 1978) supported such discrimination in well-documented and controlled studies for N and K. The aforementioned citations suggest that foliar analysis could serve as a tool to avaluate nutrient concentration in the foliage and the potential of further uptake. However, Carlyle (1995) found that even though uptake rates fell after an initial uptake of 103 kg ha^{-1} N, the fall in uptake was associated with a period of low soil moisture when conditions were not conducive to uptake. This was the only period that high soil mineral N concentrations coincided with a period of low uptake. This suggests that there is no active discrimination of the type suggested by Raison and associates (1992). Carlyle (1995) and Raison *et al.* (1992) found similar N uptake in their studies. The basal area of the former was 1.8 times more than that of the latter, which indicates that there was a much greater capacity to sequester N.

Cromer and associates (1995), investigating fertiliser applications to young stands of *E. grandis*, found that the mass of the nitrogen in the foliage of trees in plots without fertiliser application accumulated quite slowly with an increase from 23 kg ha^{-1} to 27 kg ha^{-1} in 18 months. By comparison, the plots that received fertiliser developed rapidly to 130 kg ha^{-1} in the first year and increased up to 150 kg ha^{-1} in the second year. They also found that the pattern of nitrogen accumulation in live branches was similar to that of foliage although being 75% less than that of the foliage. Cromer and associates (1993a) found that the nitrogen content of foliage and live branch components increased rapidly over the first year as individual tree canopies developed in relative isolation. They found that once these canopies started competing for light, height growth continued but foliage and branches in the lower canopy died progressively so that nitrogen mass in foliage and branches became relatively stable. By comparison, the nitrogen content of the stem bark and stem wood continued to increase steadily over time. In the unfertilised plots, the rate of nutrient supply does not only limit the rate of tree growth prior to canopy closure, but also limits the absolute amount of nitrogen accumulated by their canopies after canopy closure. This leads to restriction of foliage mass, leaf area index and consequently, growth rate (Cromer *et al*., 1993a). Trees that did not originally receive fertiliser may respond to fertiliser application after canopy closure, but physiological mechanisms involved may limit responses after canopy closure.

It is thus evident that fertiliser treatment in fast-growing plantations with aggrading canopies could induce uptake of nutrients in large quantities (> 100 kg N ha^{-1} a^{-1}) when sufficient water is available. The question is whether optimal nutrient concentrations can be utilised to increase the growth efficiency.

3.2 The effect of canopy closure and season with respect to nutrient uptake

Various studies have found that fertiliser can play a major role in the accumulation of nutrients, leading to higher concentrations in the biomass of a tree (Waring, 1981). Waring (1981) found that the dry-matter production of young *P. radiata* in southern Australia increased after fertilising with phosphorus (P) and nitrogen (N). Mead and Will (1976), as well as other studies (Nambiar & Bowen, 1986), indicated that in a Mediterranean climate N and P concentrations in the foliage of *P. radiata* are generally the highest in winter when more water is available and the lowest in summer when less water is available. Nambiar and Bowen (1986) and Theodorou (1986) found that N leaches rapidly in sandy soils. Theodorou (1986) further indicated that N uptake may increase when applied to *P. radiata* in the spring rather than in autumn when fertilising in a Mediterranean climate. In a study by McGrath and McArthur (1989) in a Mediterranean climate, above ground biomass increased throughout the year, but the rate of production varied both seasonally and among fertiliser treatments. They found that the most rapid growth occurred in spring. This conclusion derived from comparing spring-fertilised trees with autumn fertilised and unfertilised trees. The latter treatment proved to decrease in growth rate. McGrath and McArthur (1989) found that autumn fertilised and spring fertilised trees respectively, had an increase of 80% and 133% in dry-matter above that of the control plots by end-harvest. It suggests that fertilisation in a Mediterranean climate such as the Western Cape should focus on a springtime application.

3.3 Biomass production and carbohydrate allocation

In their study on the effect of fertilisation on above ground biomass on similar species and conditions, Cromer and associates (1993a) found that even after the mass of the foliage and branches reached a plateau or even declined in growth after canopy cover was reached, the mass of stem wood and stem bark steadily increased. The fertilised plots also showed a higher increase in mass of all above ground components (Cromer *et al.,* 1993a). It is evident that the nutrients are translocated from foliage and live branches to stem wood and stem bark, after canopy closure, to put all growth resources into height growth as trees begin to compete for sunlight. The canopy closure of given plantation could be accelerated by increasing leaf area development. Carlyle (1995) found that the increase in nutrient uptake influenced LAI.

Other studies also found that nutrition had a marked influence on patterns of dry matter allocation in seedlings of *E. grandis* (Cromer & Jarvis, 1990; Kirschbaum *et al.,* 1992). These studies proved that increased allocation in foliage occurred at the expense of roots at high addition rates of both nitrogen (Cromer & Jarvis, 1990) and phosphorus (Kirschbaum *et al.,* 1992). Studies on 15 to 20-year-old *Pinus sylvestris* showed there was a substantial decrease in the carbon allocated to the roots, following the application of fertiliser. This helps to explain large increases in above ground biomass following fertilisation (Linder & Rook, 1984).

The growth responses of *E. grandis* seedlings are dependent on nutrients required to increase specific leaf area, CO_2 assimilation rate and/or allocation of carbon to foliage at the expense of fine root growth. High rates of CO_2 assimilation occurred in fertilised plots, due to high nutrient concentrations in the foliage in the first year, but lessened over time as nutrient concentrations decreased (Leuning *et al*., 1991). Plantations with species that grow rapidly have the potential to deplete soil nutrient reserves, especially when intervals between harvests are short and when components such as bark, branches or foliage are removed (Wise & Pitman, 1981). Reducing this effect entails increasing rotation length, as heartwood formation withdraws nutrients and the proportion of heartwood increases over time (Crane & Raison, 1980; Florence, 1986).

Others found that compared with infertile sites, fertile sites or those that have been fertilised, produce a greater mass of wood with higher phosphorus concentrations (Ferreira *et al*., 1984; Raison *et al*., 1982), but often with lower concentrations of nitrogen (Birk & Turner, 1992). Hunt (1982) observed that the net gain in plant biomass results from the proportion of total biomass partitioned to foliage that fixes carbon (allocation), the distribution of leaf mass to intercept radiant energy and assimilatory efficiency of that foliage. Experiments have enabled researchers to examine the roles these mechanisms play in growth responses to nitrogen (Cromer & Jarvis, 1990) and phosphorus (Kirshbaum & Tompkins, 1990; Kirshbaum *et al.*, 1992).

Cannell (1985) concluded in his studies that decreased partitioning to fine roots was one of the most important mechanisms by which improved nutrition increased above ground dry matter production. In contrast, a study by Sanantonio (1989), found that no evidence exists that fine root production affects foliage production.

The annual net primary production (NPP) is directly related to annual nitrogen and phosphorus uptake in coniferous forests (Miller, 1984). The gross primary production in a plant community can be defined as the balance between carbon fixed via photosynthesis and the amount lost in respiration (Linder, 1985). Foresters try to manipulate the way in which the accumulated carbohydrates are partitioned to the different parts of the tree for growth with silvicultural activities (Shepherd, 1985).

The above-mentioned studies indicate that yield could potentially be increased with correct timing of fertiliser applications concerning age, thinning, season and stocking. There is also ample evidence to suggest that the response to improved nutrition may (at least partly) be attributed to changes in the allocation patterns of carbohydrates. With due consideration of the above, positive growth responses could be found when applying N and P, with correct amounts to ensure that optimal ratios between these two nutrients are present in the stem and leaves in both conifers and hardwood species.

3.4 Determination of LAI through direct and indirect methods

It is clear that fertiliser can induce high levels of nutrient uptake into the biomass of a tree, in this case *P. radiata,* which in turn induces canopy production (Mcgrath & McArthur, 1989; Hunt, 1982). Canopies set limits to production as in the case of several studies (Miller, 1981; Woolons, 1985; Snowdon & Waring, 1990). There is a linear relationship between biomass production and light interception (Cannell, 1989) and the configuration of the canopy will determine the amount of light which is intercepted. The growth of leaves and their longevity combine to determine the extent of the canopy. Canopy size or LAI is also positively correlated with the rate of accumulation of biomass. LAI could thus serve as an excellent growth indicator after fertiliser application over a period of 18 months where insufficient growth with regards to diameter and height is likely.

LAI could be measured or estimated directly or indirectly. Direct estimates can be made from litter fall data or from sequential harvests. In harvests the leaf area of several trees representative of the size-class distribution is measured. An allometric relationship is then applied to plots to estimate LAI. One commonly used relationship is that between leaf area and sapwood area. Indirect methods usually require calibration against a direct method. Direct methods can potentially estimate LAI with greater accuracy because they are independent of assumptions made in the application of direct methods. Indirect methods are based on the optical properties of canopies. The gap fraction method relates leaf area to the probability of light passing uninterrupted through the canopy (Lang *et al.,* 1985) by comparing the radiation environment at the base of the canopy with simultaneous measurement above (or outside) the canopy. Their ratio measures the amount of light which is transmitted through the canopy. Radiometric instruments are used to obtain the gap fraction. This can be done linearly by measurement of sun fleck area with an array of sensors (Bolstad & Gower, 1990).

Assumptions in gap fraction methods include: (i) foliage is optically black, that is any transmitted or reflected radiation measured at the base of the canopy is negligible; (ii) foliage is randomly distributed (if the foliage is clumped, leaves will tend to overlap others and these leaves will only receive partial radiation); (iii) stem branch make a negligible contribution to the measurement of the canopy. Branch interception may be small where the presence of foliage effectively masks the branch area. Stem interception below the canopy is usually negligible. An assumption specific to measurement of diffuse beam penetration is that sky brightness is azimuthally uniform.

A common finding is that indirect methods are well suited for examining seasonal changes in LAI and differences between treatments in relative terms. In absolute terms, they could systematically underestimate LAI. Underestimates of LAI occur because foliage is grouped rather than being randomly distributed leading to a greater degree of mutual shading than is assumed by the random model. Incorporation of a grouping parameter improves the estimate of LAI but it may still be less than the direct estimate (Chason *et al.*, 1991). LAI is usually poorly predicted by indirect methods in stands with high LAI, and in stands with a low LAI and large stem and branch component, indirect methods may over estimate LAI (Deblonde *et al.,* 1994). To increase the utility of indirect methods and to reduce the need for calibration against direct methods, conversion factors are derived which allow for the difference between the two estimates.

4. LAI and stand growth efficiency

Two relationships are often used to evaluate the impact of LAI on growth. One simply expresses dry mass production as a function of LAI; the other relates foliar efficiency to LAI. Foliar efficiency is incremental growth as a ratio of mean LAI during that period of growth. Both relationships are empirical and in many instances will be site specific. Foliar efficiency is a convenient parameter for interpreting results from comparative studies for evaluating changes in efficiency with canopy size and development. Foliar efficiency will also change if there is a change in allocation favouring above ground or below ground biomass (Heilmann & Xie, 1994) and is as such a good means of determining activity of the stand in relation to site resources (Beadle, 1997).

Canopy size is a key variable determining energy capture. The relationship between dry mass production and light interception gives a good indication on how LAI impacts productivity (Beadle, 1997). According to Smethurst and associates (2003), the LAI-growth relationship does not indicate any site specificity, suggesting that LAI may be a better predictor of growth on sites where the lack of confidence in the basal area growth relationship exists. They found that this difference arises because LAI is an indicator of the current status of a plantation and its potential to grow in the immediate future, whereas basal area is the cumulative record of the past status that may be less related to the potential for future growth. Further finding’s by Smethurst and associates (2003) indicated that there is a minimum LAI required to maintain the tree metabolism without stem growth.

High productivity is dependent on the maintenance of high leaf area index, to intercept large quantities of solar radiation (Cromer *et al.*, 1993a). Nutrient uptake strongly influences leaf mass and area (Cromer & Williams, 1982). Therefore, the development of highly productive tree growing area will depend on strategies that enhance nutrient availability.

While LAI determines energy capture, the efficiency with which captured energy is channeled to stem growth will lead to the production of a certain utilisable volume in a given stand. Growth efficiency (GE) is thus defined as the stem volume growth of a stand over a period of time, expressed per unit of LAI (du Toit & Dovey, 2005) and the units will thus be m^3 ha^{-1} a^{-1} LAI^{-1}. The growth efficiency will thus be a barometer of physiological changes that may take place in a stand following treatment. Several studies have shown that the stand may respond to improvements in nutrition through an increase in LAI, an increase in GE, or a simultaneous increase in both LAI and GE (Brix, 1981; Colter Burkes *et al.*, 2003; Smith & Long, 1989).

CHAPTER III MATERIAL AND METHODS

This section deals with the methods used in the selection and description of the study sites. Methods that were used in selecting the compartments and sampling sites are described. Fertiliser application, data capturing, mean value calculations and statistical analyses methods are also described.

1. Site and compartment selection

The area of study consists of plantations situated on different topographical areas, soils and annual precipitation in the Western Cape.

The four different plantations stretch from the Eastern Slopes of Table Mountain (Tokai) to Grabouw which is situated in the Elgin basin. The other two plantations are La Motte on the bottom lands of the Drakenstein valley and Kluitjieskraal which is situated on the footslopes of the Waterval Mountains in the Breë River Valley. The altitudes range between 200 – 500 m above sea level. The mean annual precipitation ranges between 837mm and 1100 mm and the average annual temperature is 18 ˚C. A description of the biophysical factors are indicated in Table 3.1 and 3.2

Table 3.1: Study site characteristics and conditions

Study Site	Compartment no	Age (yr)	Latitude	Longitude	Altitute (m)	MAT (˚C)	Actual annual rainfall (mm)	Soil depth (cm)	MAI ($m^3.ha^{-1}.a^{-1}$)
	D16	12	$18^{0}58'$	$34^{0}08'$				50-70	8
Grabouw	D17	9	$18^{0}58'$	$34^{0}08'$	436	18	1100 mm	70-100	8
	J22	12	$19^{0}08'$	$34^{0}12'$				80-100	8
	F31a	16	$19^{0}05'$	$33^{0}23'$				70-120	10
Kluitjieskraal	F31b	16	$19^{0}05'$	$33^{0}23'$	442	18	1100mm	90-150	10
	F31c	16	$19^{0}05'$	$33^{0}23'$				110-130	8
	G2a	14	$19^{0}00'$	$35^{0}50'$				110-150	8
La Motte	G4a	18	$19^{0}00'$	$35^{0}51'$	169	19	837 mm	130-180	10
	G8a	13	$19^{0}00'$	$35^{0}51'$				110-150	10

The compartments were all planted at 3.0 m x 3.0 m with a planting density of 1111 trees/ha.

The site (originally Mediterranean fynbos) had been planted to *Pinus* species from as early as the late 1800's. Figure 1 shows a schematic representation of the study area. La Motte plantation is situated between Franschoek and Paarl. The La Motte plantation is scattered into many parts, and was chosen because it is least variable in terms of topography because it is situated on a flat area. All three trail compartments have similar biophysical conditions. The Kluitjieskraal plantation is beside the town Woseley, approximately forty kilometres North West of Worcester. The trail compartments are in a section that is not situated in the Breë River Valley called Suurvlakte. The climate is relatively uniform with high mean annual precipitation. The Grabouw plantation is surrounding the town Grabouw, with two trail compartments situated on the foot slopes of Grabouw Mountain, and one in the Lebanon plantation. The reason for this was the lack in visual nutrient deficiencies in the foliage in more than one area of the Grabouw plantation.

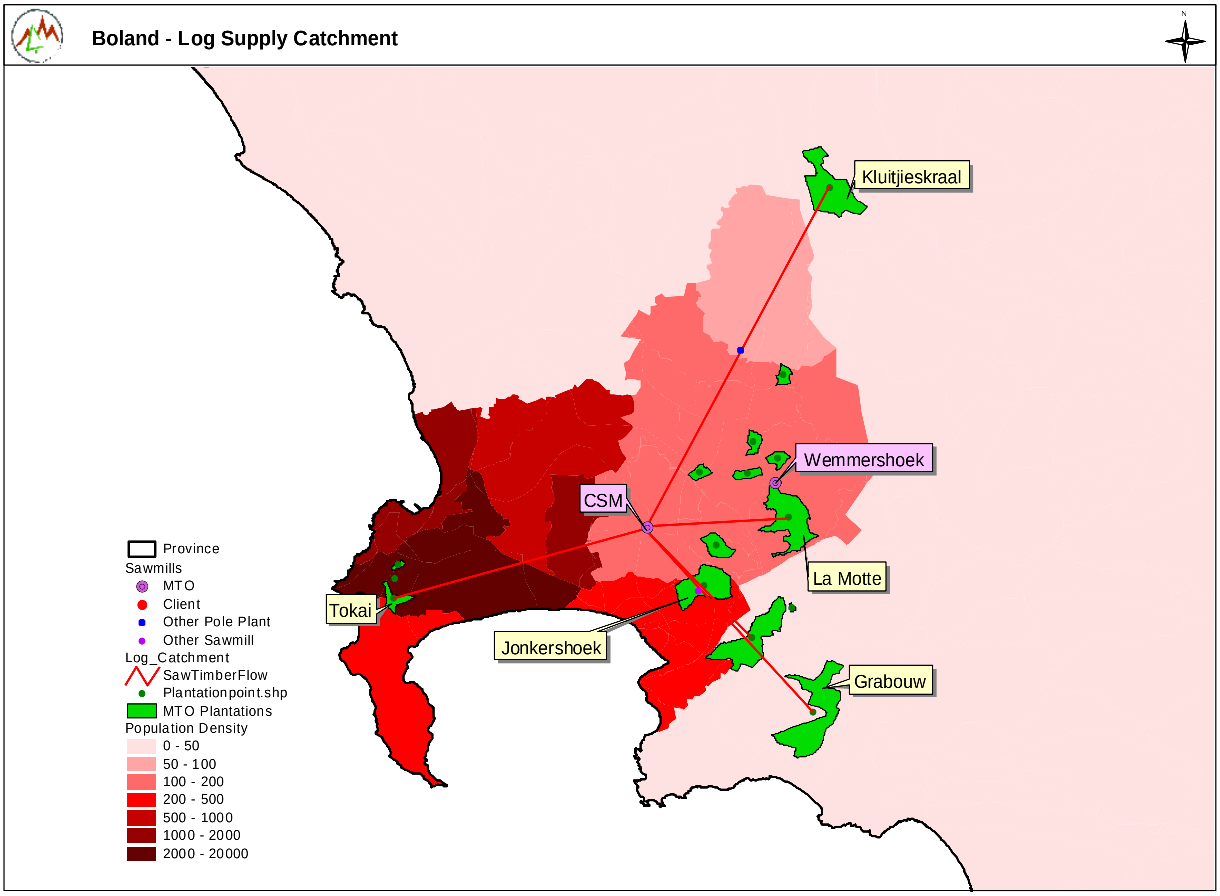

Figure 1: Schematic representation of the study area showing sawmills and pine plantations.

Symptoms of *Fusarium circinatum* developed during the two year measuring period at the Tokai site, and some of the research plots had a high mortality rate. Due to the confounding effect of the disease at Tokai, a decision was made to not include data captured from this site in the analysis.

The University of Stellenbosch was approached by MTO Forestry to evaluate compartments in the Boland plantations which could have possible nutrient deficiencies in 2006. Site visits by the Forestry department at Stellenbosch University and the help of local foresters were used to gather information with regards to visual deficiencies as well as soil data for soils that are prone to nutrient deficiencies. The main emphasis being on compartments between 12 and 18 years of age which has been reduced in stocking due to thinning operations. This evaluation yielded a list of potential sites that may respond to fertilisation at mid rotation. The current study was initiated to determine the magnitude and mechanism of the response to fertilisation in selected compartments identified by the 2006 evaluation. Soil texture, soil depth (from MTO database), mean annual precipitation including potential evaporation (Schulze, 1997) was used to characterise the relative availability of soil water as water availability can influence the effectiveness to fertilisation treatment (Brix, 1981, Sheriff, 1996, Carlyle, 1998). Table 3.2 indicates site biophysical factors, soil descriptions and conditions of the study area per plantation, per compartment.

Table 3.2: Fertiliser treatment per compartment at the three different study areas, Grabouw, Kluitjieskraal and La Motte plantations.

Compartment	Visual state of canopy and foliage	Critical Nutrient	Treatment	Kg/ha N	Kg/ha P	Kg/ha K	Soil description*	Soil depth (cm)	Stand density (s/ha)	Stand age (yr)
D16	Older foliage sparse. Tips clorotic and nerotic	P, N	DAP 38	50	50	0	Fc1	50-70	816	12
D17	Foliage medium length, discolouration present (yellow)	P, N	DAP 38	50	50	0	Fc3	70-100	816	9
J22	Canopy sparse, no old foliage present, needle tips clorotic	P, N	DAP 38	50	50	0	Cb1	80-100	816	12
F31a	Canopy fairly green, die back of older needles present.	P	MAP 33 + 0.5 % Zn	25	50	0	Ga4	70-120	389	16
F31b	Clorose present in needle tips.	P	DAP 38 + 0.5 % Zn	45	50	0	Hc1	90-150	394	16
F31c	Clorose present in needle tips.	P	MAP 33 + 0.5 % Zn	25	50	0	Ga5	110-130	417	16
G2a	Canopy sparse, with clorotic needle tips	P,K	234 (30)	20	30	40	Ga5	110-150	638	14
G4a	Canopy Sparse with short needle	P,K	232 (30)	20	30	20	Ga6	130-180	497	18
G8a	Canopies sparse with short needles and clorose spots.	P,K	234 (30)	20	30	40	Ga5	110-150	661	13

*Codes refer to Forestry soils database (FSD) format, where Fc = lithocutanic soils; Cb = hydromorphic soils with an E horizon; Ga = hydromorphic podzols; Hc = E-horizons over neocutanic subsoils.

2. Sample plot selection

Sample plots were chosen on the following base criteria; relatively even terrain which are similar for the three sample plots in each compartment, free of diseases and pests, uniform canopy, and a relatively weed free forest floor. In each compartment three plots were located and consisted of a control, one plot that received a single treatment (1F) and another that received a repeated treatment of fertiliser after 12 months of first treatment (2F). This basic layout was replicated in nearby compartments. The plots consisted of ten by ten rows with the inside eight by eight being the area where data was captured from. Figure 2 gives a schematic representation of how the plots were layed out. Kluitjieskraal plantation was used as an example.

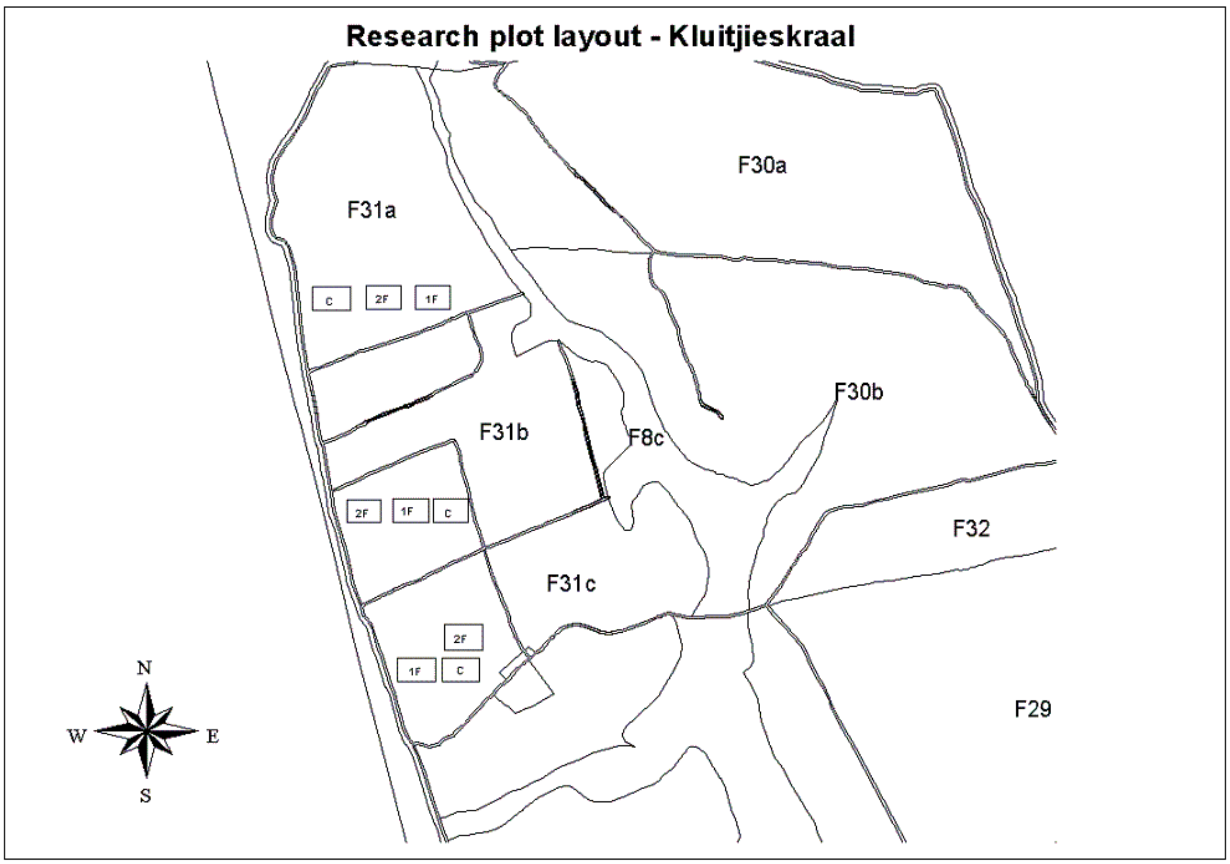

Figure 2: Schematic representation of the layout of the plots in the three trail compartments at Kluitjieskraal.

As seen in the Kluitjieskraal situation, plots were not always distributed in the same manner in each compartment. The reason for this was to minimise variability due to stocking and tree size.

None of the compartments received a thinning within 3 years prior to fertilisation but it was not possible to select plots of equal stocking between sites as natural site driven factors and mortality defines the actual stocking for each compartment.

3. Data capturing

Foliar analyses, diameter, height and LAI readings were measured on a six monthly basis from the time of treatment application. Foliar analyses were used to determine the nutrient status of the plots and used to determine the optimum fertiliser treatment. Foliar analyses were also used to assist in formulating the second fertiliser treatment, and to give an indication of the ongoing nutrient availability and uptake during the project. Foliar samples were taken in the winter months (June/July of 2006, 2007 and 2008) as it is the most suitable time to gather foliar samples in coniferous species (Payn & Clough, 1987). The accuracy of identifying nutrient deficiencies via foliar analyses is queried by some (Fisher & Binkley, 2000). With due consideration that physiological factors do play a role in foliar nutrient concentration fluctuations, variances due to season, age and position of foliage sampled were minimised.

The samples were taken manually with tree pruning scissors with extending connections to enable sampling in the upper third of the crown. Six foliar samples were taken per plot and bulked to get a representative sample of needles. Current year needles fascicles in the upper third of the tree were collected, as it has been shown that it is a good predictor of subsequent tree growth response (Timmer & Morrow, 1984). Foliar analyses was done in a commercial laboratory and presented as nutrient concentrations. These concentrations were also compared as ratios with regards to N. The ratios indicate the relationship between nitrogen (N) and the other nutrients indicated.

3.1 Foliar sampling and analyses

The critical values for these ratios were originally developed on Norway Spruce (*Picea abies)* but they are generally accepted to apply to most coniferous trees species (Linder, 1995). The increase in growth rate after various levels of fertiliser application as noted by other research projects on *P. radiata* in South Africa, New Zealand, Australia, and elsewhere were used to estimate fertiliser levels to improve growth optimally (du Toit, 2006). Although this method is not ideal it has found to be relatively successful where nutrient deficiencies are severe and where data from replicated fertiliser trial series does not exist. Further studies have more recently been commissioned in the same study area with a series of well designed fertiliser samples that take water availability into account. It will help to establish the true optimum fertiliser level that needs to be applied for optimum improvement of growth for future use.

3.2 Diameter at breast height and height measurements

Diameter and height measurements were taken on a six monthly basis. Measurements were taken with a calibrated diameter tape over bark for diameter measurements, and a vertex hypsometer calibrated at 1.3 m breast height for height measurements. To ensure that diameter measurements were taken on precisely the same height of the tree on each measurement of the total of four taken, a mark was left with loggers crayon around the circumference of the tree at breast height. In cases were knot whorls were present at breast height, measurements were taken either above or below the whorls to ensure that tree volumes were not unreliable. No height measurements were taken during windy periods and accuracy was optimised by insuring that the distance from the tree was as far as possible similar to the height of the tree.

3.3 Leaf area index estimation and measurement

Leaf area index (LAI) was estimated using a radiometric instrument called an AccuPAR (LP-80) ceptometer which measures the sun fleck area with an array of sensors. The gap fraction relates leaf area to the probability of light passing uninterrupted through the canopy (Lang *et al*., 1985) by comparing the radiation environment at the base of the canopy with a simultaneous measurement above or outside the canopy. This was done by measuring 20 readings outside the canopy and 80 readings 1m apart between the 8 rows of the sample plot underneath the canopy. The AccuPAR calculates LAI based on the above and below-canopy photosynthetically active radiation (PAR) measurements along with other variables that relate to the canopy structure and position of the sun. These variables are zenith angle, a fractional beam measurement vale, and a leaf area distribution parameter (x) for the particular canopy. The AccuPAR uses x = 1.0 as its default and it was also used as such in this study.

3.4 Moisture growing season and reference potential evaporation

An adapted FAO (1978) approach was used with actual precipitation and evaporation data for the three geographical areas to determine the moisture growing season of each area. This approach assumes that during a period when precipitation (mm) is larger or equal to 0.3 x mean monthly E_{apan}, taken as the reference potential evaporation (E_r), sustained plant growth can take place. It is important to note that this method does not account for any differences in soils. This data was compared with median long term data for each area, in order to detect any variances in the moisture growing season between the long term data and the measurement period.

3.5 Net present value and internal rate of return calculations

Net present value and internal rate of return calculations was used to determine whether the costs of fertiliser could be justified with increase in volume growth. Data taken from

Forestry Economics Services (2008) were used as costs incurred from establishment to harvesting and round log prices of products delivered at roadside. The internal rate of return was calculated using the average MAI of the Boland area (10 m^3 ha^{-1} a^{-1}) as the control and increases in CAI as found at the three plantations as seen in Table 4.4. Actual volume per product according to log classes were used as modeled for *Pinus radiata* sites with MAI 10.7, 11.6, 12.6, and 13.6 m^3 ha^{-1} a^{-1} to calculate log prices at roadside and the change in log dimensions as MAI increased. A real rate of 5.95% was calculated from the average prime rate of 12.5% and average PPI (production price index) of 6.18 % in 2009.

Four scenarios was used as possibilities of volume increase on an annual basis, and converted to mean annual increment for a 25 year rotation. A real rate was used for discounting (as by general consensus). In order to calculate the real rate or inflation free cost of capital the following relationship was used (Uys, 1991):

$$(1+k) = (1+i)\,(1+f)$$

k = nominal cost of capital (prime rate)
i = real or inflation free cost of capital
f = inflation rate according to a general price index (production price index)

4. Statistic Analyses

Microsoft Excel was used to capture the data and STATISTICA version 9 (StatSoft Inc. (2009) STATISTICA (data analysis software system) was used to analyse the data.

Summary statistics were used to describe the variables. Medians or means were used as the measures of central location for ordinal and continuous responses. Standard deviations and quartiles were used as indicators of spread during preliminary data anaylsis (not shown).

Relationships between continuous variables (like basal area, volume increment, leaf area index and growth efficiency), were analysed with regression analysis and the strength of the relationship measured with the Pearson correlation or Spearman correlation if the continuous variables are not normally distributed. If a continuous response variable (basal area, volume increment, leaf area index and growth efficiency) was related to several other continuous input variables, multiple regression analysis was used and the strength of the relationship measured with multiple correlation.

The relationships between the growth responses (basal area, volume increment, leaf area index and growth efficiency) and treatments were analysed using appropriate analysis of variance (ANOVA). When the influence of a continuous covariate, for instance volume at time zero (V_0), on a particular ANOVA was required, an appropriate analysis of covariance was done on the volume increment (I_v) versus the nominal factors (treatment and plantation) and the covariate, volume at time zero (V_0). V_0 was also used as covariate for the analyses of covariance when testing leaf area index (LAI) and growth efficiency (GE) versus treatments and plantation.

A p-value of $p < 0.05$ represents statistical significance in hypothesis testing and 95% confidence intervals were used to describe the estimation of unknown parameters.

CHAPTER IV RESULTS

By reviewing the literature it is clear that the growth efficiency of plantation trees could be increased through fertiliser application. It now remains to be seen how different compartments in the Boland region will react as influenced by different rainfall patterns and soil types, with respect to growth indicators such as LAI, GE and volume growth.

1. Nutrient status

Foliar analyses is a very good diagnostic technique to use for evaluating pronounced deficiencies as it provides an integrated assessment of the many factors that influence nutrition (Needham *et al.*, 1990).

Table 4.1(a) shows the concentration of the nutrients and their critical norms (Boardman *et al., 1997)* in the upper crown that were analysed in June 2006. Dark shaded, light shaded and non-shaded areas define which values are higher, lower and within the optimum range. The corresponding nutrient ratios (relative to N) for foliar analysis done in 2006 are shown in section (b). The ratios indicate the relationship between nitrogen (N) and the other nutrients.

Table 4.1: Nutrient concentrations (a) and ratios relative to nitrogen (b) of foliar analyses of control plots taken in June 2006.

compartment	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
(a)			%					mg/kg		
D16	1.23	0.09	0.75	0.30	0.17	116	222	4	38	31
D17	1.23	0.10	0.64	0.26	0.17	129	243	5	42	33
J22	1.18	0.09	0.78	0.26	0.19	58	217	4	35	49
F31a	1.43	0.10	0.72	0.30	0.20	88	243	3	15	20
F31b	1.34	0.12	0.57	0.23	0.22	134	225	5	14	27
F31c	1.55	0.09	0.83	0.21	0.17	103	229	4	17	41
G2a	1.62	0.15	0.58	0.32	0.26	237	208	5	34	37
G4a	1.73	0.10	0.59	0.38	0.29	440	320	7	26	46
G8a	1.60	0.12	0.46	0.30	0.24	274	166	5	29	32
NORMS	1.21	0.14	0.51	0.09	0.10	25	71	2.4	14	17

(b)

compartment	P/N	K/N	Ca/N	Mg/N	%	Mn/N	Fe/N	Cu/N	Zn/N	B/N
D16	7	61	24	14		0.9	1.8	0.03	0.31	0.25
D17	8	52	21	14		1.0	2.0	0.04	0.34	0.27
J22	8	66	22	16		0.5	1.8	0.03	0.30	0.42
F31a	7	50	21	14		0.6	1.7	0.02	0.10	0.14
F31b	9	43	17	16		1.0	1.7	0.04	0.10	0.20
F31c	6	54	14	11		0.7	1.5	0.03	0.11	0.26
G2a	9	36	20	16		1.5	1.3	0.03	0.21	0.23
G4a	6	34	22	17		2.5	1.8	0.04	0.15	0.27
G8a	8	29	19	15		1.7	1.0	0.03	0.18	0.20
NORMS	10	35	2.5	4	%	0.05	0.2	0.03	0.05	0.05

Fertiliser treatments were applied according to deficiencies as seen in Table 4.1, but focused on improving the most acute deficiencies. Visual aspects such as shortened needles, discolouration, tip die back, and the premature loss of older needles were found in all the sites (Table 3.2). The largest single problem that existed in all of the compartments studied was the acute deficiency in P (Table 4.1). These deficiencies are worsened by low N, Mg and Ca concentrations (Table 4.1). The nutrient balance in Table 4.1 indicates that the P levels are very low especially when expressed as a P/N ratio. Payn *et al.* (1988) and De Ronde (1992) recorded positive responses to P application on a variety of *radiata* pine sites were foliar P levels were deficient.

Foliar nutrient data collected 18 months after treatment (January 2008) are shown in Table 4.2. It gives an indication that the fertiliser treatments had a positive effect on foliar nutrient concentration and foliar nutrient ratios relative to nitrogen. P concentrations generally moved closer to the norms, with the N/P relationship in most cases also moved closer to or higher than the norm. This means that little dilution effect of N was found and sufficient amounts of P were applied to have a positive effect on stand nutritional status.

Table 4.2: Nutrient concentrations (a) and ratios relative to nitrogen (b) sampled in June 2008 in plots that were treated with fertiliser.

(a)

compartment	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
			%					mg/kg		
D16	1.27	0.13	0.67	0.63	0.15	227	219	4	39	36
D17	1.45	0.13	0.59	0.45	0.17	209	194	3	36	31
J22	1.05	0.16	0.71	0.47	0.15	119	183	3	24	36
F31a	1.23	0.12	0.50	0.48	0.27	351	124	15	18	32
F31b	1.14	0.10	0.46	0.44	0.31	194	104	25	16	47
F31c	1.22	0.12	0.74	0.53	0.22	227	121	4	18	28
G2a	1.23	0.12	0.51	0.47	0.21	372	101	2	18	26
G4a	1.34	0.09	0.65	0.36	0.20	381	140	2	14	25
G8a	1.68	0.20	0.61	0.41	0.23	230	154	4	28	28
NORMS	1.21	0.14	0.51	0.09	0.10	25	71	2.4	14	17

(b)

compartment	P/N	K/N	Ca/N	Mg/N	**%**	Mn/N	Fe/N	Cu/N	Zn/N	B/N
D16	10	53	50	12		1.8	1.7	0.03	0.31	0.28
D17	9	41	31	12		1.4	1.3	0.02	0.25	0.21
J22	15	68	45	14		1.1	1.7	0.03	0.23	0.34
F31a	10	41	39	22		2.9	1.0	0.12	0.15	0.26
F31b	9	40	39	27		1.7	0.9	0.22	0.14	0.41
F31c	10	61	43	18		1.9	1.0	0.03	0.15	0.23
G2a	10	41	38	17		3.0	0.8	0.02	0.15	0.21
G4a	7	49	27	15		2.8	1.0	0.01	0.10	0.19
G8a	12	36	24	14		1.4	0.9	0.02	0.17	0.17
NORMS	10	35	2.5	4	**%**	0.05	0.2	0.03	0.05	0.05

2. Effects of fertilisation on LAI

A wide range of LAI's existed before treatment implementation on sites that varied in age and soil types. An analysis of variance, with LAI at time zero as covariate, was used to give unbiased results as in some cases stocking (stand density) also varied.

The differences in growth responses were assessed by subjecting data to analyses of variance (ANOVA) and F test with vertical bars denoting 95% confidence intervals. A summary of the statistical parameters are given. The three different study areas responded differently in LAI after fertiliser treatment. No significant difference was found between plots not treated and plots fertilised, despite using the mean LAI at time zero (LAI_0) for all three plantations as covariate [F (4, 17) =0.47; p>0.76] (Figure 3; Table 4.3)

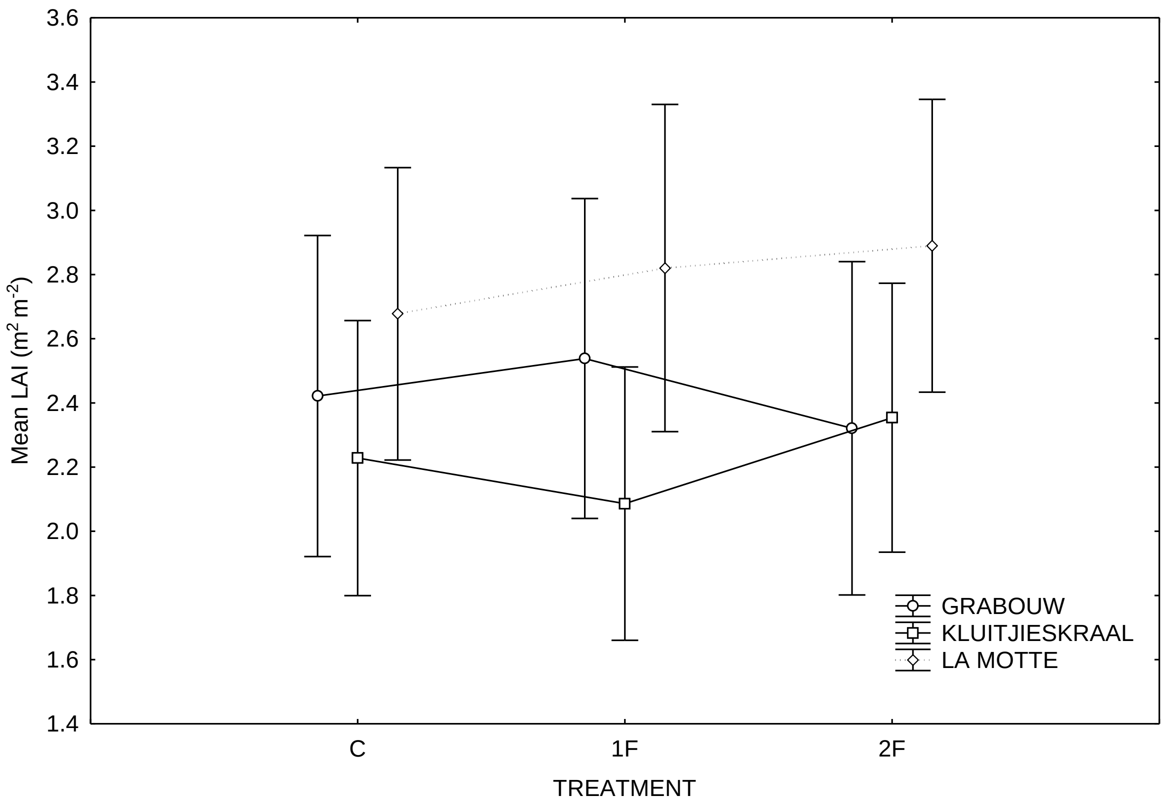

Figure 3: Mean leaf area index (LAI) measured between June 2006 and January 2008 in control (C), single fertiliser treatment (1F), and repeated fertiliser treatment (2F) with mean LAI at treatment implementation (LAI_0) of all three plantations as covariate (vertical bars denote 0.95 confidence intervals).

Mean leaf area index values were calculated for control (C), single treatment (1F) and repeated treatment (2F) per seasonal measurement (Figure 4). The mean value of all treatments were included to indicate the seasonal effect as no significant difference was found in LAI between treatments across fertiliser treatments in Figure 3. Figure 4 does however provide a good indication on the seasonal development and loss of foliage. It is clear that the LAI is higher in the winter when more water is available and lower in the summer when little water is available. A very low LAI value was present at the Grabouw site at project initiation. Even though no significant difference exists between treatments, LAI exhibits a clear seasonal trend [$F (6, 24) = 3.18$; $p > 0.019$].

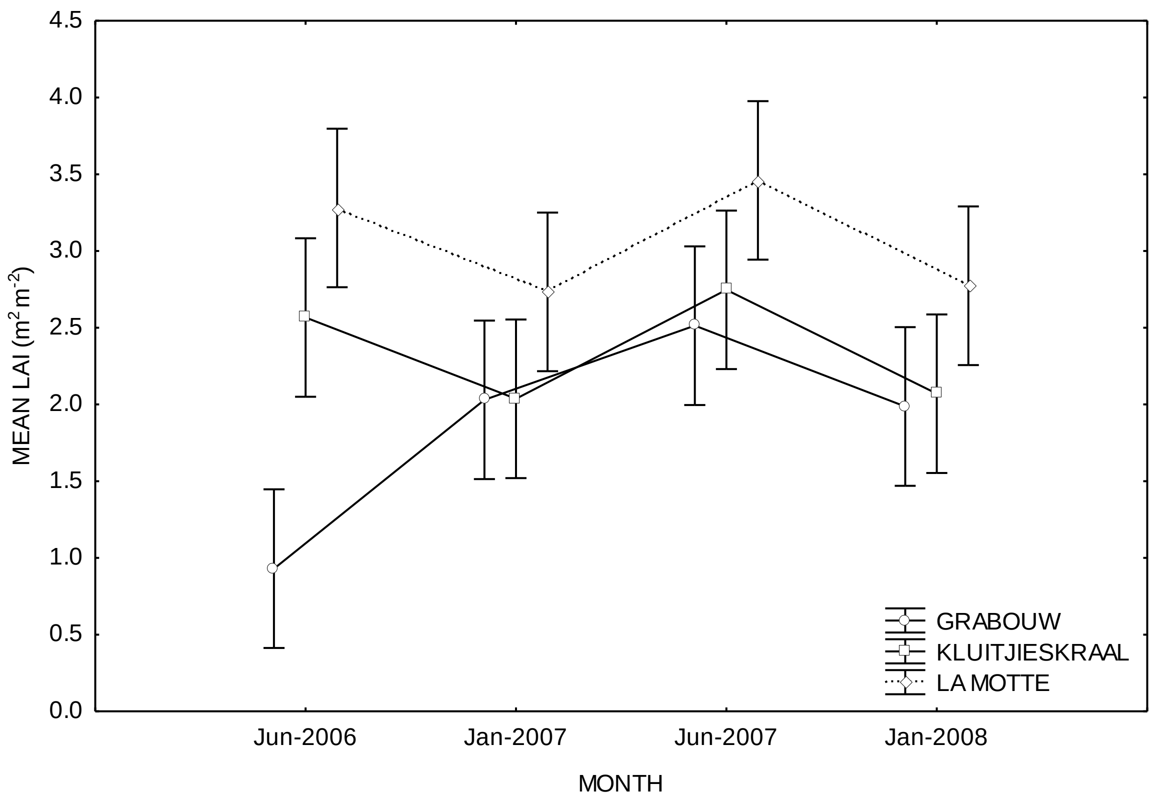

Figure 4: Mean LAI per plantation of all plots measured between June 2006 and January 2008 (vertical bars denote 0.95 confidence intervals).

The moisture growing season (MGS) was calculated for all three plantations with the FAO (1978) approach that was adapted for South Africa. Actual precipitation and evaporation data was used for the period January 2006 to January 2008. At the La Motte (Figure 5) and Kluitjieskraal (Figure 6) sites the moisture growing season lasted for 6 months between April 2006 and September 2006 as was the case in 2007. This corresponds well with the long term average data for La Motte and Kluitjieskraal (Long term data not shown).

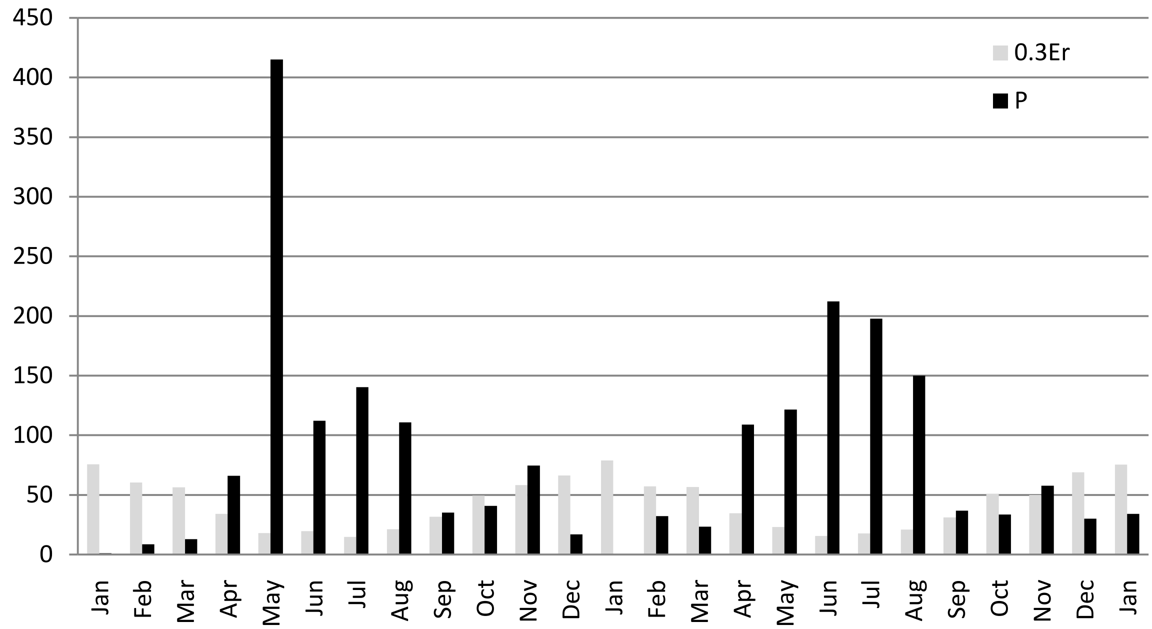

Figure 5: Moisture growing season (MGS; where monthly P> $0.3E_r$) over 24 months between January 2006 and January 2008 at La Motte plantation.

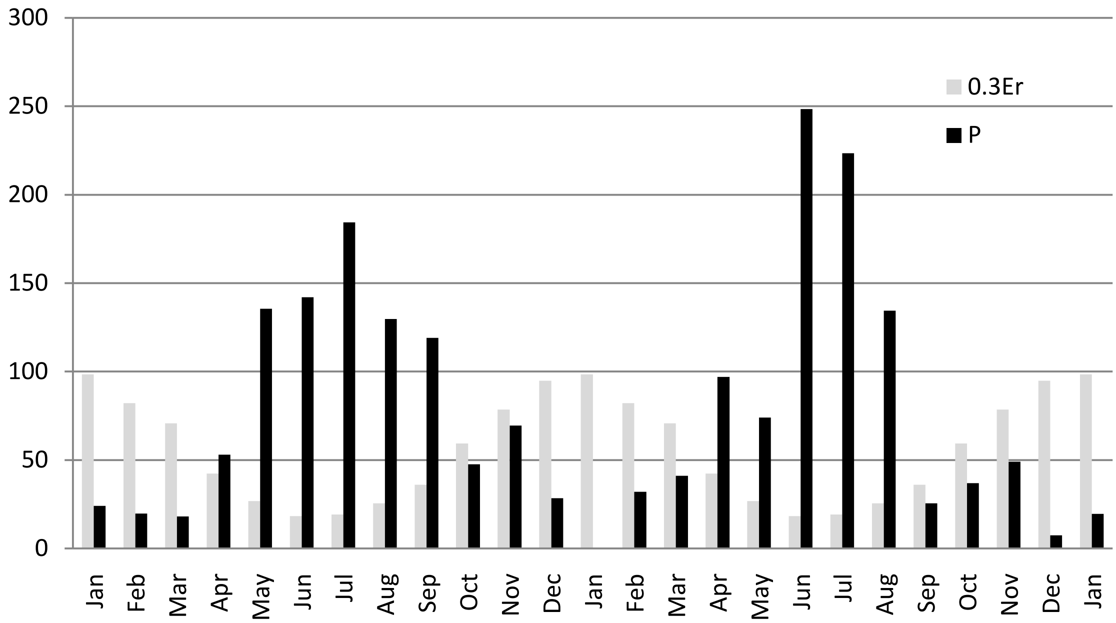

Figure 6: Moisture growing season (MGS; where monthly P> $0.3E_r$) over 24 months between January 2006 and January 2008 at Kluitjieskraal plantation.

At the Grabouw site (Figure 7) the moisture growing season lasted for 6 months between April 2006 and September 2006 (i.e. it followed a similar trend as with the long term average data in Appendix E), however, the moisture growing season lasted for 11 months in 2007. The data shows that the moisture growing season differed quite substantially at Grabouw between 2006 and 2007.

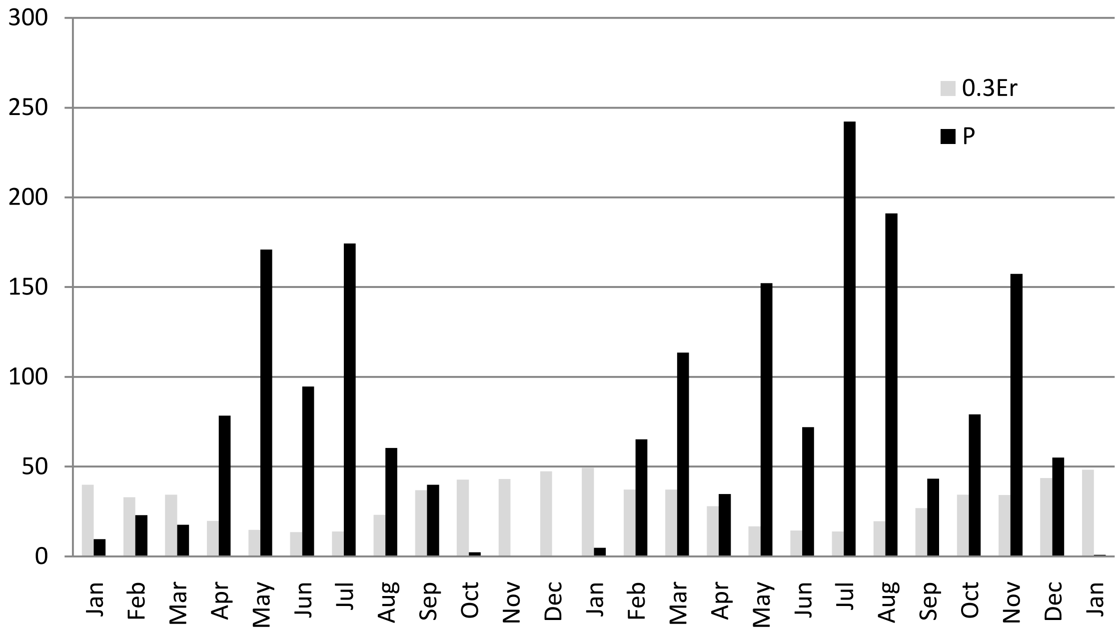

Figure 7: Moisture growing season (MGS; where monthly P> $0.3E_r$) over 24 months between January 2006 and January 2008 at Grabouw plantation.

To rule out any seasonal effect a univariate test of significance was calculated for LAI in control (C) and LAI in fertilised (1F) plots for measurements taken in June 2006 and June 2007, to establish whether LAI increases are significantly influenced by increased nutrient availability (Figure 8). No significant difference was however found between untreated plots and treated plots between June 2006 and June 2007 [$F(2, 11) = 0.021$; $p > 0.98$] but minor increases were present for all treatments.

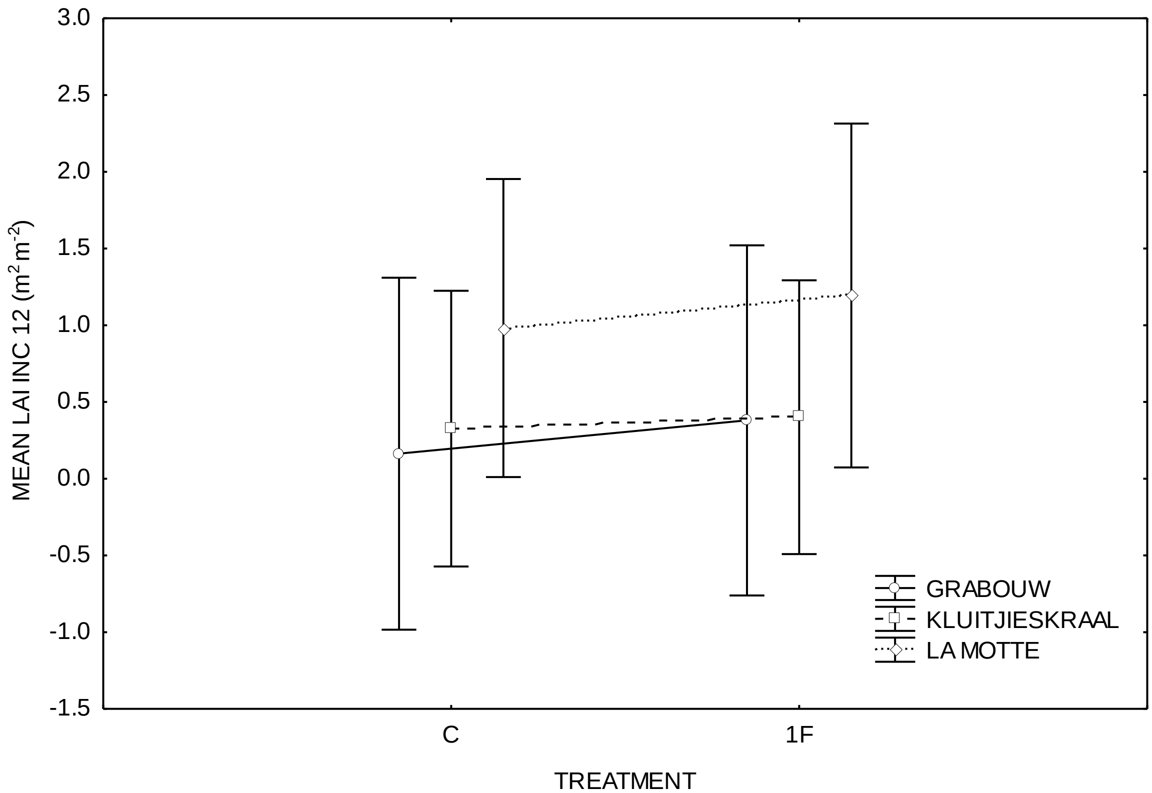

Figure 8: Mean leaf area index increment over a 12 month period (MEAN LAI INC 12) from June 2006 to June 2007, with mean leaf area index at time zero (LAI_0) as covariate (vertical bars denote 0.95 confidence intervals).

3. The effects of fertiliser treatment on volume increment and basal area increment

The utilisable volume was calculated from measured diameter at breast height and height data on a six monthly basis. Basal area increment (I_G) was also calculated using diameter at breast height. A greater volume increment (I_V) was present in the plots that received fertiliser at all three plantations (Figure 9). No significant differences in I_V were found between treatments for any of the plantations (with mean volume at time zero (V_0) for all three plantations being used as covariate); [F (4, 17) = 0.19; $p > 0.94$]. When testing I_V per treatment using volume at time zero (V_0) per plantation as covariate no significant difference was found either even though a large increase in current annual increment (CAI) between treatments were recorded (Table 4.3).

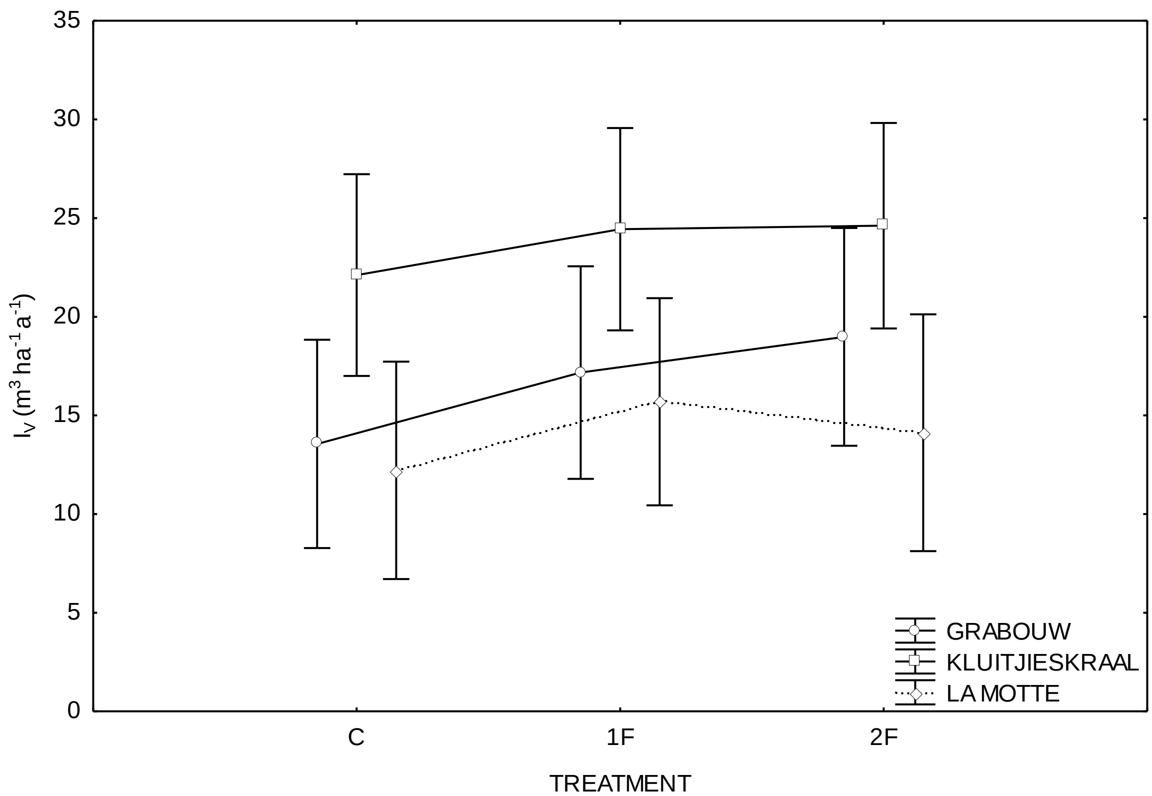

Figure 9: Mean volume increment (I_V) with initial mean volume (V_0) of all three plantations as covariate (vertical bars denote 0.95 confidence intervals).

Even though the basal area increment (I_G) increased more in 1F plots than that of C plots at all three plantations no significant difference was found with basal area at time zero (G_0) as covariate [F (4,17) = 0.81; $p > 0.54$]. At Grabouw a further non significant I_G increase was found from 1F to 2F plots but no such trend was found at La Motte or Kluitjieskraal (Figure 10) (Table 4.3).

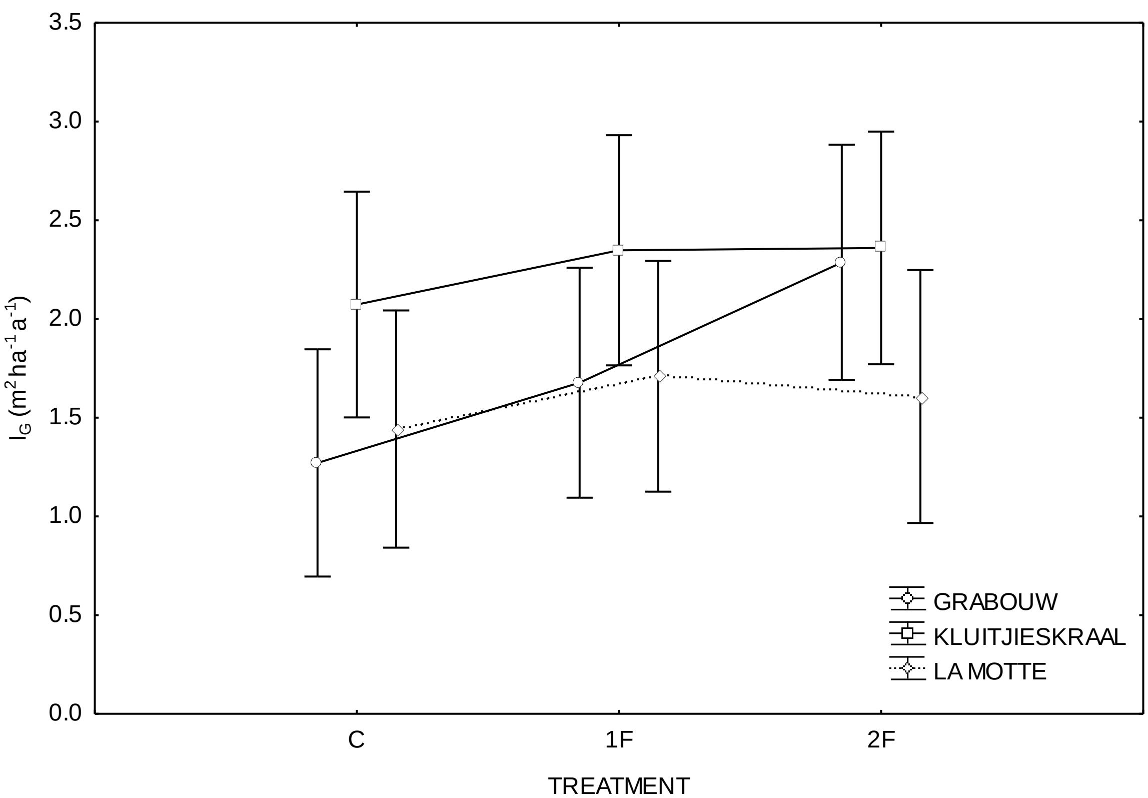

Figure 10: Mean basal area increment (I_G) with the mean basal area at time zero (G_0) of all three plantations as covariate (vertical bars denote 0.95 confidence intervals).

The I_V was 3.62 m^3 ha^{-1} a^{-1} and 3.48 m^3 ha^{-1} a^{-1} more than I_V values in C plots at Grabouw and La Motte respectively. At the Kluitjieskraal site a good I_V in 2F plots of 2.50 m^3 ha^{-1} a^{-1} more than I_V in C plots was found with the largest I_V of 5.43 m^3 ha^{-1} a^{-1} over the control occurring at Grabouw in 2F plots. On a management perspective the increase is substantial as the CAI was increased by a minimum of 2.33 m^3 ha^{-1} a^{-1} in 1F plots and a maximum 5.43 m^3 ha^{-1} a^{-1} in 2F plots (Table 4.3) when a volume increase of only 0.4 m^3 ha^{-1} a^{-1} needs to be attained to justify the cost of fertiliser treatment as discussed later in this section.

Table 4.3: Mean leaf area index (LAI), mean basal area increment (I_G) mean volume increment (I_V) and mean growth efficiency (GE) in C, 1F and 2F plots over the measurement period from June 2006 to January 2008 (None of the treatments are statistically significant at the level of $p< 0.05$).

Plantation	Treatment	Mean LAI (m^2 m^{-2})	Mean I_G (m^2 ha^{-1} a^{-1})	Mean I_V (m^3 ha^{-1} a^{-1})	Mean GE (m^3 ha^{-1} a^{-1} LAI^{-1})
Grabouw	C	2.42	1.27	13.55	6.03
	1F	2.54	1.68	17.17	7.66
	2F	2.32	2.29	18.98	8.99
Kluitjieskraal	C	2.23	2.07	22.11	9.58
	1F	2.09	2.35	24.44	10.26
	2F	2.35	2.36	24.61	9.89
La Motte	C	2.68	1.44	12.21	4.86
	1F	2.82	1.71	15.69	5.27
	2F	2.89	1.61	14.12	5.34

4. The effects of LAI and volume increment on growth efficiency

The growth efficiency (GE) comparison in the C, 1F and 2F plots of each plantation is presented in Figure 11 and Table 4.3. The GE is clearly higher in 1F and 2F plots than the C plot at the Grabouw site, albeit not statistically significant. At the La Motte and Kluitjieskraal sites GE is slightly higher in 1F plots but little difference in GE is found between control and 2F plots. No significant differences in GE exists between C, 1F and 2F plots when using mean volume at time zero (V_0) for all three plantations as covariate [F (4, 17) = 0.67; $p > 0.62$]. Suffice to say that at Grabouw the GE increases substantially in 1F and further in 2F plots as no difference is found in LAI from C to 2F plots. The growth response at Grabouw is mainly in I_V.

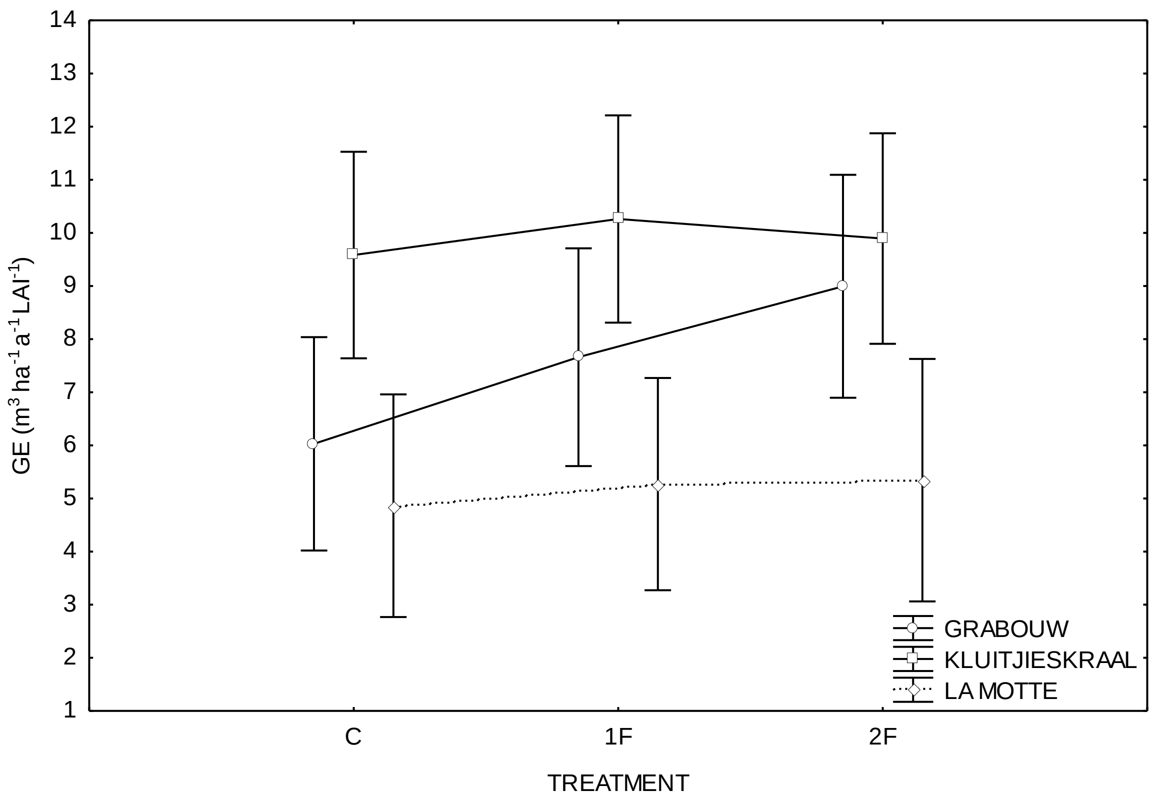

Figure 11: Mean growth efficiency (GE) in control (C), single treatment (1F), and repeated treatments (2F), with mean volume at time zero (V_0) as covariate (vertical bars denote 0.95 confidence intervals).

5. Quantification of CAI increase to evaluate financial feasibility

The net present value (NPV) and internal rate of return (IRR) when no fertiliser treatment is given (MAI 10.7) are contrasted to cases where CAI increases with 2 (MAI 11.6), 4 (MAI 12.6) and 6 (MAI 13.6) m^3 ha^{-1} a^{-1} respectively as a potential result when fertiliser is applied, and these results are presented in Appendices A, B, C and D. A summary of the key data in the appendices is given in Table 4. 4.

Table 4.4: Net present value (NPV) and internal rate of return (IRR) calculated at a real rate of 5.95%, over a 25 year rotation age.

Scenario				
Treatment (Ref. to appendix no.)	Improvement in CAI (m^3 ha^{-1} a^{-1})	MAI (m^3 ha^{-1} a^{-1})	NPV (Rand)	IRR (%)
C (A)	0	10.7	R -5,978.70	4.25%
1F (B)	2	11.6	R -4,156.05	4.86%
1F & 2F (C)	4	12.6	R -2,143.33	5.42%
2F (D)	6	13.6	R 351.38	6.03%

It is clear that the IRR can be increased closer to the real rate of 5.95% (break even rate) and even pass the real rate to give a profit margin of R 351.38 ha^{-1} at MAI 13.6 (Appendix D). Even though (according to the cost data used) a profit is only gained when CAI increases by 6 m^3 ha^{-1} a^{-1} (e.g. from 10 to 13.6 MAI) in fertilised plots, a decrease in profit lost of R 4156.05 ha^{-1} occurs when only a 2 m^3 ha^{-1} a^{-1} (12.6 MAI) increase is realised (Appendix B). The fact that the IRR is increased when fertiliser is applied indicates that it is economically feasible and desirable to apply fertiliser under the conditions tested.

CHAPTER V DISCUSSION

1. Nutrition and tree growth

The three different sites studied in the Boland area are all on sandy soils, but differ in soil type/depth, water availability and nutrient availability. Compartments are situated on sandy soils with depths between 50 – 100 cm at the Grabouw site and G (podzols), Fc (lithocutanic) soils with depths between 80-180cm with high rainfall at the Kluitjieskraal site and lower rainfall on deep sands at the La Motte site. Nutrient deficiencies in the form of nitrogen, and potassium and some micro nutrients existed on specific sites (Table 4.1), but all the sites had acute phosphorus deficiencies. Other similarities between the growth areas were sparse foliage in terms of needle length and low needle longevity (i.e. premature needle fall), (Table 3.2). The latter is apparently caused by a critical shortage of available nutrients (Table 4.1 and 4.2) whereas low LAI's can stem from a combination of nutrient shortages and low levels of available water. Undergrowth in some cases further worsened water and nutrient availability, causing a snowball effect as canopies cannot develop sufficiently to shade out undergrowth. This competition for resources limits canopy development, thus decreasing the amount of sunlight captured for photosynthesis and therefore carbon fixation which reduces the yearly volume increment (Table 4.3).

The canopy nutrition was evaluated before fertilisation, one year after fertilisation, and 18 months after initial fertilisation, with separate evaluations on control (C), single treatment (1F), and repeated treatments (2F) in the last evaluation (Table 4.1). Phosphorus concentration was found to be critically low at all the sites (Table 4.1). Although this was the only critically deficient nutrient, a study by Donald (1987) in the sandy soils of Grabouw indicated an optimum response is found when applying N and P together, as increased growth with application of the critical deficient nutrient P could cause dilution of N. This was the case at Grabouw and Kluitjieskraal, whereby at La Motte P and K was applied with low levels of N also being applied. Others (Payn *et al.,* 1988 and Turner *et al.,* 1995) also found that growth responses were limited when only applying P, and that better results were found when applying N and P together, in cases where P was the critically deficient nutrient.

As presented in the results the magnitude of the growth responses differed at each site after fertiliser and re-application of fertiliser after one year. The growth efficiency (GE) of sites Kluitjieskraal and La Motte had a similar trend: GE increased very slightly after fertilisation but remained unchanged after re-fertilisation. In contrast, GE at Grabouw increased following fertilisation, and increased even further with re-fertilisation (Figure 4.4), (Table 4.3). Growth efficiency is the quotient of volume increment and LAI (I_v/LAI), which means that if volume increment increases at a higher rate than LAI the growth efficiency will increase as in the Grabouw case.

2. Moisture, Growth and LAI

The moisture growing season at Grabouw is longer than that of the other sites (Figure 7) and is supported by long term moisture growing season data (Appendix E). Kluitjieskraal and Grabouw have a similar annual rainfall, but at Grabouw water availability is present for a longer period after winter. This means that the trees have a longer time in which nutrients could be translocated to the upper stem due to available water, especially in the case of re-application. It also means that stand response to fertilisation will not be as strongly limited by water availability, as is probably the case on many other sites.

The seasonal effect in this study played a major role in the increase in LAI (Figure 4). It was found that LAI differed significantly when water availability was higher in the winter months, but no significant difference occurred between C and 1F plots over a 12 month period (Figure 8). Although the fertilised plots had a higher LAI it was not significantly higher. This emphasises that without water being available nutrient increases will not be as effective. The shorter moisture growing season that was present in 2006 at Grabouw could play a role in the low LAI value that was measured there at project initiation.

Consideration must be given to the fact that the La Motte and Kluitjieskraal sites where older stands than the Grabouw site. Further consideration must be given to the fact that the La Motte (±650 stems per hectare) and Kluitjieskraal (±400 stems per hectare) sites had received more than one thinning operation where the Grabouw sites (±800 stems per hectare) had only received one thinning operation. Trees generally respond with increased growth when fertiliser is applied to stands that are thinned before fertiliser treatment (Donald, 1987), which indicates that the stand density could play a role in the response mechanisms found in this study.

Colter Burkes and Associates (2003) found that growth efficiency increased with an increase in stand density even though studies by others (Brix, 1981, Binkley & Reid, 1984, Sheriff, 1996) found that the amount of stem production per unit of foliage was greater due to higher average irradiance per unit foliage in stands with lower stand densities. In the Colter Burkes *et al.* (2003) study it has to be considered however that earlier measurements of light saturated net photosynthesis on foliage from the upper half of the canopy indicated no difference in photosynthetic capacity occurred due to planting density, and that other mechanisms or differences in sites could thus be possible in this study. Given these apparently contradicting results, it is thus difficult to speculate whether the increase in GE at the Grabouw site was partly due to stand density or not.

Linder and Exelsson (1982) indicated a shift in carbon allocation in cases where irrigation and fertilisation took place, which further pronounces the fact that the trees benefit from an increase in nutrient availability but adjusts the mechanism of response according the conditions present. Further evidence supports increase in growth efficiency as found in this study that fertilised stands converted more of the absorbed energy into stem wood than did unfertilised stands (Table 4.4).

Growth responses such as volume, LAI and growth efficiency give a good indication of whether a stand has been positively influenced by fertiliser treatment. The manner in which the growth responses react could be explained by physiological processes, as indicated by Landsberg (2003) that are driven by environmental elements such as radiation, nutrient availability, and water.

Photosynthesis is affected by many environmental factors, but primarily by incident radiant energy, temperature, water and nutrient availability. The basis of this study in essence was to increase the conversion of photosynthetically active radiant energy to carbohydrates by optimising the nutrient status of nutrient deficient growing areas. Nutrient availability in this case is the only factor that was enhanced. Others (Sheriff *et al.,* 1986, Reid *et al.,* 1983, Mooney *et al.,* 1978) found that a very close relationship exists between maximum photosynthesis rates and leaf nitrogen and phosphorus concentrations. It is possible to say that the photosynthetically active radiant energy conversion of carbohydrates was increased in this study in different magnitudes to the stem and foliar biomass of the stands. Water availability, seasonal changes, and ambient temperatures are some of the few variables known.

3. Fertilisation and economic benefits

Growth efficiency gives a glimpse of the possible mechanism of volume growth responses. Other studies in Douglas fir forests in Northern America found that by alleviating soil nitrogen supply with fertiliser application growth was increased by 2 to 4 m^3 ha^{-1} annually for 8 to 15 years (Chappel *et al*., 1991). More evidence exists that by fertilisation of loblolly pine plantations with nitrogen and phosphorus could increase volume growth up 5 m^3 ha^{-1} a^{-1} for 6 to 10 years. In New Zealand and Australia studies on *Eucalyptus* species have also found that fertiliser treatment in nitrogen and phosphorus poor areas increased growth by 4 to 8 m^3 ha^{-1} a^{-1} for 5 years or more (Binkley *et al.,* 1995). Herbert and Schonau (1989) indicated growth increases from 6 to 8m^3 ha^{-1} annually, in South Africa, after fertilising with nitrogen, phosphorus and potassium in *Eucalyptus* stands.

The maximum CAI increase at Grabouw of 5.43 m^3 ha^{-1} a^{-1} in the repeated fertiliser plots could probably be ascribed (at least in part) to the fact that the sites are established on deep sandy soils. Ingestad (1986) also found good results on similar soils in depth 1-100 cm where water availability was good. Volume increase was up to four times greater in fertilised plots than control plots even though foliar nutrient levels remained fairly stable in that study. Volume increases at all three plantations were not statistically significant in the fertilised plots and could be due to stocking, age or soil type and further highlights the fact that study site uniformity with regards to stocking and age can minimise variations on response differences. Studies mentioned confirm that the growth increase found in this study over an 18 month measurement period could last up to 10 years taking into consideration that phosphorus was the main deficient nutrient.

Although volume increases were not found to be significant between control plots and fertilised plots on a 95% confidence level, further examination into costs incurred and income received due to increased growth is positive. Fisher and Binkley (2000) found in a loblolly pine case study that growth increases kept pace with the compounding of interest on the fertiliser investment on a 30 year rotation basis. Growth in that case study was increased by only 1.4m^3 ha^{-1} annually which compares well with findings in this study that with only a minor increase in growth due to fertiliser application the investment would be justified. An increase of up to 5.43 m^3 ha^{-1} annually is attractive and provides large differences in profit margins when compared with control plots (Appendix D).

This study could serve as a building block for future research especially with regards to LAI measurements with the gap fraction method, and its accuracy in relation to allometric measurements or vector analyses. The LAI increase with relation to volume increment in this study did not give sufficient indication that there is a positive relationship as sites responded differently in LAI to fertiliser treatment. The seasonal fluctuation of LAI (Figure 4) however indicates that water availability is low in the summer months, and limits growth to a large extent. Foliage needs to be re-established before every growing season which limits the potential carbon allocation to stem biomass as energy is used to produce foliage.

As mentioned in chapter 4, section 3 no significant difference was found in volume increment in the 18 months of measurement although some responses were rather large. It is therefore important to quantify the economics of the actual volume increase to evaluate whether mid-rotation fertiliser treatment would ensure a positive return on the investment.

Donald (1987) found that fertiliser application to mid-rotation pine stands are more beneficial than application of fertiliser at planting describing the following reasons: (a) the quality of the additional wood is better than that derived from the first thinning, (b) the additional volume increment per ha occurs on fewer trees which therefore increases the value of each log, (c) the harvesting cost is less as log volumes are larger, and (d) the compound interest period is shorter.

Fertilisation of specific compartments (e.g. Grabouw treatments 1F and 2F) yielded large responses in basal area and volume increments (Table 4.3), with equally large error bars (Figures 9 and 10). It follows that the lack of significance may stem from the large differences in basal area, stocking and leaf area existing between compartments and even between experimental plots within compartments at the onset of the experiment and the limited number of replications. It also needs to be considered that this study was not initiated as a pre-designed experiment, but rather as an effort to monitor the response and understand the response mechanism to fertilisation applied by management. The study thus relied on the rapid establishment of monitoring plots in specific compartments of plantations where a fertilisation program had already commenced. A larger number of replications per plantation may have been desirable and the lack of statistical significance in certain of the large responses may be (at least partly) due to the fact that replications per plantation and per compartment were limited. We have therefore discussed the practical and economic significance of the larger responses obtained, despite the fact that they were not statistically significant in our (somewhat limited) statistical tests.

CHAPTER VI CONCLUSIONS AND RECOMMENDATIONS

The growth of a tree is determined by several environmental factors through their effects on physiological processes. These effects can be summarised in terms of the amount of light which is captured by canopies and with sufficient amounts of water and nutrients could be converted into biomass. In this study the nutritional status was estimated through foliar analyses, in order to establish which fertiliser treatment would alleviate deficiencies in order to increase growth efficiency.

Taking into consideration that some shortcomings were present in this study with respect to variations in study sites, and statistically insignificant growth responses, many positive outcomes have been realised. This study covers a wide variation of forestry area in the Boland region of the Western Cape that is low in productivity, due to the lack of soil nutrition and a short growing season which is generally the case in a Mediterranean climate. This emphasises that fertiliser application could enhance growth in an economically feasible manor when applied in the right areas.

Foliar nutrient analysis could be used to show that the nutrient status of trees improved following fertilisation and that these treatments resulted in growth improvements. The foliar nutrient content confirmed that substantial quantities of the applied nutrients were taken up.

Leaf area varied strongly with season with a magnitude of between 0.6 to 0.7 units between dry and wet seasons. This has implications for allometric work and future calibration of optically measured leaf area indices. While LAI responses were obtained in the first wet season following fertilisation, it is not clear if such responses will re-appear in the second wet season after fertilisation. Resource and time constraints curtailed measurements and further research should therefore look into the longevity of the response, seeing that each dry season causes LAI to drop to very low levels.

Growth improvements with single fertiliser applications ranged from 2.33 to 3.62 m^3 ha^{-1} a^{-1} and all of these responses resulted in an improvement in NPV and IRR. Even comparatively small fertiliser responses at mid-rotation can thus be economically justifiable. An increase of 0.4 m^3 ha^{-1} a^{-1} CAI on a MAI of 10.7 m^3 ha^{-1} a^{-1} is found to be the breakeven point in this study. With consideration given to the increase in the stumpage value, it relates to a MAI of 10.9 m^3 ha^{-1} a^{-1}. Some growth responses were large (improvements of 5.43 m^3 ha^{-1} a^{-1} in CAI) and I therefore recommend that in such areas it would be largely beneficial to apply fertiliser and consideration toward its implementation should be given despite them not being statistically significant.

The largest growth responses were associated with stands where increases in growth efficiency were the main response mechanism, which also coincided with the longest moisture growing season which in this study is Grabouw. It has been found in *Eucalyptus* species that responses based on efficiency mechanisms appear to be larger in magnitude, and have greater longevity than responses to increased leaf area, especially in seasonally dry climates (du Toit, 2008). The fact that the Grabouw stand showed a strong improvement in GE with fertilisation, suggests a change in stand physiology that is likely to persist for some time. This finding is in keeping with the response obtained by Donald (1987) which was sustained for 10 years.

Although positive responses were found in this study, accuracy and the potential of responses could be better researched under the following conditions:

a) If the study area consisted of compartments with similar stocking and age it would minimise variables that could bias refinement of differences in growth response outcomes. Covariates for initial LAI and volume increment were only effective to remove some of the background variability statistically. Stocking and age apparently did play a role in some of the differences that were found in growth responses, but can also play an important role as a basis for future studies where specific mechanisms for growth responses need to be researched,

b) If measurement could take place over a longer period, the seasonality of LAI responses could be better understood, especially the LAI response in the second wet season.

Until fertiliser recommendations can be bolstered with additional trial evidence, It would be recommended as an interim measure that fertilisation should take place on nutrient deficient sites (based on foliar analyses) where the duration of the moisture growing season is 6 months or longer. The limitation of water in the summer dry season is pronounced and has a significant influence on growth. Future research should focus on the interaction of water availability and fertiliser response to more clearly understand this interaction and to fine-tune recommendations for management.

As a management tool outcomes in this study can give an indication of growth responses that could be expected when deficiencies are alleviated. On a scientific basis and in an attempt to acquire precision in a locally decreasing industry, further research into mechanistic processes need to be done in order to understand variance in responses to fertiliser application, as found in this study.

REFERENCES

Anonymous, 1985. Nitrogen accumulation and growth of radiate pine on Pinaki sand. *New Zealand Forest Service, Wellington, Forestry Research Institute. Re*p*. 1985,* p*. 43.*

Beadle, C.L. 1997. Dynamics of leaf and canopy development. In E.K. Nambiar and A.G. Brown (eds.). *Management of soil, nutrients and water in tropical plantation forests*. Australian Centre for International Agriultural research, Canberra, Australia. *ACIAR Monograph 43:169-212*.

Beaufils, E.R., 1973. Diagnosis and Recommendation Integrated system (DRIS). *Soil Science, Bulletin 1. Department of Soil Science and Agrometeorology, University of Natal,* Pietermaritzburg.

Berg, B., Staaf, H. and Wessen, B., 1987. Decomposition and nutrient release in needle litter form nitrogen fertilised Scots pine (*Pinus sylvestris*) stands. *Scandinavian Journal of Forest Research*, 2:399-415.

Binkley, D. and Reid, P., 1984. Long term responses of stem growth and leaf area to thinning and fertilisation in a Douglas fir plantation. *Canadian Journal of Forest research,* 14:656-660.

Binkley, D., Smith, F.W. and Son, Y., 1995. Nutrient supply and limitation in an age sequence of lodge pole pine in south western Wyoming. *Canadian Journal of Forest Research,* 25:621-628.

Birk, E.M. and Turner, J., 1992. Response of flooded gum (*E. grandis)* to intensive cultural treatments: Biomass and nutrient content of Eucalypt plantations and native forests. *Forest Ecology and Management, 47:77-85.*

Boardman, R., Cromer, R.N., Lambert, M.J. and Webb, M.J., 1997. Forest Plantations. In Reuter D J and Robinson J B, (eds.). *Plant analysis: an inter*p*retation manual. 2nd Edition.* CSIRO Publishing, Collingwood, Australia. p. 503-566.

Bolstad, P.V. and Gower, S.G., 1990. Estimation of leaf area index in fourteen southern Wisconsin forest stands using a portable radiometer. *Tree Physiology*, 7:115-124.

Brix, H., 1981. Effects of thinning and nitrogen fertilization on branch and foliage production in Douglas-fir. *Canadian Journal of Forestry Research, 11:502-511.*

Cannell, M.G.R., 1985. Dry matter partitioning in tree crops. In M.G.R Cannell and J.E Jackson (eds.). *Attributes of trees as crop plants*. Institute of terrestrial ecology, Huntingdon, United Kindom, p*. 160-193.*

Cannell, M.G.R., 1989. Physiological basis of wood production. *Scandinavian Journal of Forest research,* 4:459-490.

Carlyle, J.C., 1995. Nutrient management in *Pinus radiata* D. Don plantation after thinning: The effect of nitrogen fertilizer on soil nitrogen fluxes and tree growth. *Canadian Journal of Forestry Research*, 25:1673-1683.

Carlyle, J.C., 1998. Relationships between nitrogen uptake, leaf area, water status and growth in an 11-year-old Pinus radiata plantation in response to thinning, thinning residue, and nitrogen fertiliser. *Forestry Ecology and Management*, 108:41-55.

Chappel, H. N., Cole, D.W., Gessel, S.P. and Walker, R.B., 1991. Forest fertilization research and practice in the Pacific Northwest. *Fertiliser,* 27:129-140.

Chason, J.W., Baldocchi, D.D. and Huston, M.A., 1991. A comparison of direct and indirect methods for estimating forest canopy leaf area. *Agricultural and Forestry Meteorology*, 57:107-128.

Cole, D.W., 1981. Nitrogen uptake and translocation by forest ecosystems. *Ecology Bulletin, 33:219- 232.*

Cole, D.W. and Rapp, M.R., 1981. Elemental cycling in forest ecosystems. In D. Reichle (ed.). *Dynamic Properties of forests ecosystems*. Synthesis Volume 23, Cambridge University Press, London, p. 341-409.

Colter Burkes, E., Will, R.E., Barron-Gafford, G.A, Teskey, R.O. and Shiver, B., 2003. Biomass Partitioning and Growth Efficiency of Intensively Managed *Pinus taeda* and *Pinus elliotii* Stands of Different Planting Densities. *Forest Science, 49(2).*

Crane, W.J.B. and Raison, R.I., 1980. Removal of phosphorus in logs when harvesting *Eucalyptus delecatensis* and *Pinus radiata* forests on short and long rotations. *Australian Journal of Forestry, 43:253- 260.*

Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A. and Brown, M., 1993a. Response to nutrients in *Eucalyptus grandis*: Biomass accumulation. *Forest Ecology and Management, 62:211-230.*

Cromer, R.N. and Jarvis, P.G., 1990. Growth and biomass partitioning in *Eucalyptus grandis* seedlings in response to nitrogen supply. *Australian Journal of Plant physiology, 17:503-515.*

Cromer, R., Smethurst, P., Turnbull, C., Misra, R., LaSala, A., Herbert, A. and Dimsey, L., 1995. Effect of nutritional and climatic factors on early growth of eucalypts in Tasmania. In Potts, B.M., Borralho, N.M.G., Reid, J.B., Cromer, R.N., Tibbits, W.N., Raymond, C.A. (eds.). *Proceedings of the CRC- IUFRO Conference on Eucalypts plantations: Improving Fibre Yield and Quality,* Hobart, p. 331-335.

Cromer, R.N. and Williams, E.R., 1982. Biomass and nutrient accumulation in a planted *Eucalyptus globulus* trail. *Australian Journal of Botany, 30:265-278.*

Deblonde, G., Penner, M. and Royer, A., 1994. Measuring leaf area index with the LI-COR LAI-2000 in pine stands. *Ecology,* 75:1507-1511.

Du Preez, A.P., 2009. Forestry Risk Manager, MTO Forestry (Pty) Ltd, Stellenbosch, Personnel correspondence. November 20, 2009.

De Ronde, C., 1992. Summary Report: Fertilisation of Pine stands in the Southern Cape and Tsitsikamma regions. *Report FOR DEA no. 514, CSIR,* Pretoria.

Du Toit, B., 2006. Information requirements to fertilise plantations with greater precision in a dry country. *Proceedings of the International Precision Forestry Symposium, Stellenbosch University, South Africa, 5-10 March 2006.* p. 245-260.

Du Toit, B., 2008. Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of *Eucalyptus grandis* in South Africa. *Forest Ecology and Management,* 255:2324-2336.

Du Toit, B. and Dovey, S.B., 2005. Effect of site management on leaf area, early biomass development, and stand growth efficiency of a *Eucalyptus grandis* plantation in South Africa. *Canadian Journal of Forestry Research,*35(4):891

Donald, D.G.M., 1987. The application of fertilizer to pines following second thinning. *South African Journal of Forestry, 142:13-16.*

FAO, 1978. Report on the Agro-Ecological Zones Project, Vol. 1: Methodology and Results for Africa. Food and Agriculture Organisation of the United Nations, Rome, Italy. World Soil Resources Report 48. p158. Cited in Schulze, R.E., 1997. South African Atlas of Agrohydrology and –Climatology. Water Research Commission, Pretoria, Report TT82/96, p. 202-203.

Ferreira, M.G.M., Kimmins, J.P. and Barros, N. F., 1984. Impact of intensive management on phosphorus cycling in *Eucalytus grandis* plantations in the savannah region, Minas Gerais , Brazil. In D.C. Grey, A.P.G., Shonau and C.J. Shultz (eds.). *IUFRO Symposium on site and productivity of fast growing plantations.* Pretoria and Pietermaritzburg, South Africa, 30 April – 11 May, 1984, Vol. 2. South African forest research institute, Pretoria*,* p*. 847 – 856.*

Fife, D.N. and Nambiar, E.K.S., 1982. Accumulation and retranslocation of mineral nutrients in developing needles in relation to seasonal growth in young radiata pine needles. *Annals of Botany,* 50:817-829.

Fisher, R.F. and Binkley, D. 2000. *Ecology and Management of Forest Soils*. John Wiley & Sons:New York.

Florence, R.G., 1986. Cultutal problems of *eucalyptus* as exotics. *Community Forestry Review*, 65:141-163.

Forestry Economic Services, 2008. *Financial analyses and costs of forestry operations*, *Southern Cape*, South Africa 2004-2007.

Herbert, M.A. and Shonau, A.P.G., 1989. Fertilising eucalyptus at plantantion establishment. *Forest Ecology and Management, 29:221-244.*

Heilmann, P.E. and Xie, F., 1994. Effects of nitrogen fertilization on leaf area, light interception, and productivity of short rotation *Populus trichocar*pa x P*. deltoides* hybrids. *Tree Physiology, 14:911-920.*

Hunt, R., 1982. Plant growth curves. *The functional approach to plant growth analyses*. Edward Arnold, London, p.248.

Ingestad, T., 1986. New concepts on soil fertility and plant nutrition as illustrated by research on forest trees and stands. *Geoderma, 40:237-252.*

Jensen, P. and Pettersen, S. 1978. Allosteric regulation of potassium uptake in plant roots. *Physiology Plant, 42: 207-213.*

Jones, H.E. ., Quarmby, C., and Harrison, A.F., 1991. A root bioassay test for nitrogen deficiency in forest trees. *Forest Ecology and Management, 42: 267-282.*

Kirshbaum, M.U.F., Bellingham, D.W. and Cromer, R.N., 1992. Growth analysis of the effects of phosphorus nutrition on seedlings of *Eucalyptus grandis. Australian Journal of Plant physiology, 19:55-66.*

Kirschbaum, M.U.F. and Tompkins, D., 1990. Photosinthetic reponses to phosphorus nutrition in *Eucalyptus grandis* seedlings. *Australian Journal of Plant Physiology, 17:527-535.*

Landsberg, J., 2003. Physiology in Forest Models: History and the Future. *Forest Biometry, Modelling and Information Sciences*, 1:49-63.

Lang, A.R.G., Yeuqin, X. and Norman, J.M., 1985. Crop structure and the development of direct sunlight. *Agricultural and Forest Meteorology*, 35:83-101.

Leuning, R., Cromer, R.N., and Rice, S., 1991. Spatial distributions of Foliar nitrogen and Phosphorus in crowns of *Eucalyptus grandis. Oecologia, 88:504-510.*

Linder. S., 1985. Potential and Actual Proeduction in Australian forest stands. In Landsberg, J.J. and Parsons, W., (eds.). *Research for forest management*, CSIRO, Melbourne Australia, p. 11-35.

Linder, S., 1995. Foliar analyses for detecting and correcting nutrient imbalances in Norway spruce. *Ecological Bulletins,* 44:178-190.

Linder, S. and Exelsson, B., 1982. Changes in Carbon uptake and allocation patterns as a result of irrigation and fertilisation in a young *Pinus sylvestris* stand. In R.H. Waring (ed.). *'Carbon Uptake and allocation in Subalpine Ecosystems as a Key to Management'*. p. 38-44. Forest Research Laboratory, Oregon State University, U.S.A.

Linder. S. and Rook , D.A., 1984. Effects of mineral nutrition on carbon dioxide exchange and partitioning of carbon in trees. In G.D. Bowen and E.K.S Nambiar (eds.). *Nutrition of plantation forests*. Academic press, London, p. 211- 236.

Mcgrath, J.F. and McArthur, S.L., 1989. Influence of fertilizer timing on seasonal nutrient uptake and Dry matter production by young *Pinus radiata* in Southern Western Australia. *Forestry Ecology and Management, 30(1990):259-269*.

Mead, D.J., 1984. Diagnosis of nutrient deficiencies in plantations. P. In G.D.Bowen and E.K.S. Nambiar (eds.). *Nutrition of plantation forests*. Academic Press, London, p. 259-291.

Mead, D.J. and Will, G.M., 1976. Seasonal and between tree variation in nutrient levels in *Pinus radiata* foliage. *New Zealand Journal for Forest Science, 6:3-13.*

Miller, H.G., 1981. Forest fertilization: some guiding concepts. *Forestry, 54:157-167.*

Miller, H.G., 1984. Dynamics of nutrient cycling in. Plantation ecosystems. In G.D. Bowen and E.K.S. Nambiar (eds.). *Nutrition of plantation forests*. Academic press, London.

Mooney, H.A., Ferrar, P.J. and Slatyer, R.O., 1978. Photosynthetic capacity and carbon allocation patterns in diverse growth forms of eucalyptus. *Oecologia* 36,103-111.

Nambiar, E.K.S. and Bowen, G.D., 1986. Uptake, distribution and retranslocation of nitrogen by *Pinus radiata* ^{15}N- labeled fertilizer applied to podzolised sandy soil. *Forest Ecology and Management., 15:269-284.*

Needham, T.D., Burger, J.A. and Oderwald, R.G., 1990. Relationship between Diagnosis and Recommendation Intergrated Sytem (DRIS) Optimal and Foliar Nutrient Critical Levels. *Soil Science Society of America Journal,* 54:883-886.

Payn, T.M. and Clough, M.E., 1987. Seasonal variation of foliar nutrient concentrations in *Pinus radiata* in the southern Cape. *South African Forestry Journal, 143:37-41.*

Payn, T.W., de Ronde, C. and Grey, D.C., 1988. Phosphate fertilization of mature *Pinus radiata* stands. *South African Forestry Journal, 147:26-31.*

Raison, R.J., Khanna, P.K., Connel, M. and Falkiner, R.A. 1989. Effect of water availability and fertilization on Nitrogen cylcling a stand of *Pinus radiata. Forest Ecology and Management,* 30:31-43*.*

Raison. R.J., Khanna, P.K. and Crane, W.J.B., 1982. Effects of intensified harvesting on rates of nitrogen and phosphorus removal from *Pinus radiata* and *Eucalyptus* forests in Australia and New Zealand. *New Zealand Journal of Forestry Sciences,* 12:394-403.

Raison, R.J., Meyers , B.J. and Benson, M.L., 1992. Dynamics of *Pinus radiata* foliage in relation to water and nitrogen stress. In Needle production and properties. *Foresty Ecology and Management,* 2:139-158*.*

Reid, C.P.P., Kidd, F.A. and Ekwebelam, S.A., 1983. Nitrogen nutrition, photosynthesis and carbon allocation in ectomycorrhizal pine. *Plant and Soil,* 71:415-432.

Sanantonio, D., 1989. Dry matter partitioning and and fine root production in forests.- new approaches to a different problem. In J.S. Perreira and J.J. Landsberg (eds.). *Biomass production by fast growing trees*. Kluwer academic press, p. 57-72.

Schulze, R.E., 1997. South African Atlas of Agrohydrology and -Climatology. Water Research Commission, Pretoria, *Report TT82/96.*

Shepherd, K. R. 1985. Carbon Balance, carbon partitioning and yield of forest crops. In Landsberg, J.J. and Parsons, W (eds.). *Research for Forest Management*. CSIRO, Melbourne. p. 36-51.

Sheriff, D.W. 1996. Responses of carbon gain and growth of *Pinus radiata* stands to thinning and fertilization. *Tree Physiology, 16:527-536.*

Sheriff, D.W., Nambiar, E.K.S. and Fife, D.N., 1986. Relationships between nutrient status, carbon assimilation and water use efficiency in *Pinus radiata* (D.Don) needles. *Tree Physiology*, 2:73-88.

Smethurst, P., Baillie, C., Cherry, M. and Holz, G., 2003. fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. *Forest Ecology and Management, 176: 531-542.*

Smith, F.W. and Long, J.N., 1989. The influence of canopy architecture on stemwood production and growth efficiency of *Pinus contorta* var. *latifolia. Journal of Applied Ecology,* 26:681-691*.*

Snowdon , P. and Waring, H.D., 1990. Growth responses by P*inus radiata* to combinations of superphosphate, urea and thinning type. *Forest Ecology and Management, 30:313-325.*

Theodorou, C., 1986. Movement of nitrogenous fertilizer applied to sandy pine plantation soils in South Australia. *Australian. Forestry Research, 16:347-355.*

Timmer, V.R. and Morrow, L.D., 1984. Predicting fertiliser growth response and nutrient status of jack pine by foliar diagnosis. In E.L. Stone (ed.). *Forest soils and treatment impacts,* University of Tennessee, Knoxville, pp. 335-351.

Turner, J., Knot, J.H. and Lambert, M., 1995. Fertlization of *Pinus radiata* plantations after thinning. I productivity gains.Research devision. *Australian Forestry, 59(1):7-21.*

Turner, J. and Lambert, M.J., 1983. Nutrient cycling within a 27 year old *Eucalyptus grandis* plantation in New South Wales. *Forestry Ecology and Management, 44:142-152.*

Ulrich, A. and Hills, F.J., 1967. Principles and practices of plant analyses. In G.W. Hardy (ed.). *Soil testing and plant analyses. SSSA Spec. Publ. 2.* SSSA, Madison, WI, p. 11-24.

Uys, H.J.E., 1991. Evaluating forestry land during inflationary times. *South African Forestry Journal*, 156:7-11.

Waring, H.D. 1981. Forest fertilization in Australia: Early and late. In N.D. Turvey (ed.). *Australian Forest nutrition workshop: Productivity in Perpetuity*, 10-14 August 1981, at Canberra. CSIRO, Melbourne, p. 201-217.

Wise, P.K. and Pitman, M.G., 1981. Nutrient removal and replacement associated with short rotation eucalyptus plantations. *Australian Forestry Journal, 44:142-152.*

Woolons, R.C., 1985. Problems associated with analyses of long term *Pinus* fertilizer x thinning experiments. *Australian Forestry Research. 15:495-507.*

APPENDICES

Appendix A – *P radiata* SAWTIMBER ROTATION (25 years) without fertiliser at MAI 10.7

Year	Operation		R/ha
-1	Land Value		6170
0	Land Clearing		1669
0	Planting & plants		856
0	Fertilizing		551
0	Blanking		166
1	Weeding Cost		1138
2	Weeding Cost		1138
3	Prune to 2.5 m		436
5	Prune to 3.5 m		515
7	Prune to 5.5 m		576
9	Prune to 7.0 m		578
12	Marking trees to thin		289
13	Fertiliser Follow Up		0
All Years	Noxious Weeds & pests		61
All Years	Fire Protection incl insurance		149
All Years	Fire extinguishing		16
All Years	Conservation		35
All Years	Road Maintenance incl harvesting roads		146
All Years	Administration Overheads		573
Harvesting	**Operation**		**R/m³**
12	Thinning		129.78
25	Harvesting		63.24
Cost	AT Roadside		193
Yield	**Product**	**MAI**	**m³/ha**
12	Other (Thinning)	7.4	88.8
25	Saw timber	10.7	268
Selling Prices			**R/m³**
12	Other (Thinning)		214.98
25	Saw timber		306.12
Stumpage	**Product**		**R/m³**
12	Other (Thinning)		85
25	Saw timber		243

NPV - IRR Calculations					5.95%
Year	Operation	Cost/ha	Annual Costs	Revenue/ha	Net Cash flow
-1	Land Value	R 6,170.00	R 572.76	R -	R -6,742.76
0	Land Clearing, Plants, Planting, Fertilizing	R 3,242.55	R 572.76	R -	R -3,815.31
1	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
2	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
3	Pruning to 2.5	R 435.86	R 979.84	R -	R - 1,415.70
4			R 979.84	R -	R -979.84
5	Pruning to 3.5	R 515.28	R 979.84	R -	R -1,495.12
6			R 979.84	R -	R -979.84
7	Pruning to 5.5	R 576.23	R 979.84	R -	R -1,556.07
8			R 979.84	R -	R -979.84
9	Pruning to 7.0	R 577.56	R 979.84	R -	R -1,557.40
10			R 979.84	R -	R -979.84
11	Marking trees to thin	R 289.12	R 979.84	R -	R -1,268.96
12	Thinning	R 11,524.46	R 979.84	R 19,090.22	R 6,585.92
13		R -	R 979.84	R -	R -979.84
14		R -	R 979.84	R -	R -979.84
15		R -	R 979.84	R -	R -979.84
16		R -	R 979.84	R -	R -979.84
17		R -	R 979.84	R -	R -979.84
18		R -	R 979.84	R -	R -979.84
19		R -	R 979.84	R -	R -979.84
20		R -	R 979.84	R -	R -979.84
21		R -	R 979.84	R -	R -979.84
22		R -	R 979.84	R -	R -979.84
23		R -	R 979.84	R -	R -979.84
24		R -	R 979.84	R -	R -979.84
25	Clear fell	R -	R 979.84	R 71,140.40	R 70,160.56
	NPV				R -5,978.70
	IRR				4.25%

Appendix B – *P. radiata* SAWTIMBER ROTATION (25 YEARS) with fertiliser application and increase in MAI by 2 m^3 ha^{-1} a^{-1}

Year	Operation		R/ha
-1	Land Value		6170
0	Land Clearing		1669
0	Planting & plants		856
0	Fertilizing		551
0	Blanking		166
1	Weeding Cost		1138
2	Weeding Cost		1138
3	Prune to 2.5 m		436
5	Prune to 3.5 m		515
7	Prune to 5.5 m		576
9	Prune to 7.0 m		578
12	Marking trees to thin		289
13	Fertiliser Follow Up		1200
All Years	Noxious Weeds & pests		61
All Years	Fire Protection incl insurance		149
All Years	Fire extinguishing		16
All Years	Conservation		35
All Years	Road Maintenance incl harvesting roads		146
All Years	Administration Overheads		573
Harvesting	**Operation**		**R/m^3**
12	Thinning		129.78
25	Harvesting		57.73
Cost	AT Roadside		188
Yield	**Product**	**MAI**	**m^3/ha**
12	Other (Thinning)	7.4	88.8
25	Saw timber	11.6	290
Selling Prices			**R/m^3**
12	Other (Thinning)		214.98
25	Saw timber		319.97
Stumpage	**Product**		**R/m^3**
12	Other (Thinning)		85
25	Saw timber		262

NPV - IRR Calculations					5.95%
Year	Operation	Cost/ha	Annual Costs	Revenue/ha	Net Cash flow
-1	Land Value	R 6,170.00	R 572.76	R -	R -6,742.76
0	Land Clearing, Plants, Planting, Fertilizing	R 3,242.55	R 572.76	R -	R -3,815.31
1	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
2	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
3	Pruning to 2.5	R 435.86	R 979.84	R -	R -1,415.70
4			R 979.84	R -	R -979.84
5	Pruning to 3.5	R 515.28	R 979.84	R -	R -1,495.12
6			R 979.84	R -	R -979.84
7	Pruning to 5.5	R 576.23	R 979.84	R -	R -1,556.07
8			R 979.84	R -	R -979.84
9	Pruning to 7.0	R 577.56	R 979.84	R -	R -1,557.40
10			R 979.84	R -	R -979.84
11	Marking trees to thin	R 289.12	R 979.84	R -	R -1,268.96
12	Thinning	R 11,524.46	R 979.84	R 19,090.22	R 6,585.92
13	Fertiliser Follow Up	R 1,200.00	R 979.84	R -	R -2,179.84
14		R -	R 979.84	R -	R -979.84
15		R -	R 979.84	R -	R -979.84
16		R -	R 979.84	R -	R -979.84
17		R -	R 979.84	R -	R -979.84
18		R -	R 979.84	R -	R -979.84
19		R -	R 979.84	R -	R -979.84
20		R -	R 979.84	R -	R -979.84
21		R -	R 979.84	R -	R -979.84
22		R -	R 979.84	R -	R -979.84
23		R -	R 979.84	R -	R -979.84
24		R -	R 979.84	R -	R -979.84
25	Clear fell	R -	R 979.84	R 82,219.60	R 81,239.76
	NPV				R -4,156.05
	IRR				4.86%

Appendix C – *P. radiata* SAWTIMBER ROTATION (25 YEARS) with fertiliser application and increase by 4 m³ ha⁻¹ a⁻¹

Year	Operation		R/ha
-1	Land Value		6170
0	Land Clearing		1669
0	Planting & plants		856
0	Fertilizing		551
0	Blanking		166
1	Weeding Cost		1138
2	Weeding Cost		1138
3	Prune to 2.5 m		436
5	Prune to 3.5 m		515
7	Prune to 5.5 m		576
9	Prune to 7.0 m		578
12	Marking trees to thin		289
13/14	Fertiliser Follow Up		1200
All Years	Noxious Weeds & pests		61
All Years	Fire Protection incl insurance		149
All Years	Fire extinguishing		16
All Years	Conservation		35
All Years	Road Maintenance incl harvesting roads		146
All Years	Administration Overheads		573
Harvesting	**Operation**		**R/m³**
12	Thinning		129.78
25	Harvesting		53.10
Cost	AT Roadside		183
Yield	**Product**	**MAI**	**m³/ha**
12	Other (Thinning)	7.4	88.8
25	Saw timber	12.6	316
Selling Prices			**R/m³**
12	Other (Thinning)		214.98
25	Saw timber		331.70
Stumpage	**Product**		**R/m³**
12	Other (Thinning)		85
25	Saw timber		279

NPV - IRR Calculations					5.95%
Year	Operation	Cost/ha	Annual Costs	Revenue/ha	Net Cash flow
-1	Land Value	R 6,170.00	R 572.76	R -	R -6,742.76
0	Land Clearing, Plants, Planting, Fertilizing	R 3,242.55	R 572.76	R -	R -3,815.31
1	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
2	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
3	Pruning to 2.5	R 435.86	R 979.84	R -	R -1,415.70
4			R 979.84	R -	R -979.84
5	Pruning to 3.5	R 515.28	R 979.84	R -	R -1,495.12
6			R 979.84	R -	R -979.84
7	Pruning to 5.5	R 576.23	R 979.84	R -	R -1,556.07
8			R 979.84	R -	R -979.84
9	Pruning to 7.0	R 577.56	R 979.84	R -	R -1,557.40
10			R 979.84	R -	R -979.84
11	Marking trees to thin	R 289.12	R 979.84	R -	R -1,268.96
12	Thinning	R 11,524.46	R 979.84	R 19,090.22	R 6,585.92
13	Fertiliser Follow Up	R 1,200.00	R 979.84	R -	R -2,179.84
14	Fertiliser Follow Up	R 1,200.00	R 979.84	R -	R -2,179.84
15		R -	R 979.84	R -	R -979.84
16		R -	R 979.84	R -	R -979.84
17		R -	R 979.84	R -	R -979.84
18		R -	R 979.84	R -	R -979.84
19		R -	R 979.84	R -	R -979.84
20		R -	R 979.84	R -	R -979.84
21		R -	R 979.84	R -	R -979.84
22		R -	R 979.84	R -	R -979.84
23		R -	R 979.84	R -	R -979.84
24		R -	R 979.84	R -	R -979.84
25	Clearfell	R -	R 979.84	R 94,068.93	R 93,089.09
	NPV				R -2,143.33
	IRR				5.42%

Appendix D – *P. radiata* SAWTIMBER ROTATION (25 YEARS) with fertiliser application and increase by 6m³ ha^{-1} a^{-1}

Year	Operation		R/ha
-1	Land Value		6170
0	Land Clearing		1669
0	Planting & plants		856
0	Fertilizing		551
0	Blanking		166
1	Weeding Cost		1138
2	Weeding Cost		1138
3	Prune to 2.5 m		436
5	Prune to 3.5 m		515
7	Prune to 5.5 m		576
9	Prune to 7.0 m		578
12	Marking trees to thin		289
13/14	Fertiliser Follow Up		1200
All Years	Noxious Weeds & pests		61
All Years	Fire Protection incl insurance		149
All Years	Fire extinguishing		16
All Years	Conservation		35
All Years	Road Maintenance incl harvesting roads		146
All Years	Administration Overheads		573
Harvesting	**Operation**		**R/m³**
12	Thinning		129.78
25	Harvesting		51.15
Cost	AT Roadside		181
Yield	**Product**	**MAI**	**m³/ha**
12	Other (Thinning)	7.4	88.8
25	Saw timber	13.6	340
Selling Prices			**R/m³**
12	Other (Thinning)		214.98
25	Saw timber		345.04
Stumpage	**Product**		**R/m³**
12	Other (Thinning)		85
25	Saw timber		294

NPV - IRR Calculations					5.95%
Year	Operation	Cost/ha	Annual Costs	Revenue/ha	Net Cash flow
-1	Land Value	R 6,170.00	R 572.76	R -	R -6,742.76
0	Land Clearing, Plants, Planting, Fertilizing	R 3,242.55	R 572.76	R -	R -3,815.31
1	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
2	Weeding Cost	R 1,137.50	R 979.84	R -	R -2,117.34
3	Pruning to 2.5	R 435.86	R 979.84	R -	R -1,415.70
4			R 979.84	R -	R -979.84
5	Pruning to 3.5	R 515.28	R 979.84	R -	R -1,495.12
6			R 979.84	R -	R -979.84
7	Pruning to 5.5	R 576.23	R 979.84	R -	R -1,556.07
8			R 979.84	R -	R -979.84
9	Pruning to 7.0	R 577.56	R 979.84	R -	R -1,557.40
10			R 979.84	R -	R -979.84
11	Marking trees to thin	R 289.12	R 979.84	R -	R -1,268.96
12	Thinning	R 11,524.46	R 979.84	R 19,090.22	R 6,585.92
13	Fertiliser Follow Up	R 1,200.00	R 979.84	R -	R -2,179.84
14	Fertiliser Follow Up	R 1,200.00	R 979.84	R -	R -2,179.84
15		R -	R 979.84	R -	R -979.84
16		R -	R 979.84	R -	R -979.84
17		R -	R 979.84	R -	R -979.84
18		R -	R 979.84	R -	R -979.84
19		R -	R 979.84	R -	R -979.84
20		R -	R 979.84	R -	R -979.84
21		R -	R 979.84	R -	R -979.84
22		R -	R 979.84	R -	R -979.84
23		R -	R 979.84	R -	R -979.84
24		R -	R 979.84	R -	R -979.84
25	Clear fell	R -	R 979.84	R 105,947.01	R 104,967.17
	NPV				R 351.38
	IRR				6.03%

Appendix E – Average long term moisture growing season (MGS; where average P> 0.3E$_r$) at Grabouw.