Growth responses to fertilizer application of thinned, mid-rotation *Pinus radiata* stands across a soil water availability gradient in the Boland area of the Western Cape

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DECLARATION

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SUMMARY

The purpose of the study was to investigate the effect of mid rotation fertilizer application on leaf area index (LAI), basal area and volume increment in thinned *Pinus radiata* stands on the most common soils of the Boland region in the Western Cape.

The study was conducted on a range of sites in the Boland region of MTO Forestry Company, chosen to reflect the two most common soil types and a water availability gradient in each soil type. A factorial combination of fertilizer treatments with three levels each for nitrogen (N) at 0, 100 and 200 kg ha^{-1} and phosphorus (P) at 0, 50 and 100 kg ha^{-1} was used. This design was replicated four times across a gradient of water availability for each of the two common soil groups, forming a complete trial series. All replications were laid out in *P. radiata* stands that had received their mid-rotation thinning prior to treatment implementation.

LAI, diameter at breast height and height measurements as well as foliar analysis were determined before the implementation of the study in 2008 and then subsequently at predetermined intervals in 2009 and 2010. Leaf area index and stem volume increment were measured in order to evaluate the influence on growth efficiency. LAI was estimated using the gap fraction method with the use of a ceptometer. Volume increment was calculated using diameter and height measurements and basal area was calculated by means of diameter measurements. The abovementioned growth responses were then used to determine the effect of increased nutrient availability on stand growth.

There were no significant interactions detected between any of the factors, N, P and water availability class in their effect on LAI, basal area, volume increment and growth efficiency. LAI increment responded significantly to N and P in the first year but only to P in the

second year after treatment. Significant basal area responses to N and P were recorded in the second but not the first year. This might have been due to the fact that trees had to re-build their canopies after thinning before a basal area response could be obtained. For the variables where an analysis of total growth response over the two year period was done, basal area increment and volume increment significantly responded to the application of nitrogen but not to phosphorus. Growth efficiency was not significantly influenced by either nitrogen or phosphorus over the full two year monitoring period. Water availability class consistently and significantly influenced basal area increment, volume increment and growth efficiency over the two year period as well as during year one and year two.

The best responses generally occurred as a result of the additive effects of N and P. The growth response did not remain the same across the water availability classes. The wetter sites tended to have greater responses than the drier sites. Although these are still early results, the growth responses could be attributed to an increase in LAI. Nutrient analysis through vector analysis indicated that the additional N and P from fertilizer application were taken up by the trees thereby resulting in greater LAI and increased stem wood production.

OPSOMMING

Die studie het ten doel gestel om die effek van mid-rotasie bemesting op blaar oppervlak indeks (BOI), basale oppervlakte- en volume aanwas te ondersoek in gedunde opstande van *Pinus radiata* op die mees algemene grondtipes van die Bolandstreek, Wes-Kaapland.

Eksperimente is uitgelê oor 'n reeks van groeiplekke in die Bolandstreek wat gekies is om 'n water beskibaarheidsgradient te verteenwoordig oor elk van die twee mees algemene grondtipes. 'n Faktoriaal-kombinasie van kunsmisbehandelings met drie vlakke elk van stikstof [(N) teen 0, 100 en 200 kg ha^{-1}] en fosfor [(P) teen 0, 50 en 100 kg ha^{-1}] is toegedien. Hierdie ontwerp is vier maal herhaal oor 'n gradient van grondwater beskikbaarheid, oor elk van die twee mees algemene grondtipes, om sodoende 'n volledige eksperimentele reeks te vorm. Elke herhaling is uitgelê in 'n *P. radiata* opstand wat reeds 'n mid-rotasie dunning ondergaan het voor implementering van die kunsmis behandelings.

Metings van BOI, deursnee op borshoogte, boomhoogte asook blaarmonsters is geneem voor implementering in 2008 en daarna met vooraf bepaalde tussenposes in 2009 en 2010. Die BOI en stam volume aanwas is bepaal om die effek van behandelings op groei-effektiwiteit te evalueer. Die gaping fraksie tegniek is gebruik om BOI te skat met behulp van 'n sonvlek septometer. Volume aanwas is bereken vanaf deursnee en hoogtemetings en basale oppervlak aanwas vanaf deursnee-metings. Metings van al bogenoemde groeireaksies is gebruik om die effek van verhoogde voedingstof beskikbaarheid op opstandsgroei te evalueer.

Daar was geen betekenisvolle interaksies tussen enige van die faktore N, P of water beskikbaarheidsklas met betrekking tot reaksies op BOI, basale oppervlak- en volume

aanwas of groei-effektiwiteit nie. Die BOI het betekenisvol gereageer op N en P in die eerste jaar, maar slegs op P in die tweede jaar na behandeling. Basale oppervlakte aanwas is betekenisvol verbeter deur N en P in die tweede jaar maar nie in die eerste jaar nie. Dit is waarskynlik as gevolg van die feit dat opstande eers hul kroondak moes herstel (na dunnings) voordat 'n reaksie in basale oppervlak verkry kon word. Vir die veranderlikes waar 'n analise van die groeireaksie oor die volle twee jaar moniteringsperiode gedoen is, het basale oppervlak- en volume aanwas betekenisvol gereageer op stikstof maar nie op fosfor nie. Groei-effektiwiteit is nie betekenisvol geaffekteer deur N of P oor die volle twee jaar moniteringsperiode nie. Water beskikbaarheidsklas het basale oppervlak en volume aanwas asook groei-effektiwiteit betekenisvol en voortdurend beïnvloed in die eerste en tweede jaar, asook gedurende die volle twee jaar moniteringsperiode.

Die beste groeireaksie is oor die algemeen verkry waar N en P gesamentlik toegedien is en waar dus aanvullende reaksies verkry is. Groeireaksies het betekenisvol verskil na gelang van water beskikbaarheidsklas, met die grootste reaksie op die natste groeiplekke. Hoewel hierdie vroeë resultate is, kan ons die meganisme van die reaksie primêr toeskryf aan 'n toename in BOI. Vektor analise van blaar voedingstof vlakke het aangedui dat addisionele N en P na kunsmis toediening opgeneem is, wat die weg gebaan het vir 'n toename in BOI en verhoogde volume aanwas.

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ANOVA	Analysis of variance
a	Annum
B	Boron
Ca	Calcium
cm	centimeter
Cu	Copper
DBH	Diameter at breast height
Df	Degrees of freedom
Fe	Iron
GE	Growth efficiency
ha	Hectares
ICFR	Institute for Commercial Forestry Research
IPAR	Intercepted photosynthetically active radiation
Ht	Tree height
K	Potassium
kg	Kilogram
LAI	Leaf area index
lbs	Pound
LS	Least squares
LSD	Least significant difference
Mg	Magnesium
mg	Milligram
Mn	Manganese
m	meter
m^3	cubic meter
m^2	square meter
mm	millimeter
MTO	MTO Forestry Company (Pty) Ltd.
N	Nitrogen
P	Phosphorus
PAR	Photosynthetically active radiation
SE	Standard error
Zn	Zinc

CHAPTER 1: INTRODUCTION

1.1 Background

The South African forestry industry depends almost entirely on a man-made resource for its commercial softwood supply. The total area that is currently under plantation is 1 257 341 hectares (ha). Pine plantation accounts for 660 104 ha (52.5%) of this total area (Forestry South Africa, 2009). The saw log and veneer industry is an economically important component of the South African forestry sector producing approximately 4 895 000 m^3 of timber annually, valued at close to R1,8 billion in 2008 (Forestry South Africa, 2009). The demand for timber and timber based products is expected to increase in the country in future. The current softwood sawlog resource of 660 104 ha is unable to sustain the demand for sawn timber and South Africa has already become an importer, rather than an exporter of sawn timber (Crickmay and Associates, 2004).

This increase in demand will require the total area under plantation forestry to be increased in order to satisfy this increase by locally produced timber. It is however, an option that cannot be expected to yield much as the area under forestry has actually been decreasing over the years. It has decreased by 9.1% from 1998 to 2008 (Forestry South Africa, 2009). Table 1.1 presents a steady downward trend in new afforestation for softwood sawlog production for a decade since 1991. Plantation fires have added on to the problem by causing widespread damage in commercial plantations. Table 1.1 also shows the area of softwood plantation damaged by fire for the same period.

Table 1.1: New afforestation as well as fire damage in commercial softwood sawlog plantations in South Africa for one decade since 1991 collated from (Crickmay and Associates, 2004)

Year	Area afforested for softwood sawlog production (ha)	Area damaged by Fire (ha)
1991/92	5 450	5 684
1992/93	5 067	7 590
1993/94	3 650	14 124
1994/95	2 405	20 106
1995/96	1 853	7 044
1996/97	2 297	8 071
1997/98	583	5 109
1998/99	1 279	11 001
1999/00	427	10 649
2000/01	1 180	12 219
2001/02	1 740	11 860
Average	**2 352**	**10 314**

[1] This data refers to new afforestation only and does not include the replanting of the existing plantation land once it has been harvested.
[2] The term "damaged" includes totally destroyed timber.

With the area under softwood plantation declining, this implies that production has to be increased on the areas that are currently under plantation forests. This can be achieved through some of the following strategies;

i) Increasing growth rates through tree breeding

ii) Better site species matching and

iii) Improved silvicultural practices.

These strategies will help to reduce the shortfall in the forestry industry (Donald *et al.*, 1987).

The commercial forestry resource in South Africa is managed through intensive silviculture with fast-growing exotic species, with the primary aim of optimizing yield for the saw timber industry (Louw & Scholes, 2002). The majority of areas that are under plantation forestry in South Africa are located on sites of moderate productivity. Although growth rates in South Africa may compare favourably with international norms for subtropical forestry, the productivity of many sites is below the potential and often growth rates vary widely within a relatively small geographic area (Louw & Scholes, 2002).

The growth rate of sawlog plantations in South Africa is approximately 11.2 m^3 ha^{-1} a^{-1} on 25 to 35 year rotations (Crickmay and Associates, 2004). In a recent study by Badenhorst (2010) in the Boland area in the Western Cape, the growth rate for *Pinus radiata* was pegged at 10.7 m^3 ha^{-1} a^{-1}. The soils in the Western Cape are generally nutritionally poor, extremely leached, acid and low in bases and phosphorus (Donald *et al*., 1987; Payn & Clough, 1988). In southern Australia, plantations of *P. radiata* have also been established across a wide range of soils with a low nutrient capacity with growth rates of approximately 12.35 green tons ha^{-1} a^{-1} (Fox *et al*., 2006). Productivity is therefore often limited by nutrient availability (Hopmans *et al.,* 2008). The use of fertilizers to raise the productivity is one field that holds considerable promise in the forestry industry (Fox *et al*., 2006). Research which has been undertaken in the country since 1930's indicates that there are many cases where the use of inorganic fertilizers at planting was found to increase productivity in pine stands (Donald *et al*., 1987; Herbert & Schönau, 1989 & 1990).

1.2 Justification of study

While the effects of fertilizer application at planting on plantation productivity are fairly established in South Africa, the effects of mid- and late-rotation fertilization are not well known and understood (Campion, 2006). The application of fertilizer to semi-mature conifer stands has become a standard practice in many parts of the world for example in Australia (Hopmans *et al.*, 2008) the south eastern United states (Fox *et al.*, 2006), New Zealand (Rivaie & Tillman, 2009) and Chile (Albaugh *et al.*, 2004a; Albaugh *et al.*, 2007). The increasing demand for sawtimber on local and international markets has resulted in pressures to increase wood production from South African forest plantations. A key strategy for improving productivity from planted forests is to optimize tree nutrition at various stages throughout a rotation by management interventions.

The potential for economic gains that can be obtained by the addition of fertilizers to late-rotation softwood stands has in recent years, attracted the interest of sawn timber growers in South Africa (Campion, 2006). The application of fertilizer towards the end of the rotation is an attractive option from both a wood production and an economic perspective. The economic advantages of mid- and late-rotation fertilizer applications include some of the following:

- Increased log size and therefore value per unit volume (Carlyle, 1995; Yang, 1998).
- Reduction in extraction costs per unit volume because of the larger log size (Donald, 1987; Yang, 1998).
- Reduction in the length of the compound interest period (Donald, 1987) before final harvesting, leading to a maximization of return on investment in fertilization (Turner *et al.*, 1996).

- A lower risk associated with the shorter time period between nutrient addition and return on investment (harvesting) when hail or insect pests can damage the trees (Carlson *et al.*, 2000).
- The quality of the additional wood is superior to that derived from first thinning or from fertilization at planting because of less juvenile wood, as the additional wood is clear (knot free) high quality, mature wood (Schutz, 1976; Donald, 1987; Turner *et al.*, 1992).
- Fertilizer application is easier (Schutz, 1976) (broadcast as opposed to application on a per tree basis), thus preventing root scorch and mortality (Carlson *et al.*, 2000).
- When fertilizer is applied after canopy closure, it does not stimulate weed growth (Morris, 1987).

The strategy of the South African forestry industry of maximizing biological productivity as well as economic benefit will require a profound improvement in the understanding of the interrelationships in forest ecosystems to allow for the appropriate implementation of specific management strategies (Louw & Scholes, 2002). In some of the South African research programmes that have been conducted so far, failure to understand the stand response mechanism to changes in resource availability resulted in poor or erratic responses upon implementation (du Toit, 2006). Results from such research programmes cannot be easily extrapolated to other sites. Sites will always have varying fertilizer element requirements and the magnitude of the responses will also vary. Many stands that did not respond to improved nutrition, or responded poorly, did so under conditions of water stress (Donald *et al.*, 1987; Payn & Clough, 1988; Herbert & Schonau, 1990). It is therefore important to implement fertilization with adequate precision on a site-specific basis. It is also necessary to understand the interrelationships between nutrition and water availability gradient in nutritional experiments in order to better understand the response mechanisms under areas of varying soil water availability and enable extrapolation of the results to areas of similar characteristics (du Toit, 2006).

In most countries where application of fertiliser is done as a standard practice to semi-mature conifer stands, nutrition is the factor limiting growth; moisture is seldom limiting (Donald, 1987). In South Africa however, moisture rather than nutrition is usually the factor limiting growth (Donald, 1987). Hydrological research in South Africa indicates that water is the most important limiting input in the growth of exotic trees such as *eucalyptus*, pine, and wattle (Tewari, 2005). Drought is a normal feature of South Africa's climate and its occurrence is inevitable (Kunz & Smith, 2001).
Widespread and sustained droughts have periodically affected southern Africa including South Africa over the past three decades (Dube & Jury, 2000). One of the worst droughts experienced in the country was in 1992/1993. This drought had a devastating effect on the survival and growth of trees in forestry plantations (Forest Owner's Association, 1993). A water availability gradient was therefore an important factor incorporated in this study.

Nitrogen is the element most likely to be limiting at late stages of the rotation in many plantations (Miller, 1981; Fox *et al.*, 2006). It is apparent from some research results that applications of N will not result in an increase in growth if there is a dominating deficiency of P (Snowdon & Waring, 1990; Turner *et al.*, 1996). The bulk of soils planted *with P. radiata* in the Cape forestry regions are poor compared with agricultural soils and low in both macro and micro nutrients (Donald *et al.*, 1987; Payn *et al.*, 1988; Payn & Clough, 1988). One of the major problems affecting plantation forestry in the Cape regions of South Africa and indeed throughout most Southern Africa is an inherent phosphate deficiency (Payn & Clough 1987). The problem can be diagnosed visually from some stands with characteristic spindly tree form and low biomass with needles concentrated at the end of branches, dead top occurrence, flaky bark and resin production (Payn *et al.,* 1988).

The study therefore focused on N and P as these are the elements that several local studies in the past have identified to be the major limitations to optimum production in South African plantations, and most specifically so in the Southern and Western Cape.

It is necessary for a forestry manager to accurately identify sites and stands which will provide an economic response to fertilization in order to manage plantations efficiently (Carlyle, 1998). This can be achieved by the development of a decision support system that can be used by forest managers to better predict responsive stands in their plantations. This can have economic benefits as companies will not blindly follow the general application of fertilizer to all compartments, but only to those where a response to fertilization has been predicted (Fisher & Binkley, 2000).

The study therefore developed key components that can be built into a future decision support system.

1.3 Objectives of the study

The objectives of the study were to:

1. Determine the effect of mid rotation fertilizer application on leaf area index (LAI), basal area increment and volume increment in thinned *P. radiata* compartments on the most common soils of the Boland region.
2. Determine the effect of soil water availability on the magnitude of the growth response.
3. Develop building blocks that can be built into a decision support system that can be used by forest managers to predict the potential response of a stand to fertilization on a site-specific basis.

1.3.1 Hypotheses

The basic hypotheses for the study were:

1. N and P fertilization increases stand LAI, basal area and volume increment.
2. The magnitude of the response is related to soil water availability.

1.3.1.1 Key Research Questions

The following questions were key to achieving the objectives of the study:

- Does N and/or P application affect foliar nutrient concentration, stand LAI, basal area increment and volume increment?
- What are the optimum quantities of N and P needed in order to maximise growth on the most common soil groups?
- Does the optimum N:P ratio stay the same across the soil water availability gradient?
- What is the magnitude of the response across the water availability gradient?
- Is the growth response mainly attributable to an increase in LAI?

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

How does a stand translate higher nutrient availability into greater stem growth? This is a question that has been asked by D. Binkley as far back as 1986. The answer(s) to this question is (are) critical in any analysis of the effect of fertilization on tree growth. Though there has been work done in the country on mid-rotation fertilization of pine stands, there is however, limited local literature linking the studies to water availability and light interception (through changes in LAI) on pines in South Africa. This has led to considerable reliance on studies done on pines in other countries like the United States, New Zealand and Australia reported in this section on literature review.

This chapter presents an overview of the literature on this topic with a focus on the following:

- Effects of fertilization after canopy closure on LAI, basal area increment and volume response under pines and
- Effects of water and nutrient availability on growth in existing mid rotation stands.

2.2 Effect of fertilization on basal area and stem volume increment

Why do nutrient limitations appear to be so common in forest plantations? Nutrient limitations develop when a stand's potential nutrient use can no longer be met by soil nutrient supply (Figure 2.1**).**

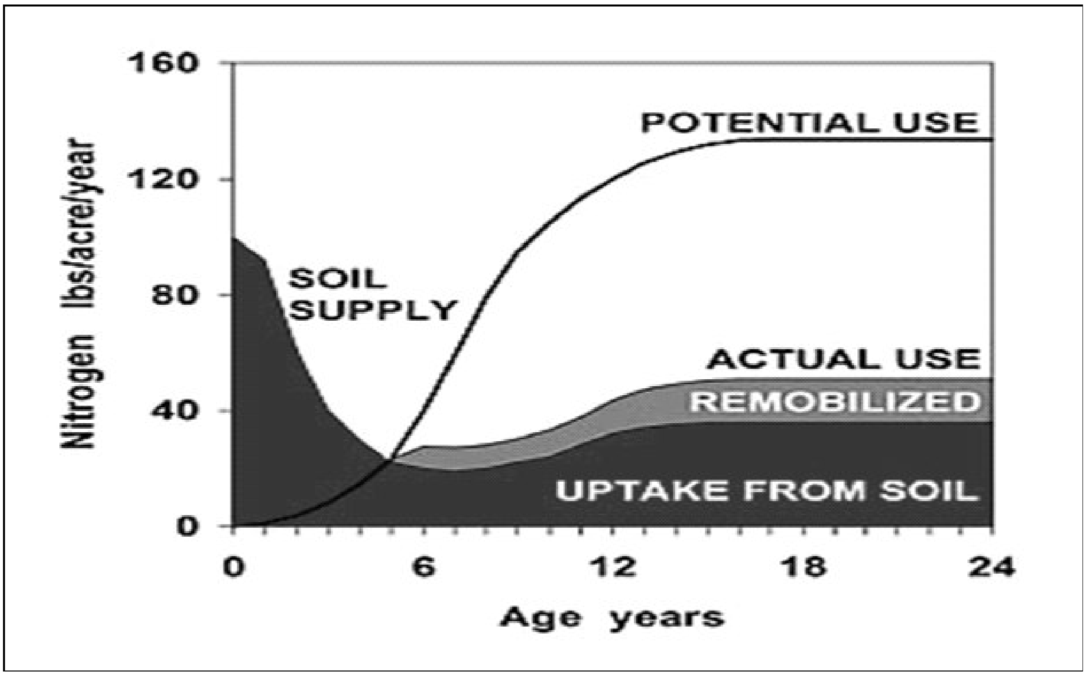


Figure 2.1: The concept of soil nitrogen supply and a stand's potential and actual use of nitrogen as related to stand age (from Fox *et al*., 2007). 100 lbs / acre on the Y-axis is approximately equal to 112 kg ha $^{-1}$

When trees are young, use of nutrients is minimal owing to their small size, low leaf area, and lack of site occupancy. As leaf area development and stand growth accelerates, use of nutrients also increases rapidly. The supply of readily available nutrients is however, being rapidly sequestered within the accumulating forest floor and tree biomass. As the canopy closes, the environmental conditions conducive to high nutrient availability are no longer present (Allen *et al*., 1990). The result is that a stand's nutrient requirement for maximum growth will therefore generally outstrip soil supply (particularly for N) around time of canopy closure. As nutrient supply diminishes, leaf area production and, in turn, growth become regulated (and limited) by the available nutrient pools. The majority of field trials in mid-rotation southern pine stands (8 to 20 years old) in the Southeast United States have shown strong responses to additions of N and P (Martin *et al*., 1999).

Several other studies on fertilization effects on basal area and volume have produced different reports on the responses and sometimes conflicting reports. Some studies even recorded no responses or even negative responses. This section will explore some of the various responses that have been reported in literature. Volume growth responses vary depending on stand/site attributes and the rates of N and/or P applied. Results from an extensive series of mid-rotation fertilizer trials in *P. taeda* stands established by the Forest Nutrition Cooperative in America indicated that over 85 percent of the stands fertilized were responsive to additions of N+P. Growth gains averaging 30% (3.48 m^3 ha^{-1} a^{-1}) over a six-year period following a one-time application of approximately 223 kg ha^{-1} N and 28 kg ha^{-1} P were typical (Fox, *et al.,* 2006).

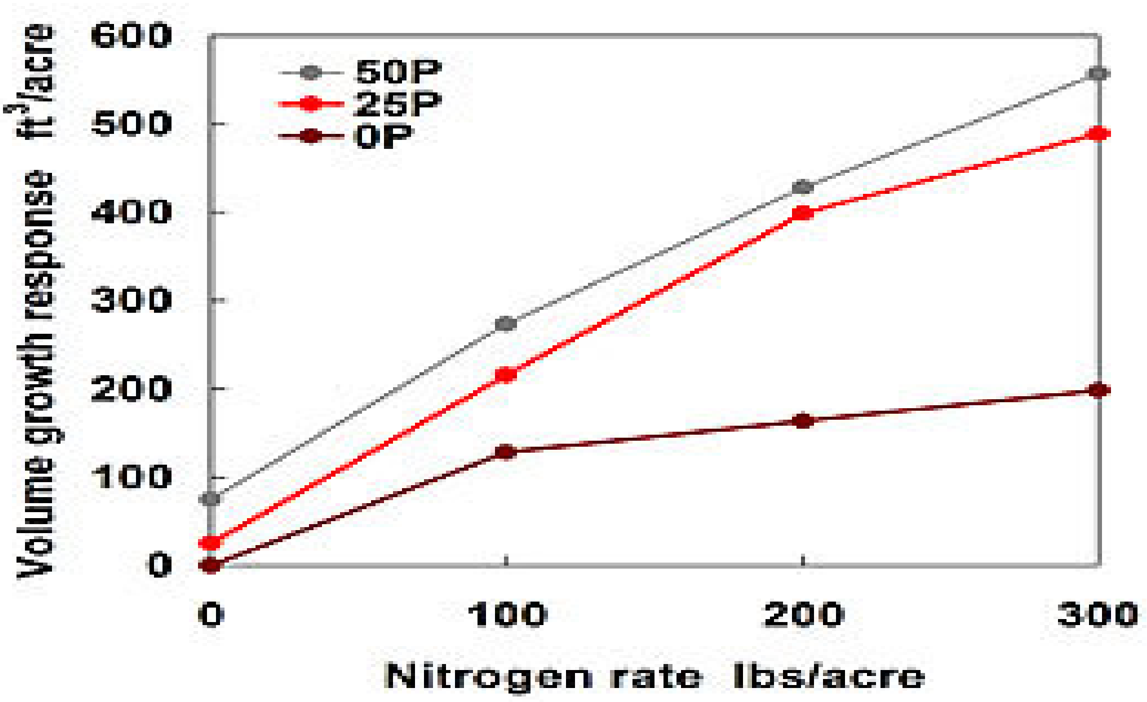


Figure 2.2: Volume growth response to N and P applications to mid-rotation *Pinus taeda* stands. (from Fox *et al*., 2006). 100 lbs / acre on the X-axis is approximately equal to 112 kg ha^{-1} and 100 ft^3/ acre is approximately equal to 7.0 m^3 ha^{-1}.

It was observed in these intermediate-aged stands (Figure 2.2), that little response occurred when P was added alone except on very P-deficient sites as indicated by low foliar P concentrations and very low leaf areas (Fox *et al*., 2006).

Turner *et al.* (1996) reported a 21% volume response in another study with 21 trials that investigated the effect of post thinning fertilization in *P. radiata* in New South Wales in Australia. While the reported trials were on sites with differing site characteristics, all sites showed that significant growth responses could be obtained. The highest responses for both basal area and volume increment on all sites were with the highest level of N (400 kg ha^{-1}) in conjunction with P application. There was however, no significant response to N and P alone in these trials. Many other different studies confirm the increase in basal area and volume increment after applying fertilizer (Carlson *et al.,* 2000). No significant response to N or P alone has been reported in some South African studies in agreement with Turner *et al.*, 1996's findings (ICFR, 1985, 1986). Across a variety of site types in South Africa and abroad, fertilizers have commonly produced larger growth responses when N and P are applied together than either element applied alone (Donald, 1987; Jokela and Stearns-Smith, 1993; Turner *et al.*, 1996). There were relatively few exceptions to this finding, mostly confined to stands that were very strongly deficient in a single nutrient.

A selection of documented responses to mid-rotation fertilization is presented in Table 2.1a & b. In the study by Donald (1987), the highest level of N (50 kg ha^{-1}) was required to obtain a significant response to 50 kg P ha^{-1} and *vice versa* (Table 2.1a). There was no additional response to the 100 kg ha^{-1} P level.

In a separate experiment by Vose and Allen (1988), on a site which was N deficient before the study, the highest level of N (336 kg ha^{-1}) had the highest volume production. In this same experiment, similar treatments were applied on another site which was not N deficient before the experiment and there were no significant differences in the responses. Fife and Nambiar (1995) also found the highest N treatment (600 kg ha^{-1}) to give the highest response in 6-year old *P. radiata* stands in an experiment in which four levels of N were used (0, 150, 300 and 600 kg ha^{-1}). An analysis of Table 2.1a & b shows that quantities of nutrients used in experiments in which trees were 6 years and above ranged from 0 - 400 and 0 - 240 kg ha^{-1} for N and P respectively. The optimum levels found in these different studies ranged from 50 to 400 and from 35 to 120 kg ha^{-1} for N and P respectively. However, in some cases the optimum was due to application of a single element. Recommendations of a rate of about 35 kg P ha^{-1} to intermediate aged stands where the soil water and depth (> 450 mm) requirements are met were put forward by Herbert and Schönau (1990) for the Cape area. They recommended about 60 kg ha^{-1} of P for deeper soils where a N response can be expected as well.

Table 2.1a: Summary of fertilizer rates used by different studies in established conifer stands in Africa (mid and late rotation fertilizer application)

	Location	Species	Stand age at which fertilizer was applied	No. of sites	Soil types and characteristics	Trial design, levels and amounts of elements used (kg/ha)	Optimum combination from study	References
CAPE TRIALS	Grabouw Western Cape	*P. radiata*	15	1	Shallow, strongly leached Cartref soil	3*3 factorial design -3 levels of N (0, 25, 50) -3 levels of P(0, 50, 100)	$N_{50}P_{50}$	Donald, 1987
	Kruisfontein Southern Cape	*P. radiata*	16	1	Kroonstad, Vilafontes, and Pinedene -greyish-yellow colours	3*2 factorial design -3 levels of P (0, 35, 70) -2 levels of K (0, 30)	$P_{35}K_{0}$	Payne *et al.*, 1988
	Gouna Southern Cape	*P. radiata*	20	1	Longlands Pinedine -Greyish-yellow colours	5 levels of P (30, 60, 90, 120, 240)	P_{60-120}	Payne *et al.*,1988
MPUMALANGA TRIALS	Venus, Mpumalanga	*P.patula*	6	1	Granite derived soils	3*2 factorial 3 levels of N (0, 150, 300) -3 levels of P(0, 30, 60)	No significant response from all	Carlson *et al.*, 2000
	Helvetia, Mpumalanga	*P.patula*	9	3	Shale derived soils	3*3 factorial 3 levels of N (0, 100, 200) -3 levels of P(0, 50, 100) 3 levels of K(0, 50, 100)	$N_{200}P_{50}K_{100}$	Carlson *et al.*, 2000
	Westra, Mpumalanga	*P.patula*	12	2	Shale derived soils	4*2 factorial 4 levels of N (0, 128, 257,385) -4 levels of P(0, 64, 129, 203)	N_{128}	Carlson *et al.*, 2000

Table 2.1a: Continued

	Location	Species	Stand age at which fertilizer was applied	No. of sites	Soil types and characteristics	Trial design, levels and amounts of elements used (kg/ha)	Optimum combination from study	References
MPUMALANGA TRIALS	Mpumalanga	*P.patula*	8	4 groups	-Lowveld granite derived soils -Highveld granite derived soils -Highveld quartzite derived soils -Escarpment soil groups	2*5 factorial -2 levels of N (0, 150) -2 levels of P (0, 150) -2 levels of K (0, 150) -2 levels of Ca (0, 140) -No additional fertilizer, or a fertilizer re-application of the above elements, which co-incided with the second thinning operation.	The application of 150 kg ha^{-1} of combinations of the following elements at first thinning yielded an economic response: PK applied to Highveld granitic sites, ·NPK added to sites with shale parent materials as well as the escarpment soil groups. Quartzitic and Highveld granitic soils had erratic or non significant responses at first thinning.	Carlson & Soko, 2000
	Mpumalanga	*P.patula*	13	4 groups	-Lowveld granite derived soils -Highveld granite derived soils -Highveld quartzite derived soils -Escarpment soil groups	2*5 factorial -2 levels of N (0, 150) -2 levels of P (0, 150) -2 levels of K (0, 150) -2 levels of Ca (0, 140) -No additional fertilizer, or a fertilizer re-application of the above elements, which co-incided with the second thinning operation.	The application of 150 kg ha^{-1} of the following elements at second thinning yielded an economic response: 150 kg ha^{-1} K applied to Lowveld granitic sites, ·N added to sites with shale parent materials, either as a sole application at second thinning, or in combination with NPK at first thinning, and Single applications of N or K at second thinning to Highveld granitic sites.	Campion & du Toit, 2003

Table 2.1a: Continued

	Location	Species	Stand age at which fertilizer was applied	No. of sites	Soil types and characteristics	Trial design, levels and amounts of elements used (kg/ha)	Optimum combination from study	References
SWAZILAND TRIALS	Usutu Pulp Swaziland	*P.patula*	7	1	Granite derived soils	4*2 factorial 4 levels of P (0, 50, 100, 200) 2 levels of K (0, 150) - a single rate of N with and without a PK application	-Growth rates improved by P and K	Morris, 1986
	Usutu Pulp Swaziland	*P.patula*	7	1	Gabbro derived soils	4*2 factorial 4 levels of P (0, 50, 100, 200) 2 levels of K (0, 150) - a single rate of N with and without a PK application	Growth rates improved by P and K	Morris, 1986
	Usutu Pulp Swaziland	*P.patula*	12	1	Granite derived soils	4*2 factorial 4 levels of P (0, 50, 100, 200) 2 levels of K (0, 150) - a single rate of N with and without a PK application	Growth rates improved by N	Morris, 1986
	Usutu Pulp Swaziland	*P.patula*	12	1	Gabbro derived soils	Same as for granite derived soil	Growth rates improved by N	Morris, 1986
	Usuthu Swaziland	*P. patula*	6	1	Gabbro derived soils	75kg ha^{-1} P and 75kg ha^{-1} K	Effect of PK fertilizer more apparent towards end of rotation	Crous *et al.*, (2008)
	Usuthu Swaziland	*P. patula*	6	1	Gabbro derived soils	3 levels of P (0, 25, 50) at planting and 5 years after planting 3 levels of K (0, 25, 50) at planting and 5 years after planting	Volume growth increased when foliar nutrient concentration of either element was above the critical level	Crous *et al.*, (2008)

Table 2.1b: Summary of fertilizer rates used by different studies in established conifer stands outside Africa (mid and late rotation fertilizer application

Location	Species	Stand age at which fertilizer was applied	No. of sites	Soil types and characteristics	Trial design, levels and amounts of elements used (kg/ha)	Optimum combination from study	References
Hinton Canada	*P.contorta*	40	1	-well drained orthic gray luvisols	4 levels of N (0, 180, 360, 540)	N_{360}	Yang, 1998
New South Wales Australia	*P. radiata*	14-36	9	-quartzose sandstones -quartz conglomerate -quartz sands	(3*3 factorial design) 3 levels of N (0, 200, 400) 3 levels of P (0, 75, 225)	$N_{400}P_{75}$ $N_{200}P_{75}$	Turner *et al.*, 1996
New South Wales Australia	*P. radiata*	14-36	9	-slates -shales - mudstones	(3*3 factorial design) 3 levels of N (0, 200, 400) 3 levels of P (0, 75, 225)	$N_{400}P_{75}$	Turner *et al.*, 1996
North and South Carolina		9, 12, 14	3	-nitrogen deficient soils and non nitrogen deficient soils	N*P factorial design 4 levels of N (0, 112, 224, 336) 3 levels of P (0,28, 56)	$N_{336}P_0$ (no significant differences in responses between N deficient and non nitrogen deficient soils)	Vose & Allen, 1988
South eastern South Australia	*P. radiata*	6	1	Podzolised sand	4 Levels of N (0, 150, 300 and 600)	N_{600}	Fife and Nambiar, 1995

Gholz and Fisher (1984) reported that the response of pole-sized pine stands in the south eastern U.S. to a combination of N and P fertilization was much more uniform across sites than the response to either element alone. Carlyle (1998) in a thinning, thinning residue and fertilizer application experiment also reported that basal area increment increased in response to the rate of N fertilizer applied. There was however neither response to P nor any N × P interaction as reported by other studies. In N fertilized treatments, growth was highly correlated with N uptake in the year after fertilizer application.

In a N and P fertilization study by Hunter *et al*. (1986) in New Zealand, basal area response averaged 1.35 m^2 ha^{-1} and ranged from -1.1 m^2 ha^{-1} to 5.0 m^2 ha^{-1}. The largest responses occurred in stands that had received fertilizer at an early age and were on soils poor in nitrogen such as sandy soils. Small positive responses were associated with older stands or better soils.

In Mpumalanga (South Africa), *P. patula* stands responded significantly after first thinning to 150 kg ha^{-1} applications of PK (Lowveld granitic sites) and NPK (shale-derived and escarpment soils). A sub-group of the same trials responded significantly to 150 kg ha^{-1} applications of N or K (Highveld granitic soils) and K alone (Lowveld granitic sites), after second thinning (Carlson, 2000; Carlson & Soko, 2000; Campion & du Toit, 2003). In the Western Cape, combined N and P experiments in 26 year-old *P. radiata* stands were conducted. The N application improved basal area in two of the trials and depressed it in the third (Donald *et al.,* 1987). Crous *et al*. (2008) conducted a P and K fertilizer experiment in Swaziland in the third rotation and then superimposed a P and K factorial trial in the fourth rotation. Details of the levels of P and K are presented in Table 2.1a. The results from Crous *et al.*'s studies suggested that fertilizer application to successive rotations can be adjusted to allow for the benefit of residual P fertilizer. A summary of some of the values for stand level volume responses, stand level basal area responses and the rates of elements producing the results compiled from many authors on *Pinus* species are presented in Table 2.2 :

Table 2.2: Examples of stand level volume and basal area responses of established conifer stands to mid and late rotation fertilizer application (Adapted from Campion, 2006)

Location	***Species***	**Age at which fertilizer was applied (years)**	**Elements applied (kg ha^{-1})**	**No. of sites**	**Growth period (years)**	**Response (m^{3}ha^{-1})**	**Response (m^{2}ha^{-1})**	**Reference**
New South Wales, Australia	*P. radiata*	16	$N_{324} + P_{128}$	3	4	4.3	Data not presented	Crane (1981)
Boland Region, Western Cape	*P. radiata*	15	$N_{50} + P_{50}$	1	10	59.2	Data not presented	Donald (1987)
New South Wales, Australia	*P. radiata*	30	$N_{400} + P_{75}$	4	7	67	4.7	Turner *et al* (1996)
New South Wales, Australia	*P. radiata*	24	$N_{200} + P_{75}$	3	6	8	1.4	Turner *et al* (1992)
Mpumalanga Highveld granite	*P. patula*	8	$P_{150} + K_{150}$	1	6	19.2	2.4	Carlson and Soko (2000)
Mpumalanga shale	*P. patula*	8	$N_{150} + P_{150} + K_{150}$	1	5	27.1	2.9	Carlson and Soko (2000)
Mpumalanga escarpment	*P. patula*	8	$N_{150} + P_{150} + K_{150}$	1	5	30.3	2.6	Carlson and Soko (2000)
Mpumalanga escarpment shale	*P. patula*	13	N_{150}	1	5	30.6	1.4	Campion and du Toit (2003)
Mpumalanga Shale derived soils	*P. patula*	9	$P_{50}K_{100}$	3	6	Not indicated	2.52	Carlson *et al.*, 2000

2.3 Effect of fertilization on leaf area index

Forest production is driven by the interception of radiation and the efficiency with which leaves use this energy to produce stem biomass through the process of photosynthesis (Linder, 1985). These processes are strongly influenced by the supply of water and nutrients (Linder and Rook, 1984). High levels of intercepted radiation are associated with high levels of photosynthesis, and this results in high productivity.

Leaf area index influences productivity through the interception of light (Gholz *et al*., 1990) and the LAI that can be maintained at a given site will be determined by the availability of water and nutrients (Beadle, 1997). An increase in the availability of water and nutrient supply will enable a forest to deploy a large leaf area with a high canopy quantum efficiency level. In addition, it will partition comparatively small amounts of fixed carbon to root growth as resources are plentiful and easy to obtain (Linder, 1987; Binkley *et al*., 2004). *P. radiata* is usually grown from 30^0 to 46^0 latitude, mainly in the southern hemisphere. Photosynthetically active radiation (PAR) is sufficient for optimum yields in these areas and therefore radiation as such is seldom limiting but the interception of adequate quantities may be constrained by sub-optimal leaf area indices brought about by water or nutrient deficiencies (Linder, 1985). It follows that the availability of water, nutrients and the interaction between these two factors effectively determine the magnitude of the response to additional fertilizer supplements (Linder, 1987; Goncalves *et al*., 1997).

Canopies provide a direct link between the biophysical environment and the photosynthetic processes which convert solar energy into dry matter production and wood yield (Beadle, 1997). Canopies set limits to production. The size of a canopy at any one time is defined by its leaf area index (LAI) defined as the leaf area per unit land area

(Beadle, 1997). LAI drives both the within and the below-canopy microclimate, determines and controls canopy water interception, radiation extinction, water and carbon gas exchange and is, therefore, a key component of biogeochemical cycles in ecosystems. Any change in canopy LAI by management practice is therefore accompanied by modifications in stand productivity.

The amount, display and duration of leaf area largely determine the amount of radiation intercepted by forest canopies (Vose and Allen, 1988).

Strong relationships have been reported between productivity and leaf area index for several conifers in different trials (Binkley & Reid, 1984). These observations support the proposition that a forest stand's ability to intercept radiation is the major determinant of its biomass production (Linder, 1985). Canopy leaf area intercepts PAR and, through photosynthesis, converts absorbed light energy into dry matter (Cannell, 1989). The empirical relationship between intercepted photosynthetically active radiation (IPAR) and dry matter production suggests that increased radiation absorbed, or increased efficiency of conversion of absorbed radiation to biomass, will increase dry matter produced (Cannell, 1989). Since the early fifties it has been suggested that the environment regulates plant productivity through its influence on leaf area, carbon fixation and carbon allocation patterns (Vose & Allen, 1988). Environmental factors limiting leaf area include nutrient availability, water availability and temperature. Photosynthetic efficiency is influenced by the same environmental factors. Because of the difficulties involved in determining the relationships between carbohydrate production and allocation to stem wood, growth efficiency has been used as a surrogate parameter for this relationship in some fertilization studies (Binkely and Reid, 1984).

According to a study of *P.taeda* growing on sites of varying nitrogen limitations in North Carolina, nitrogen fertilization significantly increased LAI (up to 60%) on N deficient sites while as P additions had no effect (Vose & Allen, 1988). When tree growth is stimulated by fertilization, a significant part, and if not most of the response is due to an increase in the total leaf area of the photosynthetic surface (Linder & Rook, 1984). An increased nutrient supply may however result in a denser canopy which will reduce the light levels in the lower crown, reducing the depth of the green crown, so even though photosynthesis may be improved by fertilization, the dense shade in the canopy decreases the photosynthetic production per unit leaf (Linder and Rook, 1984). In another study by Allen *et al*. (2005) where production efficiency was assessed, LAI was not significantly affected by fertilization for stands of *P.taeda* and *P.elliottii.* The response in LAI due to fertilization may therefore be proportional to the degree of resource limitations that exist at a given site, since poorer sites have greater room for improvement.

2.4 Effects of water and nutrient availability on growth in mid-rotation pine stands

Much of the variation in wood production in forest plantations is due to variation in light interception and the leaves' efficiency to produce stem biomass through photosynthesis (Linder, 1985; Fox *et al*., 2006). The supply of water and nutrients has a very strong influence on these processes (Linder and Rook, 1984). Figure 2.3 illustrates the relationship between volume growth and leaf area in southern pine plantations in the Southeast United States of America.

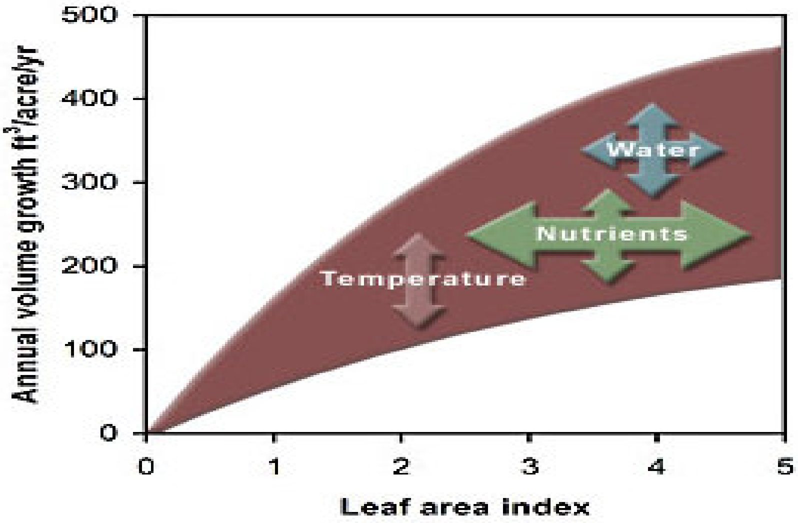


Figure 2.3: Relationship between annual volume growth and leaf area and factors known to affect productivity. 100 ft^3/ acre is approximately equal to 7.0 m ^{3} ha^{-1} (from Forest Nutrition Cooperative, 2006).

Conversely if resources are limited, the forest will have to deploy a large amount of fixed carbon to the roots and not to above ground growth. It follows that the availability of water, nutrients and the interaction between these two factors effectively determine the magnitude of the response to additional fertilizer supplements (Gonçalves, *et al.*, 1997; Linder, 1987). Herbert and Schönau (1990) also concluded that the availability of soil water is critical for responses to P and that once foliar P is well above the critical level of 0.10%, nitrogen may become a limiting nutrient on sandy soils. Thus the better the site quality (with respect to available soil water) the larger the response to fertilizer and the greater the benefits of adding N to P. Studies of *P radiata*, *P. sylvestris* and *Eucalyptus globulus* have indicated that leaf area and consequently wood production are below optimum levels in many parts of the world (Fox *et al*, 2006).

Low nutrient availability and low soil water availability, high vapour pressure deficits and high temperatures also adversely affect leaf area production and/or retention. In a study by McMurtrie *et al*. (1990) done in Canberra in southeastern Australia, values of LAI were consistently higher for stands that had received both fertilizer and irrigation than those that had received no fertilization and irrigation.

Chronically low levels of available soil nutrients, principally nitrogen and phosphorus on loamy or sandy soils, were found to be more limiting to growth in established stands than water limitations in the Southeast United States (Albaugh *et al*., 1998). Both water and nutrient limitations can reduce leaf area through reduced foliage production or early senescence and they can also affect growth efficiency through effects on photosynthesis and carbon allocation. In the Southeast United States, water availability is however thought to have less effect on leaf area than nutrient availability because most leaf area production in the region occurs in the spring when soil water availability is high and evapotranspiration demand is low. In contrast, water availability is thought to have a greater effect on growth efficiency because photosynthesis of existing leaf area can be reduced by drought during summer months when soil water availability may be low and evapotranspiration demand is high (Sampson & Allen 1999, Albaugh *et al.,* 2004b).

2.5 Interaction of soil water and nutrient availability

To be absorbed by plant roots, nutrients need to be released from the solid to the solution phase of the soil. All processes controlling the transfer and changes in form of nutrients are closely related to soil water content. Soil water content is one of the main factors affecting diffusion and ion activity in the soil solution (Goncalves *et al.,* 1997). Water availability and its interaction with nutrients may have overriding influences on the magnitude of stand response to silvicultural practices (Nambiar *et al*., 1984). There are strong interactions between water and fertilizer in water-limited environments (Sheriff, 1996). On sites with low soil water availability, stands may respond poorly to fertilization, even when levels of nutrient availability are low (Allen, 1987; Jokela *et al*., 1988; McMurtrie *et al*., 1990). Under similar management regimes, the variability in fertilizer responses is likely to stem primarily from variations in inherent nutrient supply capacity of soils and the availability of soil water (du Toit, 2006). Numerous studies have shown that fertilization is most beneficial when trees are not water stressed (Sands and Mulligan, 1990). In a study of *P. radiata* stands in Australia, the magnitude of the response to fertilizer applied after the first, second and third thinning operations were influenced by climatic conditions, particularly rainfall during the growing season over the period one to four years following fertilization (Turner *et al*., 1996). When fertilizer is applied late in the rotation, the response can be determined by available water and may not occur unless fertilization is combined with an increase in available water as is the case after thinning (Nambiar *et al*., 1984).

Experimental data suggest that nutrient uptake of e.g. Ca and Mg is relatively insensitive to water deficits, but the uptake rates of N and especially P may be reduced (Sands & Mulligan, 1990). The interaction between soil water and nutrients is thus complex. Fertilizing on sites where rainfall is high and soils are permeable can lead to excessive leaching and low efficiency of fertilizer uptake (Ballard, 1984). The response to fertilization on sites where rainfall is low or erratic can be uncertain, because moist conditions which are conducive to uptake of added fertilizer cannot be relied upon. On the other hand, if fertilizer uptake is high, perhaps because of sufficient rainfall following fertilization, it is possible that leaf-area index will increase to a level which is unsustainable in relation to long-term moisture availability (Nambiar, 1985; Linder, 1987). Temporal or seasonal changes in water availablilty may thus also have a profound impact on a stand's response to fertilization.

However, Allen *et al., (*2005) found that LAI was not significantly affected by irrigation in an experiment where *P.taeda* and *P.elliottii* were involved.

What then is the key to optimizing leaf area and growth efficiency and thereby achieving optimum value? According to Fox, *et al.*, (2006) and du Toit (2006), there is need to develop and implement site specific silvicultural practices. These practices may include:

- Use of high quality planting stock
- Matching the right species to the right site
- Suppression of competing vegetation and
- Site-specific fertilizer application

2.6. Diagnosis of nutrient deficiencies and effect of fertilization on foliar nutrients and relationship to growth responses

Diagnostic techniques are important in a forest fertilization program in order to ensure the most effective use of the fertilizer material. Some of the methods that can be used include the following:

i. Visual symptoms
ii. Foliar analysis
iii. Soil analysis and
iv. Fertilizer trials (Pritchett, 1979)

Each of these methods can have a useful place in diagnosing instances of deficiencies and likely response of trees to fertilizer treatment. The focus of this section will however be on foliar analysis though an overview of soil analysis will be given.

2.6.1 Soil Tests

Soil analyses, though useful in forestry can be limited by;

i. Lack of correlation data for interpreting test results in terms of tree response to fertilizers,

ii. Lack of information on what soil layer (depth) to sample, and

iii. Uncertainty as to what nutrient form or fraction to extract (Pritchett, 1979).

When the above challenges are overcome, soil analysis can yield results that can be very useful in predicting sites that are potentially responsive to fertilizer treatment.

2.6.2 Foliar Analysis

Analysis of foliar nutrient levels is very useful for monitoring the growth and nutrient status of trees (Payne & Clough, 1987). It is widely used to identify nutrient-deficient stands, e.g. *P. taeda* in the southern United States (Wells & Allen, 1985), *P. radiata* in New Zealand (Mead and Gadgil, 1978), and *P. radiata* in Australia (Snowdon & Waring, 1990). Foliar analysis is a more reliable method of diagnosing pronounced deficiencies in older trees, and this technique does suffer from sampling difficulties (Pritchett & Comerford, 1983) (e.g. difficulties in accessing the upper third of the crown). The method can also be affected by other factors like climate (Louw & Scholes, 2002), season (Schönau, 1981), genetic variation, competition, plant age, and position in the plant (Schutz, 1990). Furthermore, the "dilution effect" on needle concentrations, associated with the increase in dry weight due to the storage of carbohydrates, can also lead to substantial variation in foliar nutrient concentration (Linder, 1995).

It is essential, therefore, to use standardized procedures when sampling and processing foliage; otherwise, a reliable comparison of measured foliar values with published interpretative criteria may not be possible (Brockley, 2001).

If foliar analysis is to be of any meaningful use, sampling should yield foliar material that is representative of the stand sampled, and accurately reflect the nutrient status of the trees (Payne & Clough, 1987). Samples should represent the best possible relationships with growth and growth response (Lambert, 1984). As a number of factors can affect nutrient foliar concentrations, sampling procedures must be carefully controlled to reduce variation. A particular time of year is usually chosen for sampling as the concentrations of nutrient elements can vary from one season to another. In the Western Cape (winter rainfall area) the most stable period for sampling is considered to be January to March, when nutrient levels are lowest because the nutrient levels reach a maximum during winter (Schutz, 1976). This period of sampling is in agreement with Mead and Will, (1976) where foliar sampling of *P radiata* in New Zealand was recommended to be done from late January to March for both N and P. Fife and Nambiar (1997) also noted that in an experimental site in South eastern South Australia with a cool wet winter (June–September) N concentration was at its lowest between November and March. Sampling in this experiment was done between September and March. It is recommended by most authorities that sampling be done during the dormant period when there is relatively slow growth when concentrations should be most stable and in equilibrium with the nutrients in the soil (Schutz, 1976; Fife & Nambiar, 1997; Brockley, 2001).

Foliar analysis has been widely used to evaluate the probability of response to fertilization in the south eastern United States of America (Jokela *et al.*, 1988). This technique is based on the assumption that a particular stand will respond to added nutrients when foliar concentrations fall below established critical levels (Jokela *et al.*, 1988). The "critical" level of a nutrient is defined as the concentration below which a significant increase in growth would be expected from the application of that nutrient provided other factors are not limiting (Pritchett & Comerford, 1983). Foliar analyses can be used to identify sites where an acute nutrient deficiency occurs, but are less suitable for reliably predicting growth and fertilizer response in areas of marginal deficiency, or where other growth limiting factors, such as soil moisture, may limit response to improved nutrition (Allen, 1987; Jokela *et al.*, 1988). In Australia, foliar analysis can generally discriminate between highly deficient and sufficient mid-rotation *P. radiata* stands, however, this technique may prove unreliable when nutritional status is intermediate (Carlyle, 1998).

Of all the diagnostic tools available for selecting responsive stands, foliar analysis appears to have the most potential according to Crane (1984) because it provides a combined assessment of all the factors that influence nutrition, such as nutrient supply, plant uptake, translocation and growth and is therefore an integrated index of site supply as well as stand demand for a nutrient (Allen, 1987). However, foliar analysis does not take water availability into account. Water limitations could therefore limit responses. The diagnostic techniques for identifying intermediate-aged stands that will be biologically responsive to fertilization have undergone substantial revision (Albaugh *et al.,* 1998). The linkages among stand productivity, leaf area, and nutrient availability can be used. Differences between a stand's current leaf area and its potential leaf area can be used to estimate responsiveness to nutrient additions. LAI of a fully stocked stands of *P. taeda* in the Southeastern United States (basal area >23 m^2 ha^{-1}) should generally be 3.5 or greater; otherwise, the stand is probably in need of N+P (Forest Nutrition Cooperative, 2006). The probability and magnitude of response will be greater at lower leaf areas.

Nitrogen fertilization often increases foliar nitrogen concentration which in turn may increase photosynthetic capacity. A positive relationship between foliar N and photosynthetic capacity may be dependent on the inherent fertility of the site, i.e., larger increases for sites with more nutrient limitations (Allen *et al*., 2005). A study of induced nutrient deficiency in *Picea sitchensis* seedlings showed that, under nutrient-limiting conditions, additions of nitrogen increased foliar N and net photosynthesis up to a point, after which, further additions of nitrogen yielded increases in foliar N, but no change in photosynthesis (Chandler & Dale, 1995). In mature pine stands however, higher foliar N may not necessarily enhance photosynthesis. Turner *et al.,* (1992) also found out that application of N led to high concentration of N in the foliage but this declined with time. Phosphorus concentrations were actually depressed by the application of N. This could have been caused by an antagonism between these elements.

2.6.3 Vector analysis and use for predicting growth responses to fertilizer application

Unlike techniques that are based on a single measure of nutrient concentration, vector analysis compares nutrient concentration, nutrient content and a measure of plant growth simultaneously in a graphical format (Haase & Rose, 1995). Timmer and Armstrong (1987) reported that diagnoses based on vector analysis matched visual symptoms, growth performance and nutritional responses due to fertilizer treatments more accurately than methods based on critical or optimum nutrient levels. With vector analysis preliminary growth response data and nutrient-deficiency diagnoses, based on increases in needle weight and shifts in foliar nutrient concentration and content of added and non-added nutrients, can be obtained within a year of treatment (Haase & Rose, 1995). There is documented evidence from some studies that there is a strong positive correlation between the needle weight produced during the first year after treatment and subsequent stem wood response (Valentine & Allen, 1990).

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

This chapter gives a description of the study sites, treatments applied, measurements done and statistical data analysis methods used. The study was conducted on a range of sites in the Boland region of MTO Forestry Company (MTO), chosen to reflect the two most common soil types and a water availability gradient in each soil type. We opted for a factorial combination of fertilizer treatments with three levels each for nitrogen and phosphorus. This design was replicated four times across a gradient of water availability for each of the two common soil groups, forming a complete trial series. All replications were laid out in *P. radiata* stands that had received their mid-rotation thinning prior to treatment implementation.

3.2 Description of study sites

The study was conducted at MTO's Grabouw and Kluitjieskraal plantations. These plantations are located in the Western Cape’s Boland region. The Boland region has a typical Mediterranean type climate with cool and wet winters (Donald *et al*, 1987). Winter rainfall in the Boland region predominantly falls from May/June to August/September. Grabouw is situated in the Elgin basin and Kluitjieskraal is situated on the footslopes of the Waterval Mountains in the Breë River Valley. The Kluitjieskraal plantation is beside the town of Wolseley, approximately forty kilometres North West of Worcester.

3.2.1 Description of selected compartments

Pinus radiata compartments that had received second thinning with a stand density ranging from 396 to 501 stems ha $^{-1}$ and a slope of less than 15^0 were used in the study. The age of the stands ranged from 13 to 17 years (Table 3.4). Mean annual precipitation within the study sites ranged from 754 mm to 1188 mm (Table 3.4).

The replications were renamed for the purposes of use in this study as indicated in Table 3.1. They were spread over four wetness categories for each broad soil group (1 - 4) with 1 being the driest and 4 the wettest. A description of the wetness categories follows:

There is evidence that some of the sites (Kluitjieskraal B7 in particular) receive water inputs by lateral flow from upslope positions.

A complementary M.Sc. study has been conducted to gauge available water across sites with higher precision using a soil water balance complemented by a carbon isotope approach (Fischer, 2011). Seeing that these findings have not yet been applied to the fertilizer trial series, a tentative ranking of water availability (categories 1 - 4) had to be used in this thesis, based partly on quantitative and partly on qualitative data. We thus evaluated rainfall and its distribution, potential evaporation data, effective soil depth classes, detailed water balance information (where available), and evidence of additional water supply to sites through lateral flow (supported by stand LAI values before and after treatment implementation), to construct the tentative ranking.

Considerable effort went into selecting compartments where each one had fairly homogeneous soil and stand conditions. The study sites were distributed between two major soil groups in the Boland area as follows:

(a) Sandy soils, which will be referred to as sands in this document (mostly lithic soils i.e. Cartref, Glenrosa and Fernwood soil families) and

(b) Chromatic soils with a loamy texture, which will be referred to as loams (mostly cumulic or oxidic soils derived from shale or granite and represented by the soil families Oakleaf, Tukulu, Clovelly, Hutton Griffin, Inanda and Kranskop) (Ellis, 2008; Fey, 2010).

One of the replications (L_3) as shown in Table 3.1 was destroyed by a wildfire soon after treatment implementation in 2009 before any measurements could be taken.

Table 3.1: Wetness and soil group categories for each replication in the trial series.

Compartment	Replication code[1,2]
Grabouw J27	S_1
Grabouw D12	S_2
Grabouw E14	S_3
Kluitjieskraal B7	S_4
Kluitjieskraal B39	L_1
Grabouw M13a	L_2
Jonkershoek M42[3]	L_3
Grabouw G36a	L_4

1 The letters S and L in the replication code column refer to the major soil groups of Sands and Loams respectively.
2 The subscript numbers (1 – 4) refer to the water availability classes with 1 being the driest and 4 the wettest.
3 This replication was destroyed in a wildfire shortly after treatment.

The replications are distributed as shown in Figures 3.1-3.2 below.

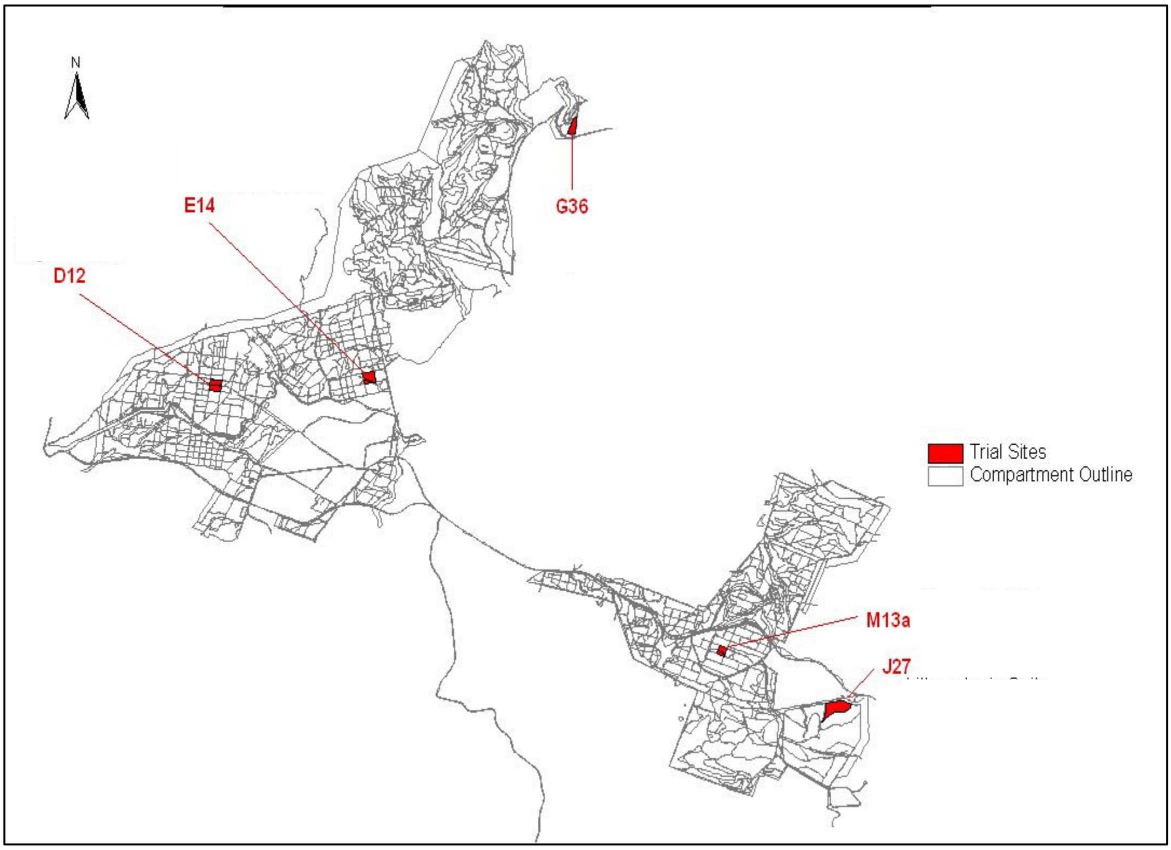


Figure 3.1: The location of fertilizer trial replications in Grabouw plantation compartments D12 (S_2), E14 (S_3), G36 (L_4), M13a (L_2) and J27 (S_1).

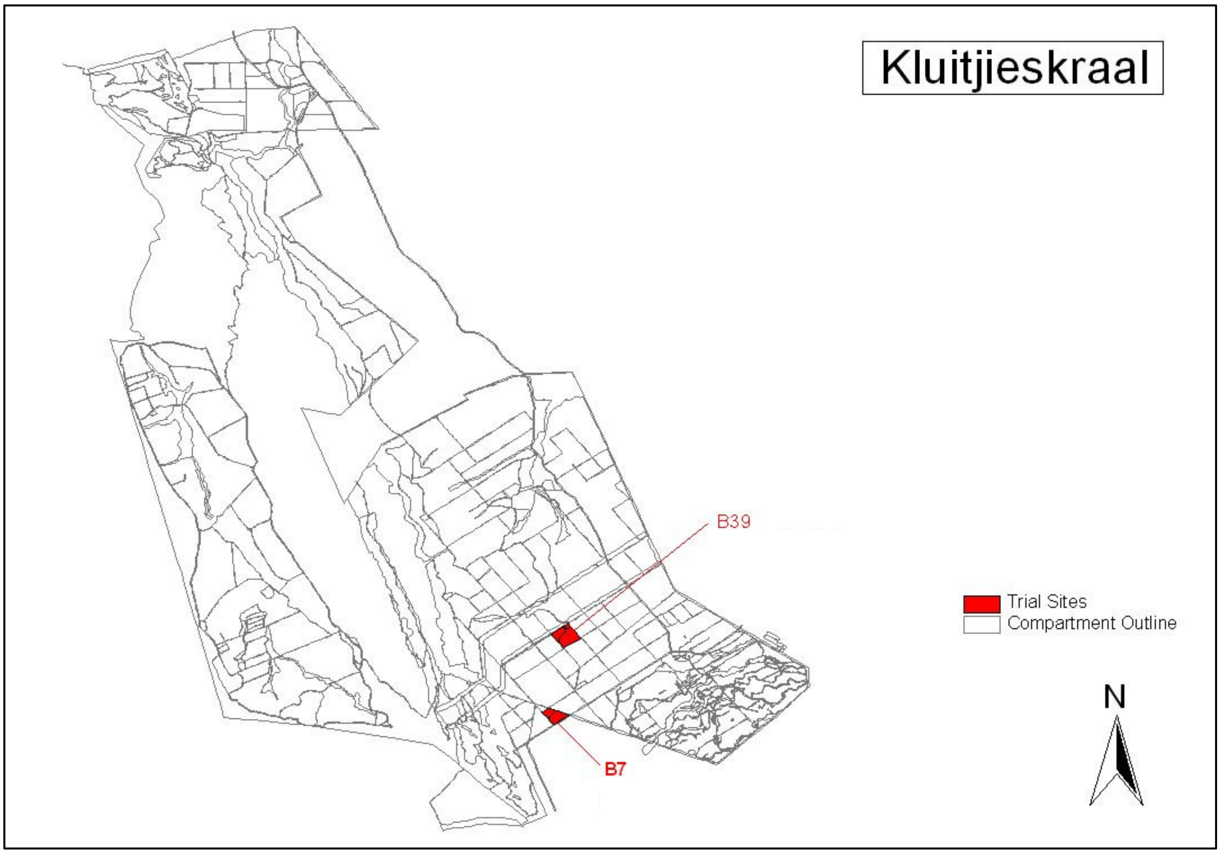


Figure 3.2: The location of fertilizer trial replications in Kluitjieskraal plantation compartments B39 (L_1) and B7 (S_4).

3.3 Treatments

Sample plots in each compartment were chosen based on the following;

- Relatively uniform terrain,
- Healthy trees free of diseases and pests,
- Uniform canopy.

N was applied as limestone ammonium nitrate (LAN 28% N) and P was applied as concentrated superphosphate (20.3% P + 0.5% added Zn). Table 3.2 shows the levels of N and P that were used in the trial. The experiment had four replications across a gradient of soil water availability. Fertilizer was broadcast and split into two equal applications, 50% in winter (June/July) and 50% in spring (September/October) 2008. The splitting was done in order to avoid situations of fertilizer being leached out if all was to be applied at once.

Table 3.2: Levels of N and P used in the mid-rotation fertilizer trial.

Element and level	Nutrient element applied (kg ha^{-1})
N_0	0
N_1	100
N_2	200
P_0	0
P_1	50
P_2	100

3.4 Measurements

Diameter, height, LAI measurements and foliar analysis were done as detailed in this section. The dimensions of the outer and measurement plots used in the study are given in Table 3.3.

Table 3.3: Plot dimensions used in the N x P mid-rotation fertilizer trial.

Replication	**Inner plot dimensions(m)**	**Inner plot area (m^2)**	**Outer plot dimensions (m)**	**Outer plot area (m^2)**
S_1	20.5 x 28	574	30 x 40	1200
S_2:	10 x 50	500	20 x 60	1200
S_3:	20.5 x 28	574	30 x 40	1200
S_4:	18 x 28	504	30 x 40	1200
L_1:	18 x 28	504	30 x 40	1200
L_2:	18 x 34	612	25 x 48	1200
L_4:	18 x 28	504	30 x 40	1200

Each inner plot was surrounded by a buffer ranging from 3.5 m to 6 m.

Existing tree row spacing and the location of extraction rows in field compelled us to allow for slight variations on the plot dimensions to maximise stand uniformity. We planned to establish all replications in compartments that had been selectively thinned from below, however, this was not possible as MTO had implemented large-scale third row thinnings to catch up on thinning backlogs. This forced us to implement two replications in sites that had received third row thinnings (Table 3.4). Table 3.4 presents the stand characteristics before fertilizer application.

Table 3.4: Summary of *P. radiata* stand characteristics at the commencement of the mid-rotation study in 2008 when the trees where 13 to 17 years old.

Rep Code	Mean annual precipitation (mm) [1]	Effective soil depth class [2]	Lithology	Soil description[3]	Age of stand (years)	Mean dbh (cm)	Mean Ht (m)	Stocking (Stems ha^{-1})	Basal area (m^2 ha^{-1})	Initial LAI (m^2 m^{-2})	Initial VOL (m^3 ha^{-1})
[4]S_1	±754	Very shallow	Sandstone	Cb 2	15	17.9	14.2	501	12.6	1.1	71.6
S_2	±1138	Very shallow	Sandstone	Fc 1	15	25.3	16.9	458	23.1	2.2	147.6
[4]S_3	±1188	Deep	Sandstone	Cb 4 & 5	13	19.4	16.1	476	14.3	1.5	90.1
S_4	±782 [5]	Deep	Sandstone	Hf 1	14	23.1	16.2	406	17.1	2.9	106.2
L_1	±782	Very shallow	Shales	Db 4	14	17.6	12.3	432	10.5	1.9	51.9
L_2	±800	Shallow	Shales	Db 1	17	21.5	15.3	396	14.4	1.4	86.3
L_3	-[6]										
L_4	±954	Mod. to deep	Shales	Ba 1	16	26.8	19.8	401	22.7	2.8	169

[1] Rainfall estimates were interpolated between closest reliable weather stations.
[2] Derived from a combination of stone content, effective soil depth and soil texture classes, after Herbert (2000)
[3] Codes refer to Forestry soils database (FSD) format, where Cb = hydromorphic soils with an E horizon; Fc = lithocutanic soils; Hf = soils with E horizon and high carbon topsoils; Db = Non-red duplex soils; Ba = chromatic neocutanic soils.
[4] Compartments where non-selective (third row) thinning was used.
[5] Site enriched by substantial subsurface water flow from upslope positions which greatly prolongs the duration of the season of water availability, thus rated as S_4, i.e. having highest water availability,
[6] Replication destroyed in a wildfire soon after treatment.

3.4.1 Foliar analysis

Pre-fertilization foliar samples were taken in September in 2008. Foliage was taken from six trees in the control plot of each compartment. These were then bulked to give a representation of the before fertilization scenario per compartment. Post fertilization data in the trial was planned for collection in year 1 (2009), 3 (2011),

5 (2013) and 7 (2015) as there were no resources to get more frequent data. The foliar data used in this study was therefore collected in 2009. Post fertilization samples were taken from each plot of each replication in September 2009. Post fertilization foliage samples were collected from six trees in each measurement plot. The current season's foliage that had reached maturity was collected from second-order branches in the top third of the crown. At least two branches per tree were sampled. The samples were taken manually with tree pruning scissors with extending connections to enable sampling in the upper third of the crown. The six samples collected from each plot were then bulked by equal weight to give a representative sample for the plot. The dry weight of 300 needles was determined for each plot. The samples were then dispatched to a commercial laboratory for nutrient concentration determination.

3.4.2 Vector analysis

Vector analysis (Timmer and Stone, 1978) was used to determine the nutrient status and growth responses to treatment. The results of nutrient concentration as determined in the laboratory from the foliar samples described under 3.4.1 were used for vector analysis calculations. The nutrient content was calculated for each nutrient for each treatment by taking the product of nutrient concentration and unit dry weight. The weight of 300 needles was used as the unit dry weight. Post-fertilizer control plot in each replication was used as the reference point for calculations of relative nutrient concentration, relative nutrient content and relative dry weight for the different nutrients for all the treatments in that given replication.

A software called Sigma plot was then used to produce nomograms for each of the nutrients for each replication. A table was then constructed to summarise the vector analysis results for the one year period after fertilizer application. An arbitrary classification of the vectors was used where negligible referred to a vector with a relative nutrient content below 100, small with a relative nutrient content from +100 to 200, medium with a relative nutrient content from +200 to 300 and large any vector with a relative nutrient content above 300. Relative nutrient content was used as it captures both the nutrient concentration and the unit dry weight. Vector analysis was also conducted on the average response observed across all the trials with mean volume increment per treatment used as a surrogate for needle dry weight.

Critical levels, nutrient ratios and vector analysis techniques were then compared in order to identify where the techniques corresponded in identifying nutrient deficiencies and where they did not.

3.4.3 LAI measurements

Pre-fertilization LAI of each compartment was determined in spring 2008 (September). Post-fertilization LAI was taken after a period of approximately six months. Measurements were therefore taken during the autumn period (March-May 2009), spring of 2009 and the last measurements were taken during autumn 2010 (March-May). Leaf area index (LAI) was estimated using a ceptometer (AccuPAR (LP-80)) 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. 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 value, and a leaf area distribution parameter (x) for the particular canopy (Decagon Devices Inc, 2004). An extinction coefficient of 0.5 was used.

3.4.4 Volume estimation

Diameter at breast height (Dbh, 1.3 m above ground) and the height of all trees in each measurement plot were measured in June/July 2008 before fertilizer application. Post fertilization measurements were then done in June/July 2009 (1 year after fertilizer application) and the last measurements were taken in June/July 2010 (2 years after fertilizer application).

All diameter measurements were done using diameter tapes. All height measurements were done using a hypsometer (Vertex IV).

To ensure that diameter measurements were taken on precisely the same height of the tree (1.3 m) on each measurement, a white band was painted around the circumference of the tree at breast height. In cases were knot whorls were present at breast height, measurements were taken above and below the whorls and the average determined to ensure that tree volumes were not unreliable. Windy conditions were avoided when height measurements were taken. These measurements were used to estimate plot volume and basal area.

The following equation based on the Schumacher and Hall model was used to estimate standing tree volume: (Bredenkamp, 2000)

$\ln V = b_0 + b_1 \ln(dbh + f) + b_2 \ln H$

where: ln = natural logarithim to base *e*

V = Stem volume (m^3, underbark) to 75mm tip diameter

dbh = breast height diameter(cm, over bark)

f = correction factor

H = tree height (m)

b_0 = -9.9651

b_1 = 1.8454

b_2 = 1.0139

f = 0

The volume of each tree in the plot was calculated and summed to determine the plot volume. The plot volume was then scaled up to stand volume per hectare (m^3 ha^{-1})

3.4.5 Basal area estimation

The basal area of each tree in the plot was calculated and summed to determine the plot basal area. The plot basal area was then scaled up to basal area per hectare.

3.4.6 Growth Efficiency

Growth efficiency was taken as the volume increment produced per unit of leaf area during the period under consideration and expressed as m^3 ha^{-1} a^{-1} LAI^{-1}. The average leaf area index over the measurement period was used in calculations. The average for the different measurement periods was calculated as follows:

Year 1 (2009): $(LAI_1 + LAI_2)/2$

Year 2 (2010): $(LAI_2 + LAI_3)/2$

Over the two year period (2008 – 2010): $(LAI_1 + LAI_2 + LAI_3)/3$

Where:

LAI_1 was the autumn LAI in 2009

LAI_2 was the spring LAI in 2009

LAI_3 was the autumn LAI in 2010

The spring 2010 LAI has not been included as it had not been measured by the time of the thesis write up.

3.5 Statistical Analysis

The statistical significance of N, P and water availability class as main effects and the two-way interactions thereof were analysed using the General linear models (GLM) procedure in STATISTICA version 10 (Statsoft Inc., 2010). The experiment could not be designed to interpret the highest order interactions among N, P, soil type and water availability class, as this would have meant doubling the size of the experiment. There were no adequate stands to accommodate this large size of an experiment in the chosen area of study.

With limited possibilities for testing interactions, it was more prudent to investigate the effects of water availability class, as soil water availability is the major limiting factor to plantation forestry in the region. Soil type was thus not used as a factor in the treatment structure of the statistical analyses. However, the replications were laid out across two of the most common soil types in the area, and as such, the results are highly representative of plantation forest sites in the Boland region.

LAI, basal area and volume at the start of the study before treatment application were used as covariates for the analyses where LAI increment, basal area increment and volume increment were the dependant variables respectively. Volume at the start of the study was used as a covariate for the GE analyses. Whenever the covariate was not significant, it was excluded from the analysis to improve the power of the test. The use of covariates provided a means of removing the confounding effect of differences in initial stocking and standing volume between plots. Seeing that the work was done in fairly variable stands, the F probability was set at 10%.

A complete ANOVA was also done to determine the effect of N and P fertilizer on foliar nutrient levels one year after applying the treatments.

Linear regression analysis was used to examine the relationship between initial LAI before treatment and volume increment over the two year period after treatment. It was also used to examine the relationship between initial basal area before treatment and volume increment over the two year period after treatment.

CHAPTER 4: RESULTS

4.1 Nutrient Analysis

4.1.1 Critical levels and nutrient ratios

The foliar nutrient concentrations of each replication were determined before fertilizer treatments were implemented and are presented in Table 4.1a.

Table 4.1 a: Foliar nutrient concentrations of 13 to 17 year old *P. radiata* trees in control plots of each replication taken before mid-rotation fertilizer application in 2008.

Replication code & Compartment	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Cu**	**Zn**	**B**
	%					mg kg^{-1}				
S_1: Gr-J27	1.24	0.06	0.71	0.41	0.14	58	152	4	17	36
S_2: Gr-D12	*1.17*	0.08	*0.48*	0.39	0.15	66	113	3	15	23
S_3: Gr- E14	*1.06*	0.08	0.54	0.29	0.13	101	128	3	16	37
S_4: Kk-B7	1.31	0.15	0.85	0.33	0.17	212	**1006**	5	25	27
L_1: Kk-B39	1.38	*0.10*	0.79	0.18	0.15	**836**	**1419**	5	17	23
L_2: Gr-M13a	*1.21*	0.06	0.65	0.38	0.16	146	97	3	15	36
L_3: Jh-M42	No data as replication was lost in a wildfire.									
L_4: Gr-G36	1.4	0.07	*0.46*	0.35	0.22	384	95	4	10	32
NORMS[5]	1.21	0.14	0.50	0.08	0.10	25	70	2.4	14	17
Adequate	1.2-2.0	0.14-0.3	>0.5	0.08-0.45	0.1-0.4	25-400	70-200	2.4-9.0	14-64	16-70
marginal	1-1.2	0.1-0.14	0.35-0.5	0.06-0.07	0.06-0.08	11.0-20	40-70	2.1-2.3	11-13	10-16.0
deficient	<1.0	<0.1	<0.35	<0.06	<0.05	<10	<35	<2	<11	5-12

[1]Non shaded =adequate; [2] Light shaded and italicised = marginal; [3] Dark shaded = deficient; [4] Bolded = very high levels ;

[5]Norms according to Boardman *et al.*, 1997

According to critical norms by Boardman *et al*., (1997) all the replications used in the study (Table 4.1a) had adequate nutrient concentrations of Ca, Mg, Mn, Fe, Cu, B and Zn at the beginning of the study except L_4 which had a deficiency of Zn and L_1 and S_4 which had Fe concentrations above the accepted levels. Replication L_1 also had Mn levels above the acceptable, although levels below 2000 mg kg^{-1} are usually still not toxic to most conifers. Potassium was adequate in all replications except in S_2 and L_4 which had marginal concentrations of the element. There was a P deficiency in all replications in Grabouw. However, in Kluitjieskraal, L_1 had marginally deficient concentrations of P while S_4 had borderline adequate levels. According to Boardman *et al*., (1997), there was a marginal N deficiency in all the Grabouw sites except L_4 which had adequate concentrations of N. Both replications at Kluitjieskraal had adequate nitrogen levels. If however one uses the 1.5% critical level according to Will (1985), all the replications did not have N at the sufficiency level.

Table 4.1 b below shows the nutrient ratios within the control plot of each replication before treatment.

Table 4.1 b: Foliar nutrient ratios relative to nitrogen of 13 to 17 year old *P. radiata* trees in control plots of each replication before fertilizer application in 2008.

Rep	P/N %	K/N %	Ca/N %	Mg/N %	Mn/N %	Fe/N %	Cu/N %	Zn/N %	B/N %
S_1	5	**57**	**33**	**11**	**0.47**	**1.23**	0.03	**0.14**	**0.29**
S_2	7	**41**	**33**	**13**	**0.56**	**0.97**	0.03	**0.13**	**0.20**
S_3	8	**51**	**27**	**12**	**0.95**	**1.21**	0.03	**0.15**	**0.35**
S_4	**11**	**65**	**25**	**13**	**1.62**	**7.68**	0.04	**0.19**	**0.21**
L_1	7	**57**	**13**	**11**	**6.06**	**10.28**	0.04	**0.12**	**0.17**
L_2	5	**54**	**31**	**13**	**1.21**	**0.80**	0.02	**0.12**	**0.30**
L_3			No	data					
L_4	5	33	**25**	**16**	**2.74**	**0.68**	0.03	**0.07**	**0.23**
NORMS[4]	**10**	**35**	**2.5**	**4**	**0.05**	**0.2**	**0.03**	**0.05**	**0.05**

[1]No shading = Optimum; [2]Dark shaded = below optimum level; [3] Bolded = above optimum

[4]Norms according to Linder, 1995

Nutrient ratio analysis (Table 4.1b) of the replications before treatment revealed that the ratios for K, Ca, Mg, Mn, Fe, Zn and B relative to nitrogen were above the optimum ratios except for Cu in L_2 and K in L_4. The P/N ratio was below the optimum for all the replications except in S_4 where it was above the optimum level.

The nutrient concentrations one year after fertilization are shown in Table 4.2a.

Table 4.2a: Foliar nutrient concentrations of 14 to 18 year old *P. radiata* trees in treatment plots of each replication taken one year after mid- rotation fertilizer application in 2009. Highlighted values are below the critical levels.

Site	Treatment	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
				%					mg kg^{-1}		
	Optimum[1]	>1.5[2]	0.14	0.5	0.08	0.1	25	70	14	2.4	17
S_1 Gr-J27	N_0P_0	1.3	0.05	0.57	0.22	0.06	61	144	16	3	25
	N_0P_1	1.23	0.08	0.76	0.36	0.05	91	139	23	3	27
	N_0P_2	1	0.11	0.61	0.33	0.08	73	103	20	3	20
	N_1P_0	1.66	0.04	0.63	0.16	0.07	54	89	15	3	25
	N_1P_1	1.2	0.1	0.78	0.26	0.04	51	102	15	3	25
	N_1P_2	1.14	0.1	0.62	0.32	0.1	60	92	15	3	24
	N_2P_0	1.66	0.03	0.4	0.15	0.02	43	98	21	3	18
	N_2P_1	1.29	0.08	0.48	0.24	0.12	45	114	16	4	28
	N_2P_2	1.57	0.12	0.62	0.37	0.07	127	111	17	3	29
S_2 Gr-D12	N_0P_0	1.04	0.07	0.28	0.42	0.09	99	94	19	2	22
	N_0P_1	1.07	0.13	0.45	0.42	0.1	94	92	27	3	21
	N_0P_2	1.18	0.11	0.51	0.44	0.07	100	79	20	6	21
	N_1P_0	1.27	0.09	0.51	0.36	0.07	116	72	27	4	18
	N_1P_1	1.22	0.12	0.43	0.37	0.08	157	67	26	3	24
	N_1P_2	1.3	0.16	0.39	0.44	0.11	105	85	25	3	21
	N_2P_0	1.52	0.11	0.42	0.35	0.05	96	96	19	5	18
	N_2P_1	1.47	0.12	0.38	0.42	0.08	95	87	20	3	19
	N_2P_2	1.44	0.14	0.34	0.38	0.09	110	94	22	4	26
S_3 Gr-E14:	N_0P_0	1.2	0.1	0.53	0.21	0.03	105	92	18	3	27
	N_0P_1	1.16	0.15	0.47	0.28	0.05	96	99	18	3	20
	N_0P_2	1.22	0.2	0.47	0.3	0.07	147	89	21	7	24
	N_1P_0	1.43	0.14	0.62	0.31	0.11	110	78	19	3	26
	N_1P_1	1.35	0.14	0.52	0.35	0.1	109	72	19	3	19
	N_1P_2	1.36	0.17	0.61	0.33	0.06	104	82	18	5	18
	N_2P_0	1.61	0.11	0.44	0.23	0.05	85	95	19	5	19
	N_2P_1	1.36	0.11	0.48	0.38	0.02	179	79	23	3	21
	N_2P_2	1.46	0.12	0.42	0.33	0.08	116	79	28	4	16

Table 4.2a continued

		N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
				%					$mg\ kg^{-1}$		
	Optimum	>1.5[2]	0.14	0.5	0.08	0.1	25	70	2.4	14	17
S_4: Kk-B7	N_0P_0	1.39	0.13	0.82	0.36	0.13	212	153	4	18	25
	N_0P_1	1.34	0.12	0.62	0.27	0.09	209	149	4	22	23
	N_0P_2	1.21	0.11	0.8	0.48	0.16	231	208	3	17	31
	N_1P_0	1.72	0.15	0.67	0.62	0.29	448	128	4	25	38
	N_1P_1	1.6	0.13	0.75	0.35	0.14	269	125	4	18	20
	N_1P_2	1.28	0.11	0.53	0.5	0.14	275	226	3	16	19
	N_2P_0	2.01	0.12	0.76	0.42	0.16	250	112	5	25	24
	N_2P_1	1.93	0.12	0.62	0.39	0.17	273	133	5	25	21
	N_2P_2	1.77	0.12	0.66	0.23	0.09	113	142	4	19	28
L_1: Kk-B39	N_0P_0	1.97	0.08	0.53	0.06	0.08	195	183	5	15	24
	N_0P_1	1.72	0.1	0.69	0.13	0.02	607	153	5	28	23
	N_0P_2	1.44	0.1	0.57	0.13	0.1	505	193	5	37	36
	N_1P_0	1.53	0.07	0.51	0.12	0.06	283	107	4	18	20
	N_1P_1	1.57	0.11	0.56	0.15	0.1	346	158	5	18	23
	N_1P_2	1.87	0.12	0.5	0.3	0.13	552	165	5	28	18
	N_2P_0	2.2	0.1	0.55	0.13	0.03	461	135	5	26	29
	N_2P_1	1.91	0.11	0.48	0.17	0.08	229	233	4	19	26
	N_2P_2	1.87	0.1	0.5	0.1	0.05	377	131	4	17	22
L_2: Gr-M13a	N_0P_0	0.94	0.05	0.42	0.29	0.07	100	102	2	22	24
	N_0P_1	1.03	0.08	0.52	0.32	0.15	212	109	3	38	30
	N_0P_2	0.89	0.07	0.5	0.35	0.11	169	75	3	30	30
	N_1P_0	1.48	0.05	0.51	0.34	0.1	97	105	3	30	28
	N_1P_1	1.15	0.08	0.46	0.24	0.09	83	76	3	22	26
	N_1P_2	1	0.1	0.48	0.4	0.09	113	96	2	30	26
	N_2P_0	1.69	0.05	0.47	0.18	0.05	70	97	3	24	22
	N_2P_1	1.51	0.08	0.48	0.3	0.04	118	115	3	22	37
	N_2P_2	1.4	0.1	0.53	0.37	0.11	112	111	6	31	26
L_4: Gr-G36	N_0P_0	1.49	0.08	0.3	0.41	0.21	390	80	3	14	32
	N_0P_1	1.22	0.09	0.18	0.33	0.18	403	74	4	19	29
	N_0P_2	1.29	0.06	0.2	0.47	0.15	385	84	4	15	27
	N_1P_0	1.64	0.07	0.3	0.28	0.12	266	70	4	15	20
	N_1P_1	1.58	0.09	0.4	0.42	0.13	221	108	4	13	19
	N_1P_2	1.41	0.09	0.48	0.33	0.1	222	84	3	16	29
	N_2P_0	1.53	0.09	0.36	0.46	0.15	371	86	4	16	28
	N_2P_1	1.7	0.1	0.23	0.4	0.19	598	63	4	15	31
	N_2P_2	1.57	0.18	0.94	1.33	0.32	217	102	6	82	36

[1] Norms according to Boardman *et al.*, 1997
[2] Optimum for N according to Will, 1985

Nitrogen concentration in Table 4.2a was found to be generally below the critical level of 1.5% according to Will (1985) for all treatments except in S_1 (N_1P_0; N_2P_0; N_2P_2), S_2 (N_2P_0), S_3 (N_0P_1), S_3 (N_2P_0), S_4 (N_1P_0; N_1P_1 ; N_2P_0; N_2P_1 ; N_2P_2), L_1 (all were above the critical except N_0P_2), L_2 (N_2P_0; N_2P_1) and L_4 (N_1P_0; N_1P_1 ; N_2P_0; N_2P_1 ; N_2P_2). Phosphorus concentration was below the critical levels for most of the treatments in all replications except S_2 (N_1P_2; N_2P_2), S_3 (N_0P_1; N_0P_2; N_1P_0; N_1P_1; N_1P_2) and S_4 (N_1P_0). Potassium levels were above the critical for all treatments in S_4 and for all treatments in L_1 except N_2P_1. The nutrient concentration for Ca was above the critical for all treatments in all replications except in L_1 (N_0P_0). Magnesium concentration was generally below the critical level except in S_4 and L_4. Nutrient concentrations for all the micronutrients measured were above the critical levels for all treatments in all replications except for isolated cases such as for Fe in S_2 (N_1P_1) and Cu (N_0P_0), Zn, L_4 (N_1P_1) and B in S_3 (N_2P_2).

A complete ANOVA (Appendix 4.3l) was conducted for N and P to determine if the treatments had any statistically significant effect on foliar nutrient concentration. The p values revealed that the treatments had a statistically significant effect on N (p<0.001) and P (p=0.059). There was no significant interaction between N and P (p=0.990). Table 4.2b and 4.2c show the effect of N and P fertilizer on foliar N and P respectively one year after applying the fertilizer treatments.

Table 4.2b: Effect of N and P fertilizer on foliar N levels one year after applying the treatments to mid-rotation *P. radiata* trees. Different letters indicate significant differences between the means at the 10% level of significance (upper case for P fertilizer quantity means and lower case for N fertilizer quantity means).

	Kg P ha^{-1}			
Kg N ha^{-1}	0	50	100	**Means**
0	1.33	1.25	1.18	1.25 c
100	1.53	1.38	1.34	1.42 b
200	1.75	1.60	1.58	1.64 a
Means	1.54 A	1.41 B	1.37 B	1.44

Table 4.2c: Effect of N and P fertilizer on foliar P levels one year after applying the treatments to mid-rotation *P. radiata* trees. Different letters indicate significant differences between the means at the 10% level of significance (upper case for P fertilizer quantity means and lower case for N fertilizer quantity means).

	Kg P ha^{-1}			
Kg N ha^{-1}	0	50	100	**Means**
0	0.08	0.12	0.11	0.11 a
100	0.09	0.11	0.12	0.11 a
200	0.09	0.10	0.13	0.11 a
Means	0.09 A	0.11 B	0.12 B	0.11

The foliar N was increased by increasing quantities of N fertilizer. However, the application of P fertilizer had a negative effect on foliar N levels and resulted in a decrease in foliar N when either 50 or 100 kg P ha^{-1} was applied (Table 4.2b).

Foliar P concentration was only affected by P fertilizer. Foliar P concentration increased significantly from 0.09 to 0.11 when 50 kg P ha^{-1} was applied. Although an increase in P fertilizer to 100 kg P ha^{-1} increased foliar P further to 0.12 this was not statistically different from P_{50} level. Even the highest application of P did not raise the foliar P concentration above the 0.14 critical limit (Table 4.2c).

A complete ANOVA was also conducted for K, Ca, Mg, Mn, Fe, Cu, Zn and B to determine if the treatments had any statistically significant effect on foliar nutrient concentration. The *p* values revealed that the treatments had no statistically significant effect on all these elements and there was no significant interaction between N and P (Data not presented).

The P/N ratio was generally below the optimum level for all treatments in all replications one year after fertilizer application (Table 4.3). The following ratios were above the optimum for all treatments in all replications: Ca/N, Mn/N, Fe/N Zn/N and B/N. Because fertilizer N and P affected foliar N, it had an indirect effect on the element: N as well.

Table 4.3: Foliar nutrient ratios of 14 to 18 year old *P. radiata* trees in treatment plots of each replication taken a year after mid-rotation fertilizer application in 2009. Highlighted values are below the critical level.

Rep		P/N	K/N	Ca/N	Mg/N	Mn/N	Fe/N	Cu/N	Zn/N	B/N
						%				
	[1]Optimum	10	35	2.5	4	0.05	0.2	0.03	0.05	0.05
S1 Gr-J27	N_0P_0	4	44	17	5	0.47	1.11	0.02	0.12	0.19
	N_0P_1	7	62	29	4	0.74	1.13	0.02	0.19	0.22
	N_0P_2	11	61	33	8	0.73	1.03	0.03	0.20	0.20
	N_1P_0	2	38	10	4	0.33	0.54	0.02	0.09	0.15
	N_1P_1	8	65	22	3	0.43	0.85	0.03	0.13	0.21
	N_1P_2	9	54	28	9	0.53	0.81	0.03	0.13	0.21
	N_2P_0	2	24	9	1	0.26	0.59	0.02	0.13	0.11
	N_2P_1	6	37	19	9	0.35	0.88	0.03	0.12	0.22
	N_2P_2	8	39	24	4	0.81	0.71	0.02	0.11	0.18
S2 Gr-D12	N_0P_0	7	27	40	9	0.95	0.90	0.02	0.18	0.21
	N_0P_1	12	42	39	9	0.88	0.86	0.03	0.25	0.20
	N_0P_2	9	43	37	6	0.85	0.67	0.05	0.17	0.18
	N_1P_0	7	40	28	6	0.91	0.57	0.03	0.21	0.14
	N_1P_1	10	35	30	7	1.29	0.55	0.02	0.21	0.20
	N_1P_2	12	30	34	8	0.81	0.65	0.02	0.19	0.16
	N_2P_0	7	28	23	3	0.63	0.63	0.03	0.13	0.12
	N_2P_1	8	26	29	5	0.65	0.59	0.02	0.14	0.13
	N_2P_2	10	24	26	6	0.76	0.65	0.03	0.15	0.18
S3 Gr-E14	N_0P_0	8	44	18	3	0.88	0.77	0.03	0.15	0.23
	N_0P_1	13	41	24	4	0.83	0.85	0.03	0.16	0.17
	N_0P_2	16	39	25	6	1.20	0.73	0.06	0.17	0.20
	N_1P_0	10	43	22	8	0.77	0.55	0.02	0.13	0.18
	N_1P_1	10	39	26	7	0.81	0.53	0.02	0.14	0.14
	N_1P_2	13	45	24	4	0.76	0.60	0.04	0.13	0.13
	N_2P_0	7	27	14	3	0.53	0.59	0.03	0.12	0.12
	N_2P_1	8	35	28	1	1.32	0.58	0.02	0.17	0.15
	N_2P_2	8	29	23	5	0.79	0.54	0.03	0.19	0.11
S4 Kk-B7	N_0P_0	9	59	26	9	1.53	1.10	0.03	0.13	0.18
	N_0P_1	9	46	20	7	1.56	1.11	0.03	0.16	0.17
	N_0P_2	9	66	40	13	1.91	1.72	0.02	0.14	0.26
	N_1P_0	9	39	36	17	2.60	0.74	0.02	0.15	0.22
	N_1P_1	8	47	22	9	1.68	0.78	0.03	0.11	0.13
	N_1P_2	9	41	39	11	2.15	1.77	0.02	0.13	0.15
	N_2P_0	6	38	21	8	1.24	0.56	0.02	0.12	0.12
	N_2P_1	6	32	20	9	1.41	0.69	0.03	0.13	0.11
	N_2P_2	7	37	13	5	0.64	0.80	0.02	0.11	0.16

Table 4.3 continued

Rep		P/N	K/N	Ca/N	Mg/N	Mn/N	Fe/N	Cu/N	Zn/N	B/N
						%				
	Optimum	**10**	**35**	**2.5**	**4**	**0.05**	**0.2**	**0.03**	**0.05**	**0.05**
L1 Kk-B39	N_0P_0	4	27	3	4	0.99	0.93	0.03	0.08	0.12
	N_0P_1	6	40	8	1	3.53	0.89	0.03	0.16	0.13
	N_0P_2	7	40	9	7	3.51	1.34	0.03	0.26	0.25
	N_1P_0	5	33	8	4	1.85	0.70	0.03	0.12	0.13
	N_1P_1	7	36	10	6	2.20	1.01	0.03	0.11	0.15
	N_1P_2	6	27	16	7	2.95	0.88	0.03	0.15	0.10
	N_2P_0	5	25	6	1	2.10	0.61	0.02	0.12	0.13
	N_2P_1	6	25	9	4	1.20	1.22	0.02	0.10	0.14
	N_2P_2	5	27	5	3	2.02	0.70	0.02	0.09	0.12
L2 Gr M13a	N_0P_0	5	45	31	7	1.06	1.09	0.02	0.23	0.26
	N_0P_1	8	50	31	15	2.06	1.06	0.03	0.37	0.29
	N_0P_2	8	56	39	12	1.90	0.84	0.03	0.34	0.34
	N_1P_0	3	34	23	7	0.66	0.71	0.02	0.20	0.19
	N_1P_1	7	40	21	8	0.72	0.66	0.03	0.19	0.23
	N_1P_2	10	48	40	9	1.13	0.96	0.02	0.30	0.26
	N_2P_0	3	28	11	3	0.41	0.57	0.02	0.14	0.13
	N_2P_1	5	32	20	3	0.78	0.76	0.02	0.15	0.25
	N_2P_2	7	38	26	8	0.80	0.79	0.04	0.22	0.19
L4 Gr-G36	N_0P_0	5	20	28	14	2.62	0.54	0.02	0.09	0.21
	N_0P_1	7	15	27	15	3.30	0.61	0.03	0.16	0.24
	N_0P_2	5	16	36	12	2.98	0.65	0.03	0.12	0.21
	N_1P_0	4	18	17	7	1.62	0.43	0.02	0.09	0.12
	N_1P_1	6	25	27	8	1.40	0.68	0.03	0.08	0.12
	N_1P_2	6	34	23	7	1.57	0.60	0.02	0.11	0.21
	N_2P_0	6	24	30	10	2.42	0.56	0.03	0.10	0.18
	N_2P_1	6	14	24	11	3.52	0.37	0.02	0.09	0.18
	N_2P_2	11	60	85	20	1.38	0.65	0.04	0.52	0.23

[1]Norms according to Linder, 1995

The changes in nutrient concentration for the different treatments a year after treatment are presented in Table 4.4. When P is added the foliar N concentration decreases across all levels of N and when no N is applied. The application of N had no significant effect on foliar P levels and in absolute terms, except for the $N_{200}P_{50}$ treatment, the P foliar levels increased very slightly with an increase in N quantity across all levels of P fertilizer. Both

N and P application did not have a significant effect on the foliar concentration for all the other elements.

Table 4.4: Change in foliar nutrient concentration of each element relative to control plots of each replication after fertilizer application in 2009.

Rep	Treatment	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
		%					mg/kg				
S_1 Gr-J27	N_0P_1	-0.07	0.03	0.19	0.14	-0.01	30	-5	0	7	2
	N_0P_2	-0.3	0.06	0.04	0.11	0.02	12	-41	0	4	-5
	N_1P_0	0.36	-0.01	0.06	-0.06	0.01	-7	-55	0	-1	0
	N_1P_1	-0.1	0.05	0.21	0.04	-0.02	-10	-42	0	-1	0
	N_1P_2	-0.16	0.05	0.05	0.1	0.04	-1	-52	0	-1	-1
	N_2P_0	0.36	-0.02	-0.17	-0.07	-0.04	-18	-46	0	5	-7
	N_2P_1	-0.01	0.03	-0.09	0.02	0.06	-16	-30	1	0	3
	N_2P_2	0.27	0.07	0.05	0.15	0.01	66	-33	0	1	4
S_2 Gr-D12	N_0P_1	0.03	0.06	0.17	0	0.01	-5	-2	1	8	-1
	N_0P_2	0.14	0.04	0.23	0.02	-0.02	1	-15	4	1	-1
	N_1P_0	0.23	0.02	0.23	-0.06	-0.02	17	-22	2	8	-4
	N_1P_1	0.18	0.05	0.15	-0.05	-0.01	58	-27	1	7	2
	N_1P_2	0.26	0.09	0.11	0.02	0.02	6	-9	1	6	-1
	N_2P_0	0.48	0.04	0.14	-0.07	-0.04	-3	2	3	0	-4
	N_2P_1	0.43	0.05	0.1	0	-0.01	-4	-7	1	1	-3
	N_2P_2	0.4	0.07	0.06	-0.04	0	11	0	2	3	4

Table 4.4 continued

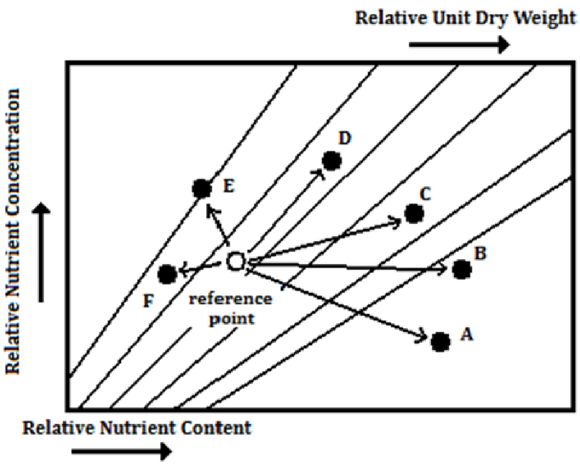
Rep	Treatment	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
		%					mg/kg				
S_3 Gr-E14:	N_0P_1	-0.04	0.05	-0.06	0.07	0.02	-9	7	0	0	-7
	N_0P_2	0.02	0.1	-0.06	0.09	0.04	42	-3	4	3	-3
	N_1P_0	0.23	0.04	0.09	0.1	0.08	5	-14	0	1	-1
	N_1P_1	0.15	0.04	-0.01	0.14	0.07	4	-20	0	1	-8
	N_1P_2	0.16	0.07	0.08	0.12	0.03	-1	-10	2	0	-9
	N_2P_0	0.41	0.01	-0.09	0.02	0.02	-20	3	2	1	-8
	N_2P_1	0.16	0.01	-0.05	0.17	-0.01	74	-13	0	5	-6
	N_2P_2	0.26	0.02	-0.11	0.12	0.05	11	-13	1	10	-11
S_4: Kk-B7	N_0P_1	-0.05	-0.01	-0.2	-0.09	-0.04	-3	-4	0	4	-2
	N_0P_2	-0.18	-0.02	-0.02	0.12	0.03	19	55	-1	-1	6
	N_1P_0	0.33	0.02	-0.15	0.26	0.16	236	-25	0	7	13
	N_1P_1	0.21	0	-0.07	-0.01	0.01	57	-28	0	0	-5
	N_1P_2	-0.11	-0.02	-0.29	0.14	0.01	63	73	-1	-2	-6
	N_2P_0	0.62	-0.01	-0.06	0.06	0.03	38	-41	1	7	-1
	N_2P_1	0.54	-0.01	-0.2	0.03	0.04	61	-20	1	7	-4
	N_2P_2	0.38	-0.01	-0.16	-0.13	-0.04	-99	-11	0	1	3

Table 4.4 continued

Rep	Treatment	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
		%					mg/kg				
L_1: Kk-B39	N_0P_1	-0.25	0.02	0.16	0.07	-0.06	412	-30	0	13	-1
	N_0P_2	-0.53	0.02	0.04	0.07	0.02	310	10	0	22	12
	N_1P_0	-0.44	-0.01	-0.02	0.06	-0.02	88	-76	-1	3	-4
	N_1P_1	-0.4	0.03	0.03	0.09	0.02	151	-25	0	3	-1
	N_1P_2	-0.1	0.04	-0.03	0.24	0.05	357	-18	0	13	-6
	N_2P_0	0.23	0.02	0.02	0.07	-0.05	266	-48	0	11	5
	N_2P_1	-0.06	0.03	-0.05	0.11	0	34	50	-1	4	2
	N_2P_2	-0.1	0.02	-0.03	0.04	-0.03	182	-52	-1	2	-2
L_2: Gr-M13a	N_0P_1	0.09	0.03	0.1	0.03	0.08	112	7	1	16	6
	N_0P_2	-0.05	0.02	0.08	0.06	0.04	69	-27	1	8	6
	N_1P_0	0.54	0	0.09	0.05	0.03	-3	3	1	8	4
	N_1P_1	0.21	0.03	0.04	-0.05	0.02	-17	-26	1	0	2
	N_1P_2	0.06	0.05	0.06	0.11	0.02	13	-6	0	8	2
	N_2P_0	0.75	0	0.05	-0.11	-0.02	-30	-5	1	2	-2
	N_2P_1	0.57	0.03	0.06	0.01	-0.03	18	13	1	0	13
	N_2P_2	0.46	0.05	0.11	0.08	0.04	12	9	4	9	2
L_4: Gr-G36	N_0P_1	-0.27	0.01	-0.12	-0.08	-0.03	13	-6	1	5	-3
	N_0P_2	-0.2	-0.02	-0.1	0.06	-0.06	-5	4	1	1	-5
	N_1P_0	0.15	-0.01	0	-0.13	-0.09	-124	-10	1	1	-12
	N_1P_1	0.09	0.01	0.1	0.01	-0.08	-169	28	1	-1	-13
	N_1P_2	-0.08	0.01	0.18	-0.08	-0.11	-168	4	0	2	-3
	N_2P_0	0.04	0.01	0.06	0.05	-0.06	-19	6	1	2	-4
	N_2P_1	0.21	0.02	-0.07	-0.01	-0.02	208	-17	1	1	-1
	N_2P_2	0.08	0.1	0.64	0.92	0.11	-173	22	3	68	4

4.1.2 Vector Analysis

Vector analysis (Timmer and Stone, 1978) was also used to determine the responses to the treatments one year after fertilization. Interpretation of the vectors is based on the magnitude and direction of each vector. These aspects depend on the changes in nutrient concentration, content and unit dry weight as shown in Figure 4.1 (Haase & Rose, 1995). The weight of 300 needles was used as the unit dry weight for this study.



Direction of shift	Response in			Interpretation	Possible diagnosis
	Dry weight	Nutrient			
		Conc.	Content		
A	+	-	+	Dilution	Non-limiting
B	+	0	+	Sufficiency	Non-limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury consumption	Non-toxic
E	-	++	±	Excess	Toxic
F	-	-	-	Excess	Antagonistic

Figure 4.1: Interpretation of shifts in dry weight, nutrient concentration and nutrient content (figure and table from Haase & Rose, 1995. Forest Science: Vol 41. No. 1: 54 – 66).

Shifts to the right or left of the diagonal represent increases or decreases respectively, shifts along a diagonal line indicate no change in dry weight. Shifts along the horizontal indicate no change in nutrient concentration but shifts along the vertical represent a change in concentration. Shifts along the vertical indicate no change in content but shifts along the horizontal indicate a change in content. Table 4.5 constructed according to the description under 3.4.2 shows a summary of the vectors for all the elements investigated. The response of each element to the application of the treatment that yielded the largest volume growth response for the site is presented in Table 4.5.

Table 4.5: Vector analysis results one year after fertilizer application (2009) with largest (most important) vectors in shaded cells. The treatment with largest growth response (for which all vectors on that specific replication are shown) is indicated in the first column. For each nutrient element in turn, the relative size of the vector (negligible, small, medium or large), as well as its components (using coding from Figure 4.1, i.e. + or - for nutrient mass, concentration and content), a vector shift symbol and a possible diagnosis is given.

Replication & Compartment (Best treatment)	**Vector description**	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Cu**	**Zn**	**B**
S_1: Gr-J27 ($N_{200}P_{100}$)	Relative size	Small	**Large**	Small	Medium	Small	Medium	Negligible	Small	Small	Small
	Code (shift)	+++ (C)	**+++ (C)**	+++ (C)	+++ (C)	+++ (C)	+++ (C)	- - - (F)	+0+ (B)	+0+ (B)	+++ (C)
	Interpretation	Deficiency	**Deficiency**	Deficiency	Deficiency	Deficiency	Deficiency	Excess	Sufficiency	Sufficiency	Deficiency
	Diagnosis	Limiting	**Limiting**	Limiting	Limiting	Limiting	Limiting	Non limiting	Non limiting	Non limiting	Limiting
S_2: Gr-D12 ($N_{200}P_0$)	Relative size	**Large**	**Large**	**Large**	Medium	Small	Medium	Medium	**Large**	Medium	Medium
	Code (shift)	**+++** (C)	**+++** (C)	**+++ (C)**	+-+ (A)	+-+ (A)	+-+ (A)	+0+ (B)	**+++** (C)	+0+ (B)	+-+ (A)
	Interpretation	**Deficiency**	**Deficiency**	**Deficiency**	Dilution	Dilution	Dilution	Sufficiency	**Deficiency**	Sufficiency	Dilution
	Diagnosis	**Limiting**	**Limiting**	**Limiting**	Non limiting	Non limiting	Non limiting	Non limiting	**Limiting**	Non limiting	Non limiting
S_3: Gr- E14 ($N_{200}P_0$)	Relative size	Small	Small	Small	Small	Medium	Small	Small	Medium	Small	Negligible
	Code (shift)	+++ (C)	+++ (C)	+-+ (A)	+++ (C)	+++ (C)	+ - + (A)	+++ (C)	+++ (C)	+++ (C)	- - - (F)
	Interpretation	Deficiency	Deficiency	Dilution	Deficiency	Deficiency	Dilution	Deficiency	Deficiency	Deficiency	Excess
	Diagnosis	Limiting	Limiting	Non limiting	Limiting	Limiting	Non-Limiting	Limiting	Limiting	Limiting	Non limiting
S_4: Kk-B7 ($N_{200}P_{50}$)	Relative size	Small	Negligible	Negligible	Negligible	Small	Small	Negligible	Small	Small	Small
	Code (shift)	-++ (E)	--- (F)	+-+ (A)	--- (F)	-++ (E)	-++ (E)	--- (F)	-++ (E)	-++ (E)	-++ (E)
	Interpretation	Excess	Excess	Dilution	Excess	Excess	Excess	Excess	Excess	Excess	Excess
	Diagnosis	Non limiting	Non limiting	Non limiting	Non limiting	Non limiting	Non limiting	Non limiting	Non limiting	Non limiting	Non limiting
L_1: Kk-B39 ($N_{100}P_{50}$)	Relative size	Small	Medium	Small	**Large**	Small	**Medium**	Small	Small	Small	Small
	Code (shift)	+-+ (A)	+++ (C)	**+++ (C)**	**+++** (C)	+0+ (B)	**+++ (C)**	+++ (C)	+-+ (A)	+++ (C)	+++ (C)
	Interpretation	Dilution	Deficiency	**Deficiency**	**Deficiency**	Sufficiency	**Deficiency**	Deficiency	Dilution	Deficiency	Deficiency
	Diagnosis	Non limiting	Limiting	**Limiting**	**Limiting**	Non limiting	**Limiting**	Limiting	Non limiting	Limiting	Limiting
L_2: Gr-M13a ($N_{200}P_{100}$)	Relative size	Small	Small	Small	Small	Small	Small	Small	Medium	Small	Small
	Code (shift)	-++ (E)	+++ (C)	+++ (C)	+++ (C)	+++ (C)	+++ (C)	+-+ (A)	+0+ (B)	+++ (C)	+++ (C)
	Interpretation	Excess	Deficiency	Deficiency	Deficiency	Deficiency	Deficiency	Dilution	Sufficiency	Deficiency	Deficiency
	Diagnosis	Non limiting	Limiting	Limiting	Limiting	Limiting	Limiting	Non limiting	Non limiting	Limiting	Limiting
L_3: Jh-M42		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
L_4: Gr-G36 ($N_{200}P_{50}$)	Relative size	Small	Small	Small	Small	Small	Medium	Small	Small	Small	Small
	Code (shift)	+++ (C)	+++ (C)	+-+ (A)	+-+ (A)	+-+ (A)	+++ (C)	+-+ (A)	+++ (C)	+0+ (B)	+-+ (A)
	Interpretation	Deficiency	Deficiency	Dilution	Dilution	Dilution	Deficiency	Dilution	Deficiency	sufficiency	Dilution
	Diagnosis	Limiting	Limiting	Non limiting	Non limiting	Non limiting	Limiting	Non limiting	Limiting	Non limiting	Non limiting

The plus, minus or zero in Table 4.5 indicate the shifts in direction. A vector description is provided in which the terms, deficiency, excess, sufficiency and dilution refer to the nutrient concentration status of the element before fertilizer application. The terms limiting and non - limiting indicate whether the initial nutrient concentration before fertilizer application could have limited growth or not. Seeing that the size of a particular vector is an indication of the degree of, e.g. limitation or excess, only the cells with relatively large vectors have been shaded in Table 4.5. Vector nomograms with largest (most important) vectors per compartment are presented in Appendix 4.1. Grabouw S_2 had four of the ten elements investigated classified as large responses.

Nitrogen was found to be deficient in all compartments used except in replications S_4, L_1 and L_2 and was most likely limiting growth. Phosphorus was deficient in all sites except in replication S_4. It appears that fertilization with N and P allowed stands to also take up substantially more Cu in S_2 and Ca in L_1, thereby alleviating pronounced growth limitations posed by low levels of these nutrients. Other than the cases mentioned above, other elements were generally present in foliage in adequate concentrations. A growth response is likely to be observed in those compartments indicated as limiting, if the elements indicated as deficient are applied. Alternatively, application of one or more limiting nutrient(s) may improve growth to a point where uptake of an additional limiting nutrient (not present in the fertilizer treatment) is also improved, as shown above. Replications on sites with fast growth rates in the unfertilized state (S_4 and L_4) generally had smaller vectors, indicating that fewer acute deficiencies exist there, however these replications still responded strongly to fertilisation as demonstrated in the following sections.

Vector analysis was also conducted on the average response observed across all the replications and the results are shown in Figure 4.2 - 4.3 compared to the post fertilization control treatment (N_0P_0). The data that was used for this is presented in Appendix 4.2 (a) – (b).

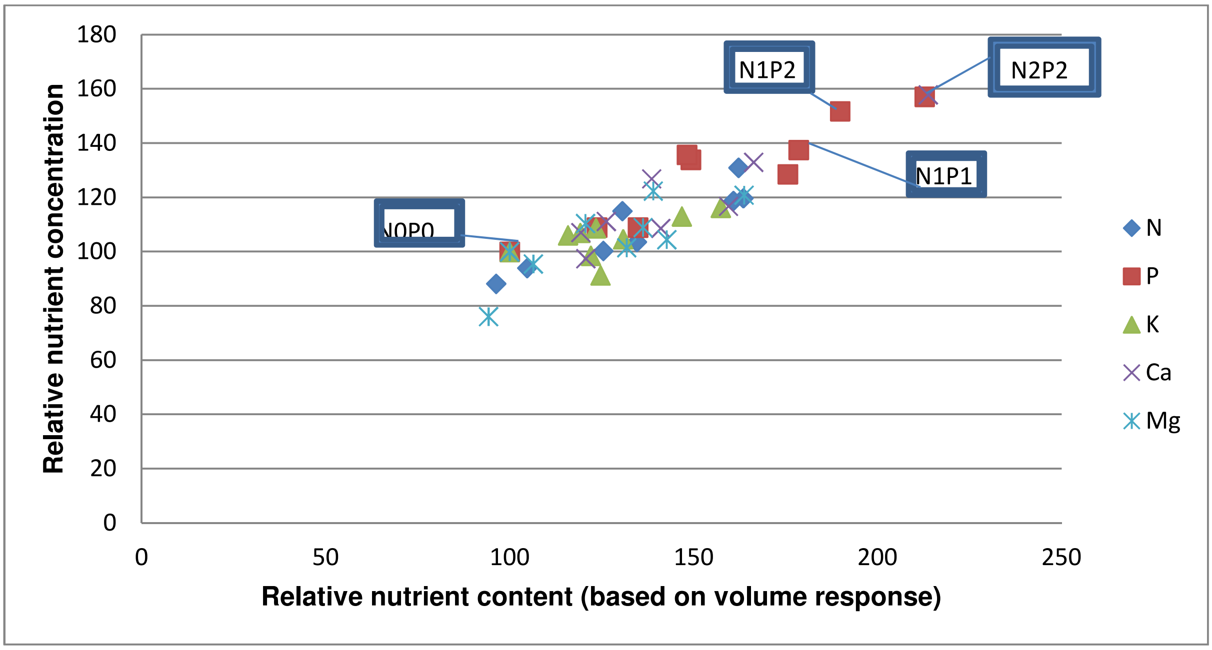


Figure 4.2: Relative response of foliar N, P, K, Ca and Mg nutrient levels for all the treatments compared to the control treatment from a mid-rotation fertilizer trial to illustrate vector analysis.

The vector analysis shows that of the macro nutrients, P was the main limiting nutrient as compared to the others as the major vectors were associated with P, indicating that addition of P corrected a deficiency.

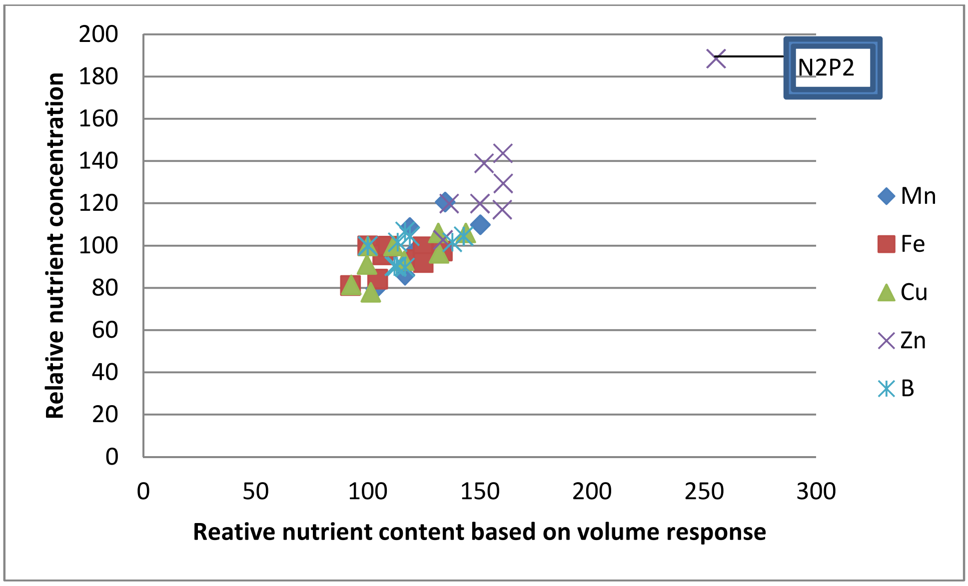


Figure 4.3: Relative response of foliar Mn, Fe, Cu, Zn and B nutrient levels for all the treatments compared to the control treatment from a mid-rotation fertilizer trial to illustrate vector analysis.

The vector analysis shows that of the micro nutrients, Zn was the main limiting nutrient as compared to the others as the major vectors were associated with Zn, indicating that treatment corrected a Zn deficiency.

4.1.3 Comparison of vector analysis, critical values and nutrient ratios in the prediction of stands with nutrient deficiencies

Table 4.6 presents a comparison of the three methods, vector analysis, critical levels and nutrient ratios in identifying nutrient deficiencies before the application of the fertilizer treatments. This table is a summary of findings from Table 4.2a, 4.3 and 4.5. The control plot of each replication one year after fertilizer application was used as the before fertilization status for the critical levels and nutrient ratios.

Table 4.6: Comparison of vector analysis, critical levels and nutrient ratios. Critical levels and nutrient ratio's were calculated from the unfertilized control. The set of vector analysis results are contrasts between the treatment with the largest growth response and the unfertilized control for each replication (see Table 4.5). Standard terminology for each method was adhered to.

Replication & Compartment		N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
S_1: Gr-J27	Vector Analysis	Deficient	Deficient	Deficient	Deficient	Deficient	Deficient	Excess	Sufficient	Sufficient	Deficient
	Critical levels	marginal	Deficient	Adequate	Adequate	[1]B/l m & d	Adequate	Adequate	Adequate	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient	Deficient	Not deficient	Not deficient
S_2: Gr-D12	Vector Analysis	Deficient	Deficient	Deficient	Dilution	Dilution	Dilution	Sufficient	Deficient	Sufficient	Dilution
	Critical levels	Deficient	Deficient	Deficient	Adequate	Marginal	Adequate	Adequate	Deficient	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient	Deficient	Not deficient
S_3: Gr- E14	Vector Analysis	Deficient	Deficient	Dilution	Deficient	Deficient	Dilution	Deficient	Deficient	Deficient	Excess
	Critical levels	Marginal	[1]B/l m & d	Adequate	Adequate	Deficient	Adequate	Adequate	Adequate	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Not deficient	Not deficient	Deficient	Not deficient	Not deficient	Borderline	Not deficient	Not deficient
S_4: Kk-B7	Vector Analysis	Excess	Excess	Dilution	Excess	Excess	Excess	Excess	Excess	Excess	Excess
	Critical levels	Marginal	Marginal	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient	Borderline	Not deficient	Not deficient
L_1: Kk-B39	Vector Analysis	Dilution	Deficient	Deficient	Deficient	Sufficient	Deficient	Deficient	Dilution	Deficient	Deficient
	Critical levels	Marginal	Deficient	Adequate	Marginal	Marginal	Adequate	Adequate	Adequate	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient
L_2: Gr-M13a	Vector Analysis	Excess	Deficient	Deficient	Deficient	Deficient	Deficient	Dilution	Sufficient	Deficient	Deficient
	Critical levels	Deficient	Deficient	Marginal	Adequate	Marginal	Adequate	Adequate	Deficient	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Not deficient	Not deficient	Not deficient	Not deficient	Not deficient	Deficient	Not deficient	Not deficient
L_4: Gr-G36	Vector Analysis	Deficient	Deficient	Dilution	Dilution	Dilution	Deficient	Dilution	Deficient	Sufficient	Dilution
	Critical levels	Marginall	Deficient	Deficient	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
	Nutrient Ratios	N/A	Deficient	Deficient	Not deficient	Not deficient	Not deficient	Not deficient	Deficient	Not deficient	Not deficient

[1] =borderline between marginal and deficient

The three methods predicted the same result of P deficiency in all replications but differed in the prediction for P in S_4. They also predicted the same non deficiency result for all elements in S_4 except for P where vector analysis predicted an excess as compared to marginal for critical levels and deficient for nutrient ratio. The critical levels and nutrient ratio methods generally predicted the same outcome for all nutrients in all replications, except in a few cases where they differed for example; Cu in S_1 and L_4 and K in L_1. Vector analysis generally differed with the other two methods when it came to the deficiency of nutrients. Where vector analysis predicted deficiency of a nutrient, in most cases the other two methods predicted no deficiency for the same nutrient; for example K, Ca, Mn, and B in S_1 and Mn, Fe, Zn and B in L_1.

4.2 Leaf area index response to N, P and water availability class

LAI at time of treatment implementation was used as a covariate for the analysis. Where the covariate was found not to be statistically significant, it was excluded from the model to increase the power of the test. The ANOVA outputs for the analyses done for LAI at 12 months and at 24 months are presented in Appendix 4.3 (a) and (b). There was no covariate used for the analysis for LAI at 12 months as it was not significant but the analysis for LAI at 24 months used the covariate. There was no significant interaction between N and P (p=0.925), water and N (p=0.519) or water and P (p=0.696) when LAI increment data from all replications were pooled together at 12 months. No significant interaction between N and P (p=0.322), water and N (p=0.829) or water and P (p=0.659) was detected at 24 months. There was however a significant effect of N (p=0.020 and P (p=0.056) as single factors on LAI increment at 12 months (Figure 4.4 - 4.5). The increase for N (up to 200 kg ha $^{-1}$) was linear (Figure 4.4). An LSD test showed that the highest level of N (N_{200}) was significantly different from the control (p=0.003) but not significantly different from N_{100} (Appendix 4.4(a). Both P_{50} (p=0.011) and P_{100} (p=0.030) significantly increased LAI over that of the control although there was no statistically significant difference between the two (Appendix 4.4(b)). Water availability class did not significantly influence LAI at 12 months (p=0.227).

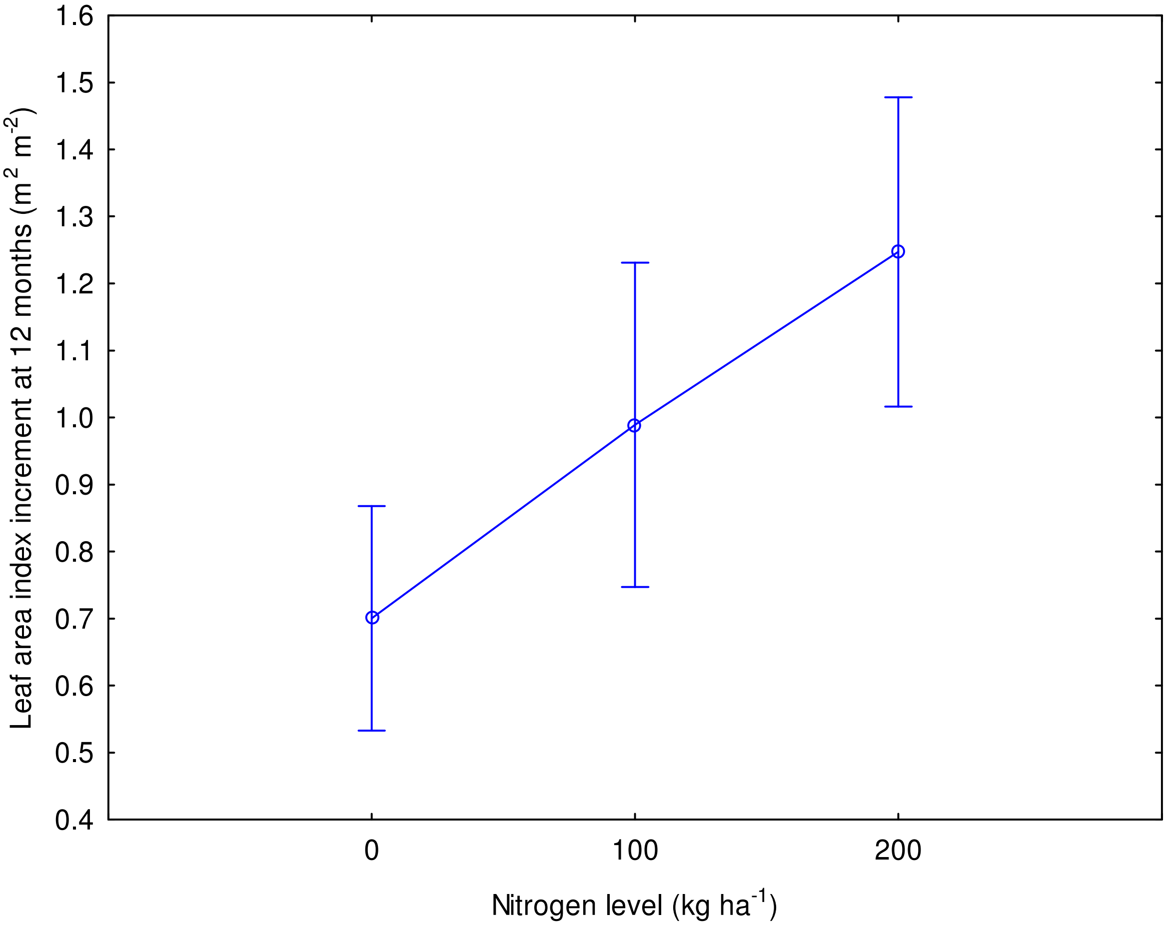


Figure 4.4: Leaf area index increment response to N at 12 months after treatment (vertical bars denote p = 0.90 confidence intervals)

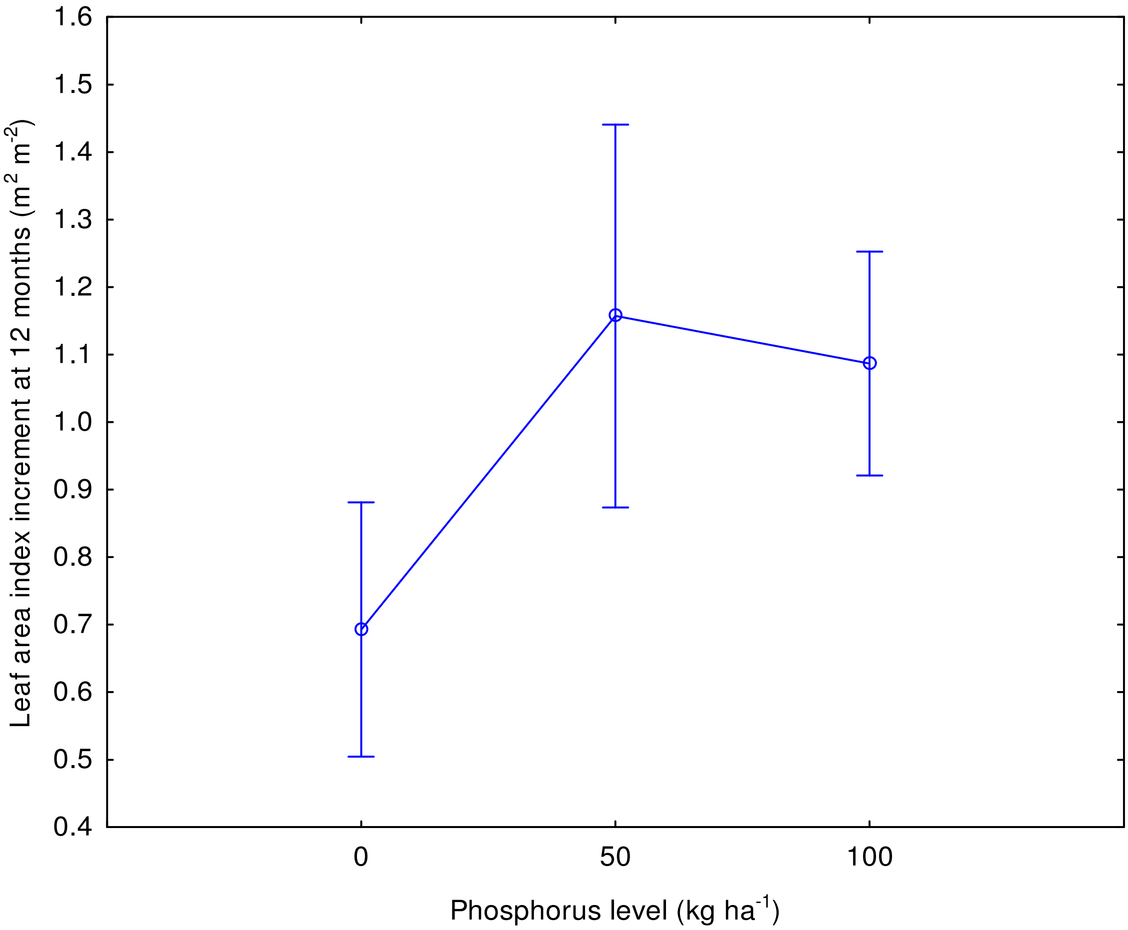


Figure 4.5: Leaf area index increment response to P at 12 months after treatment (vertical bars denote *p*=0.90 confidence intervals)

Figure 4.6 shows a photographic representation of treatment $N_{200}P_{100}$ and the control (N_0P_0) in replication S_1.

Figure 4.6: A photograph taken in 2009 in a 16 year old stand showing the control N_0P_0 (left) and $N_{200}P_{100}$ (right) in replication S_1 (Sandy soils) as described in Chapter 3.

There was a marked observable difference in the amount and density of foliage between these treatments with $N_{200}P_{100}$ having more and darker green foliage than the control. Figure 4.7 shows treatment $N_{200}P_{100}$, which is adjacent to treatment $N_{200}P_0$ in replication L_2.

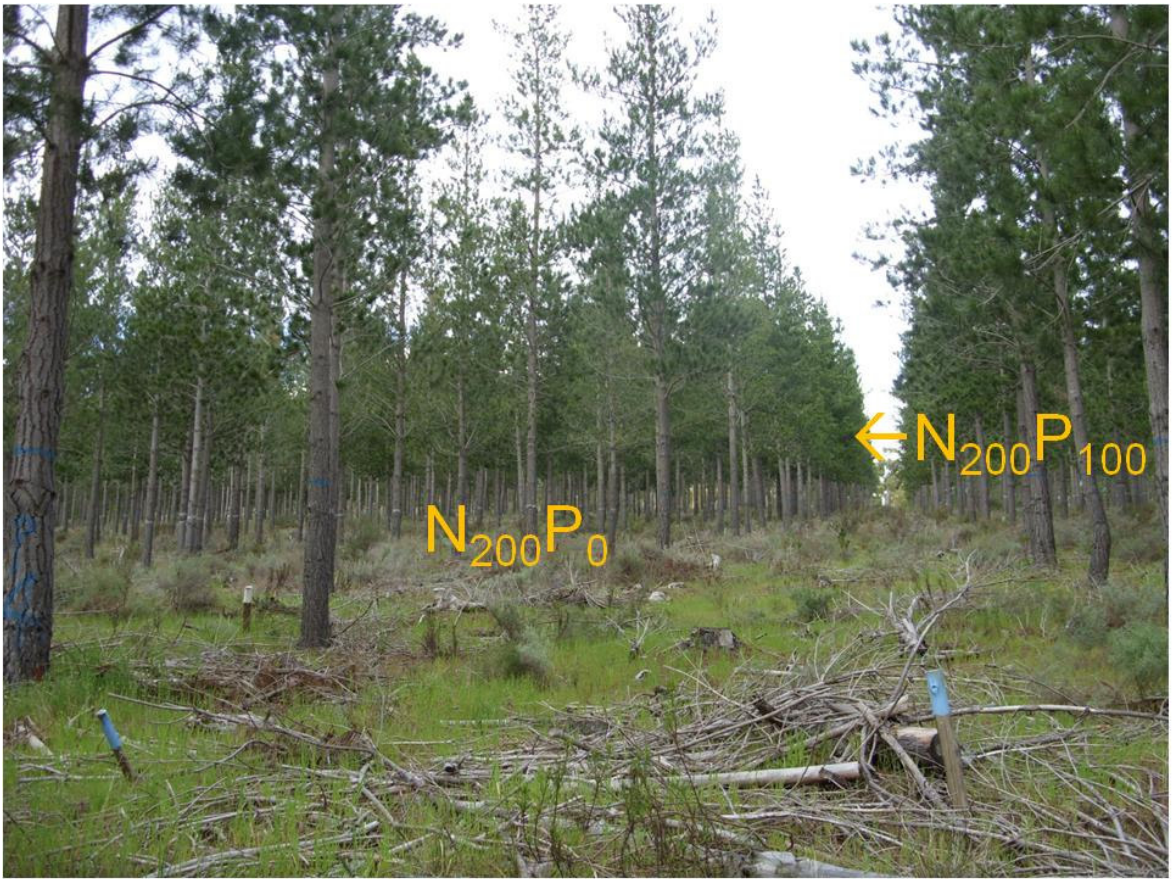


Figure 4.7: A photograph taken in 2009 in an 18 year old stand showing treatment $N_{200}P_0$ (foreground) and $N_{200}P_{100}$ (background) in replication L_2 (Loam soils) as described in Chapter 3.

The trees clearly have very sparse foliage in treatment $N_{200}P_0$ but dark and dense foliage for $N_{200}P_{100}$.

There was no significant effect of N (p=0.131) but there was a significant effect of P (p=0.031) and water availability class (p=0.014) as single factors on LAI increment at 24 months (Figure 4.8 - 4.9).

The LSD analysis at 24 months revealed that both P_{50} (p=0.003) and P_{100} (p=0.001) were significantly different from the control but were not themselves statistically different from each other as shown in Appendix 4.4(c).

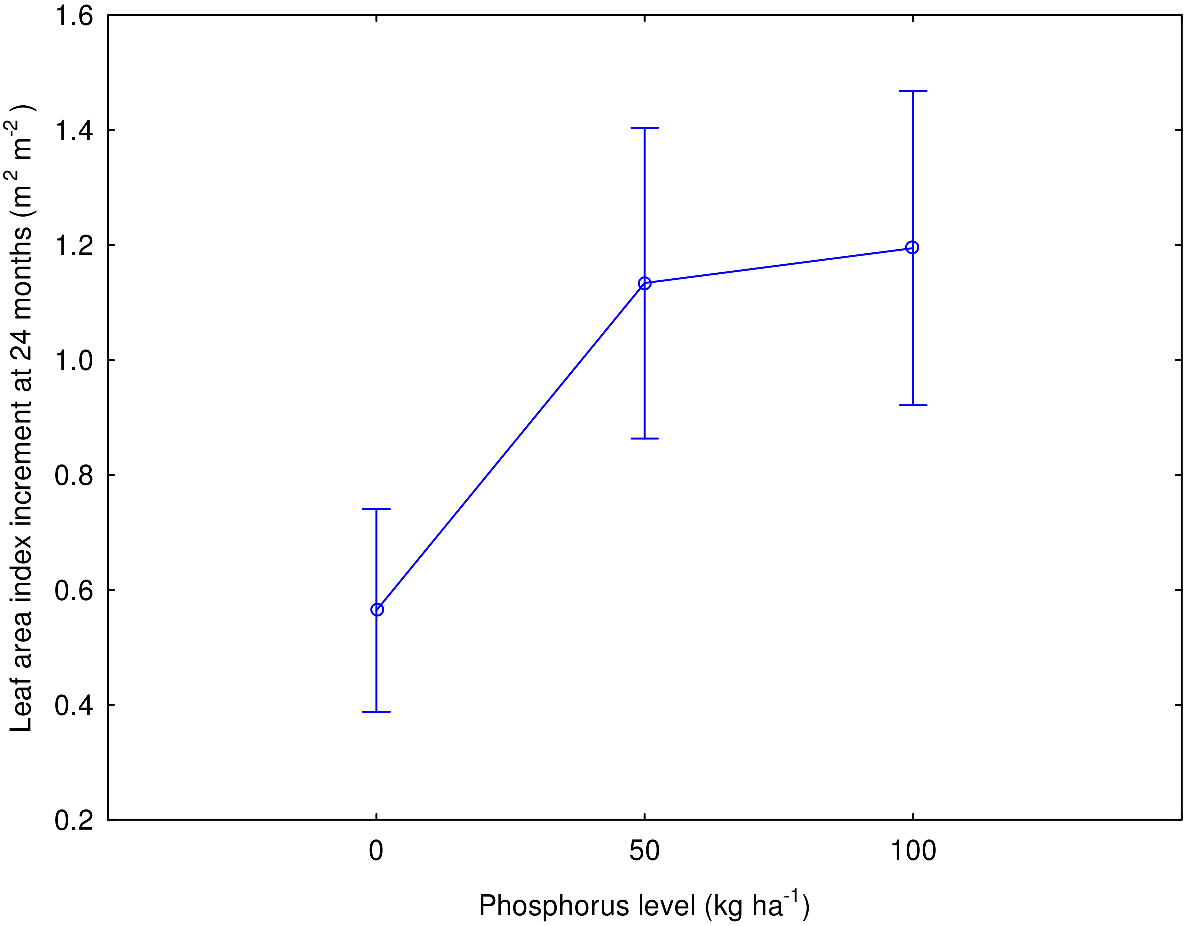


Figure 4.8: Leaf area index increment response to P at 24 months (vertical bars denote *p*=0.90 confidence intervals)

Water availability had a significant effect on LAI increment at 24 months after treatment. The highest water availability class (class 4) increased with a significantly larger margin than class 2 and class 3 (Figure 4.9 and Appendix 4.4d).

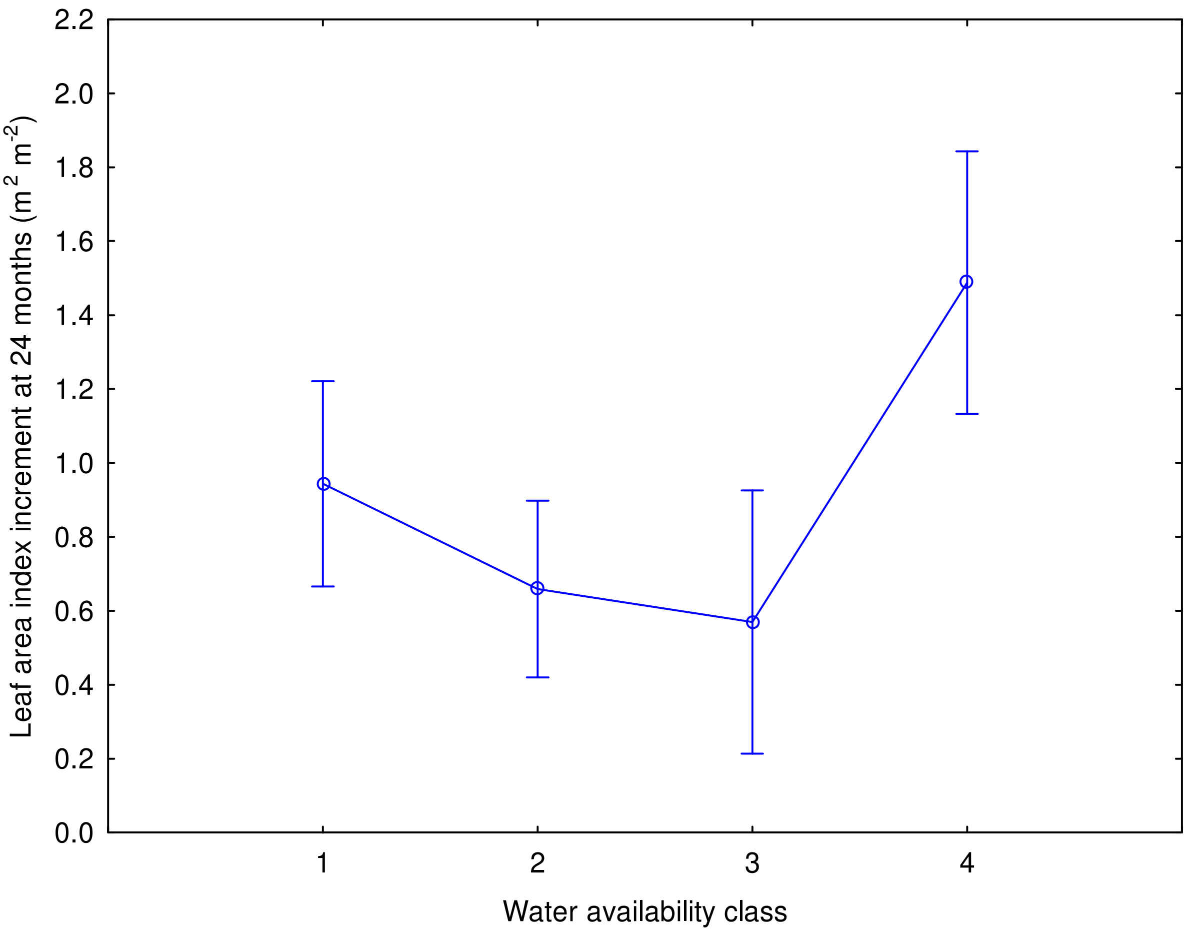


Figure 4.9: Leaf area index increment response to water availability class at 24 months (vertical bars denote *p*=0.90 confidence intervals)

A stepwise regression that was done with LAI increment at 24 months (when water availability class had a significant effect) as the dependent variable and N, P and water availability class as the predictor variables retained N and P as better predictors for LAI increment but dropped water availability class (Appendix 4.5). This indicates that of the two, nutrient availability and water availability, nutrient availability may have had a greater impact on LAI. This will be explored further in the discussion section. Linear regression was done between initial LAI and the leaf area increment at 24 months (Appendix 4.11). There was a weak but negative linear relationship with r^2= 0.07.

4.3 Basal area increment response to N, P and water availability class

Initial basal area in 2008 was used as a covariate for this analysis. Where the covariate was found not to be statistically significant, it was excluded from the model to increase the power of the test. The covariate was not significant for the analysis of basal area increment response in year 1 to N, P and water availability class. No covariate was used for total basal area increment analysis over the two years as it was also no significant.
The ANOVA outputs for all the analysis done for basal area increment in year 1, year 2 and total over the two year period are presented in Appendix 4.3 (c) - (e).

There was no interaction between N and P (p=0.999), N and water availability class (p=0.993) and P and water availability class (p=1.000) in 2009. Both N (p=0.518) and P (p=0.951) did not have a significant effect on basal area increment in 2009 as single factors but water availability class had a significant effect (p=0.003). Figure 4.10 shows the graph for the response of basal area increment in year 1 to water availability.

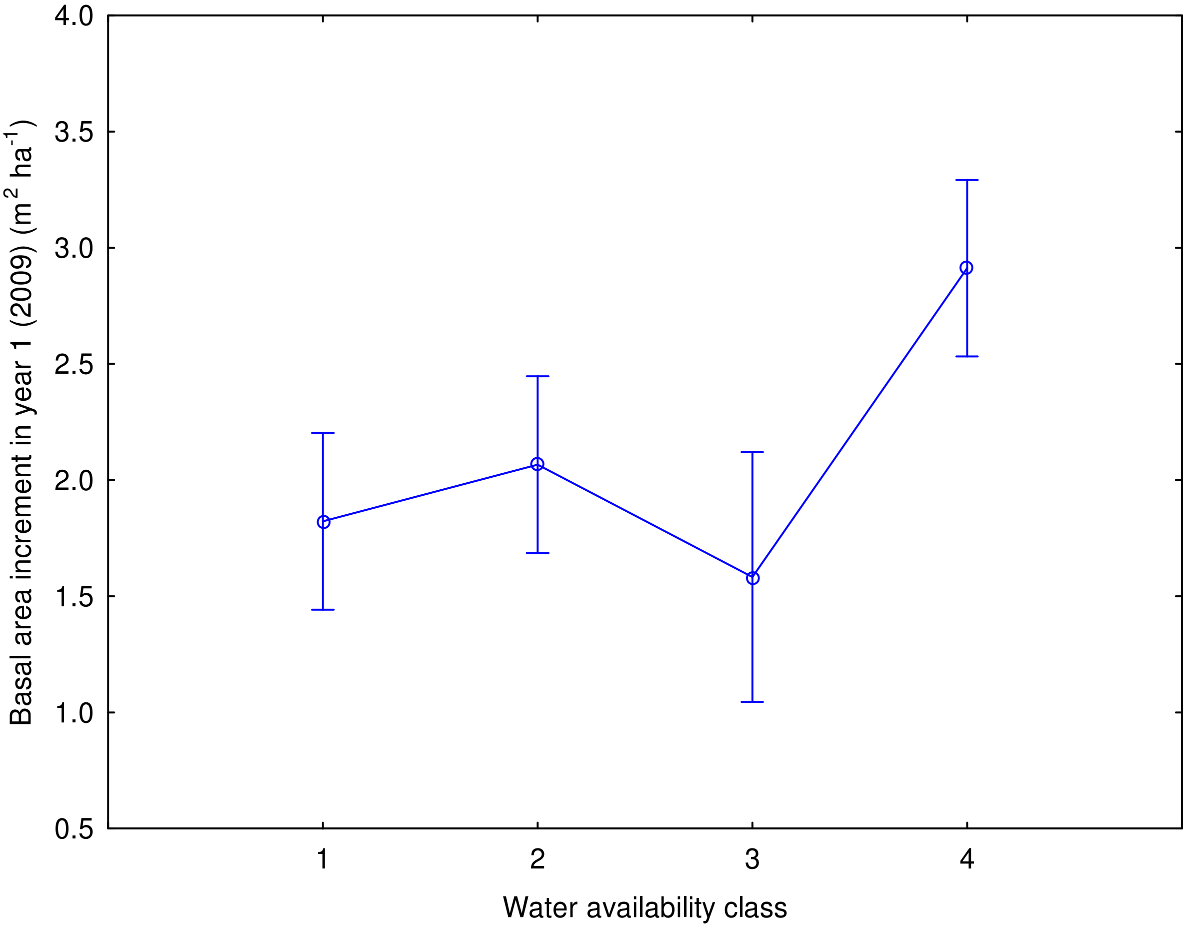


Figure 4.10: Basal area increment response to water availability class in year 1 (2009) (vertical bars denote *p*= 0.90 confidence intervals)

An LSD test showed that water availability class 4 was significantly different from all the other classes (Appendix 4.4e).

There was a significant effect due to N (p<0.001), P (p=0.061) and water availability class (p=0.044) as main effects in 2010. No significant interaction was detected between N and P (p=0.762), N and water availability class (p=0.869) and P and water availability class (p=0.907) in 2010. Figures 4.11 – 4.13 show the graphs for the significant effects of the main factors. Both N_{100} (p=0.016) and N_{200} (p<0.001) were significantly different from the control although they were not significantly different from each other (Figure 4.11 and Appendix 4.4f).

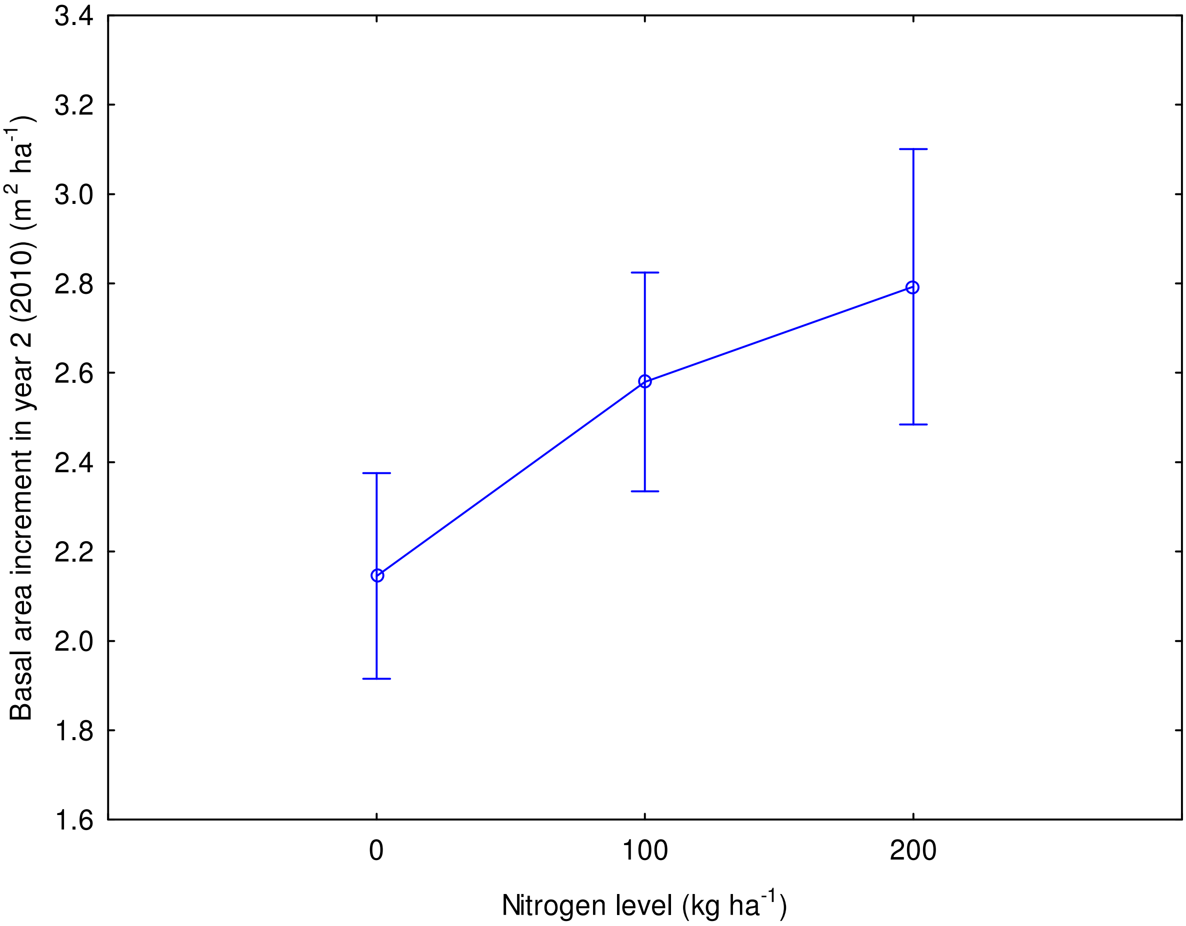


Figure 4.11: Basal area increment response to N in 2010 (vertical bars denote *p*=0.90 confidence intervals)

The two levels of P, P_{50} (p=0.029) and P_{100} (p=0.043) were significantly different from the control but they were also not significantly different from each other (Figure 4.12 and Appendix 4.4g).

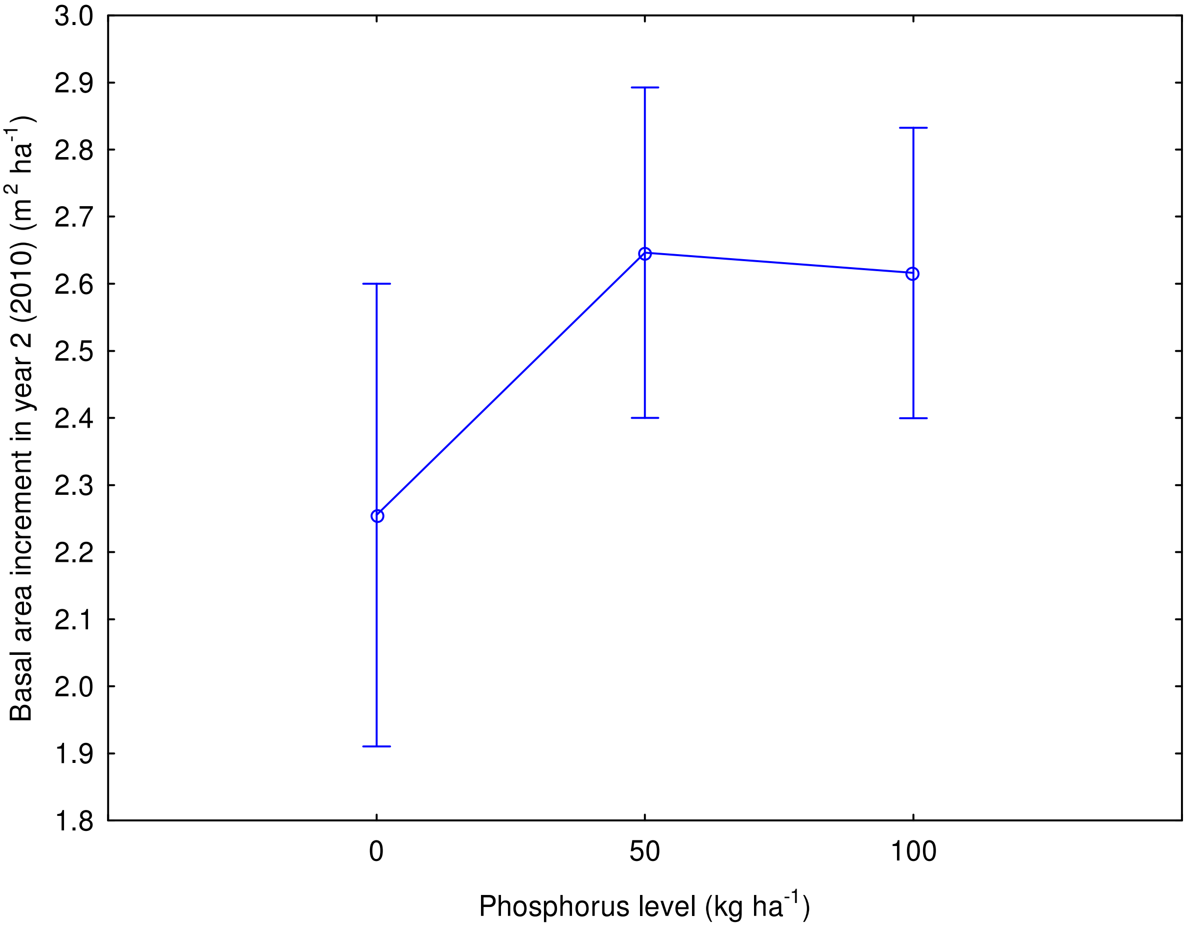


Figure 4.12: Basal area increment response to P in 2010 (vertical bars denote p=0.90 confidence intervals)

Water availability had a significant effect on basal area increment in year 2 after treatment, The highest water availability class (class 4) increased with a significantly larger margin than the other three classes (Figure 4.13 and Appendix 4.4h).

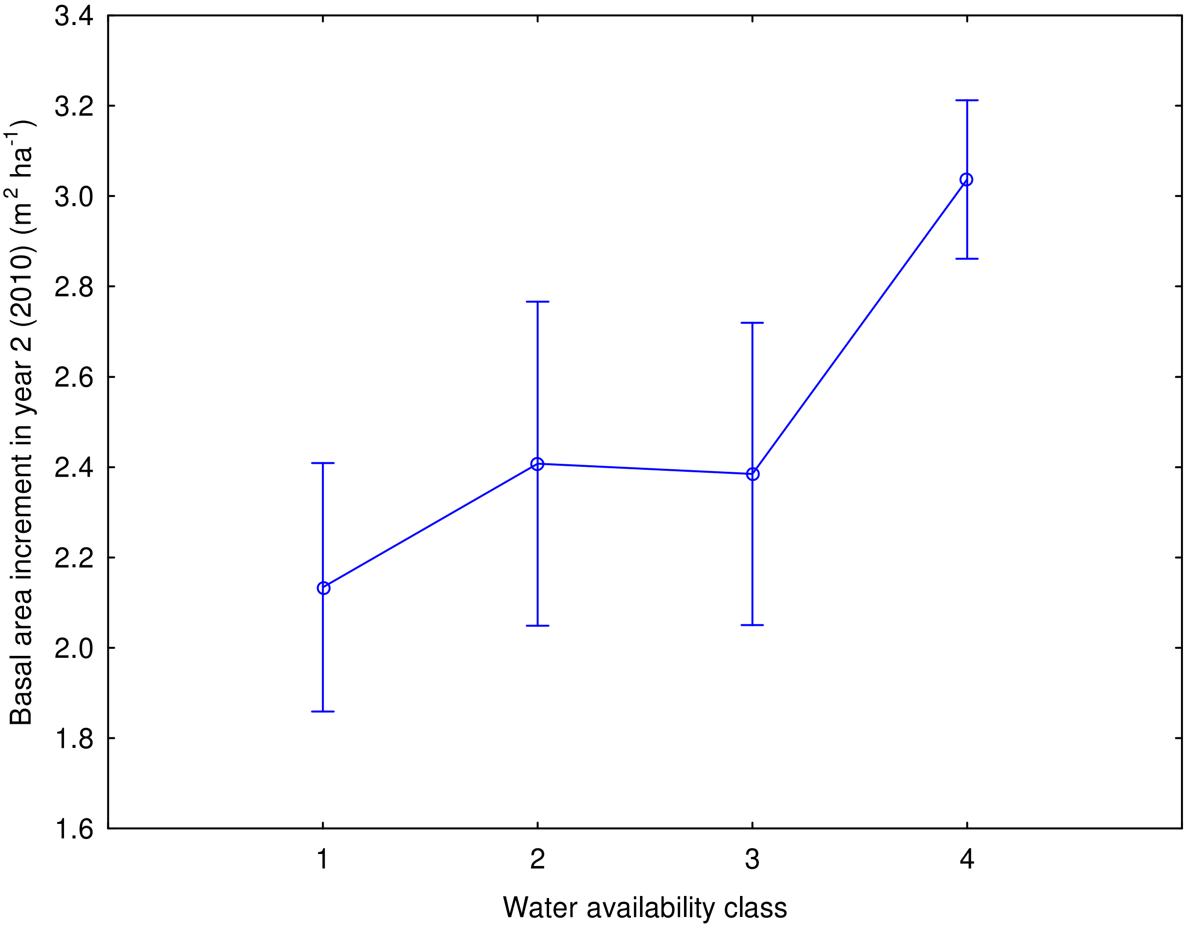


Figure 4.13: Basal area increment response to water availability class in year 2 (2010) (vertical bars denote p=0.90 confidence intervals)

When total basal increment (2008-2010) was considered, no significant interaction was detected between N and P (p=0.967), N and water availability class (p=0.987) and P and water availability class (p=0.997). Nitrogen (p=0.074) and water availability class (p<0.001) had a significant effect on total basal area increment but P was not significant (p=0.573). Figures 4.14 - 4.15 show graphs for total basal area increment response to N and water availability class.

The highest level, N_{200} (p=0.033) was significantly different from the control but N_{100} was not (Figure 4.14 and Appendix 4.4i).

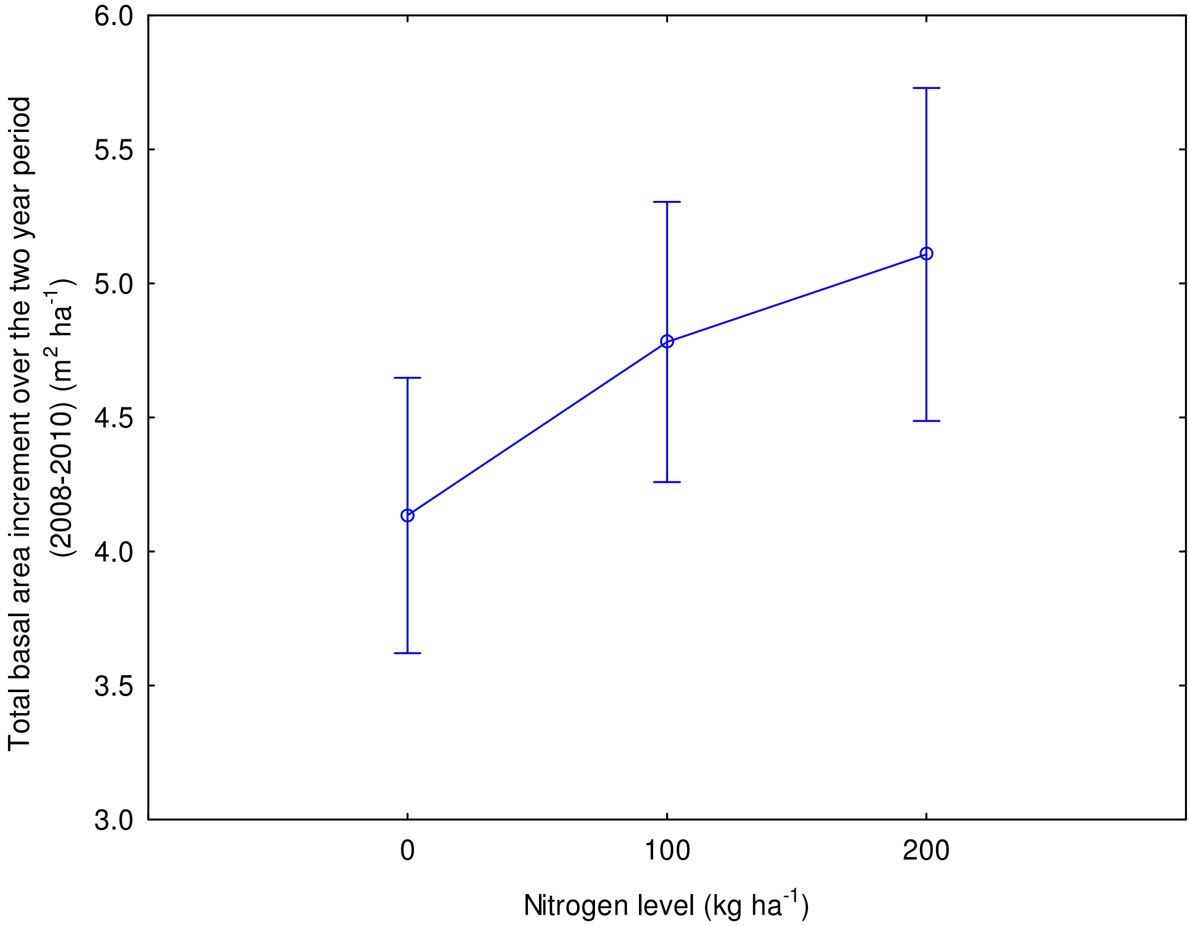


Figure 4.14: Total basal area increment response to N over the two year period (2008 – 2010) (vertical bars denote *p*=0.90 confidence intervals)

Water availability class 4 had a significantly higher increment than all the other classes (Figure 4.15 and Appendix 4.4j). The other three classes were however, not significantly different from each other.

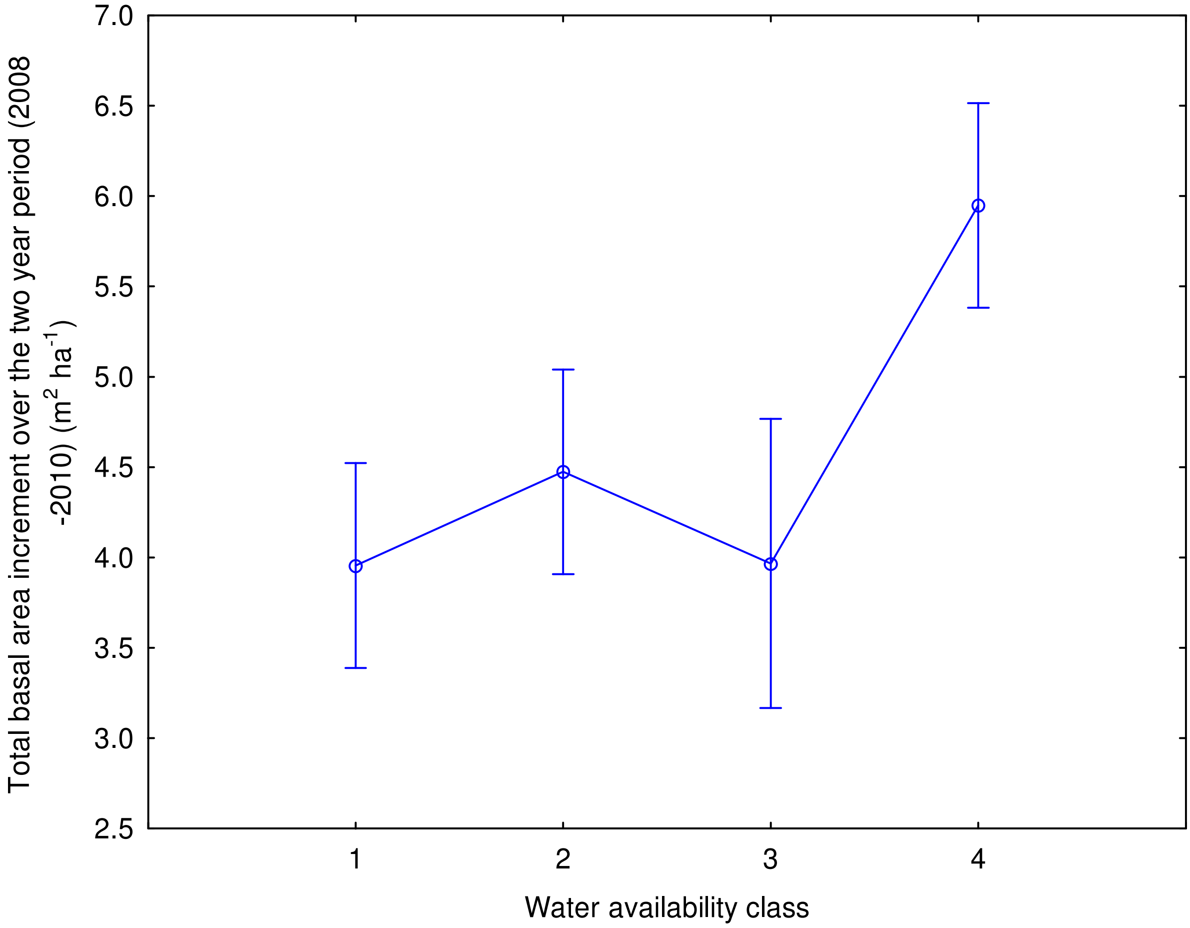


Figure 4.15: Total basal area increment response to water availability class (2008-2010) (vertical bars denote p=0.90 confidence intervals)

4.4 Analysis of volume growth response to N, P and water availability class

Initial volume at the start of the study before fertilizer application in 2008 was used as a covariate for this analysis. Where the covariate was found not to be statistically significant, it was excluded from the model to increase the power of the test. The covariate was significant for volume increment analyses in year 2 and when total volume increment was considered. No covariate was used for year 1 analysis as it was not significant.

The ANOVA outputs for all the analyses done for volume increment in year 1, year 2 and total over the two year period are presented in Appendix 4.3(f)-(h).

There was no interaction between N and P (p=0.992), N and water availability class (p=0.943) and P and water availability class (p=0.867) in 2009. Nitrogen (p=0.185) and P

(p=0.901) did not have a significant effect on volume increment in 2009 as single factors but water availability class had a significant effect (p<0.001).

Figure 4.16 and Appendix 4.4(k) show that water availability class 4 was significantly different from all the other classes (all p values<0.001) and had the greatest volume increment in 2009. Class 2 was significantly different from class 1 (p<0.001) and class 3 from class 2 (p=0.068).

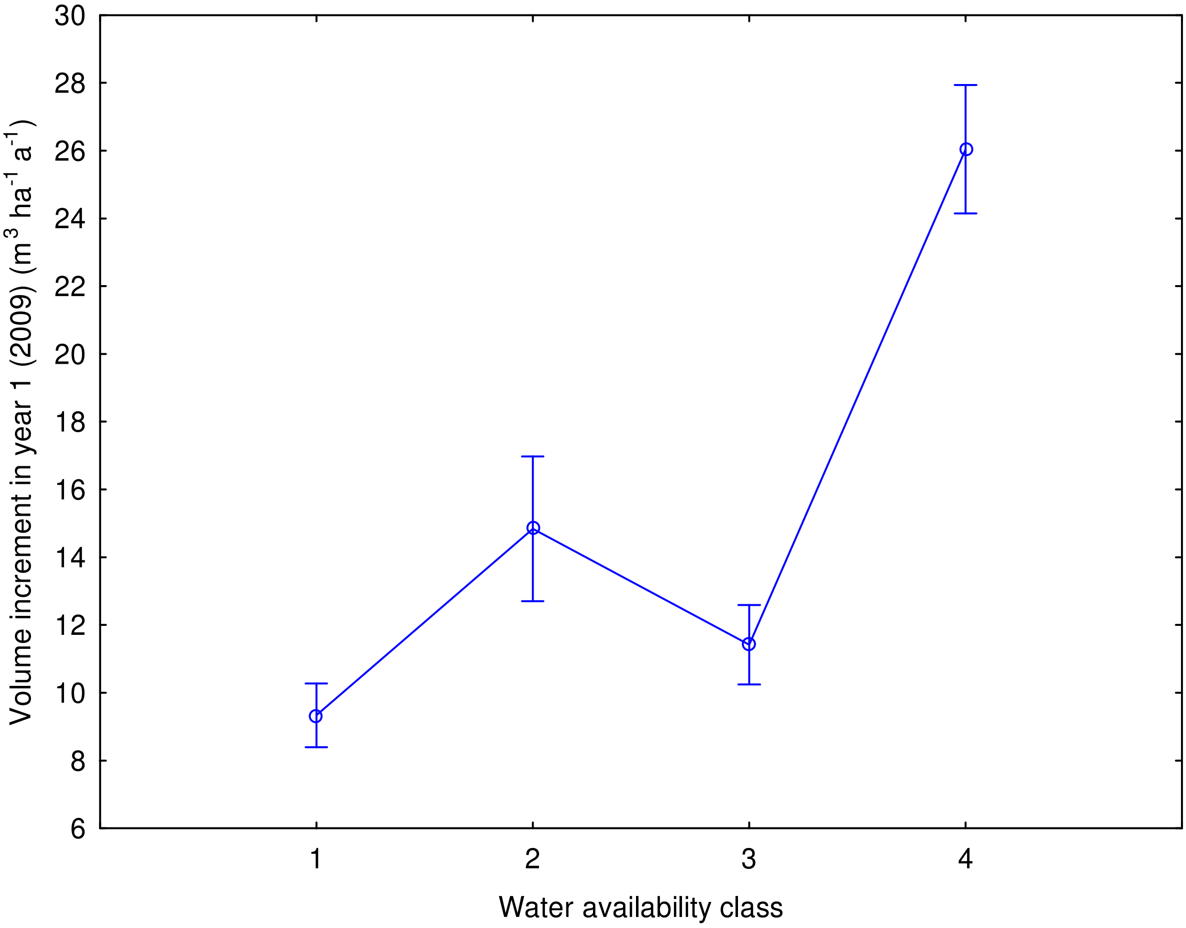


Figure 4.16: Volume increment response to water availability class in year 1 (2009) (vertical bars denote p=0.90 confidence intervals)

No significant interaction was detected between N and P (p=0.991), N and water availability class (p=0.977) and P and water availability class (p=0.968) in 2010.

There was however a significant effect due to both N (p=0.028), and water availability class (p<0.001) as main effects in 2010 (Figure 4.17-4.18) but P had no significant effect (p=0.142). Figure 4.17 shows the linear increase up to 200 kg ha^{-1} for N in 2010. The highest level of N, N_{200} had a significantly higher increment than the control (Appendix 4.4.l).

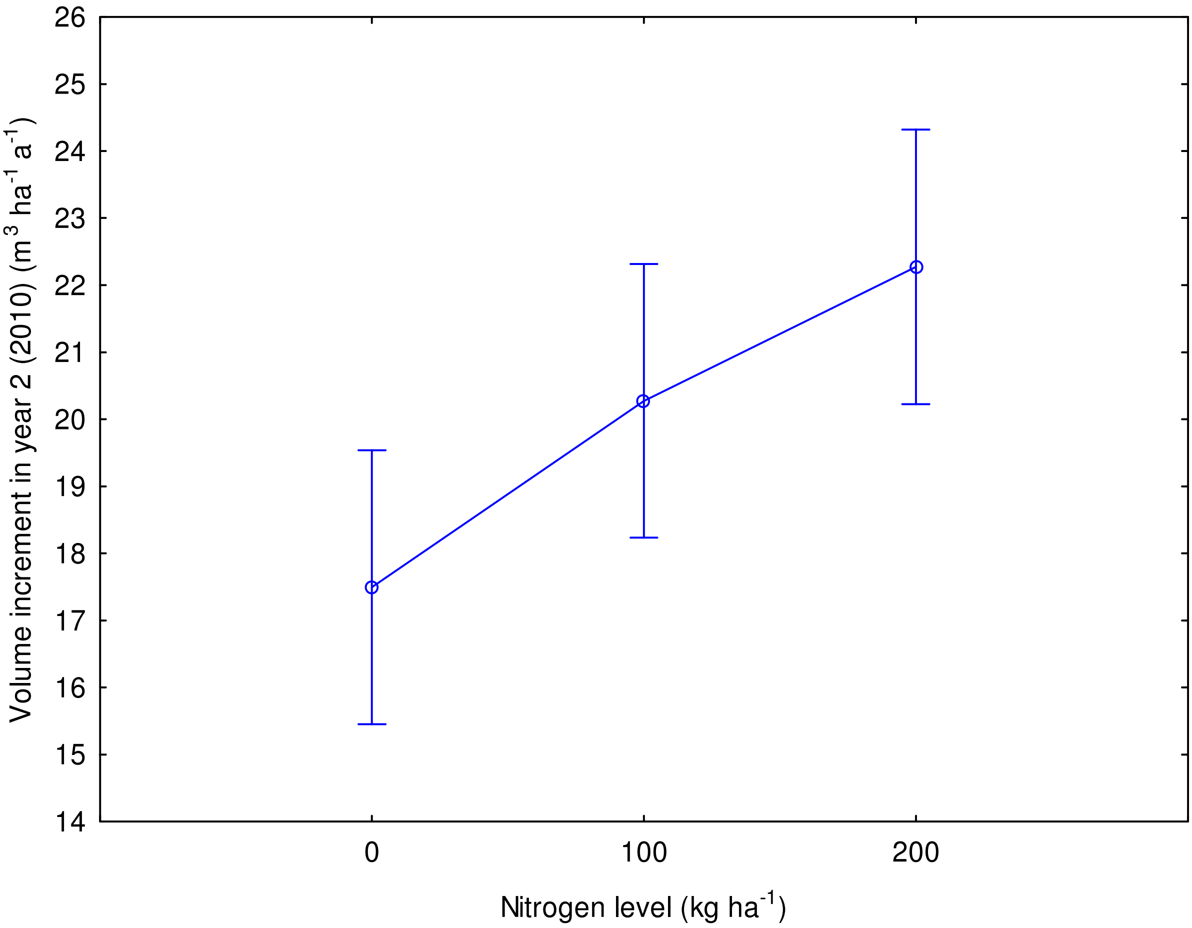


Figure 4.17: Volume increment response to N in year 2 (2010) (vertical bars denote p=0.90 confidence intervals)

Figure 4.18 and Appendix 4.4(m) show that only water availability class 4 was significantly different from all the other classes (all p values<0.001). Classes 1, 2 and 3 were however, not significantly different from each other.

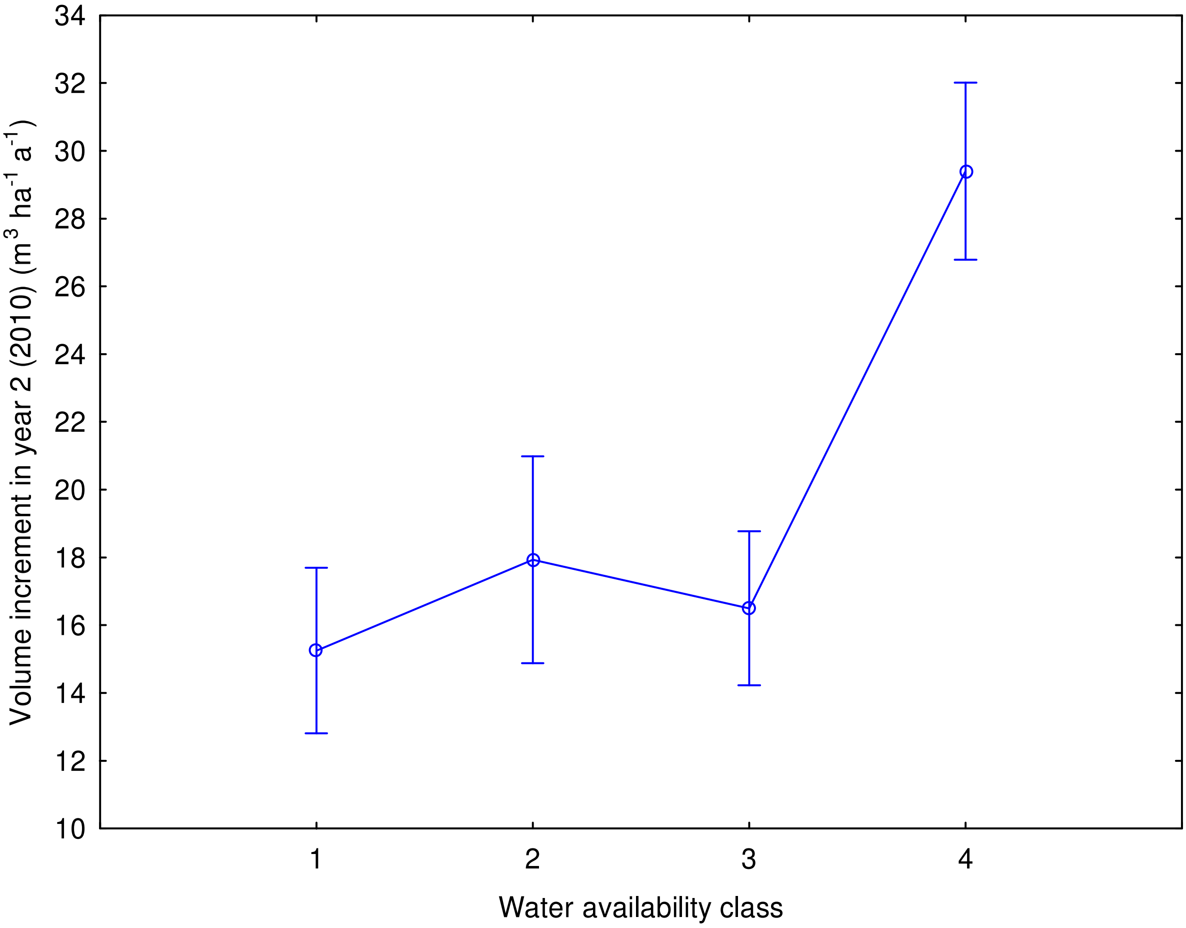


Figure 4.18: Volume increment response to water availability class in year 2 (2010) (vertical bars denote p=0.90 confidence intervals)

No significant interaction was detected between N and P (p=0.998), N and water availability class (p=0.994) and P and water availability class (p=0.935) when total volume increment over the two year period was considered.

There was however a significant effect due to both N (p=0.036), and water availability class (p<0.001) as main effects (Figure 4.19 - 4.20) but P had no significant effect (p=0.327).

The highest level of N, N_{200} (p=0.059) was significantly different from the control but not significantly different from N_{100} (Appendix 4.4n).

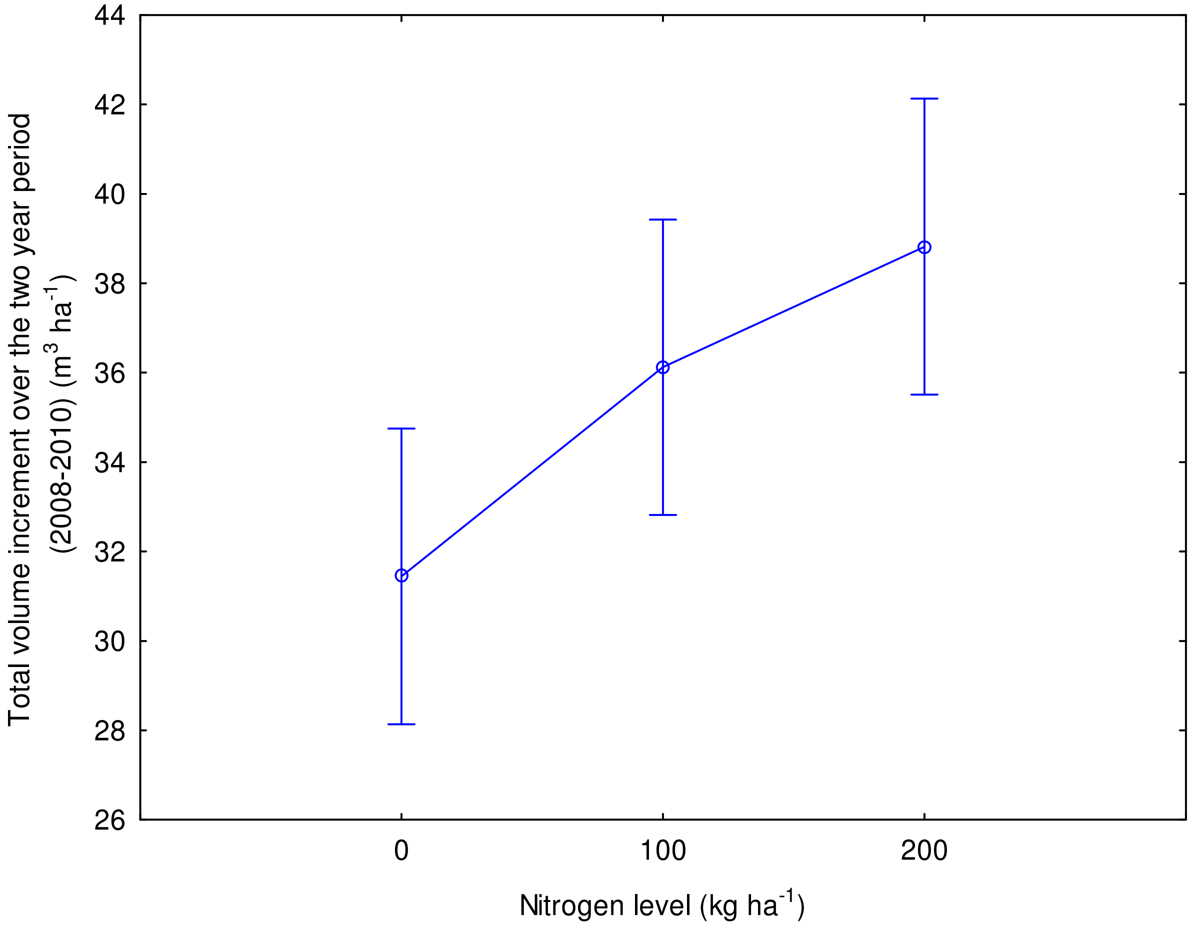


Figure 4.19: Volume increment response to N over the two year period (2008-2010) (vertical bars denote *p*=0.90 confidence intervals)

Table 4.7 below shows the significant N response as well as the trend if of a further increase in volume (although not significant at this stage) if P is applied. The N fertilizer increased the mean as the quantity of fertilizer increased from 0 to 200 kg ha $^{-1}$.

Table 4.7: Mean volume increment per treatment over two year period (m^3 ha^{-1}) in a *P.radiata* mid-rotation fertilizer. Different letters indicate a significant difference between the N fertilizer means at the 10% level.

	Mean volume increment over two years(m^3 ha^{-1})			
	Kg P ha^{-1}			
Kg N ha^{-1}	0	50	100	**Means**
0	29.6	32.6	32.1	31.4b
100	33.1	38.3	36.9	36.1a
200	36.5	40.2	39.8	38.8a
Means	33.1	37.0	36.3	35.5

Water availability class 4 was significantly different from all the other classes (p<0.001 for all) and class 2 was also significantly different from class 1 (p=0.007) (Appendix 4.4o)

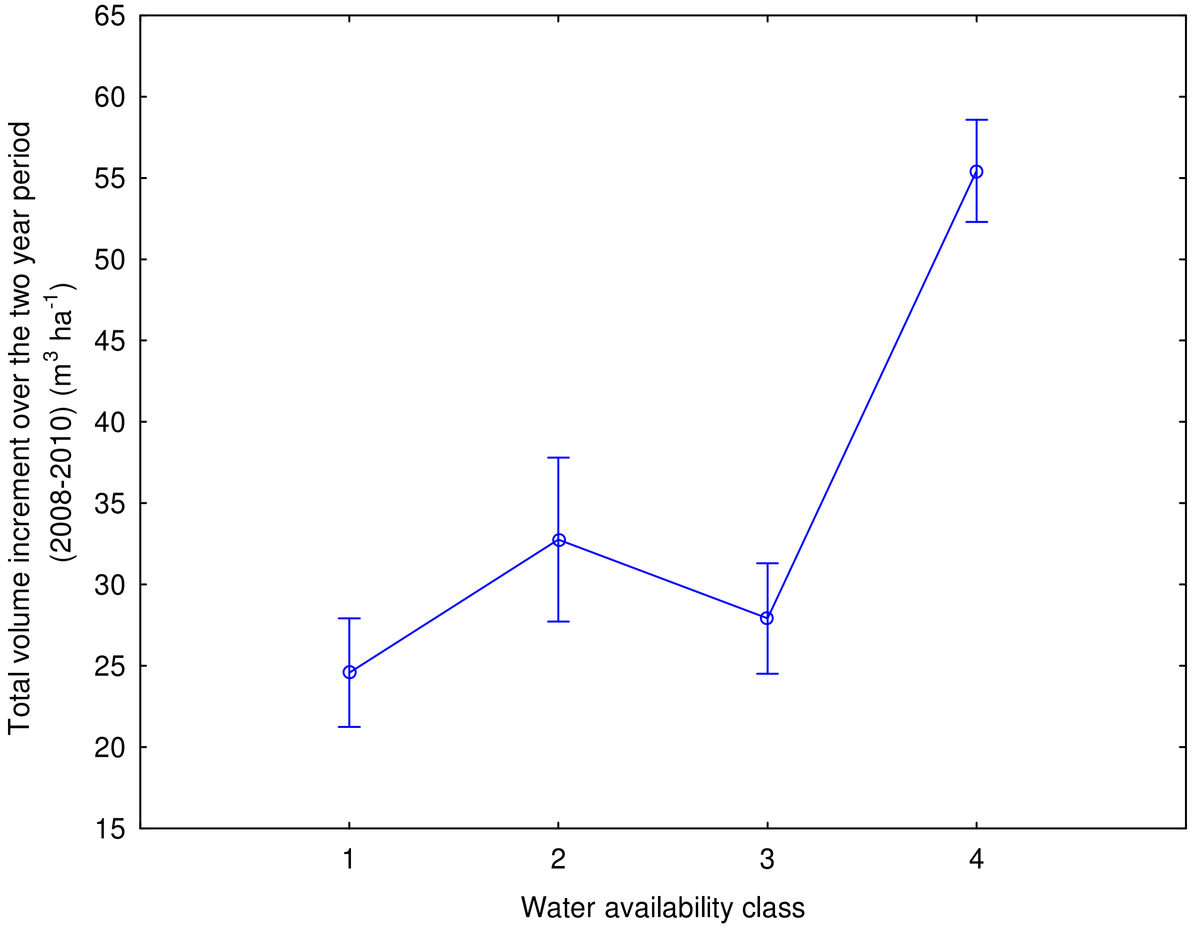


Figure 4.20: Volume increment response to water availability class over the two year period (2008-2010) (vertical bars denote *p*=0.90 confidence intervals)

Water availability class 4 (the wettest) consistently had the highest increment which was significantly different from all the other classes in 2009, 2010 and when total volume increment from 2008-2010 was considered.

4.5 Analysis of Growth efficiency response to N, P and water availability

Initial volume in 2008 was used as a covariate for this analysis. Where the covariate was found not to be statistically significant, it was excluded from the model to increase the power of the test. The covariate was not significant for year 1 but was significant for year 2 and over the two year period. The ANOVA outputs for all the analyses done for growth efficiency in year 1, year 2 and over the two year period are presented in Appendix 4.3 (i) – (k).

There was no significant interaction detected between N and P (p=0.936), N and water availability class (p=0.908) and P and water availability class (p=0.559) in 2009.
There was however a significant effect due to water availability class (p=<0.001) (Figure 4.21). Both N (p=0.733) and P (p=0.746) had no significant effect. Water availability class 4 had a significantly higher increment than all the other classes. (Appendix 4.4p). Class 2 was also significantly different from class 1 (p=0.001).

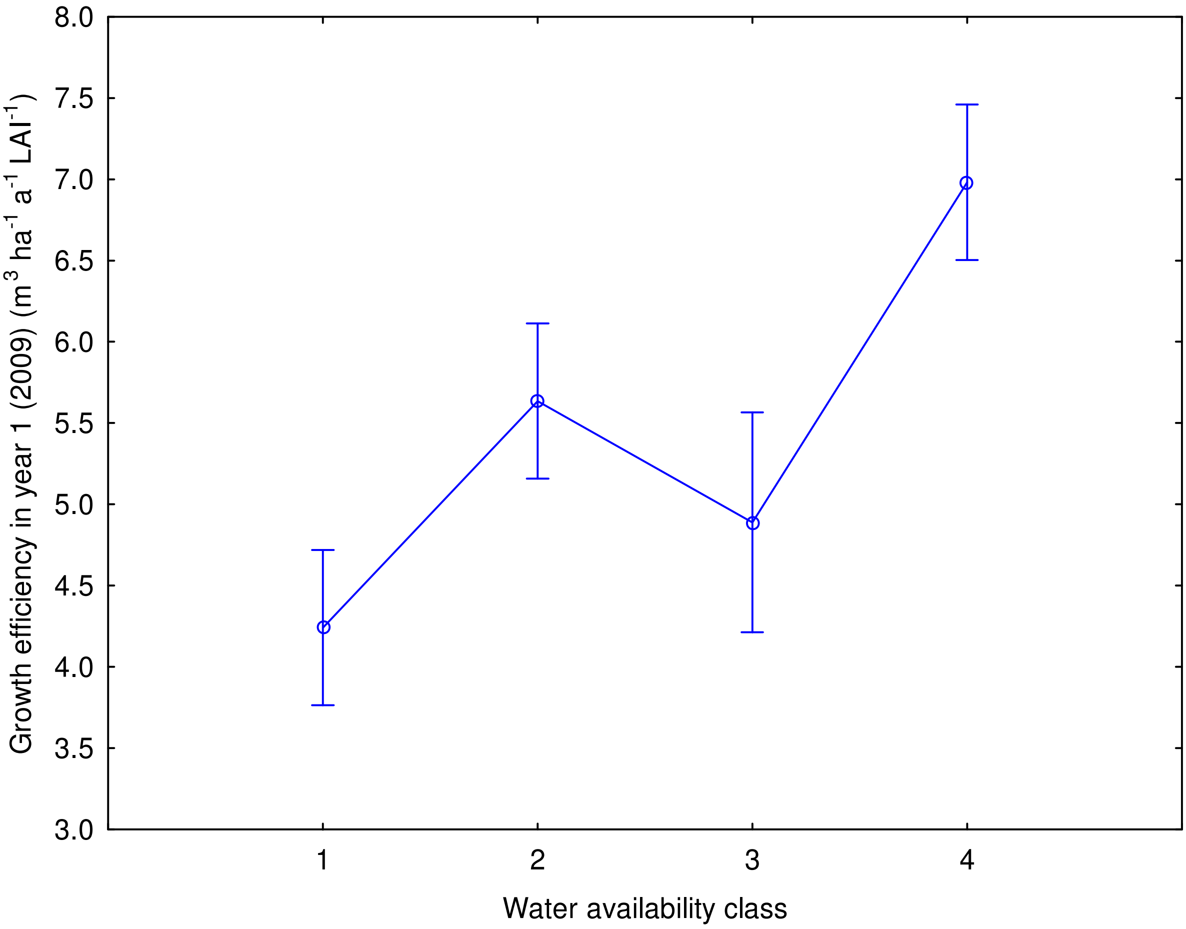


Figure 4.21: Growth efficiency responses to water availability classes in 2009 with vertical bars denoting p=0.90 confidence intervals.

There was no significant interaction detected between N and P (*p*=0.964), N and water availability class (*p*=0.332) and P and water availability class (*p*=0.268) in 2010. There was however a significant effect due to water availability class (*p*=<0.010) and N (*p*=0.057). Phosphorous was not significant (*p*=0.142). Class 4 had the highest growth efficiency which was significantly different from class 1 (*p*=0.003) and from class 2 (*p*=0.007) but not significantly different from class 3 (Figure 4.22 and Appendix 4.4q).

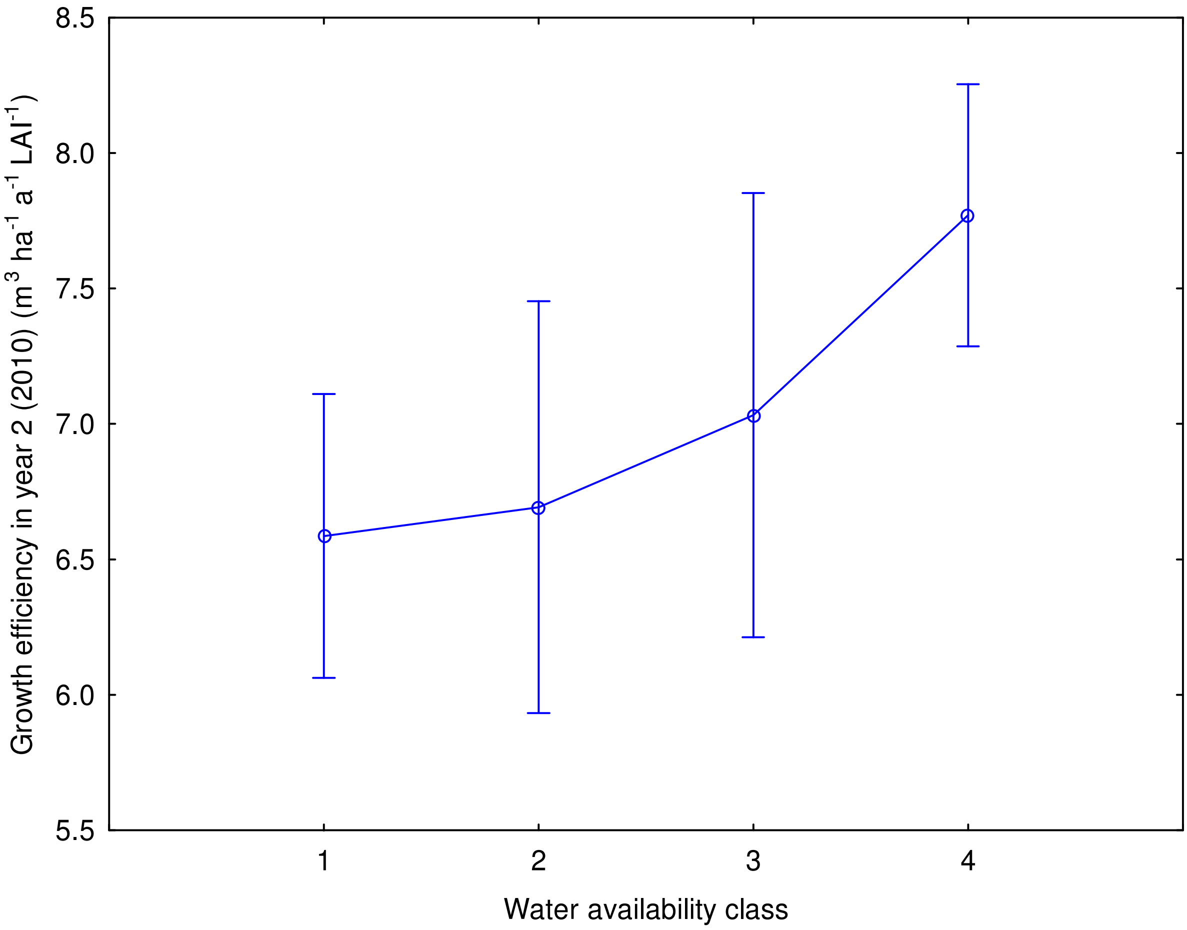


Figure 4.22: Growth efficiency responses across different water availability classes in 2010 with vertical bars denoting *p*=0.90 confidence intervals.

No significant interaction was detected between N and P (*p*=0.974), N and water availability class (*p*=0.621) and P and water availability class (*p*=0.351) when total GE was considered. Only water availability class had a significant effect on total growth efficiency (*p*=0.091) (Figure 4.23). Both N (*p*=0.179) and P (*p*=0.742) did not have a significant effect. Water availability class 4 was significantly different from all the other classes (Appendix 4.4r).

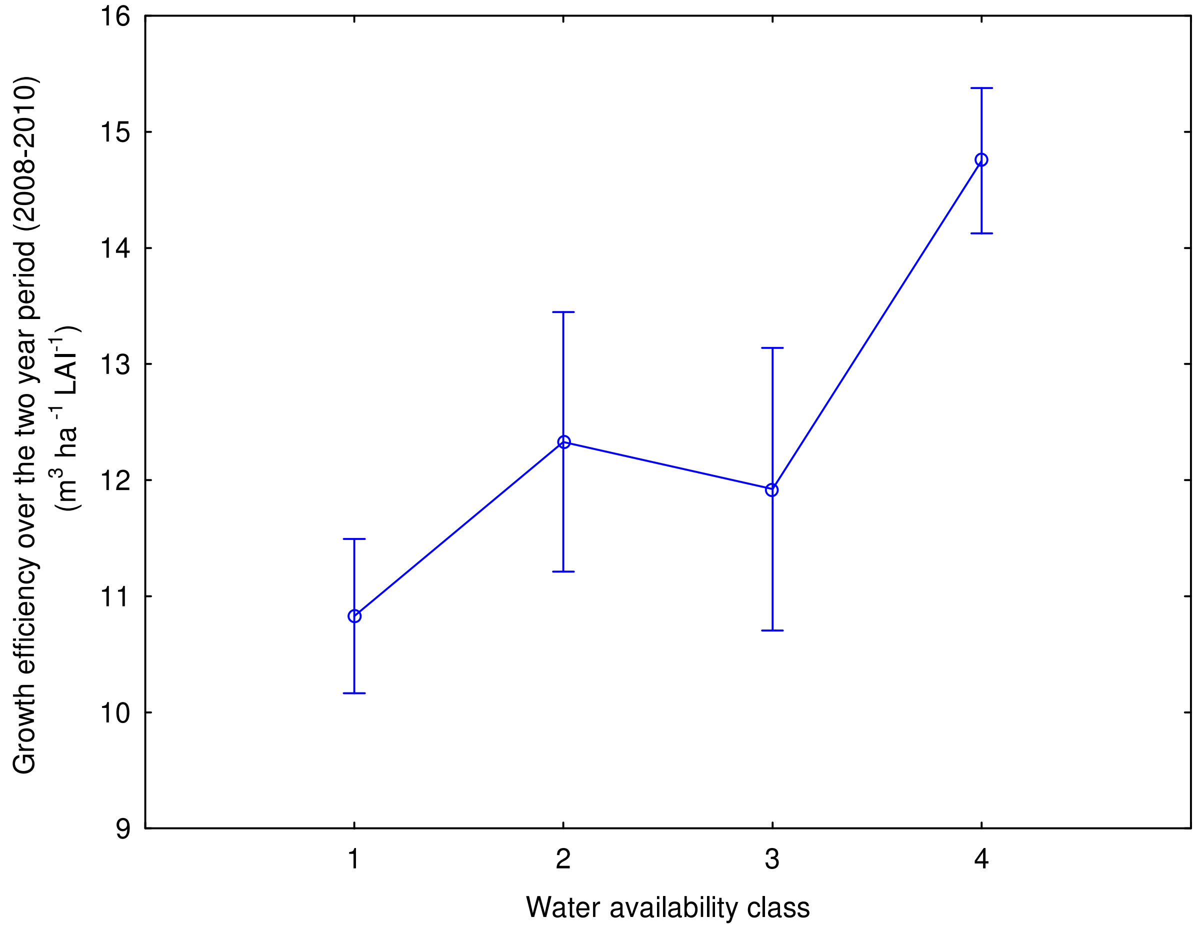


Figure 4.23: Growth efficiency responses across different water availability classes (2008-2010) with vertical bars denoting *p*= 0.90 confidence intervals.

Table 4.8 below presents a summary of the *p* values for the response of all the measurement variables analysed in this study to N, P and water availability class.

Table 4.8: A summary of all *p* values from the separate ANOVAs for the response of leaf area index, basal area and volume increment, growth efficiency in year 1, year 2 and over the two year period and foliar N and P concentration a year after treatment.

FACTOR	MEASUREMENT VARIABLE	RESPONSE IN YEAR 1(2009)	RESPONSE IN YEAR 2 (2010)	RESPONSE (2008 - 2010)
NITROGEN	LAI increment	0.020	0.131	N/A
	Basal area increment	0.518	$p<0.001$	0.074
	Volume increment	0.185	0.028	0.036
	Growth efficiency	0.733	0.057	0.179
	Foliar N	$p<0.001$	N/A	N/A
PHOSPHORUS	LAI increment	0.056	0.031	N/A
	Basal area increment	0.951	0.061	0.573
	Volume increment	0.901	0.142	0.327
	Growth efficiency	0.746	0.142	0.742
	Foliar P	0.059	N/A	N/A
WATER	LAI increment	0.227	0.014	N/A
	Basal area increment	0.003	0.044	$p<0.001$
	Volume increment	$p<0.001$	$p<0.001$	$p<0.001$
	Growth efficiency	$p<0.001$	0.010	0.091

[1] **All shaded *p* values were significant at the 10% level of significance.**

Table 4.8 shows that LAI increment responded significantly to N and P in the first but not the second year after treatment. It also shows that significant basal area responses to N and P were recorded in the second but not the first year. The fact that trees had to re-build their canopies before a basal area response could be obtained will be explored in the discussion section. Table 4.8 also shows that for the variables where an analysis for the total response over the two year period was possible, basal area increment and volume increment significantly responded to the application of nitrogen but not to phosphorus. Foliar N and P were significantly affected by application of N and P fertilizer.

Growth efficiency was not significantly influenced by both nitrogen and phosphorus over the two year period.

Water availability class consistently and significantly influenced basal area increment, volume increment and growth efficiency over the two year period as well as during year 1 and year 2.

Appendix 4.6 presents a summary of the least squares mean values for all the response variables over the study period (2008 – 2010) across the different water availability classes. Although there was no significant interaction between N and P, this appendix shows the expected LS means if the various combinations of N and P are applied in the different water availability classes.

4.6 Relationships between variables in the study

Various linear relationships between variables were explored and are presented below.

4.6.1 Relationship between LAI and volume increment

The scatter graph in Figure 4.24 shows that there is generally a positive relationship between initial LAI before treatment and the volume increment obtained. A linear regression for each of the treatments revealed that there was a positive linear relationship as all the treatments had an r^2 >0.60 except for $N_{100}P_{50}$ which had
r^2 = 0.23 (Appendix 4.7).

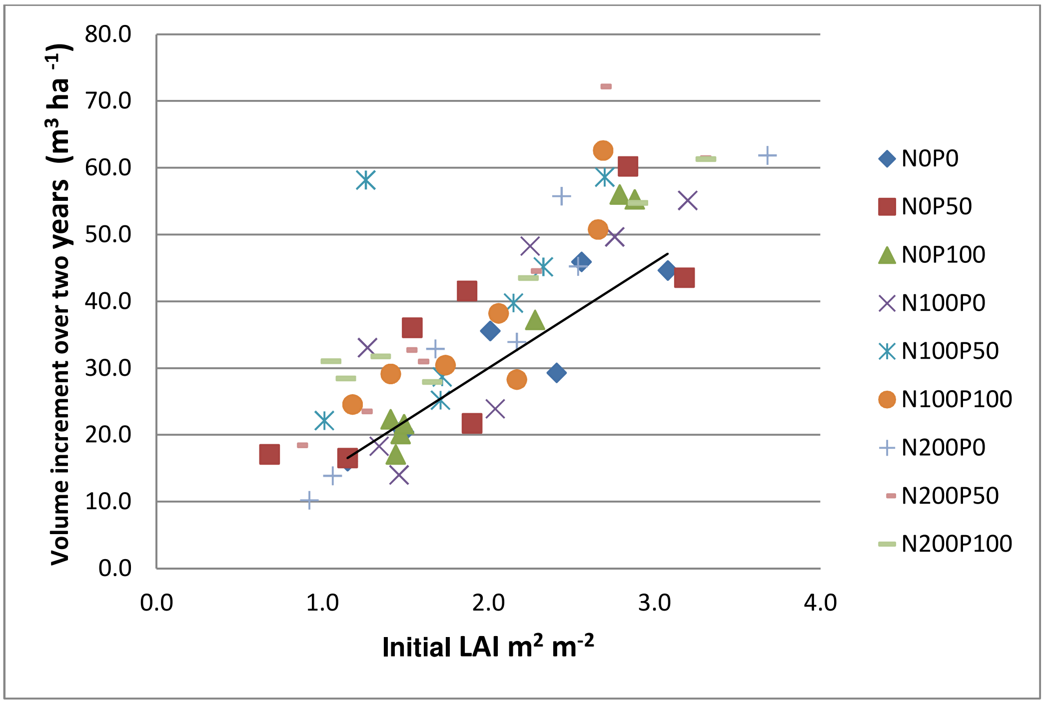


Figure 4.24: Relationship between initial LAI before treatment and volume increment over the two year period.

The separate linear regression analysis lines for each treatment are presented in Appendix 4.7

Appendix 4.8 shows the positive linear relationship (r^2 =0.67) between initial LAI at the start of 2010 and the volume increment obtained in the same year. As the initial LAI increased, the volume increment also increased.

4.6.2 Relationship between basal area and volume increment

The scatter graph in Figure 4.25 shows that there is generally a positive relationship between initial basal area before treatment and the volume increment obtained. A linear regression for each of the treatments revealed that there was a positive linear relationship as most of the treatments had an r^2 >0.50 except for N_0P_0 which had r^2 = 0.41, $N_{100}P_{50}$ which had r^2 =0.39 and $N_{100}P_{100}$ which had r^2 =0.32 (Appendix 4.9).

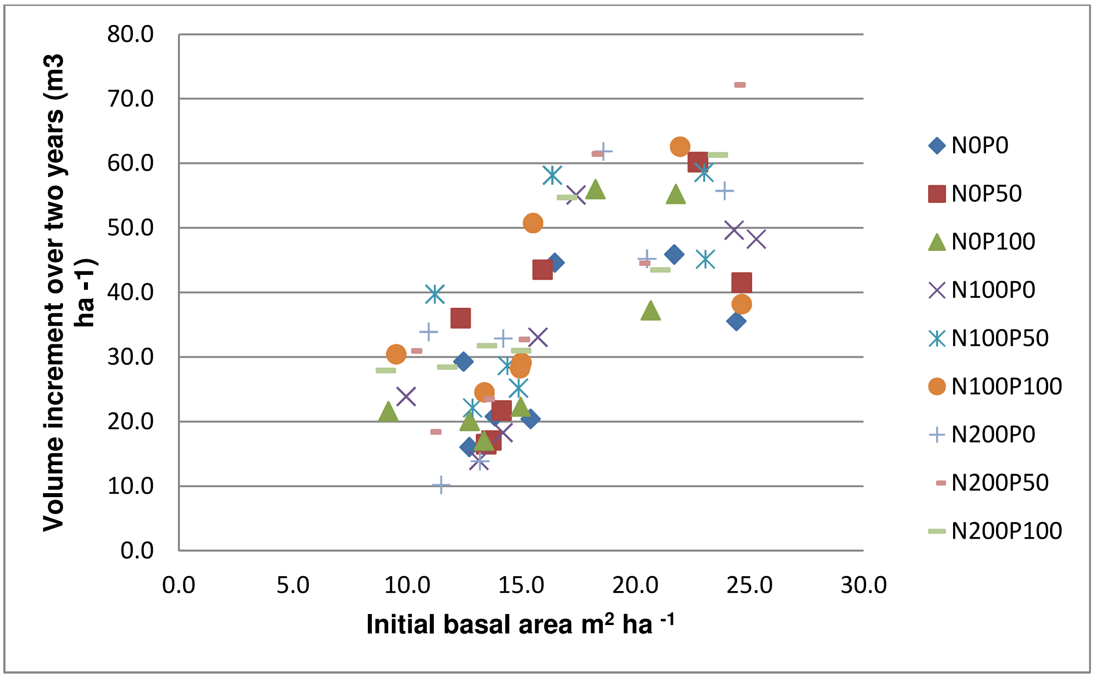


Figure 4.25: Relationship between initial basal area before treatment and volume increment over the two year period.

4.6.3 Other relationships investigated

Appendix 4.10 shows the positive linear relationship (r^2 =0.65) between initial LAI at the start of 2010 and the basal area increment obtained in the same year. As the initial LAI increased, the basal area increment also increased.

Linear regression was done to determine the relationship between initial LAI and the LAI increment in 2010. The positive linear relationship had a low r^2 value of 0.26 (Appendix 4.11).

CHAPTER 5: DISCUSSION

5.1 Nutrient analysis

This study based the interpretation of the nutrient concentrations on Boardman *et al.,* (1997)'s norms. Critical values for *P. radiata* have not been developed in the Western and Southern Cape regions hence the use of values from other areas. An interpretation of the foliar results before treatment according to the norms by Boardman *et al.,* (1997) indicated that phosphorus was the only macro element with levels below the critical one in replications S_1, S_2, S3, L_2, and L_4. Replication L_1 had a marginal P concentration while S_4 had adequate concentrations (Table 4.1a). All the other elements were marginal or adequate. Relative to the norms by Boardman *et al.,* (1997), the nutrient concentrations in our study were generally not too low except for P. All the replications had adequate nutrient concentrations of Ca, Mg, Mn, Fe, Cu, B and Zn at the beginning of the study except L_4 which had a deficiency of Zn and L_1 and S_4 which had Fe concentrations above the accepted levels. Replication L_1 also had Mn levels above the acceptable, although levels below 2 000 mg kg^{-1} are usually still not toxic to most conifers. Potassium was adequate in all replications except in S_2 and L_4 which had marginal concentrations of the element.

Foliar P concentration was only affected by P fertilizer. Foliar P concentration increased significantly from 0.09 to 0.11 when 50 kg P ha^{-1} was applied. Although an increase in P fertilizer to 100 kg P ha^{-1} increased foliar P further to 0.12 this was not statistically different from P_{50} level. Even the highest application of P did not raise the foliar P concentration above the 0.14 critical limit. (Table 4.2c and Appendix 4.2 a).

In absolute terms the highest level of N and P resulted in the highest P concentration. Carlson and Soko, (2001) reported an increased foliar P concentration in a *Pinus patula* stand after fertilizer application. Tritchet *et al.*, (2008) also found that for *Pinus pinaster*, foliar P concentration was increased when fertilizer was applied. Fertilization with P significantly increased foliar P concentrations in all treatments in *Pinus taeda* stands in Texas (Sypert, 2006).

Foliar N concentration was generally adequate in all the sites before treatment in our study according to Boardman *et al.*, (1997) (Table 4.1a). Although the values for N were mostly above the critical value, they were still not in the upper range for sufficiency. If the value of 1.5% developed for N in *P. radiata* in New Zealand and published by Will (1985), is applied to the study's data in Table 4.1a (before treatment), all replications show that N is not available at the adequate levels. The mean foliar N concentration for each treatment was below the critical level of 1.5% a year after treatment except for N_{200} where it was 1.64% (Table 4.2b) . An ANOVA revealed that the treatments had a significant effect on foliar N level (Table 4.2b). The foliar N was increased by increasing quantities of N fertilizer. However, the application of P fertilizer had a negative effect on foliar N levels and resulted in a decrease in foliar N when either 50 or 100 kg P ha^{-1} was applied (Table 4.2b). It is interesting to note that due to the antagonistic effect of fertilizer P on foliar N values (possibly inducing a deficiency), the 1.5% level was only achieved when at least 200 kg ha^{-1} N was applied together with P or when N was applied on its own.

Carlson and Soko, (2001) reported an increase in foliar N concentration when fertilizer was applied to *Pinus patula*. Fertilization with N significantly increased N concentrations of *Pinus taeda* in most treatments in a study by Sypert, (2006) in Texas. Pre-treatment N concentrations, though generally marginal in our study, they still displayed concentration increases with N applications. We conclude that tree growth may have been limited by low N supply, but that this was not detected by the critical level approach since several other factors are also limiting growth, for example P and soil water. Under these conditions of sub-optimal growth, N levels may appear sufficient at first inspection. However, when other growth limitations are removed or partially removed, N actually becomes limiting too. The fertilizer treatments therefore successfully increased foliar N and P nutrient levels close to or even above the critical target concentrations. These results confirm that N and P were growth-limiting nutrients at our experimental sites. Nitrogen and P fertilizer did not have a statistically significant effect on foliar nutrient concentrations for all the other elements considered in this study.

Nutrient ratios have been traditionally used as indicators of the nutrient balance occurring in the foliar tissue (Linder, 1995; Carlson & Soko, 2001, du Toit and Oscroft, 2003). The P/N ratio before treatment was below the optimum for all replications except S_4 where it was optimum (Table 4.1 b). The other nutrient ratios were generally above the optimum. The P/N ratio remained generally below the optimum level for all treatments in all replications one year after fertilizer application (Table 4.3). However, in treatments where the highest level of P (100 kg ha^{-1}) was applied, P/N ratios generally approached (and sometimes exceeded) the norm of 10 proposed by Linder (1995). It can be concluded that P is strongly limiting growth across all replications and that the application of P fertilizer has addressed this problem partially or fully.

When vector analysis was used for the average response across all sites, P was found to be the main limiting nutrient as compared to the others as the major vectors were associated with P, indicating that addition of P corrected a deficiency (Figure 4.2). The vector analysis also showed that of the micro nutrients, Zn was the main limiting nutrient as compared to the others as the major vectors were associated with Zn, indicating that treatment corrected a Zn deficiency (Figure 4.3). Zn is often used as an additive in P-containing fertilizers to counter possible antagonistic effects of P and Zn uptake by higher plants. The application of Zn-containing P fertilizers appears to have been the appropriate choice in this trial series.

The application of fertilizer also affected other elements that were not applied. For example K and Cu in S_2 had the deficiency addressed by fertilization as well as Ca in L_1.

The three methods, critical levels, nutrient ratios and vector analysis detected a P deficiency in all replications except in S_4 where they differed. The critical levels method and nutrient ratios generally predicted the same outcome in most cases. Vector analysis predicted more deficiencies than the other two methods. This might have been due to the fact that vector analysis incorporated growth response as well as nutrient content, which might have eliminated effects associated with dilution and luxury consumption when only foliar or nutrient ratios are used.

Vector analysis indicated that the N and P deficiencies that existed in the sites at the start of the study were alleviated by the application of the best treatment for each site (Table 4.5). Best treatment refers to the treatment that had the largest volume response. Figure 4.2 also confirmed the deficiency of P before treatment, when vector analysis was conducted on the average response observed across all the replications compared to the post fertilization control treatment (N_0P_0). This study did show that foliar responses to N and P fertilization are likely when they are found to be in the marginal level.

In a study by Ngono and Fisher, (2004) where different methods were also compared, it was concluded that vector analysis was more reliable than critical levels and that the two methods differed in predicting volume response across sites. In our study vector analysis was fundamentally different in that it incorporated growth response as well as nutrient content. While critical levels and nutrient ratios required the use of predetermined standards, vector analysis did not need these. This can be one of the biggest advantages of the method especially when different conditions occur in factors that were used to come up with the predetermined standards for critical levels and nutrient ratios. Critical values for *P. radiata* in the study area were not available and the values from other areas according to Boardman *et al.,* (1997) and Will (1985) for critical values and by Linder (1995) for nutrient ratio norms were therefore used. A small change in the critical value can change the classification. Between critical and sufficient levels, growth response is expected although it might not be economically viable.

The three methods have their advantages and disadvantages and work best when used together, thus, greater diagnostic result could be obtained by combining the diagnostic results of the three techniques.

5.2 Leaf area index response

There were no significant interactions detected among N, P and water availability class at 12 months and at 24 months. There was a significant effect of N on LAI at 12 months but not at 24 months. The highest level of nitrogen (N_{200}) gave the highest response which was 79% higher than the control (Figure 4.4). There was a linear increase in LAI increment up to 200kg ha $^{-1}$. A significant response to P was detected at both 12 months and 24 months. When P levels were considered, both P_{50} and P_{100} were significantly higher than the control at both 12 and 24 months (Figure 4.5 & 4.8). There was a 68% and 57 % increase for P_{50} and P_{100} respectively over the control at 12 months and a 102% and 113 % increase for P_{50} and P_{100} respectively over the control at 24 months. Water availability class had a significant influence only at 24 but not at 12 months.

The response at 12 months for N agrees with a study of *P. taeda* growing on sites of varying nitrogen limitations in North Carolina, where nitrogen fertilization significantly increased LAI (up to 60%) on N deficient sites (Vose & Allen, 1988). In our study, vector analysis revealed that both N and P were generally deficient in the study sites (Table 4.5). Low nutrient availability has been found to be a principal factor causing suboptimal levels of leaf area in many areas (Vose & Allen, 1988; Albaugh *et al*., 1998). When tree growth is stimulated by fertilization, a significant part, and if not most of the response is due to an increase in the total leaf area of the photosynthetic surface (Linder and Rook, 1984). In another study by Allen *et al.,* (2005), LAI was not significantly affected by fertilization for stands of *P. taeda* and *P. elliottii.* In our study, there was a general trend that an increased level of N caused an increase in LAI. More increment was obtained on the wettest sites than on the driest sites at 24 months (Figure 4.9). This is also supported by Appendix 4.6 where water availability class 4 generally has higher means than the driest site (class 1). Some studies suggest that chronically low levels of available soil nutrients, particularly N and P on loamy or sandy soils, are more limiting to growth in established stands than water limitations (Albaugh *et al*., 1998; Albaugh *et al*., 2004b; Sampson & Allen 1999).

The soils in the Boland are known to be poor and deficient particularly in P (Donald *et al*., 1987; Payn *et al*.,1988; Badenhorst, 2010). Vector analysis, critical levels and nutrient ratios all confirmed the P deficiency in most of the sites. Although both water and nutrient limitations can reduce leaf area through reduced foliage production or early senescence, water availability is thought to have less effect on leaf area than nutrient availability (in the cited literature) because most leaf area production in the southeast United States occurs in springtime, a period when soil water availability is high and evapotranspiration demand is low (Forest Nutrition Cooperative, 2006). The effects of water availability and nutrient resources on forest productivity according to Trichet *et al.*, (2008), depend on local climate and soil conditions, with irrigation (water availability) having a more marked effect in Mediterranean type climates and fertilization having a stronger effect on growth responses where annual evapotranspiration rates are lower and precipitation levels are higher. A stepwise regression that was done in this study with LAI increment at 24 months (when water availability class had a significant effect) as the dependent variable and N, P and water availability class as the predictor variables retained N and P as better predictors but dropped water availability class (Appendix 4.5). This may indicate that in our study nutrient availability could have had a greater influence on leaf area increment than water availability class.

On sites that have few limitations on leaf area production before fertilization, it may happen that the response of LAI is relatively small after fertilization and that a larger, perhaps more significant response would be expected after fertilization on those sites where serious limitations on LAI existed before fertilizer application. A few such cases (S_1 and L_2 are depicted in the left hand side of the scatter plot of Appendix 4.11 (these are sites where LAI was predominantly limited by N and P, not water). However, linear regression of initial LAI versus LAI increment at 24 months in our study revealed that there was an insignificant negative linear relationship. It showed that the LAI before treatment was a very poor predictor of increment in LAI after treatment (Appendix 4.11). Initial LAI before treatment did not therefore drive LAI increment in our study. Low LAI can indicate poor nutrition and/or low soil water supply. Fertilization will partially correct poor nutrition but will not alleviate a site water limitation, hence a poor response can be obtained when LAI is low to start with as a result of a water limitation. LAI will therefore not always be a good predictor of canopy response to fertilization.

5.3 Basal area increment response

There was no interaction among N, P and water availability class in 2009, 2010 and when the total basal area increment over the two year period was considered. Both N and P did not have a significant effect on basal area increment in 2009. There was however, a significant effect due to water availability class (p=0.002) in 2009 (Figure 4.10). Basal area increment was found to be influenced by N, P and water availability class in the second year after fertilizer application. In a study by Carlson and Soko (2000), of 17 fertilizer trials in eight year old *Pinus patula* compartments in Mpumalanga, trials that were on shale parent material responded immediately to N with responses to P becoming significant three years after fertilizer application. Basal area increment did not respond to either N or P fertilizer in the first year, but did respond in the second year.

When total basal area increment was considered (2008-2010), only N and water availability class had a significant effect with phosphorus not making a significant influence (Figure 4.14 - 4.15). Archibald and Smith, (2010) also obtained similar results at Bracken (KwaZulu-Natal) where a rate of 200 kg ha $^{-1}$ of nitrogen and 100 kg ha $^{-1}$ of phosphorous was applied in a 22.1 year old *Pinus patula* stand. Their early results two years after fertilization revealed that the application of N significantly increased the two year basal area increment compared to the control and no significant growth response to P or interaction between N and P were recorded. The increase in basal area due to fertilizer application observed in our study agrees with Turner *et al*. (1995) where, in eleven of the twelve N+P factorial trials, application of N and/or P resulted in significant gains in tree basal area increment over a four year study period. The annual productivity gains due to N and P treatments were not apparent until the second year in our study as it was in Turner's study where it peaked in the period 2-4 years post-treatment.

Since the magnitude of the response in basal area increment was greater in 2010 than in 2009, alongside a greater response in LAI increment in 2009 but not in 2010, the leaf area put on in 2009 was responsible for the significant basal area increment detected in the second year after fertilizer application. There was a positive correlation ($r = 0.51$) between 2009 LAI increment and basal area increment in 2010. Linear regression of LAI at the start of 2010 and the basal area increment in the same year indicated that there was a strong positive linear relationship with $r^2 = 0.65$ (Appendix 4.10). The greater the initial LAI therefore, the greater the basal area increment that is likely to be obtained after treatment. This result is striking because stands with poor initial LAI first had to invest in rebuilding LAI and then had a very limited amount of time to increase basal area growth (effectively only during 2010). If we allow a longer response time after the canopy rebuilding phase of 2009, we may even find that some stands with poor initial LAI may perhaps rebuild their canopies and thereafter still achieve a fair basal area growth response. Longer term monitoring will be needed to see if this may happen. Based on these very early responses, one might recommend that due to the larger responses, sites with higher LAI values and that show nutrient deficiency should give a better return on investment.

In stands of *P. taeda* and *P. elliottii* in the southeast United States of America, it is considered that the LAI of a fully stocked stand (basal area >23 m^2 ha^{-1}) should be at least 3.5 m^2 m^{-2}; otherwise, the stand will probably be in need of N+P (Forest Nutrition Cooperative, 2006; Fox *et al.*, 2007). Minimum LAI that a stand needs to have in order for it to have optimum production was not determined in this study as longer term monitoring is needed. However, Figure 4.24 showed that most of the treatments that produced periodic volume increments of more than 40 m^3 ha^{-1} over the two year period had LAI values exceeding 2 m^2 m^{-2}.

Basal area increment for the levels, N_{100} (20%) and N_{200} (30%) significantly differed from the control although not different from each other in 2010 (Figure 4.11). However level N_{200} (24% basal area increment) was the only one significantly different from the control when total basal increment was considered (Figure 4.14). These percentage increases due to N are higher than those reported by Archibald and Smith, (2010) where the increase was 2.9 % higher on fertilized sites than on those not fertilized. The magnitude of the response to N ranged from nil to 25% in the first year after treatment in a study by Carlson and Soko, (2000). Water availability class 4 (the wettest) significantly differed from all the other classes in 2009, 2010 and 2008-2010 (Figure 4.10, 4.13 & 4.15). Class 4 had a basal area that was 50% more than that of Class1 for the total basal area increment. The effects of water availability on stem wood growth will be discussed in more detail under volume growth response.

5.4 Volume growth response

There was no significant interaction among N, P and water availability class in 2009, 2010 and when the total over the two year period was considered. Both N and P did not have a significant effect on volume increment in 2009. In 2010, N had a significant effect where N_{200} had a response of 4.15 m^3 ha^{-1} (23%) more than the control (Figure 4.17). When the volume increment over the two year period was considered (Figure 4.19 and Table 4.7), N_{200} had a response of 6.53 m^3 ha^{-1} (20% more than the control) which is more than what Carlson and Soko reported, an increase of 2.9 m^3 ha^{-1} in *Pinus patula* over a five year period. Archibald and Smith, (2010) found an increment that translated to 13.8 m^3 ha^{-1} over a two year period in a *Pinus patula* stand at Bracken. Phosphorus had no significant effect in 2009, 2010 and over the two year period in our study. The lack of a significant response over the two year period for P is similar to Archibald and Smith's findings where there was no significant P response and also no interaction between N and P. Volume increment was found to be significantly influenced by water availability class in 2009, 2010 and over the two year period (Figure 4.16, 4.18 & 4.20). Class 4, the wettest had a volume increment response that was 30.85 m^3 ha^{-1} (125%) over that of the driest class, class1 over the two year period.

Although there was no significant volume increment response to N and P application in 2009, there was a significant response to N in 2010. Leaf area index significantly increased in 2009, a year after fertilizer application. Forest production is mainly driven by the interception of radiation and the efficiency with which tree leaves use this energy to produce stem biomass through the process of photosynthesis (Linder, 1985). These processes are strongly influenced by the supply of water and nutrients (Linder and Rook, 1984). High levels of intercepted radiation are therefore associated with high levels of photosynthesis, and this will result in high productivity. Since the magnitude of the response for volume was greater in 2010 than in 2009, the leaf area put on in 2009 was responsible for the significant volume increment detected in the second year after fertilizer application. There was a positive correlation (r = 0.52) between 2009 LAI increment and volume increment in 2010. Linear regression between the LAI at the start of 2010 against the volume increment in that year revealed a positive relationship with r^2 = 0.67 (Appendix 4.8). An increase in the availability of nutrient supply after fertilizer application might have enabled the trees to deploy a large leaf area with a high canopy quantum efficiency level. When initial LAI before treatment was regressed against the total volume increment over the two year period, a strong positive linear relationship was also obtained (Figure 4.24 and Appendix 4.7) where r^2 was generally above 0.65 for most treatments. A high LAI therefore results in better volume increment compared to a low initial LAI. Besides a high initial LAI, a high initial basal area before treatment also had a positive linear relationship (r^2 generally above 0.5 for all treatments) with volume increment obtained over the two year period (Figure 4.25 and Appendix 4.9). Stands with a high initial basal area before treatment are therefore likely to yield more volume increment after treatment than stands with low initial basal area.

Donald (1987) reported that $N_{50}P_{50}$ gave the best results (34% more than the control) in 15 year old *Pinus radiata* stands on sandy soils in Grabouw, Western Cape where the highest level of N applied was 50 kg ha $^{-1}$ and for P it was
100 kg ha $^{-1}$. Our study has shown that there is some benefit in applying more than 50kg ha $^{-1}$ for N (as suggested by Donald, 1987) as there was a linear increase in volume increment up to 200 kg ha $^{-1}$. When the mean volume increment across all sites for each treatment was considered in our study (Appendix 4.2b), the treatment with the highest mean was $N_{200}P_{50}$ (37% more than the control). Our study therefore confirms Donald's results that 50 kg N ha $^{-1}$ in the Grabouw area, could be beneficial. This study also added on to Donald's findings by indicating that the N application rate can be raised above 50 kg ha $^{-1}$ and still yield more volume increment as shown by the linear increase in volume up to 200 kg ha $^{-1}$. Other studies in other site types found application rates that are in agreement with our study. Campion (2006) in a review of literature also reported typical application rates ranging from 100 – 300 kg N ha^{-1} and 50 – 100 kg P ha^{-1} in South Africa. Carlson *et al*., (2000) also found that the application of N provided a large improvement in tree growth and that the response was linear with the greatest improvement being to the application of 200 kg ha^{-1} N in a *P.patula* study in Mpumalanga. The question still to be answered is "Would the application of more than 200 kg N ha $^{-1}$ bring anymore significant growth and related economic benefit in South Africa?" The capacity of stands with low LAI's to take up large quantities of nitrogen has to be questioned. It may be better to test higher levels of application by means of re-applications in a couple of years' time. An analysis of Table 2.1 shows that N amounts used in various experiments in which trees

were 6 years and above ranged from 0 – 400 and the optimum levels found in these different studies ranged from 50 – 400 kg ha $^{-1}$. Longer term evaluation of the Boland fertilizer series (with possible additional application of fertilizer) will have to be conducted to answer this question satisfactorily. Herbert and Schönau (1990) recommended a rate of 35 kg ha $^{-1}$ of P where the soil water (moist) and depth (> 450 mm) requirements are met. An application of 60 kg ha $^{-1}$ was recommended for deeper soils. When N and P were applied separately in our study, they produced poorer volume increment results than the application of the elements in combination. There was no interaction between N and P in 2009, 2010 and over the two year period. The results for N and P were therefore additive. It is thus important to apply N and P simultaneously to get maximum benefit, as both appear to be limiting.

One of the most important factors that influenced the fertilizer responses is the water availability class. Water availability class consistently significantly influenced volume increment during year 1, year 2 and over the two year period (Table 4.8). The wettest class (class 4) had a higher volume increment response than the drier sites (Appendix 4.4 k, m and o). The magnitude of the volume increment response over the two year period for class 4 was 123% higher than that of class 1. The water availability determines not only whether a response to nutrient additions occurs, but also the magnitude of the observed response (Sands & Mulligan, 1990). Sheriff (1996) found that there are strong interactions between fertilizer and water availability in water-limited environments which was not the case in our study where there was no interaction detected between water availability and any of the nutrients applied. However, on sites where inadequate moisture limits growth, fertilization is only likely to provide modest growth gains (Allen, 1987). Results obtained from trials investigating the response of 12 year old, unthinned, *P. patula* to fertilizer applications in Swaziland, showed that the N response may be related to the rainfall (and hence soil moisture content) occurring at the time of trial establishment (Morris, 1993). The optimal N responses occurred when the soil moisture content was high in Morris's study.

5.5 Growth efficiency response

There was no interaction between N, P and water availability class in 2009, 2010 and over the two year period. Nitrogen significantly influenced growth efficiency only in 2010 but not in 2009 and over the two year period. Phosphorous did not have a significant effect in 2009, 2010 and over the two year period. There was however, a significant effect due to water availability class in 2009, 2010 and over the two year period. Class 4 had the highest growth efficiency response in 2009, 2010 and over the two year period which was significantly different from the other classes (Figure 4.21-4.23).

Irrigation and/or fertilization increased GE in several studies (Albaugh *et al.*, 1998) while having no effect in other studies (Vose and Allen, 1988). Allen *et al.,* (2005) found that GE was not affected by fertilization for *P. taeda* and *P. elliottii* but was increased by irrigation. The results from our study showed that the wettest sites generally had higher GE than the driest sites in both 2009, 2010 and over the two year period (Figure 4.21 – 4.23). Water availability class 4 had a growth efficiency which was 65 % more than class 1 in 2009, 11% in 2010 and 36% over the two year period. Nitrogen only significantly increased growth efficiency in 2010 but not in 2009 or over the two year period. Phosphorous did not significantly increase growth efficiency in both years and over the two year period. Water availability had a more significant role in growth efficiency than nitrogen and phosphorus application. Allen and Albaugh (1999) reported increases of growth efficiency of 8% due to irrigation in a *Pinus taeda* study in the southeastern U.S.A. The effects of water availability and nutrient resources on forest productivity depend on local climate and soil conditions, with irrigation (water availability) having a more marked effect in Mediterranean type climates (Trichet *et al.*, 2008). The Boland region experiences a Mediterranean type of climate which might have caused water to have a more significant role than nutrient availability on GE.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The results that have been presented in this study are preliminary responses to N and P across different water availability classes. These responses should continue to be monitored over a longer period in order to determine whether the trends observed will remain the same, and to quantify the longer term responses.

The application of N fertilizer increased the foliar N concentration linearly as the quantity of N fertilizer increased. The lowest application of P_{50} fertilizer increased the foliar P concentration but doubling this quantity did not increase the foliar P level significantly further, although there was a small increase in absolute terms.

An important finding is that the application of P fertilizer had a negative effect on the foliar N levels and might have induced a N deficiency. Application of P without N is therefore not recommended. .

Nitrogen and P increased LAI significantly in the first year and the influence of P was maintained in the second year, while that of N became insignificant in the second year. As the volume increment was positively correlated with an increase in LAI, it is anticipated that the response seen in LAI will eventually also be seen in volume increment.

The volume increment trend corresponds to that of the basal area, which indicates that the response to P fertilizer might occur over a longer period than that of N. The largest responses were observed when 200 kg ha $^{-1}$ of N was applied. Increasing this quantity might result in even a larger volume response. This should be investigated in future by applying larger quantities of N, or by means of reapplication of N in the existing trials.

All the early results indicate that there is no additional benefit of applying 100 kg ha^{-1} of P instead of 50 kg ha^{-1}. Furthermore, sites that had the largest LAI had the greatest increase in basal area after fertilizer application. Thus the early results indicate that the return on investment will probably be the highest on sites with a large LAI. However, it is not yet possible to conduct an economic analysis. The early results indicate that the application of 200 kg ha^{-1} in combination with 50 kg ha^{-1} had an additive effect, resulting in the largest volume response, in absolute terms of 7.6 m^3 ha^{-1} (23%) compared to the control, over a two year period. It is not certain if this magnitude of response will be maintained till rotation end.

Water availability significantly influenced tree growth. The wetter sites responded better than the drier sites. In cases where resources are limited and there is a mix of wet and dry sites, it would be better to fertilize the wetter sites as they are likely to yield more volume increment than if drier sites of similar soil type were to be fertilized. The magnitude of the volume response in the drier sites however, suggest that even these dry sites can still be fertilized with justifiable economic benefit in situations where the financial capacity permits.

Although these are still early results, the growth response could be attributed primarily to an increase in LAI. This is supported by the fact that there was a significant increase in LAI a year after fertilizer application while volume did not significantly increase during the same period. Volume only significantly increased in the second year after fertilizer treatment when the additional leaf area contributed to more stem wood production.

The destruction of replication L_3 by fire posed a serious limitation to the analysis of interaction of N, P, soil type and water availability. This analysis would have enabled the prediction of the best treatment within a given soil type in a particular water availability class. This can still be pursued in future nutritional studies.

Nutrient analysis through vector analysis indicated that the additional N and P from fertilizer application were taken up by the trees. This was evidenced by the existing N and P deficiencies that were corrected. Vector analysis can be a good tool to use for determining the response to fertilizer treatments in fertilizer trials. It enables the researcher to detect responses as early as one year after fertilizer application.

Due to the fact that we are dealing with early responses, we have made no attempt to present a comparison of economic viabilities of applying various treatments at this stage. A detailed economic analysis would however, be necessary in future once the responses have been monitored for over a longer period of at least five years.

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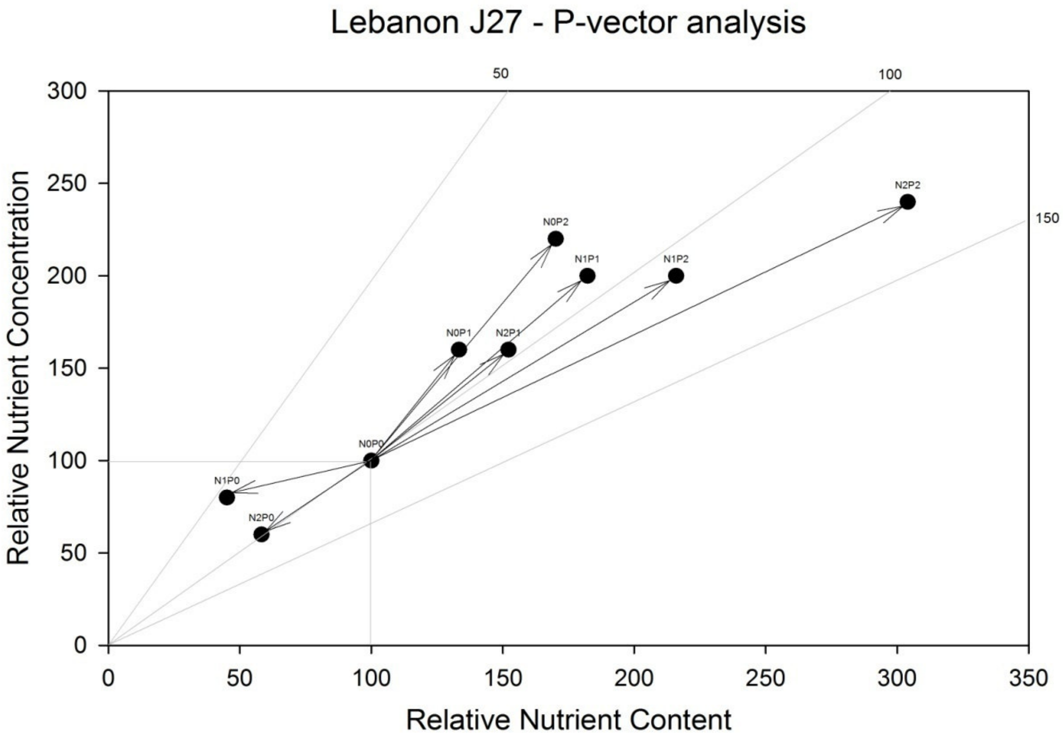
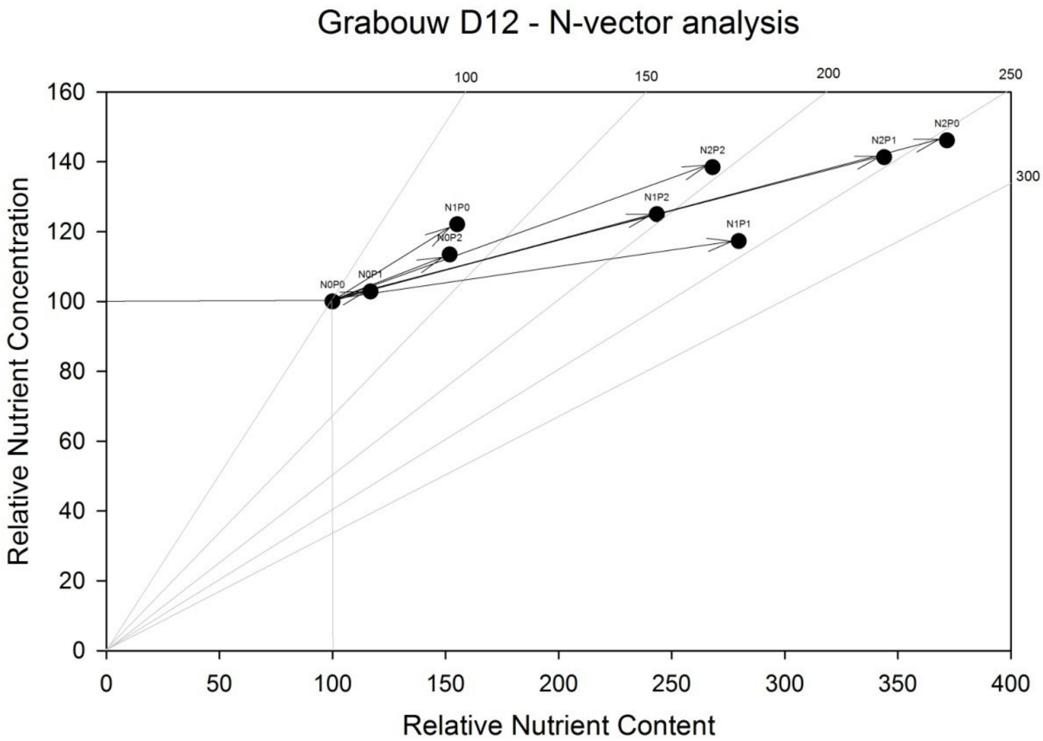
APPENDICES

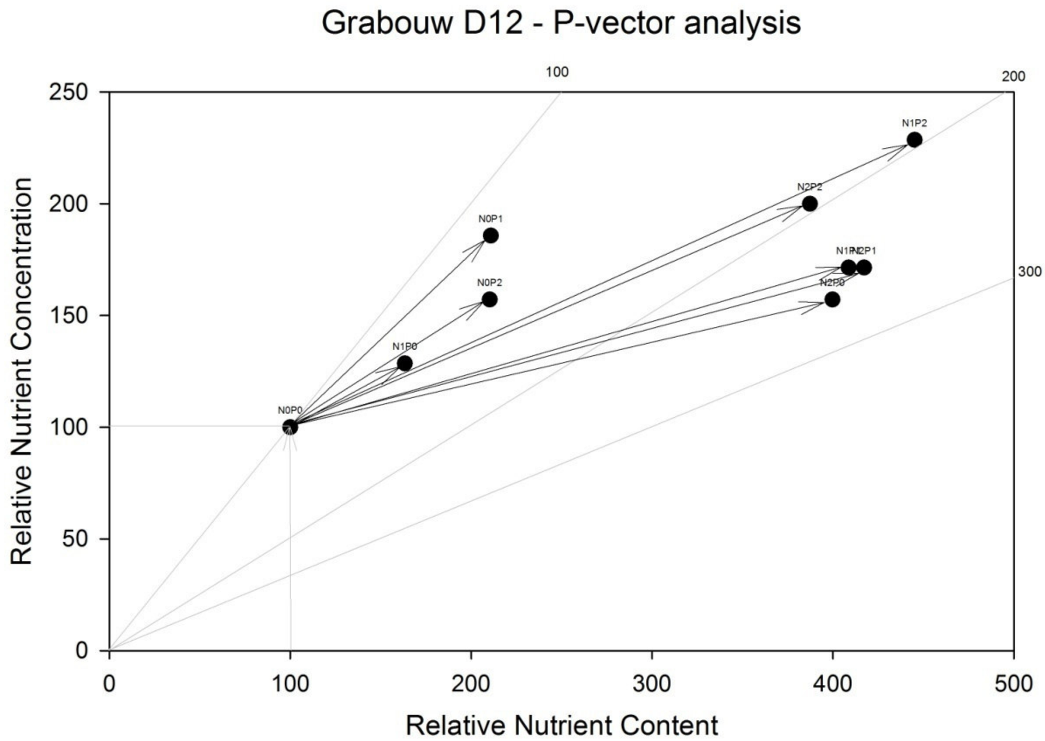
Appendix 4.1: Vector nomograms for the vectors classified as large in Table 4.5



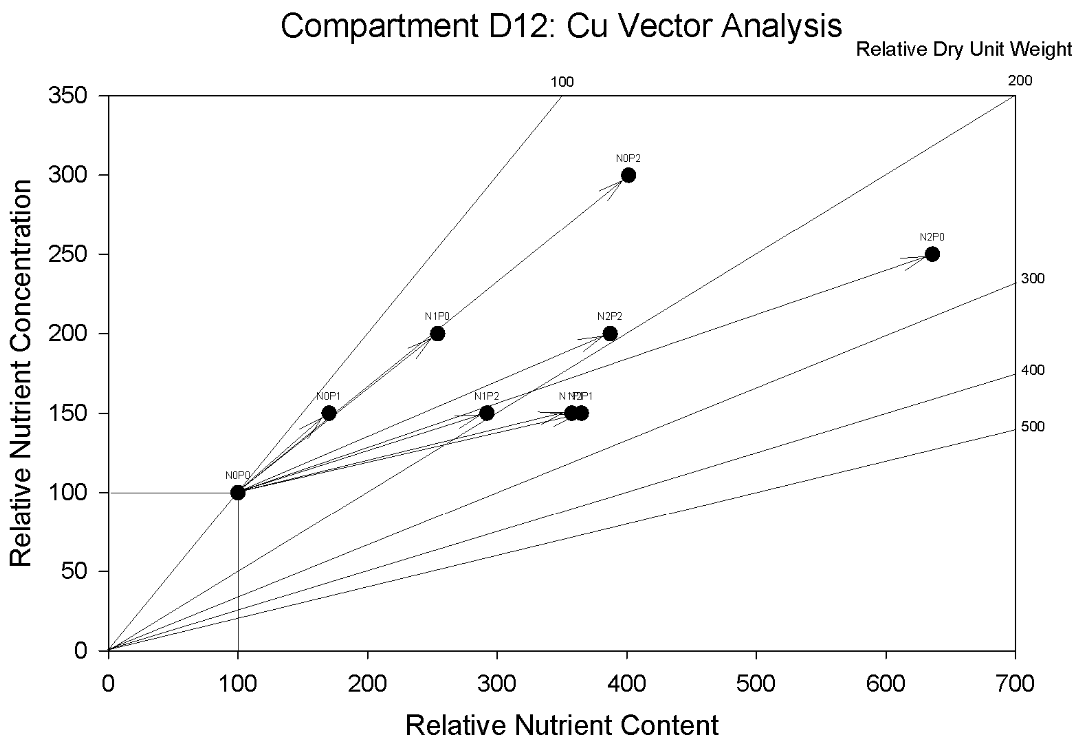
(a) Vector nomogram of replication S_1 showing a type C shift for the largest vector, treatment N_2P_2



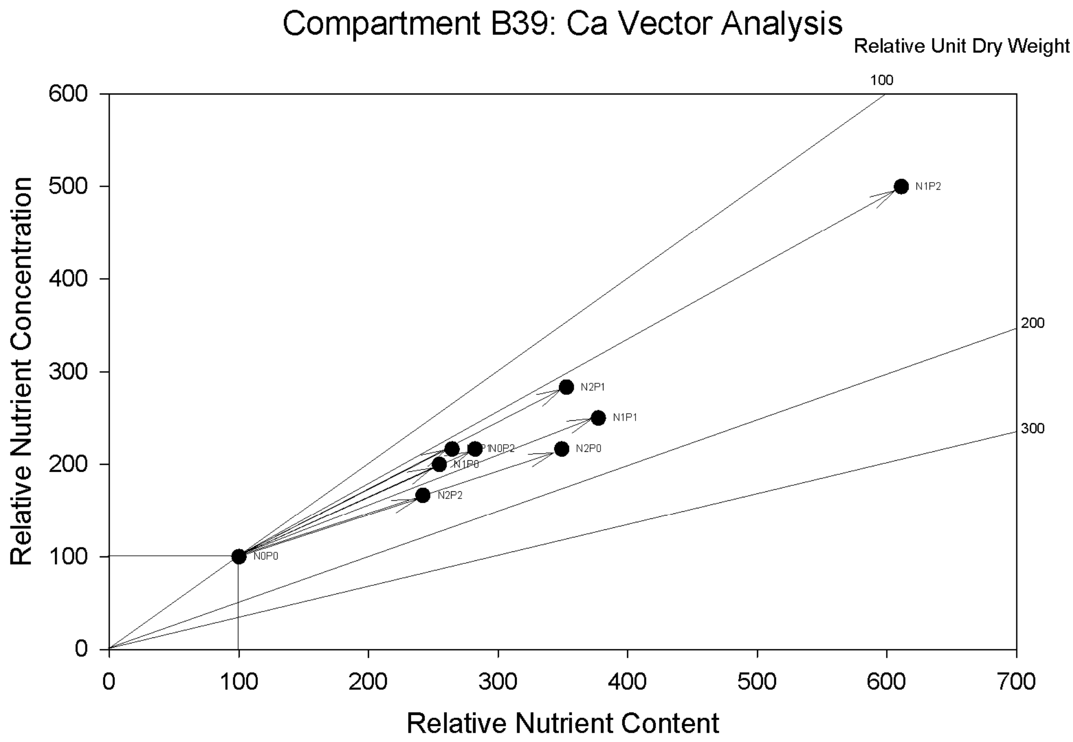
(b) Vector nomogram of replication S_2 showing a type C shift for the largest vectors, treatments N_2P_1 and N_2P_0.



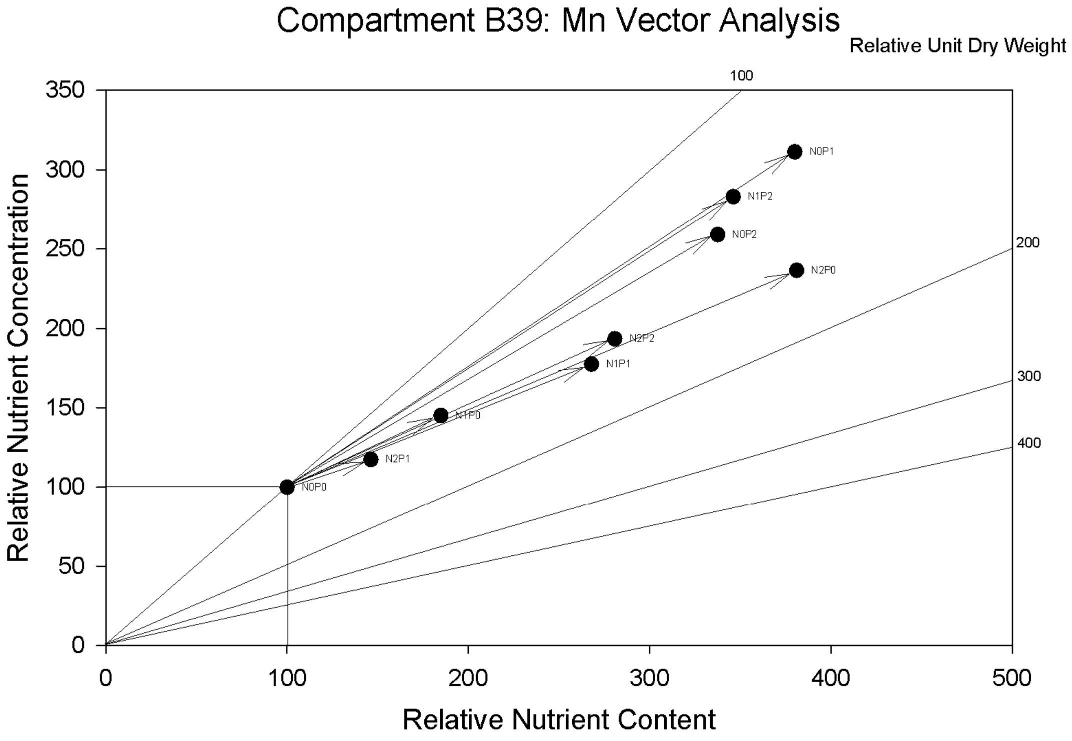
(c) Vector nomogram of replication S_2 showing a type C shift for all the vectors and for all treatments



(d) Vector nomogram of replication S_2 showing a type C shift for all the vectors and for all treatmentc



(e) Vector nomogram of replication L_1 showing a type C shift for all the vectors and for all treatments.



(f) Vector nomogram of replication L_1 showing a type C shift for all the vectors and for all treatments.

Appendix 4.2a: Data used for vector analysis for mean values across all replications of a mid-rotation NxP fertilizer trial for macro nutrients

Treatment	Volume increment (m3 ha-1 a-1)	Relative volume increment.	Foliar concentration %					Relative concentration					Relative content (based on Volume response.)				
			N	P	K	Ca	Mg	N	P	K	Ca	Mg	N	P	K	Ca	Mg
N0P0	14.71	100	1.33	0.08	0.49	0.28	0.10	100	100	100	100	100	100	100	100	100	100
N0P1	16.39	111.42	1.25	0.11	0.53	0.30	0.09	94.00	133.93	106.96	107.11	95.52	104.73	149.23	119.17	119.34	106.43
N0P2	16.06	109.20	1.18	0.11	0.52	0.36	0.11	88.21	135.71	106.09	126.90	110.45	96.32	148.19	115.84	138.57	120.60
N1P0	16.71	113.58	1.53	0.09	0.54	0.31	0.12	115.01	108.93	108.70	111.17	122.39	130.62	123.72	123.46	126.27	139.01
N1P1	19.10	129.85	1.38	0.11	0.56	0.31	0.10	103.64	137.50	113.04	108.63	101.49	134.58	178.54	146.79	141.05	131.79

Appendix 4.2a continued

N1P2	18.39	125.04	1.34	0.12	0.52	0.37	0.10	100.32	151.79	104.64	132.99	108.96	125.44	189.79	130.84	166.29	136.24
N2P0	18.21	123.83	1.75	0.09	0.49	0.27	0.07	130.98	108.93	98.55	97.46	76.12	162.19	134.89	122.04	120.69	94.26
N2P1	20.09	136.56	1.60	0.10	0.45	0.33	0.10	119.72	128.57	91.30	116.75	104.48	163.50	175.58	124.69	159.44	142.68
N2P2	19.91	135.39	1.58	0.13	0.57	0.44	0.12	118.76	157.14	116.23	157.87	120.90	160.78	212.76	157.37	213.74	163.68

Appendix 4.2b: Data used for vector analysis for mean values across all replications of a mid-rotation NxP fertilizer trial for micro nutrients

Treatment	Volume increment (m^3 ha^{-1} a^{-1})	Relative volume increment.	Foliar concentration %					Relative concentration					Relative content (based on Volume response.)				
			Mn	Fe	Cu	Zn	B	Mn	Fe	Cu	Zn	B	Mn	Fe	Cu	Zn	B
N0P0	14.71	100	0.0219	0.0122	0.0016	0.0015	0.0025	100	100	100	100	100	100	100	100	100	100
N0P1	16.39	111.42	0.0265	0.0117	0.0016	0.0022	0.0026	120.70	95.78	100.00	143.81	101.70	134.49	106.72	111.42	160.24	113.32
N0P2	16.06	109.20	0.0239	0.0122	0.0015	0.0021	0.0027	108.72	99.88	91.23	139.05	106.82	118.72	109.07	99.62	151.83	116.64
N1P0	16.71	113.58	0.0213	0.0099	0.0013	0.0018	0.0026	97.14	81.24	81.58	120.00	104.55	110.33	92.28	92.66	136.30	118.74
N1P1	19.10	129.85	0.0175	0.0114	0.0013	0.0015	0.0023	79.75	93.55	78.07	102.86	89.77	103.56	121.48	101.37	133.56	116.57
N1P2	18.39	125.04	0.0214	0.0121	0.0015	0.0018	0.0023	97.46	99.65	92.98	120.00	90.34	121.86	124.60	116.26	150.05	112.96

N2P0	18.21	123.83	0.0215	0.0103	0.0017	0.0019	0.0023	98.18	84.29	106.14	129.52	90.34	121.57	104.38	131.44	160.39	111.87
N2P1	20.09	136.56	0.0241	0.0119	0.0016	0.0018	0.0026	109.96	97.54	96.49	117.14	104.55	150.17	133.20	131.77	159.97	142.77
N2P2	19.91	135.39	0.0189	0.0112	0.0017	0.0028	0.0026	86.13	92.15	106.14	188.57	101.70	116.62	124.76	143.70	255.31	137.70

Appendix 4.3: ANOVA outputs

(a) LAI response to N, P and water availability class at 12 months (2009)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	54.48	170.60	<0.001*
Nitrogen	2	1.37	4.30	0.020*
Phosphorus	2	0.99	3.11	0.056*
Water	3	0.48	1.51	0.227
Nitrogen x Phosphorus	4	0.07	0.22	0.925
Nitrogen x Water	6	0.28	0.88	0.519
Phosphorus x Water	6	0.21	0.64	0.696
Error	39	0.32		

* **Statistically significant results of *p*<0.1**

(b) LAI response to NP and water availability class at 24 months (2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	10.76	31.07	<0.001*
Initial LAI (covariate)	1	3.11	8.99	0.005*
Nitrogen	2	0.74	2.15	0.131
Phosphorus	2	1.32	3.82	0.031*
Water	3	1.39	4.02	0.014*
Nitrogen x Phosphorus	4	0.42	1.21	0.322
Nitrogen x Water	6	0.16	0.47	0.829
Phosphorus x Water	6	0.24	0.69	0.659
Error	38	0.35		

* **Statistically significant results of *p*<0.1**

(c) Basal area increment response to N, P and water availability class in year 1 (2009)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	252.97	276.41	<0.001*
Nitrogen	2	0.61	0.67	0.518
Phosphorus	2	0.05	0.05	0.951
Water	3	5.12	5.60	0.003*
Nitrogen x Phosphorus	4	0.02	0.03	0.999
Nitrogen x Water	6	0.11	0.12	0.993
Phosphorus x Water	6	0.04	0.04	1.000
Error	39	0.92		

* **Statistically significant results of *p*<0.1**

(d) Basal area increment response to N,P and water availability class in year 2 (2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	1.57	5.05	0.031*
Initial basal area (covariate)	1	5.61	18.06	<0.001*
Nitrogen	2	2.69	8.66	<0.001*
Phosphorus	2	0.94	3.02	0.061*
Water	3	0.92	2.96	0.044*
Nitrogen x Phosphorus	4	0.14	0.46	0.762
Nitrogen x Water	6	0.13	0.41	0.869
Phosphorus x Water	6	0.11	0.35	0.907
Error	38	0.31		

* **Statistically significant results of *p*<0.1**

(e) Total basal area increment response to N,P and water availability class over the two year period (2008-2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	1211.64	595.91	<0.001*
Nitrogen	2	5.67	2.79	0.074*
Phosphorus	2	1.15	0.57	0.573
Water	3	14.57	7.17	<0.001*
Nitrogen X Phosphorus	4	0.28	0.14	0.967
Nitrogen X Water	6	0.32	0.16	0.987
Phosphorus X Water	6	0.19	0.09	0.997
Error	39	2.03		

* **Statistically significant results of *p*<0.1**

(f) Volume increment response to N,P and water availability class in year 1 (2009)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	13677.68	684.97	<0.001*
Nitrogen	2	35.16	1.76	0.185
Phosphorus	2	2.08	0.10	0.901
Water	3	942.19	47.18	<0.001*
Nitrogen X Phosphorus	4	1.27	0.06	0.992
Nitrogen X Water	6	5.61	0.28	0.943
Phosphorus X Water	6	8.22	0.41	0.867
Error	39	19.97		

* **Statistically significant results of *p*<0.1**

(g) Volume increment response to N, P and water availability class in year 2 (2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	82.16	2.93	0.095*
Initial volume (covariate)	1	857.32	30.58	<0.001*
Nitrogen	2	110.39	3.94	0.028*
Phosphorus	2	57.65	2.06	0.142
Water	3	227.87	8.12	<0.001*
Nitrogen x Phosphorus	4	1.93	0.07	0.991
Nitrogen x Water	6	5.37	0.19	0.977
Phosphorus x Water	6	6.17	0.22	0.968
Error	38	28.03		

* **Statistically significant results of *p*<0.1**

(h) Total volume increment response to N, P and water availability class over the two year period (2008-2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	1136.54	15.46	<0.001*
Initial volume (covariate)	1	1152.13	15.67	<0.001*
Nitrogen	2	267.29	3.64	0.036*
Phosphorus	2	84.56	1.15	0.327
Water	3	1091.17	14.84	<0.001*
Nitrogen x Phosphorus	4	2.45	0.03	0.998
Nitrogen x Water	6	8.73	0.12	0.994
Phosphorus x Water	6	21.74	0.30	0.935
Error	38	73.51		

* **Statistically significant results of *p*<0.1**

(i) GE response to N,P and water availability class in year 1 (2009)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	1703.02	1174.84	<0.001*
Nitrogen	2	0.45	0.31	0.733
Phosphorus	2	0.43	0.30	0.746
Water	3	23.88	16.48	<0.001*
Nitrogen X Phosphorus	4	0.29	0.20	0.936
Nitrogen X Water	6	0.50	0.35	0.908
Phosphorus X Water	6	1.19	0.82	0.559
Error	39	1.45		

* **Statistically significant results of *p*<0.1**

(j) GE response to N, P and water availability class in year 2 (2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	48.28	38.22	<0.001*
Initial volume (covariate)	1	42.84	33.92	<0.001*
Nitrogen	2	3.91	3.10	0.057*
Phosphorus	2	2.60	2.05	0.142
Water	3	5.55	4.39	0.010*
Nitrogen x Phosphorus	4	0.18	0.15	0.964
Nitrogen x Water	6	1.50	1.19	0.332
Phosphorus x Water	6	1.68	1.33	0.268
Error	38	1.26		

* **Statistically significant results of *p*<0.1**

(k) GE response to N, P and water availability class over the two year period (2008-2010)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	304.31	82.45	<0.001*
Initial volume (covariate)	1	40.12	10.87	0.002*
Nitrogen	2	6.64	1.80	0.179
Phosphorus	2	1.11	0.30	0.742
Water	3	8.56	2.32	0.091*
Nitrogen x Phosphorus	4	0.44	0.12	0.974
Nitrogen x Water	6	2.73	0.74	0.621
Phosphorus x Water	6	4.26	1.15	0.351
Error	38	3.69		

* **Statistically significant results of *p*<0.1**

(l) Foliar N response to N and P fertilizer treatment one year after treatment (2009)

Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	130.18	2326.33	<0.001*
Nitrogen	2	0.80	14.21	<0.001*
Phosphorus	2	0.17	2.99	0.059*
Nitrogen x Phosphorus	4	0.004	0.07	0.99
Error	54	0.06		

* **Statistically significant results of *p*<0.1**

Appendix 4.4: LSD tables for responses that were significant

(a) LSD test for LAI response to N at 12 months (2009)

Treatment	**N_0** 0.70	**N_{100}** 0.99	**N_{200}** 1.25
N_0			
N_{100}	0.106		
N_{200}	0.003*	0.147	

* **Statistically significant results of *p*<0.1**

(b) LSD test for LAI response to P at 12 months (2009)

Treatment	**P_0** 0.69	**P_{50}** 1.16	**P_{100}** 1.09
P_0			
P_{50}	0.011*		
P_{100}	0.030*	0.688	

* **Statistically significant results of *p*<0.1**

(c) LSD test for LAI response to P at 24 months (2010)

Treatment	**P_0** 0.56	**P_{50}** 1.13	**P_{100}** 1.19
P_0			
P_{50}	0.003*		
P_{100}	0.001*	0.739	

* **Statistically significant results of *p*<0.1**

(d) LSD test for LAI response to water availability class at 24 months (2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	0.94	0.66	0.57	1.49
Water class 1				
Water class 2	0.350			
Water class 3	0.265	0.801		
Water class 4	0.378	0.089*	0.062*	

* **Statistically significant results of *p*<0.1**

(e) LSD test for basal area increment response to water availability class in year 1 (2009)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	1.82	2.07	1.58	2.91
Water class 1				
Water class 2	0.449			
Water class 3	0.542	0.223		
Water class 4	0.002*	0.012*	0.002*	

* **Statistically significant results of *p*<0.1**

(f) LSD test for basal area increment response to N in year 2 (2010)

Treatment	N_0	N_{100}	N_{200}
	2.15	2.58	2.79
N_0			
N_{100}	0.016*		
N_{200}	<0.001*	0.223	

* **Statistically significant results of *p*<0.1**

(g) LSD test for basal area increment response to P in year 2 (2010)

Treatment	P_0	P_{50}	P_{100}
	2.26	2.65	2.62
P_0			
P_{50}	0.029*		
P_{100}	0.043*	0.862	

* **Statistically significant results of *p*<0.1**

(h) LSD test for basal area increment response to water availability class in year 2 (2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	2.13	2.41	2.39	3.04
Water class 1				
Water class 2	0.149			
Water class 3	0.276	0.922		
Water class 4	<0.001*	0.002*	0.007*	

* **Statistically significant results of *p*<0.1**

(i) LSD test for total basal area increment response to N over the two year period (2008-2010)

Treatment	N_0	N_{100}	N_{200}
	4.13	4.78	5.11
N_0			
N_{100}	0.150		
N_{200}	0.033*	0.461	

* **Statistically significant results of *p*<0.1**

(j) LSD test for total basal area increment response to water availability class over the two year period (2008-2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	3.96	4.47	3.97	5.95
Water class 1				
Water class 2	0.283			
Water class 3	0.984	0.390		
Water class 4	<0.001*	0.004*	0.002*	

* **Statistically significant results of *p*<0.1**

(k) LSD test for volume increment response to water availability class in year 1 (2009)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	9.34	14.84	11.42	26.04
Water class 1				
Water class 2	<0.001*			
Water class 3	0.261	0.068*		
Water class 4	<0.001*	<0.001*	<0.001*	

* **Statistically significant results of *p*<0.1**

(l) LSD test for volume increment response to N in year 2 (2010)

Treatment	N_0	N_{100}	N_{200}
	17.83	20.92	21.98
N_0			
N_{100}	0.181		
N_{200}	0.051*	0.811	

* **Statistically significant results of *p*<0.1**

(m) LSD test for volume increment response to water availability class in year 2 (2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	15.25	17.93	16.50	29.40
Water class 1				
Water class 2	0.137			
Water class 3	0.566	0.512		
Water class 4	<0.001*	<0.001*	<0.001*	

* **Statistically significant results of *p*<0.1**

(n) LSD test for total volume increment response to N over the two year period (2008-2010)

Treatment	N_0	N_{100}	N_{200}
	32.38	37.37	38.91
N_0			
N_{100}	0.182		
N_{200}	0.059*	0.845	

* **Statistically significant results of *p*<0.1**

(o) LSD test for total volume increment response to water availability class over the two year period (2008-2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	24.59	32.78	27.92	55.44
Water class 1				
Water class 2	0.007*			
Water class 3	0.347	0.173		
Water class 4	<0.001*	<0.001*	<0.001*	

* **Statistically significant results of *p*<0.1**

(p) LSD test for growth efficiency response to water availability class in year 1 (2009)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	4.24	5.64	4.89	6.98
Water class 1				
Water class 2	0.001*			
Water class 3	0.195	0.137		
Water class 4	<0.001*	0.002*	<0.001*	

* **Statistically significant results of *p*<0.1**

(q) LSD test for growth efficiency response to water availability class in year 2 (2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	6.59	6.69	7.03	7.77
Water class 1				
Water class 2	0.778			
Water class 3	0.337	0.464		
Water class 4	0.003*	0.007*	0.116	

* **Statistically significant results of *p*<0.1**

(r) LSD test for growth efficiency response to water availability class over the two year period (2008-2010)

Treatment	Water class 1	Water class 2	Water class 3	Water class 4
	10.83	12.33	11.92	14.75
Water class 1				
Water class 2	0.158			
Water class 3	0.589	0.965		
Water class 4	<0.001*	0.006*	0.010*	

* **Statistically significant results of *p*<0.1**

Appendix 4.5: Summary of a forward stepwise regression for LAI at 24 months where *p* to enter was 0.1 and *p* to remove was 0.2

Effect	Steps	Df	F to remove	p to remove	F to enter	p to enter	Effect status
Nitrogen	Step 1	1			3.491	0.066	Out
Phosphorus		1			9.719	0.003	Entered
Water		1			0.382	0.539	Out
Phosphorus	Step 2	1	9.719	0.003			In
Nitrogen		1			4.018	0.05	Entered
Water		1			0.436	0.512	Out
Phosphorus	Step 3	1	10.199	0.002			In
Nitrogen		1	4.018	0.0495			In
Water		1			0.458	0.501	Out

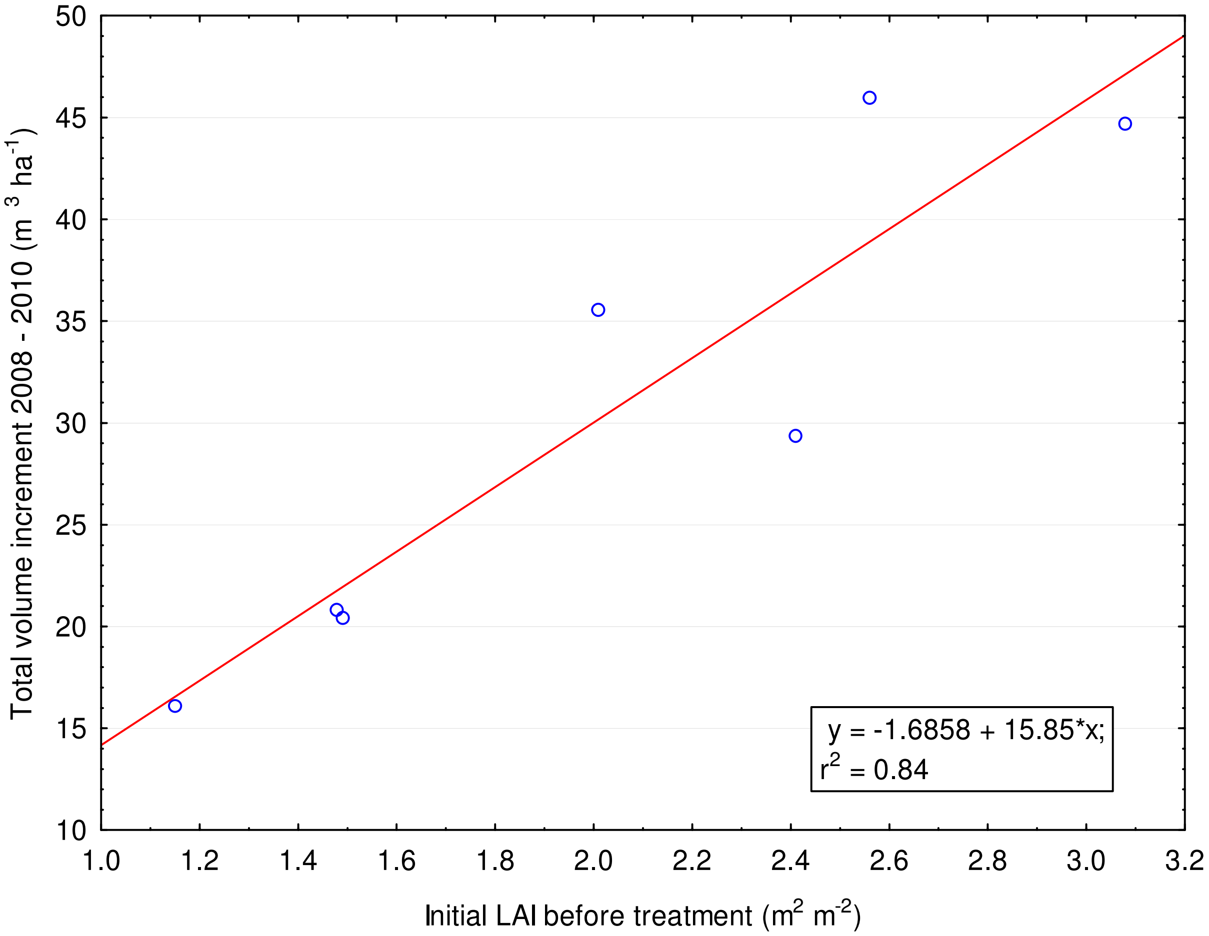
Appendix 4.6: Least squares means for leaf area, basal area, volume increment and growth efficiency for all the nitrogen and phosphorus levels over the different water availability classes. All predicted means were obtained in the presence of covariates as explained in Chapter 4.

Variable	Treatment	Water class 1	Mean SE	Water class 2	Mean SE	Water class 3	Mean SE	Water class 4	Mean SE
Mean LAI increment ($m^2\ m^{-2}$)	N_0P_0	0.55	0.33	0.07	0.33	0.47	0.47	1.19	0.35
	N_0P_{50}	1.06	0.35	0.65	0.33	0.52	0.46	1.05	0.36
	N_0P_{100}	0.62	0.33	0.84	0.33	0.71	0.47	0.97	0.35
	$N_{100}P_0$	0.08	0.33	0.77	0.33	1.06	0.47	0.83	0.36
	$N_{100}P_{50}$	1.06	0.33	0.57	0.33	0.28	0.46	2.18	0.33
	$N_{100}P_{100}$	1.08	0.33	0.71	0.33	1.06	0.47	1.43	0.34
	$N_{200}P_0$	0.88	0.33	0.31	0.33	0.75	0.46	1.00	0.37
	$N_{200}P_{50}$	1.04	0.34	1.54	0.33	1.21	0.46	1.65	0.36
	$N_{200}P_{100}$	1.62	0.34	1.81	0.33	0.75	0.47	1.66	0.37
Mean Basal area increment ($m^2\ ha^{-1}\ a^{-1}$)	N_0P_0	1.86	0.61	1.73	0.61	1.47	0.85	2.50	0.60
	N_0P_{50}	2.24	0.61	1.91	0.60	1.67	0.85	2.47	0.60
	N_0P_{100}	1.82	0.62	1.93	0.60	1.68	0.85	2.82	0.61
	$N_{100}P_0$	1.71	0.62	2.12	0.61	2.17	0.84	2.84	0.62
	$N_{100}P_{50}$	2.43	0.62	2.36	0.60	2.06	0.85	3.06	0.61
	$N_{100}P_{100}$	2.32	0.62	2.28	0.61	2.02	0.84	2.74	0.60
	$N_{200}P_0$	1.92	0.62	2.24	0.60	2.43	0.85	2.82	0.61
	$N_{200}P_{50}$	2.18	0.63	2.40	0.60	2.42	0.84	3.26	0.62
	$N_{200}P_{100}$	2.67	0.63	2.49	0.60	2.53	0.85	3.27	0.61

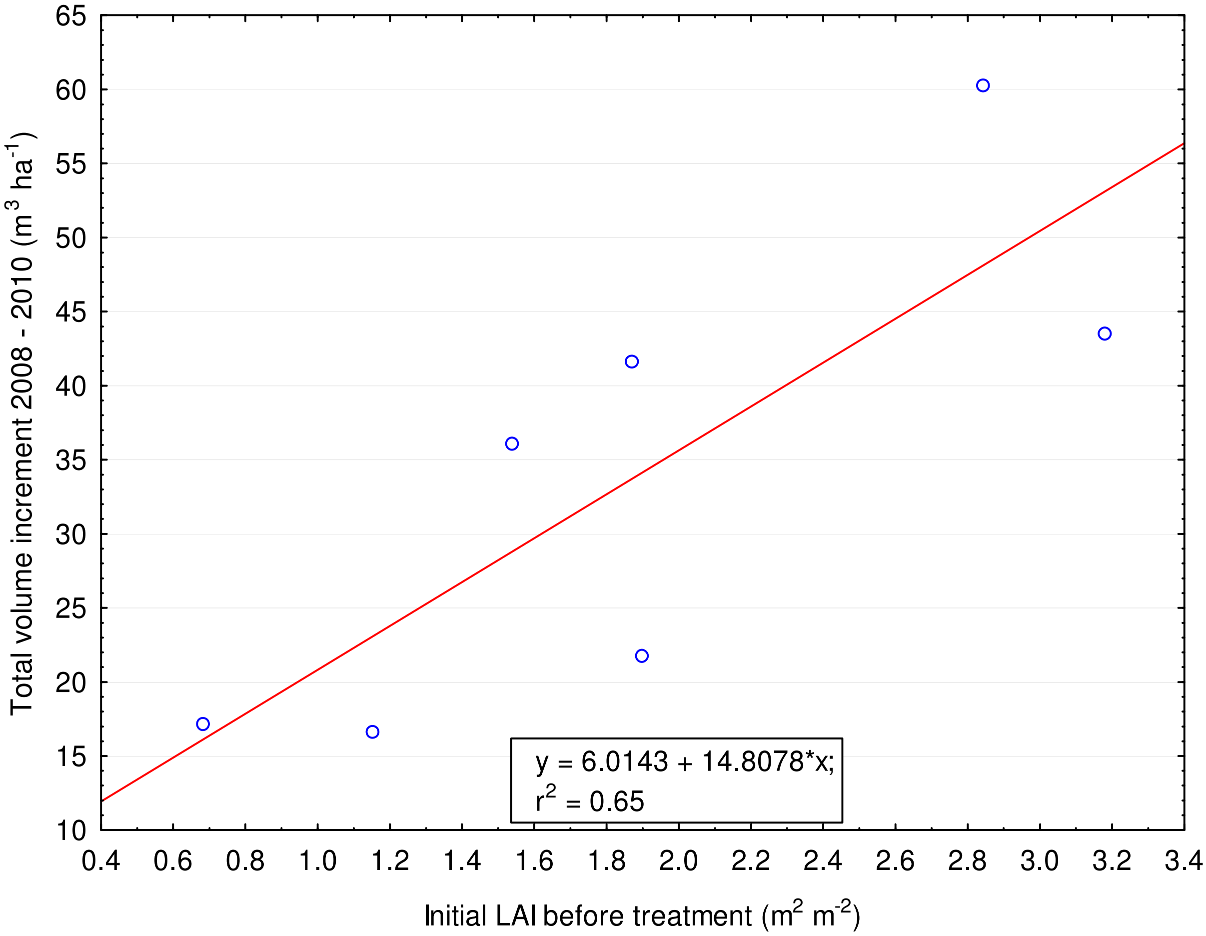
Appendix 4.6: continued

Variable	Treatment	Water class 1	Mean SE	Water class 2	Mean SE	Water class 3	Mean SE	Water class 4	Mean SE
Mean volume increment (m^3 ha $^{-1}$ a $^{-1}$)	N_0P_0	14.22	3.66	12.22	3.60	11.79	5.04	20.60	3.61
	N_0P_{50}	16.09	3.66	13.42	3.57	12.28	5.05	23.76	3.62
	N_0P_{100}	13.32	3.72	14.09	3.56	12.09	5.06	24.74	3.68
	$N_{100}P_0$	12.80	3.70	14.83	3.60	16.87	5.03	22.32	3.75
	$N_{100}P_{50}$	18.61	3.68	16.24	3.58	15.24	5.03	26.30	3.66
	$N_{100}P_{100}$	17.23	3.71	15.15	3.58	15.04	5.03	26.14	3.62
	$N_{200}P_0$	14.80	3.74	16.65	3.56	17.37	5.03	24.03	3.65
	$N_{200}P_{50}$	16.44	3.77	16.98	3.55	17.16	5.03	29.76	3.73
	$N_{200}P_{100}$	18.45	3.79	17.57	3.57	17.73	5.06	25.90	3.68
Mean growth efficiency (m3 ha -1 a -1 LAI $^{-1}$)	N_0P_0	5.77	0.75	5.84	0.74	5.47	1.04	5.91	0.74
	N_0P_{50}	6.19	0.75	6.16	0.73	4.82	1.04	6.97	0.74
	N_0P_{100}	5.45	0.77	5.56	0.73	5.07	1.04	7.75	0.76
	$N_{100}P_0$	5.46	0.76	5.80	0.74	7.26	1.03	6.54	0.77
	$N_{100}P_{50}$	6.63	0.76	6.47	0.74	6.68	1.04	6.98	0.75
	$N_{100}P_{100}$	6.85	0.76	5.44	0.74	6.00	1.04	6.84	0.74
	$N_{200}P_0$	5.26	0.77	7.01	0.73	6.94	1.04	6.53	0.75
	$N_{200}P_{50}$	6.65	0.78	5.65	0.73	5.88	1.04	7.53	0.77
	$N_{200}P_{100}$	6.14	0.78	5.67	0.73	7.34	1.04	6.62	0.76

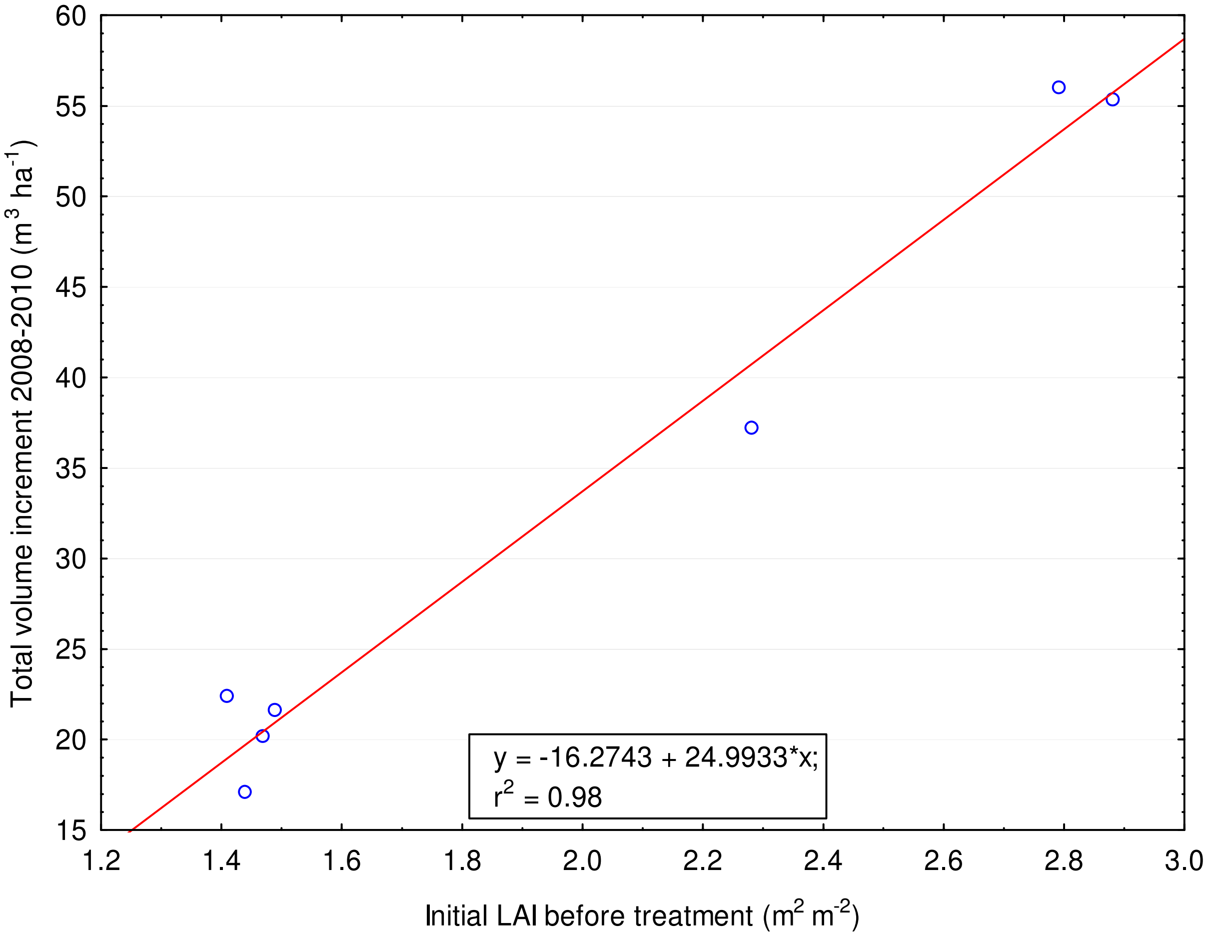
Appendix 4.7: Linear regression for initial LAI against total volume increment over the two year period



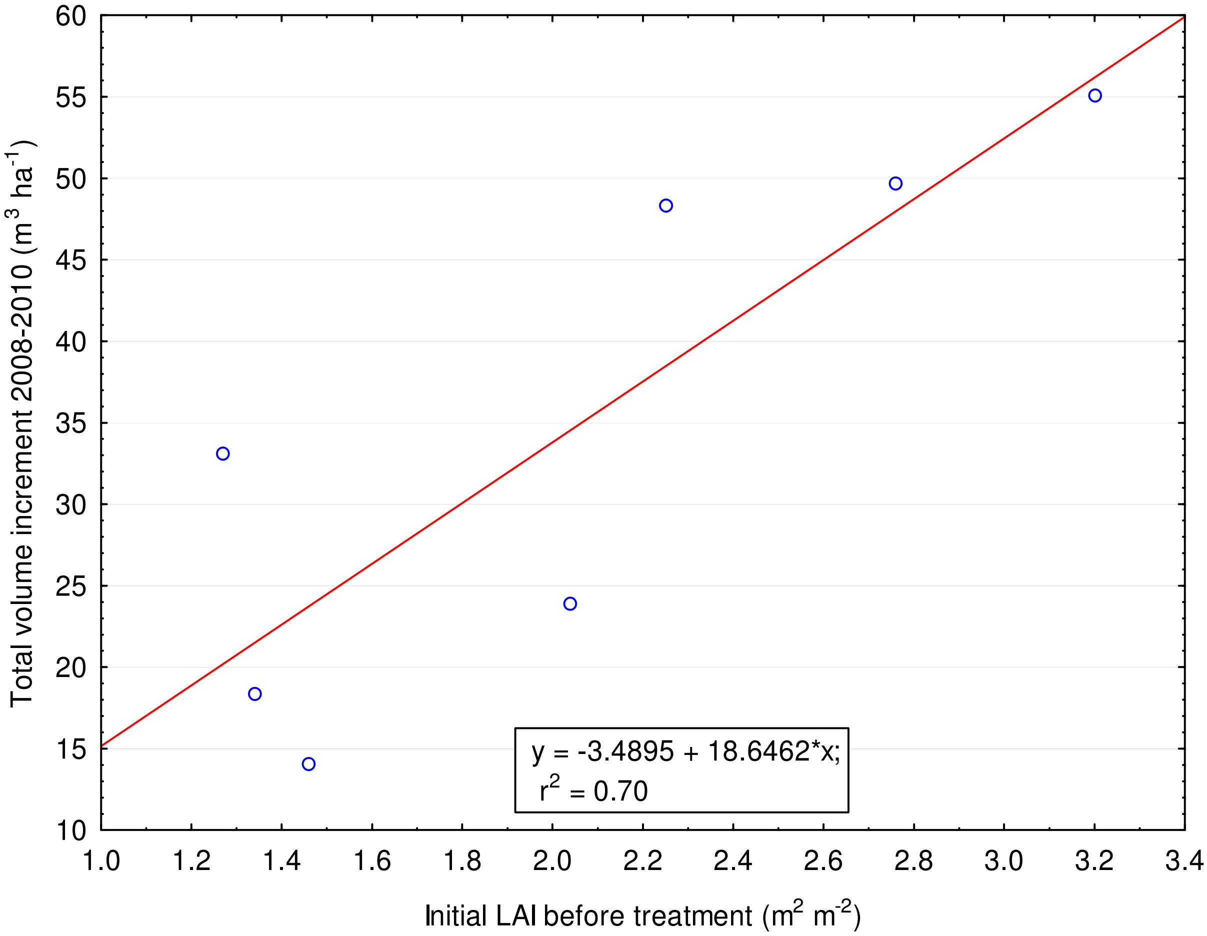
(a) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_0P_0



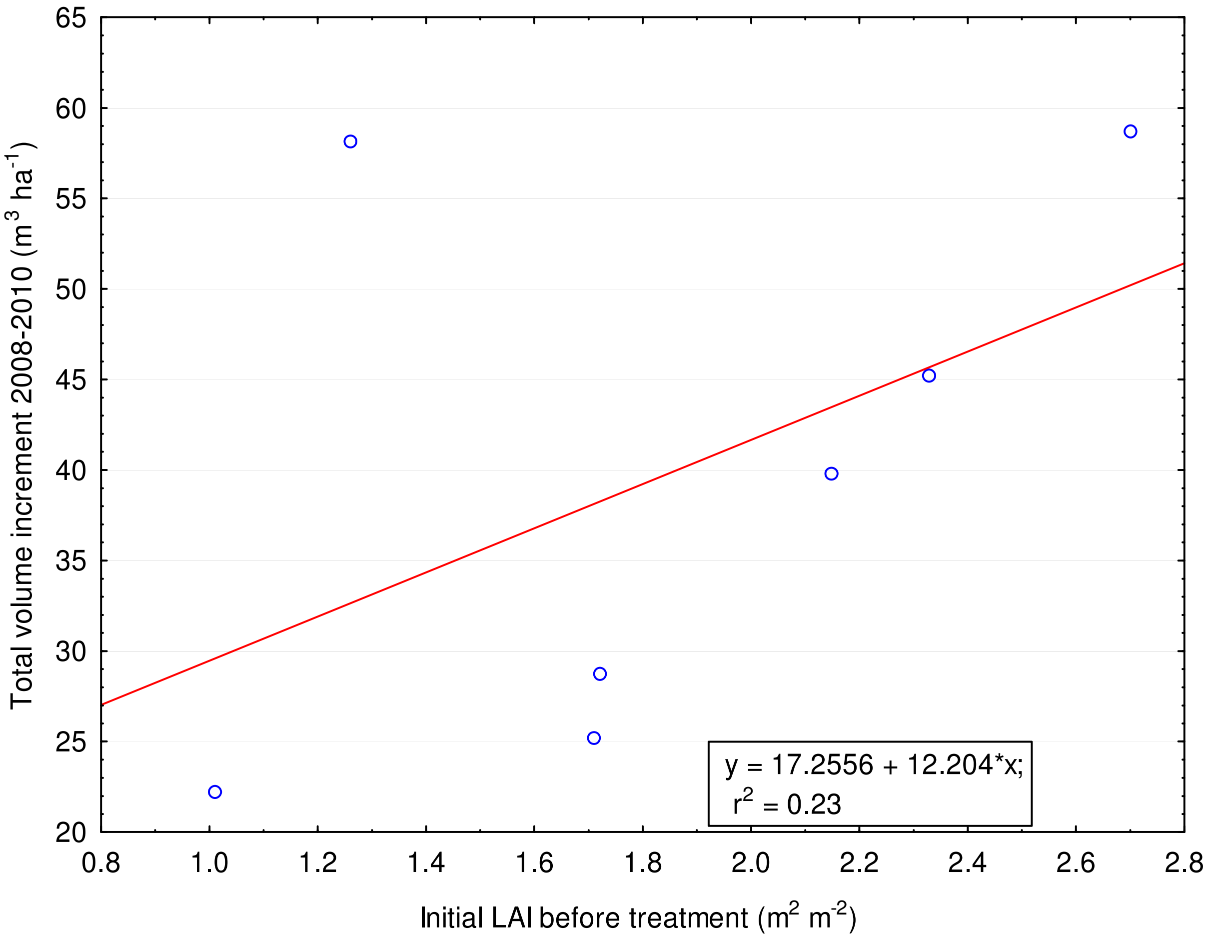
(b) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_0P_1



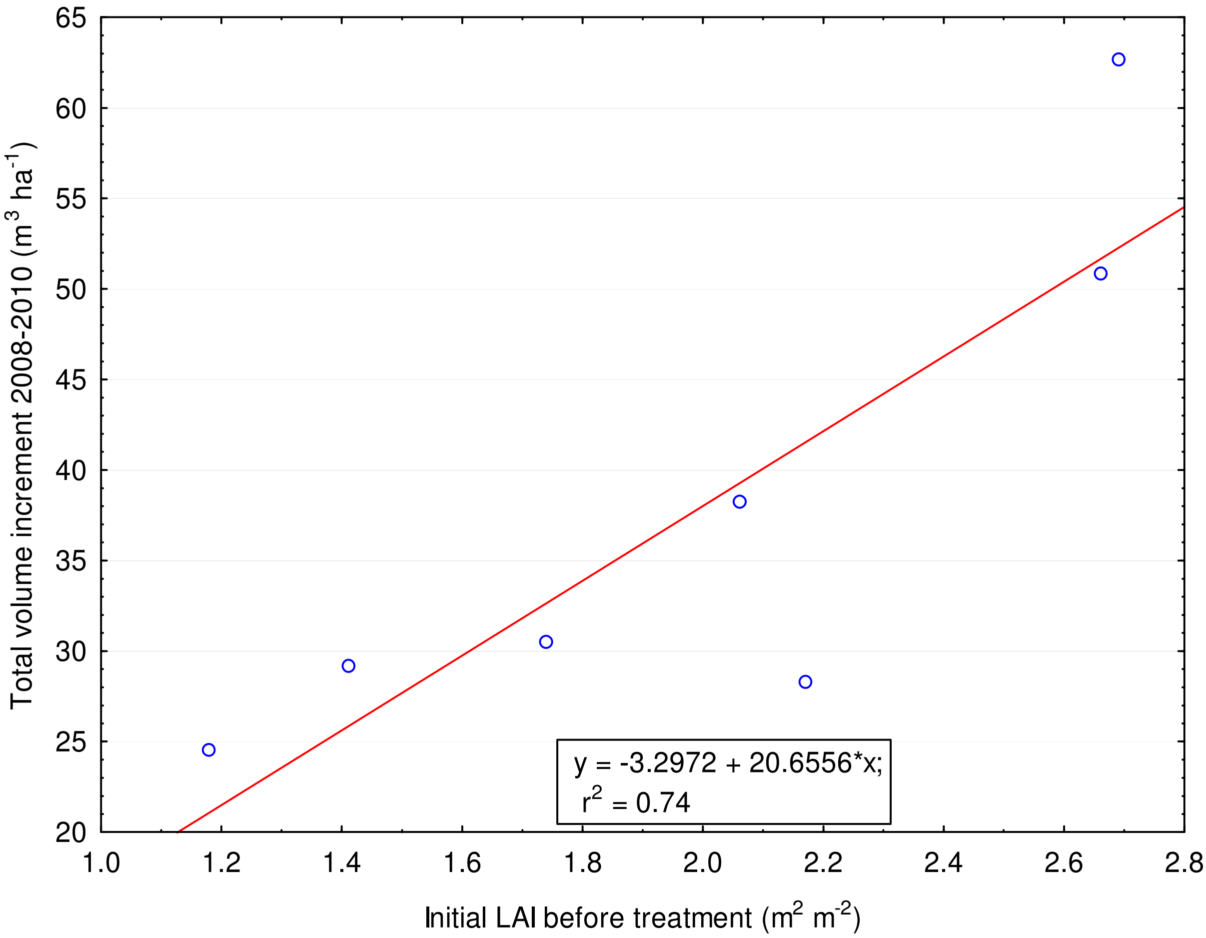
(c) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_0P_2



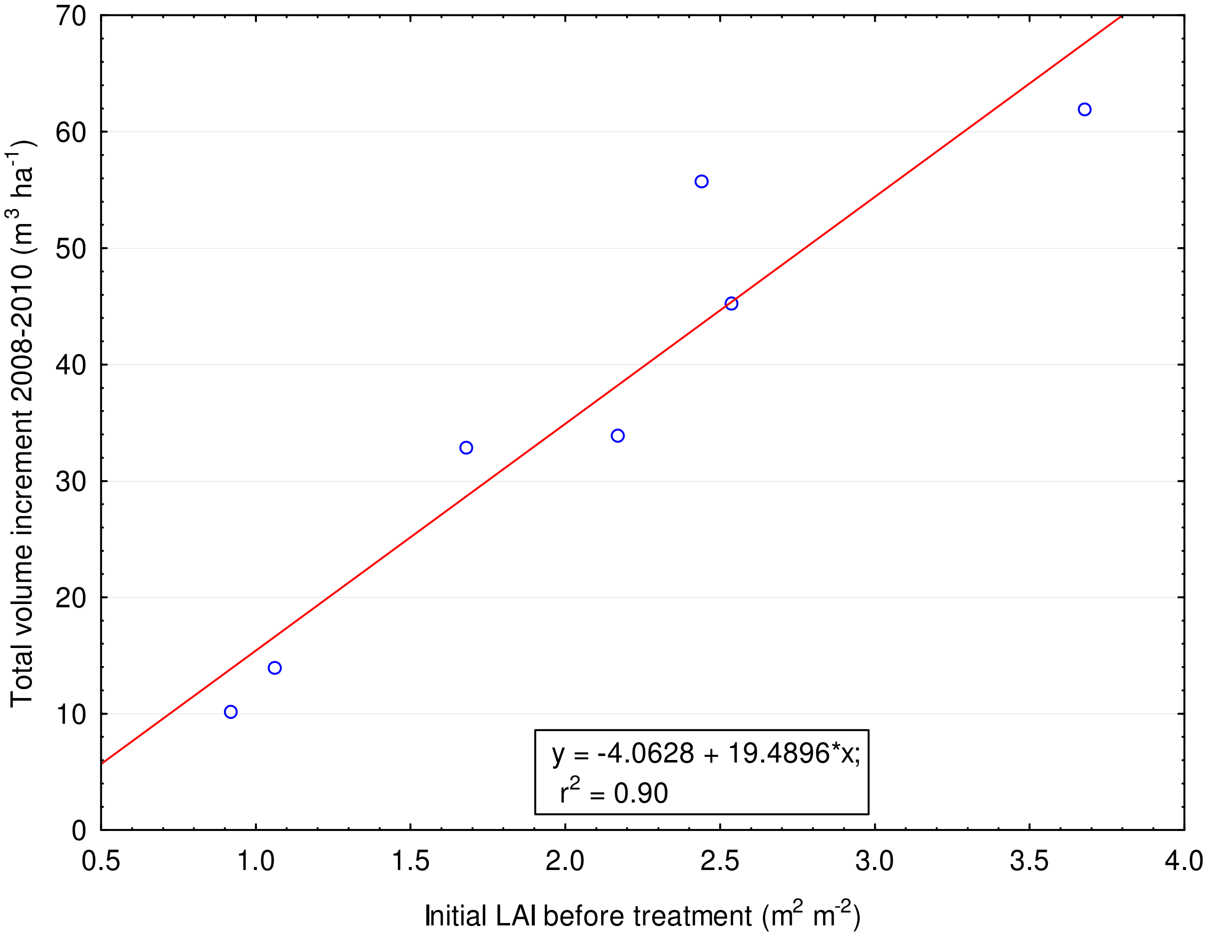
(d) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_1P_0



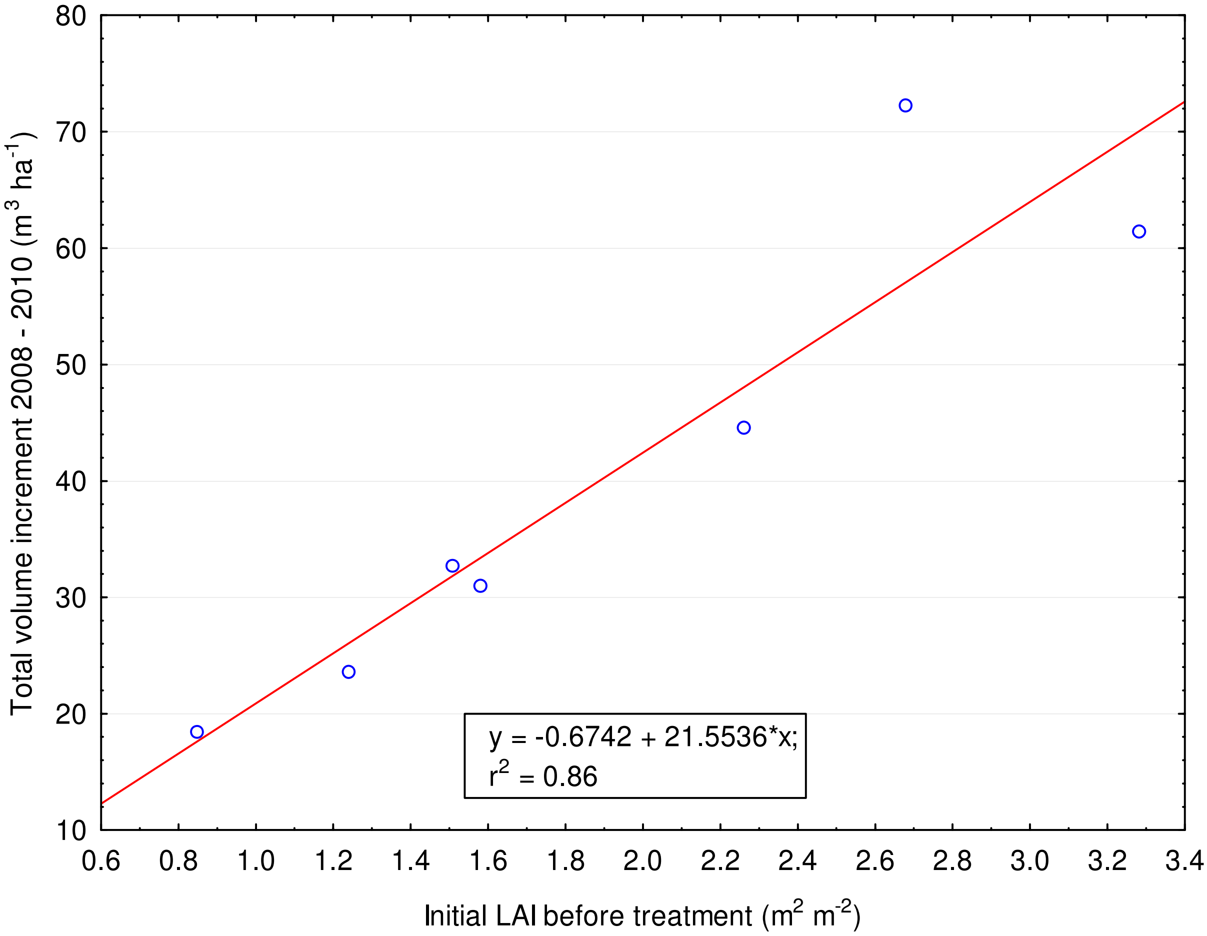
(e) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_1P_1



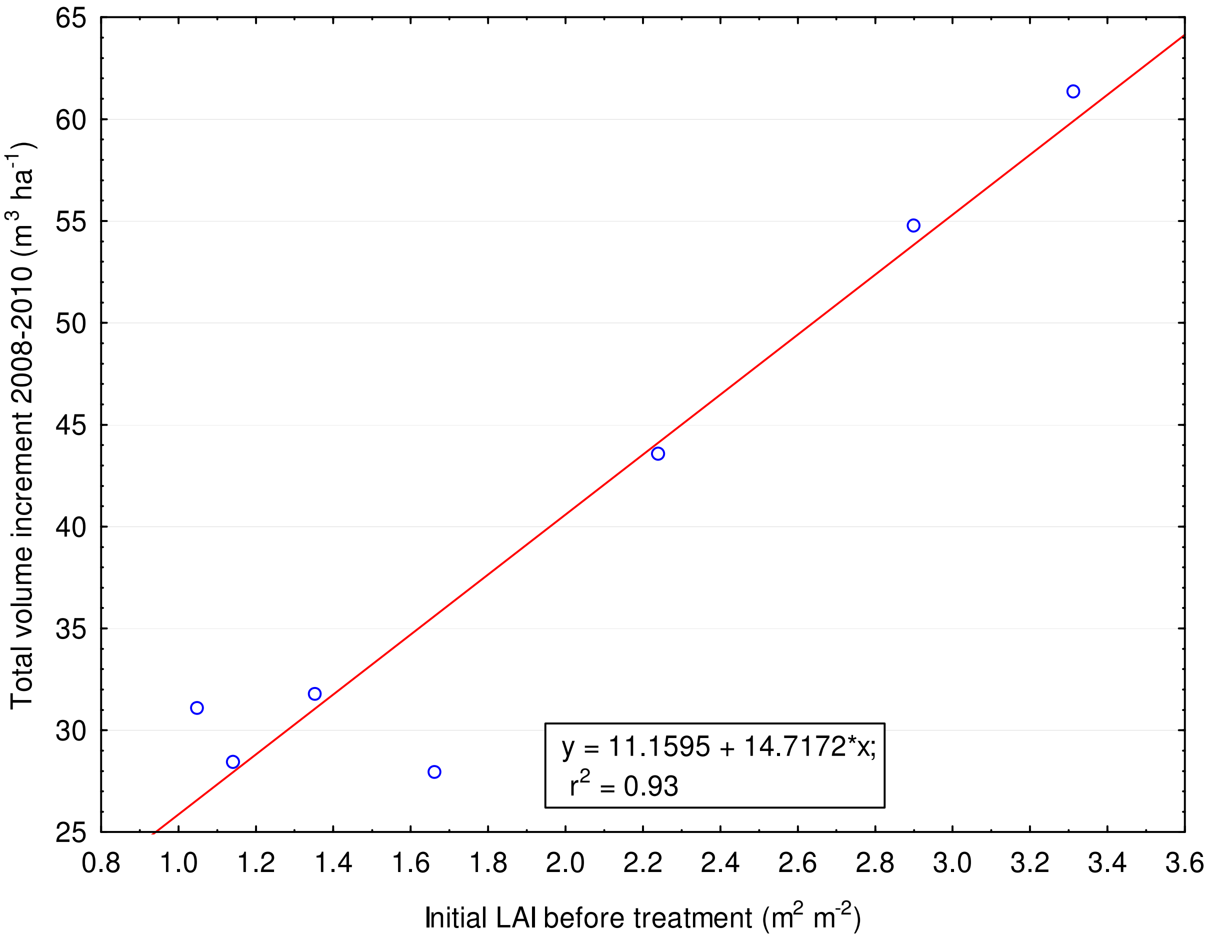
(f) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_1P_2



(g) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_2P_0

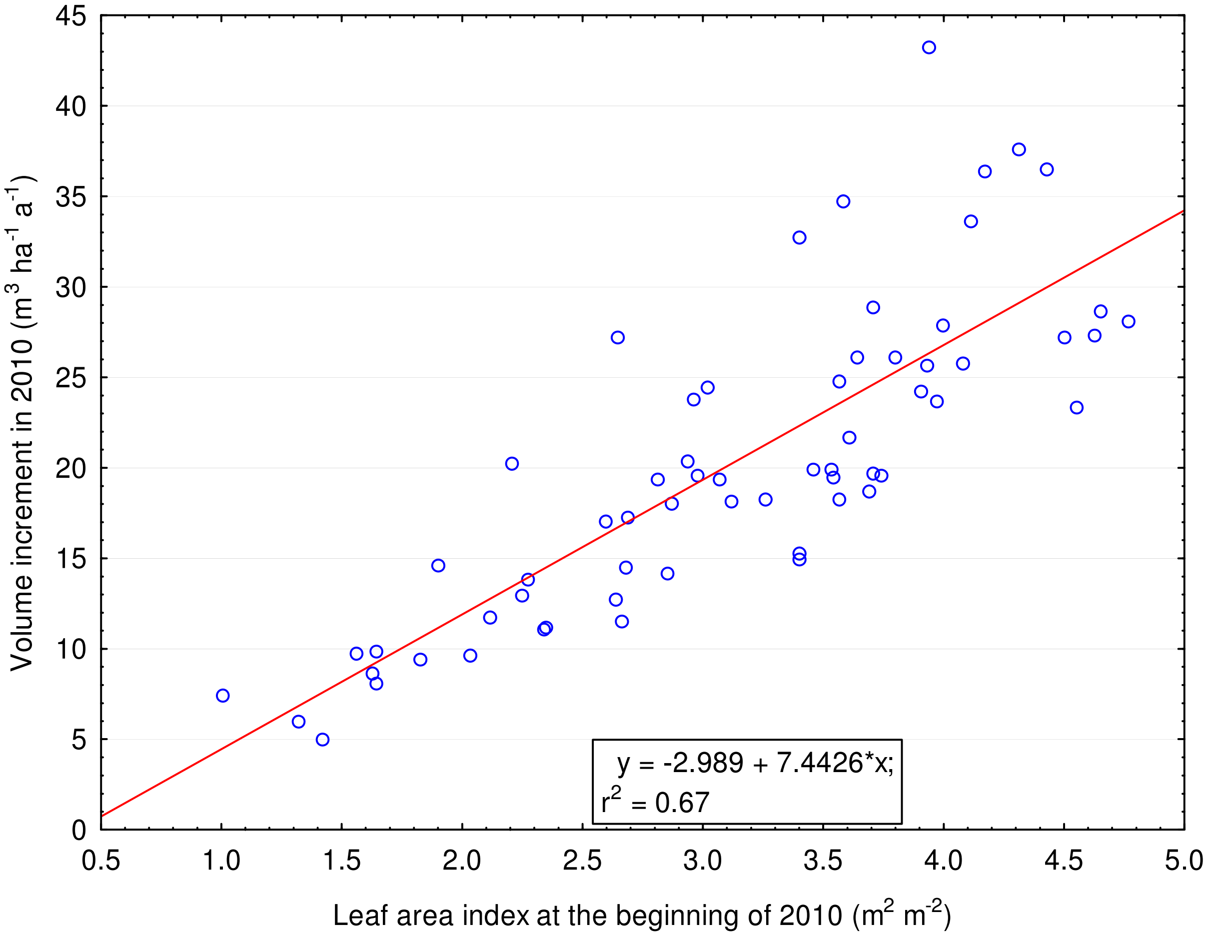


(h) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_2P_1

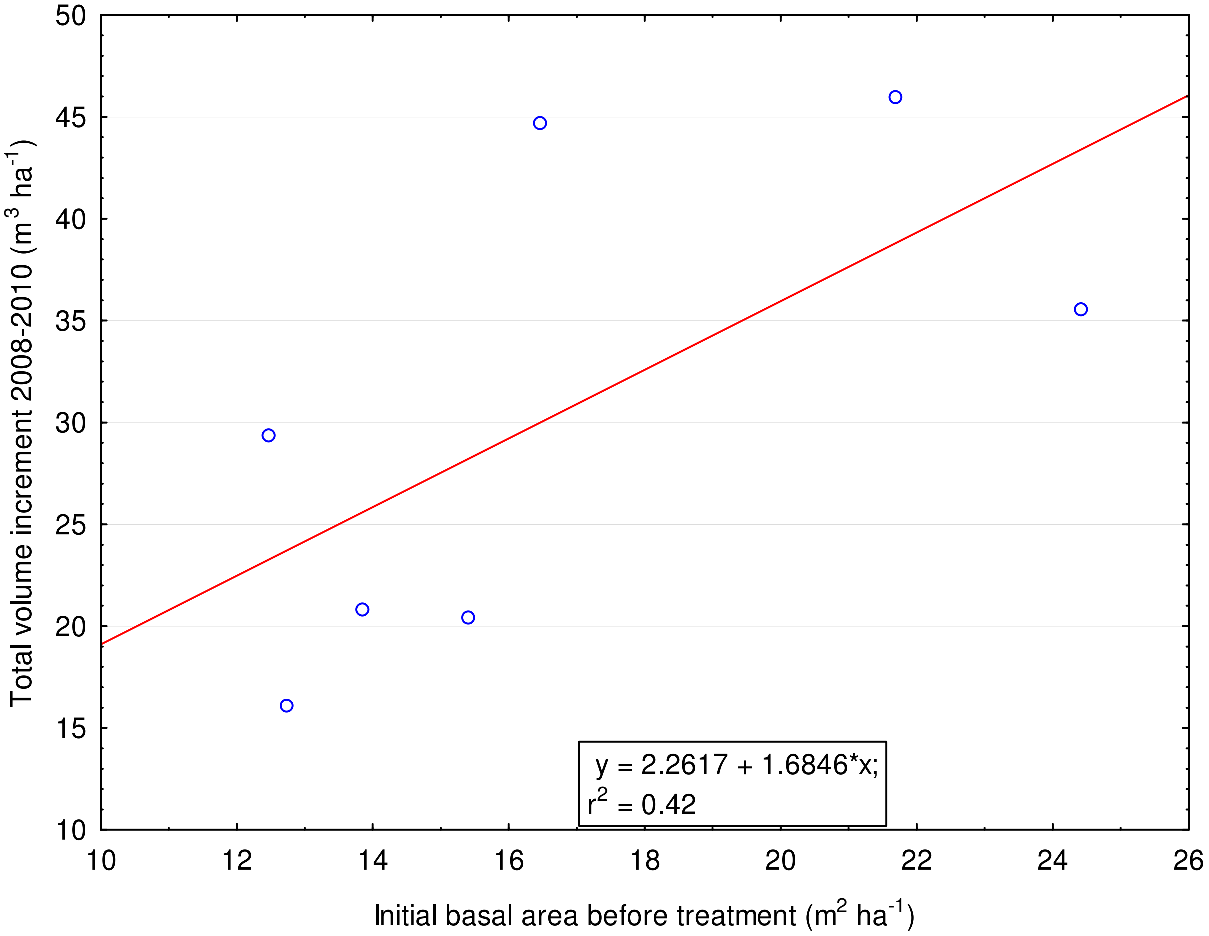


(i) Regression of total volume increment (2008-2010) against initial LAI before treatment for treatment N_2P_2

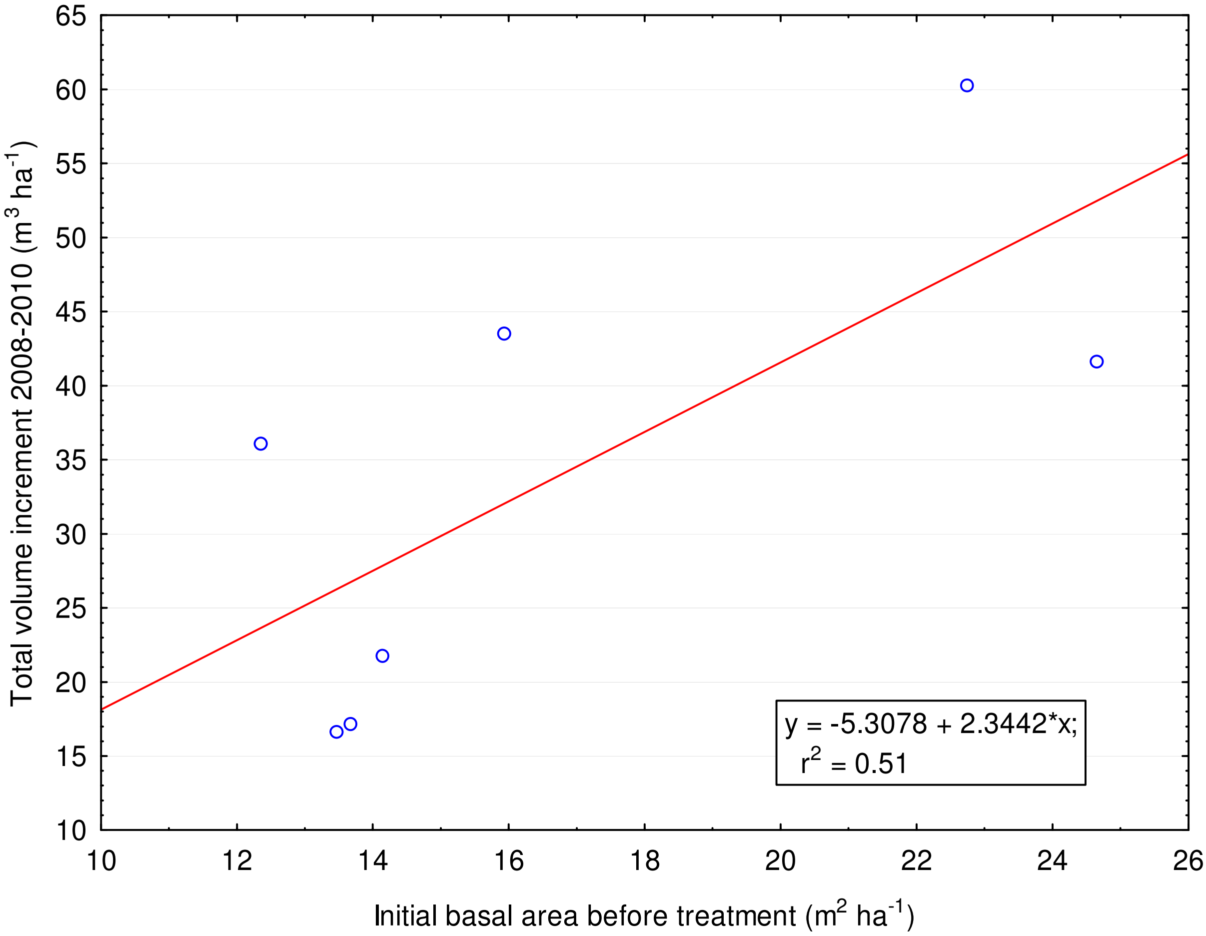
Appendix 4.8: Regression of initial LAI at the start of 2010 against volume increment in 2010.



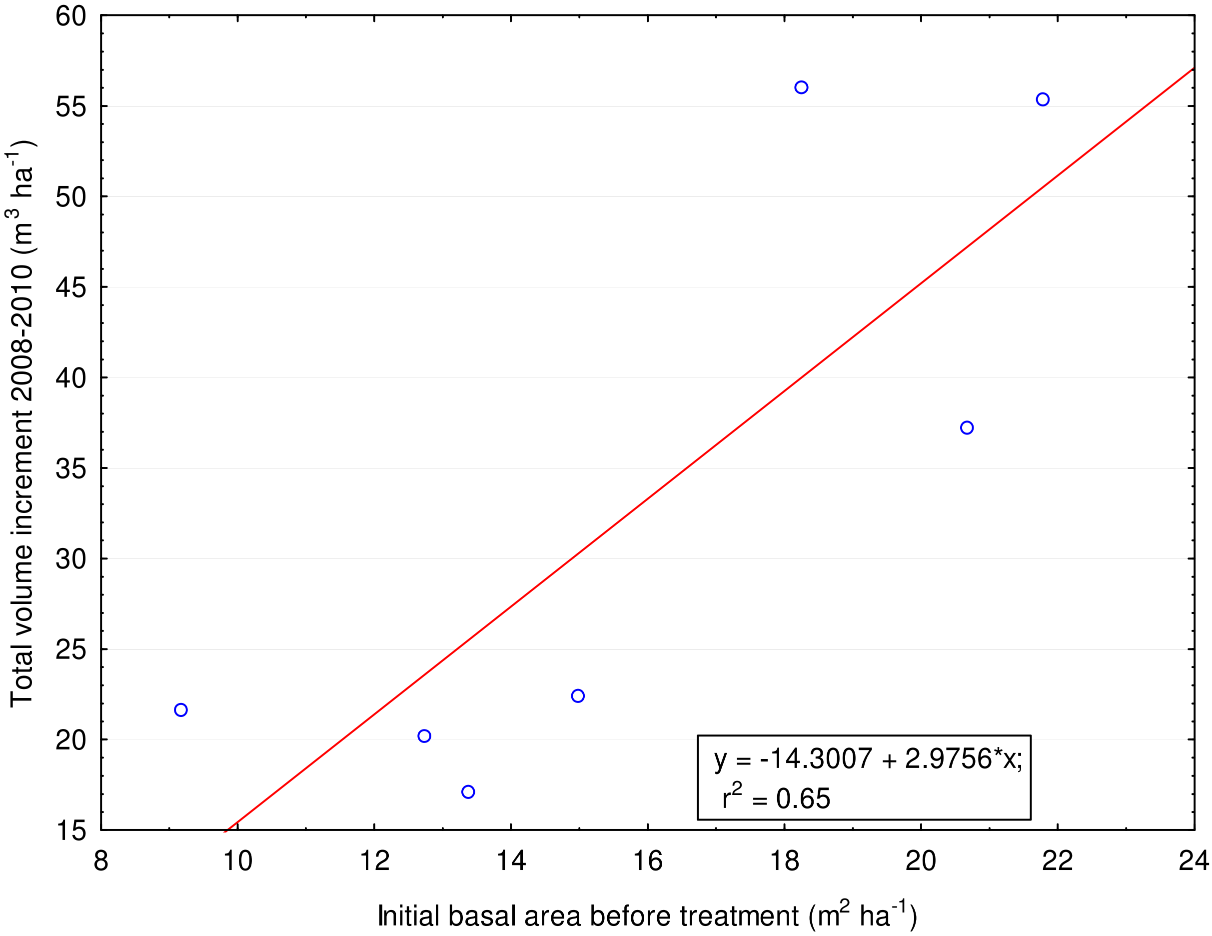
Appendix 4.9: Linear regression for initial basal area against total volume increment



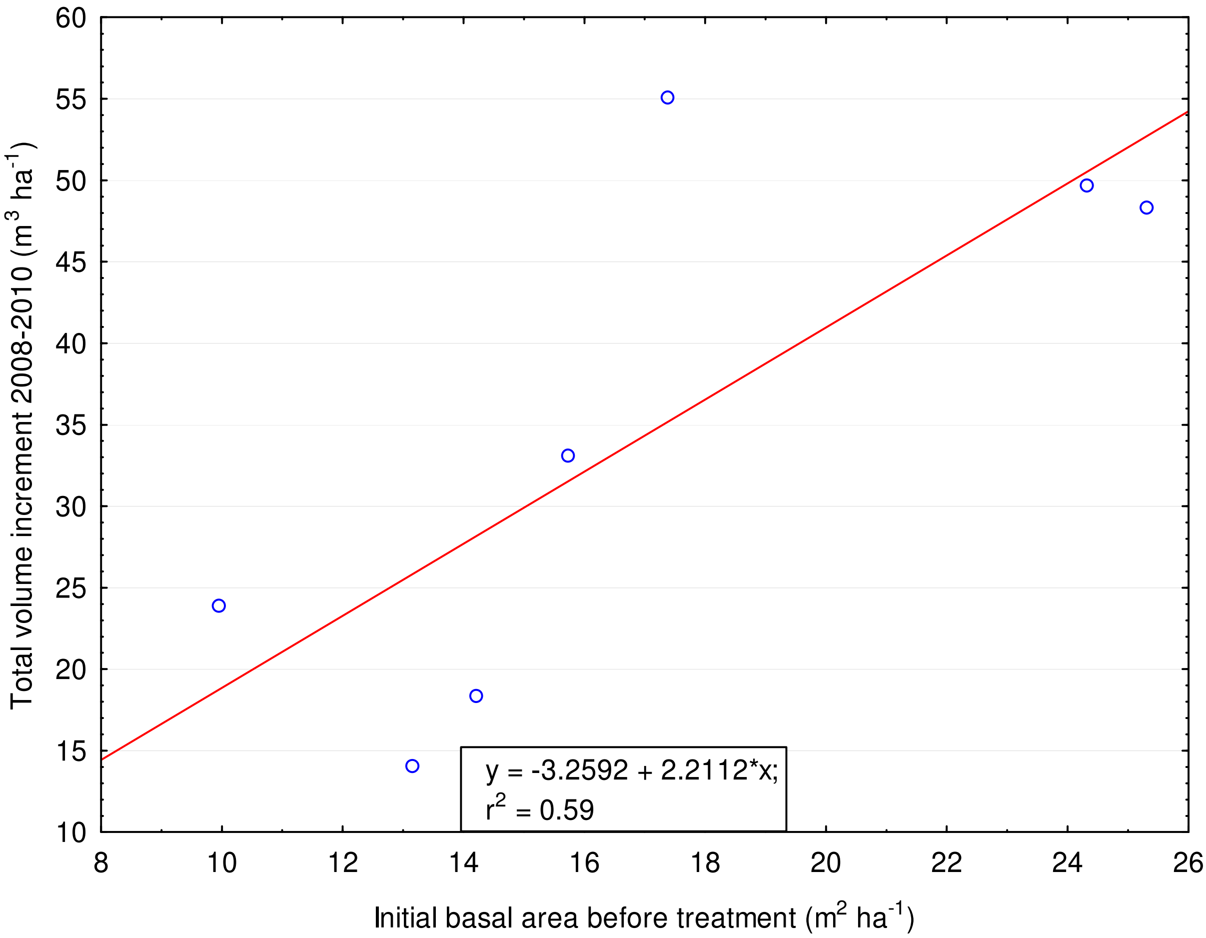
(a) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_0P_0



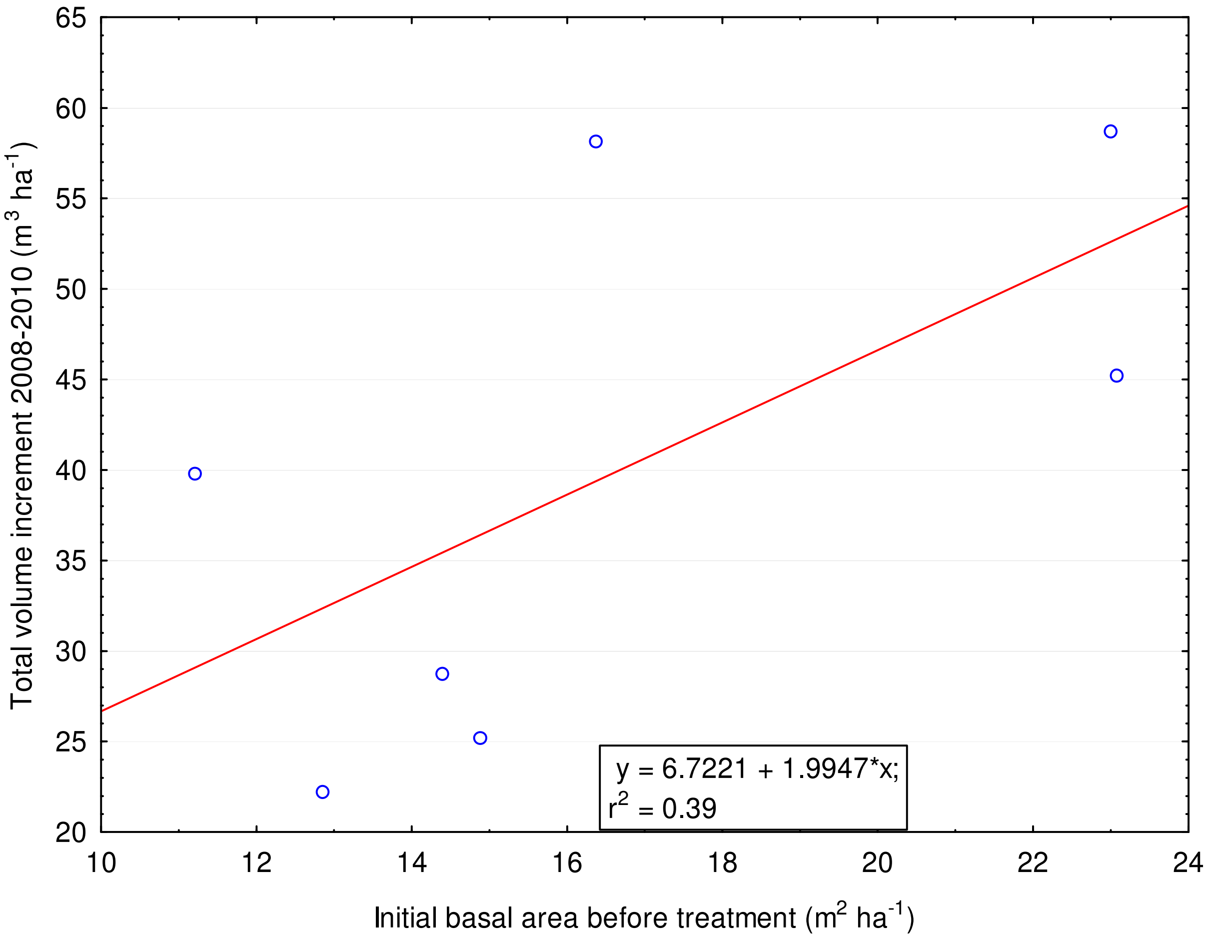
(b) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_0P_1



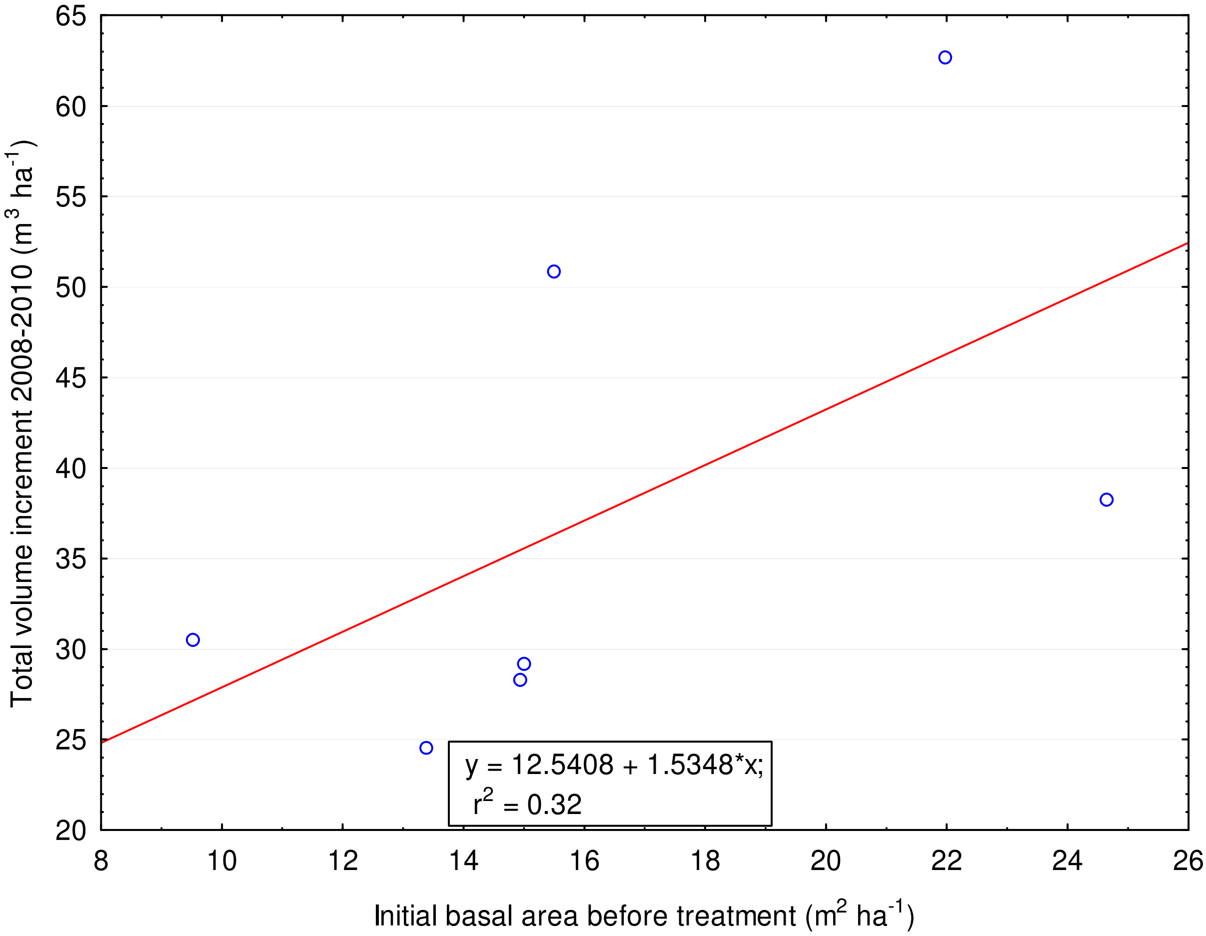
(c) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_0P_2



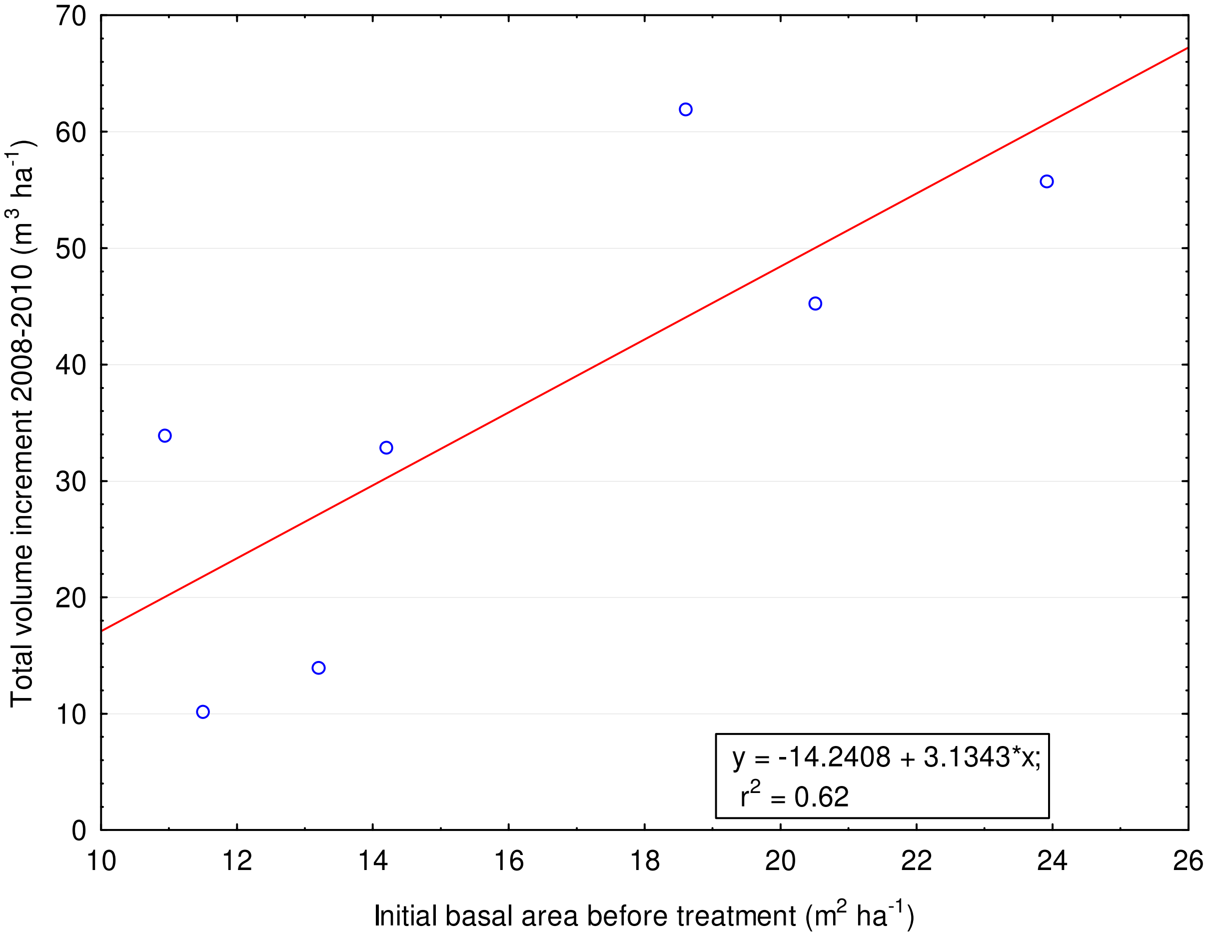
(d) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_1P_0



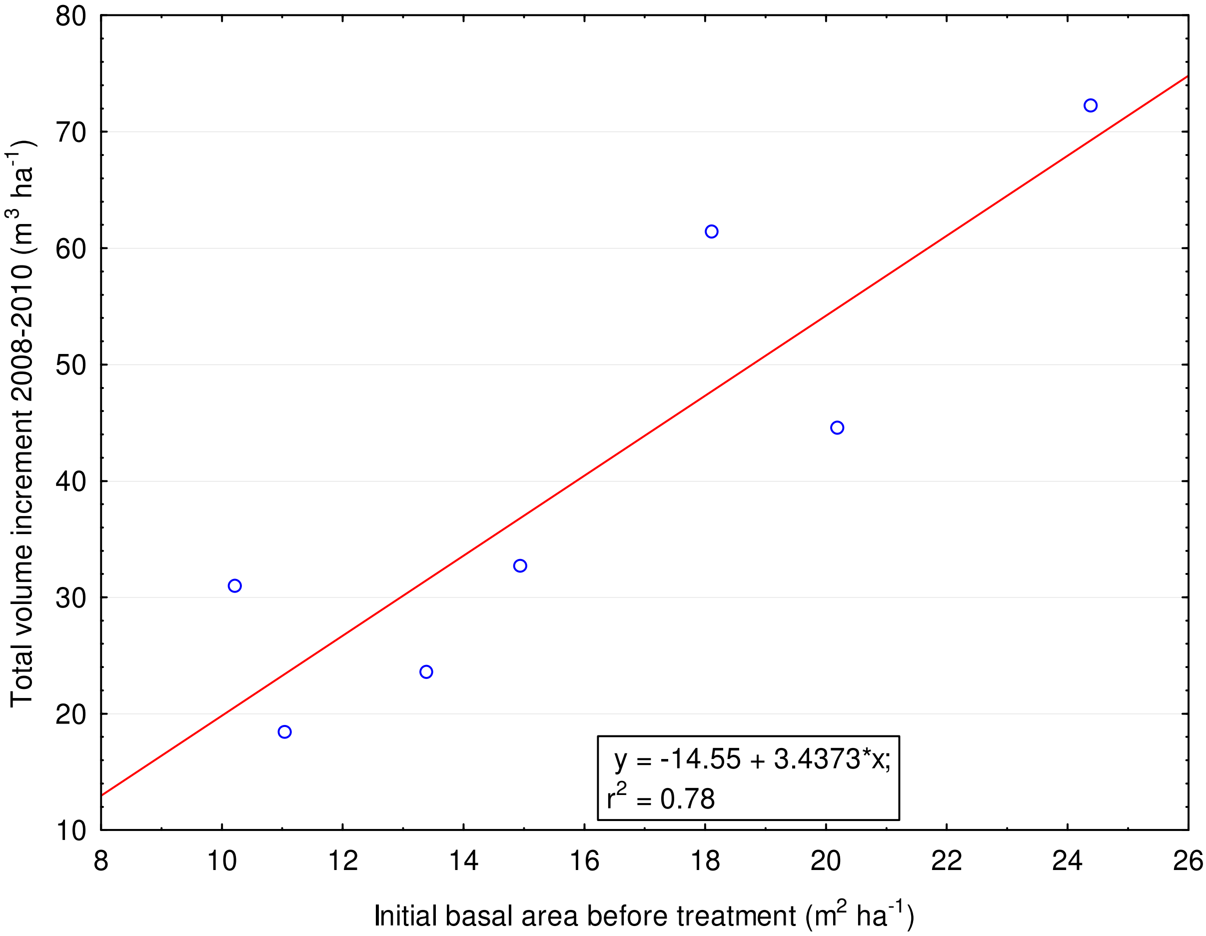
(e) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_1P_1



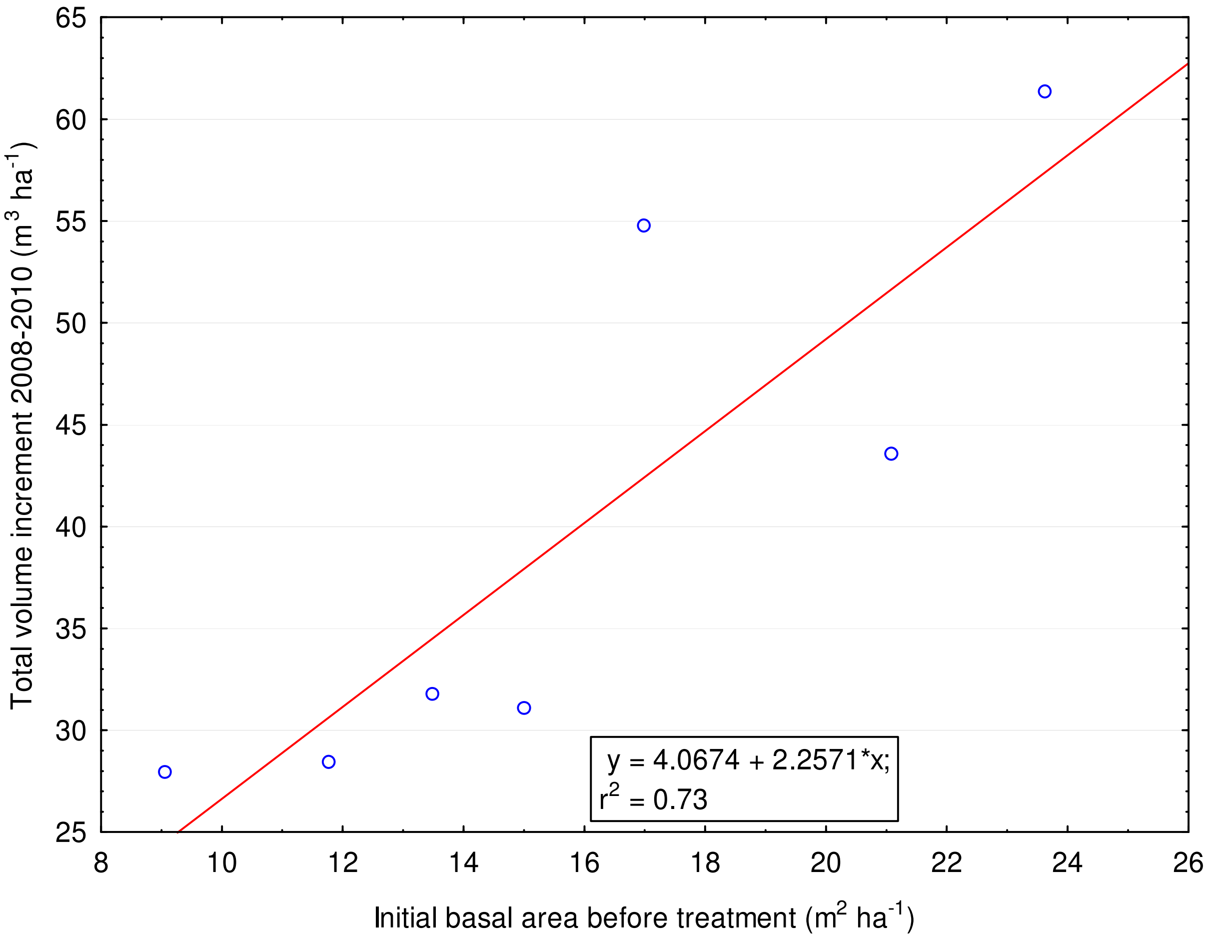
(f) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_1P_2



(g) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_2P_0

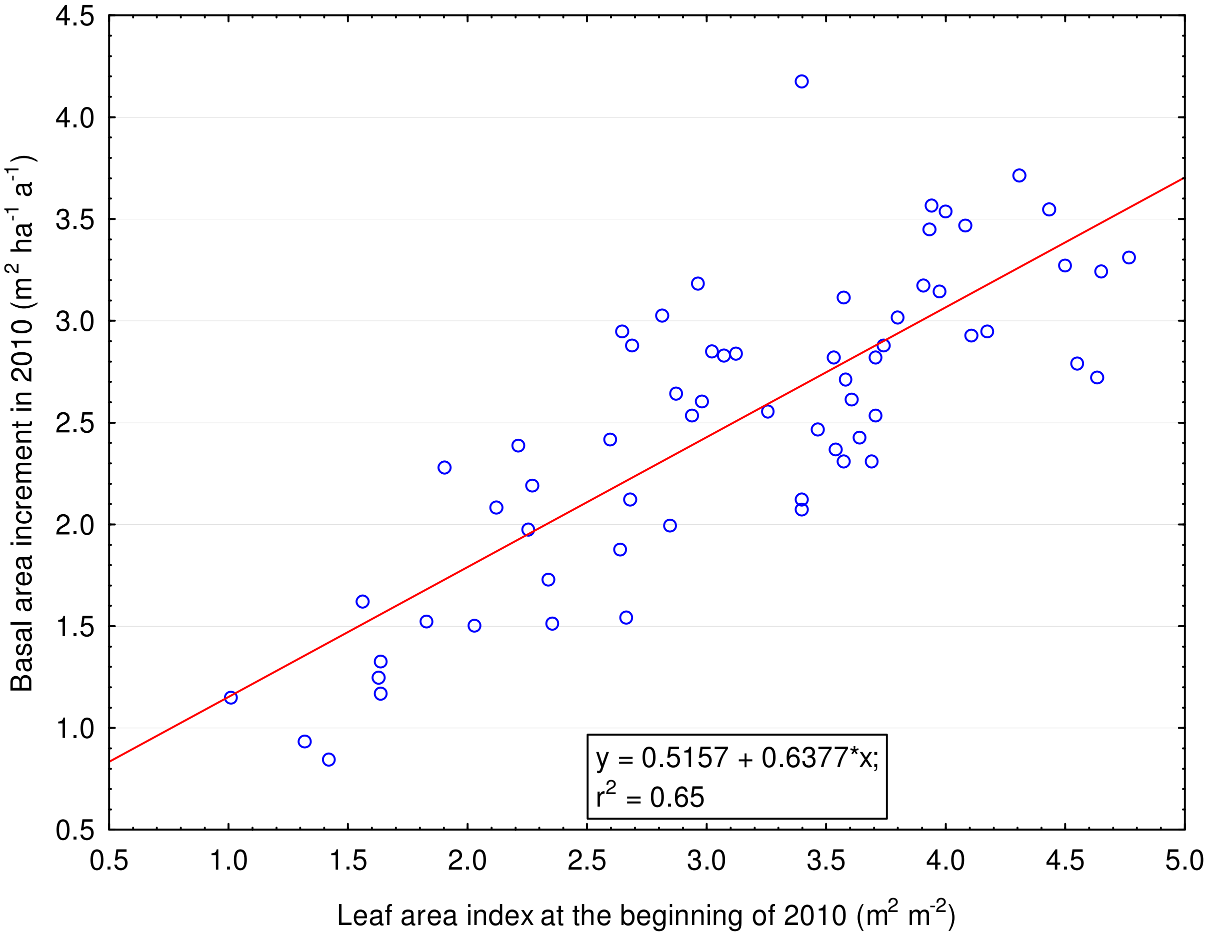


(h) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_2P_1



(i) Regression of total volume increment (2008-2010) against initial basal area before treatment for treatment N_2P_2

Appendix 4.10: Regression of initial LAI before at the start of 2010 against basal area increment in 2010.



Appendix 4.11: Regression of initial LAI before treatment against LAI increment over 24 months