Initial growth responses to controlled release fertilizer application at establishment of commercial forestry species in South Africa

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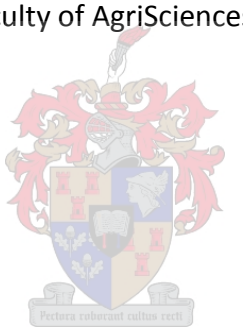
Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Forestry at the Faculty of AgriSciences, University of Stellenbosch



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December 2013

DECLARATION

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Abstract

In South Africa fertilizer applications at establishment is a common practice in the forestry industry. Recommendations are based on past research with conventional sources (CV) and as a result there have only been slight improvements in additional plantation production over recent years. The objective of this study was to investigate initial stand responses in terms of leaf are index (LAI), foliar nutrient content, biomass index (BI) and volume growth to the application of controlled release fertilizers (CRF) at re-establishment. Nitrogen (N), phosphorus (P) and potassium (K) were applied in a three way factorial combination to *Pinus radiata* at planting on a site in the Western Cape. The design was replicated five times across the study area. N (CRF) and P (CV) were applied in a two way factorial combination at planting to two *Eucalyptus grandis* x *urophylla* hybrids and *Eucalyptus dunnii* across three sites, one ex-agricultural and two re-establishment sites, on the Zululand coastal plain and the Midlands region. The design was replicated nine times on each study site. Harvesting residues were burnt on the eucalypt sites prior to establishment and may have had an impact on the responses found.

An outbreak of *Fusarium circinatum* on the *P. radiata* site resulted in unexpected and extremely variable responses. An attempt to quantify the effect of the disease had limited success. The mean BI of the control treatment reached 25. The best CV and CRF treatments yielded improvements of 42 % and 83 % in BI over the control respectively, with only the CRF treatment difference being significant. Foliar analysis results revealed marginal to deficient concentrations of P and Mg being alleviated by the treatments in question.

On the KZN Zululand sites there was a marked response of the hybrids to N with P having an additive effect on volume growth, LAI and foliar N content. Application of 120 g N and 20 g P per tree on the ex-agriculture site produced a volume of 8 m^3 ha^{-1} at one year of age, a significant increase of 118 % and 80 % over the control and best CV treatment respectively. Application of 80 g N and 20 g P per tree, on the re-establishment site, yielded a volume of 24.6 m^3 ha^{-1} at one year which equates to a significant 39 % and insignificant 7 % additional volume at one year over the control and best CV treatment respectively. A non-significant suppressive effect was found with 20 g CV P application only.

At the KZN Midlands site, the major early response in height were to P application. Applications of 20 g CV P per tree, resulted in a mean height of 162.6 cm at seven months of age, a significant 28 % higher than the control. There was no significant effect of 80 g CRF N and 20 g CV P per tree respectively.

CRF N applications up to 120 g per tree provide additional growth over recommended CV applications on coastal Zululand sites with low organic carbon (OC) content. On the KZN Midlands site with higher OC and clay content, early responses were limited to P fertilization only regardless of the fertilizer source.

Opsomming

Dit is algemene praktyk in die Suid Afrikaanse bosbou industrie om kunsmis tydens aanplanting toe te dien. Hierdie aanbeveling is gebasseer op navorsing resultate met konvensionele bronne (CV), gevolglik was slegs ‘n klein toename in bykomende plantasie produksie gemeet die afgelope paar jaar. Die doelwit tydens hierdie studie is om die aanvanklike reaksie van die bome in terme van blaar oppervlak indeks (LAI), blaar-voedingstof inhoud, biomassa indeks (BI) en volume op die toediening van beheerde vrylating kunsmis (CRF) tydens aanplanting vas te stel. Stikstof (N), fosfor (P) en kalium (K) is in drie-ledige kombinasie aan *Pinus radiata* op ’n plantasie in die Weskaap toegedien. Die ontwerp is vyf keer in die studiegebied herhaal. N en P is in twee-ledige kombinasie aan twee *Eucalyptus grandis* x *urophylla* hibriede en Eucalyptus *dunnii* op drie groeiplekke, een eks-landbou en twee eks-bosbou, op die Zoeloeland kusvlakte en in die Natalse Middellande toegedien. Die ontwerp is nege keer in elke studiegebied herhaal. Oesreste is voor aanplanting op die *Eucalyptus* groeiplekke verbrand.

Die voorkoms van *Fusarium circinatum* op die *P. radiata* groeiplek het onverwagte en hoogs uiteenlopende reaksies tot gevolg gehad. ’n Poging om die effek van die siekte te kwantifiseer, was slegs gedeeltelik suksesvol. Die gemiddelde BI van die kontrole behandeling, was 25. Die beste CV en CRF behandeling het onderskeidelik 42 % en 83 % hoër BI as die kontrole groep gehad, waarvan slegs die CRF behandeling beduidend was. Blaarontleding het gewys dat daar marginale of ontoereikende konsentrasies van P en Mg was.

In Zoeloeland het die *Eucalyptus* hibriede ’n beduidende reaksie op N en P getoon met meer volume groei, LAI en N inhoud. Die toediening van 120 g N en 20 g P per boom op die eks-landbou groeiplek het ’n volume van 8 m^3 ha^{-1} op eenjarige ouderdom tot gevolg gehad. Dis beduidend beter met 118 % en 80 % onderskeidelik vir die kontrole en beste CV behandeling. Die toediening van 80 g N en 20 g P per boom op die hervestigde eks-bosbou groeiplek, het ’n volume van 24.6 m^3 ha^{-1} op eenjarige ouderdom tot gevolg gehad. Dit is 39 % beduidend en 7 % onbeduidend addisionele volume op eenjarige ouderdom vir onderskeidelik die kontrole groep en beste CV behandeling. ’n Onbeduidende depressie effek is met die alleen toediening van 20 g CV P gevind.

In die Natalse Middellande groeiplek het die toediening van P ‘n vroeë reaksie in hoogte groei veroorsaak. Die toediening van 20 g CV P per boom, het ’n gemiddelde hoogte van 162.6 cm op die ouderdom van sewe maande tot gevolg gehad. Dit is 28 % beduidend hoër as die kontrole. Die toediening van 80 g CRF N en 20 g CV P per boom was onbeduidend.

Toedienings van CRF N tot en met 120 g per boom het in die kusgebiede van Zoeloeland met ‘n lae organiese koolstof (OC) inhoud, groter groei as die aanbevole CV toedienings gehad. Die Middellande groeiplek met ’n hoër OC en klei inhoud, was die vroeë reaksie alleenlik beperk tot P bemesting.

Acknowledgements

I would like to acknowledge:

1. My supervisors, Dr Ben du Toit and Mrs Hannél Ham, for their continued support, guidance and knowledge sharing throughout my Master's study period.

2. My sponsors, Terason, Haifa and the NRF for funding my studies. this work is based upon research supported by the National Research Foundation, any opinion, findings and conclusions or recommendations expressed in this material are those of the author(s) and the NRF does not accept any liability in regard thereto.

3. Mondi Forests, for allowing the establishment of the eucalypt trials on their property.

4. The South African Weather Service, Agricultural Research Council and Zelmari Coetzee at the Department of Viticulture and Oenology of Stellenbosch University for the provision of meteorological data.

5. The Department of Viticulture and Oenology of Stellenbosch University for allowing me access to their labs to make use of their leaf area scanner and Accupar ceptometer.

6. The staff, colleagues and fellow postgraduate students for their assistance with administration, field measurements, sample collection and lab processing.

7. Denis Oscroft, for his assistance during the establishment of the Zululand trials and for performing field measurements on time.

8. Bev Oscroft for offering her time to capture measured growth data electronically.

9. Prof Daan Nel from the Centre for Statistical consultation, for his assistance in designing the trial series and input during the data analysis phase.

10. Ralf Moshammer, from Technische Universität München, for his assistance with the crown area calculations.

11. My family and friends for their continued support, patience and encouragement.

12. Our Heavenly Father, for all the guidance, blessings and grace without which any of this would have been possible.

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List of abbreviations

°C	Degree(s) Celsius
ANOVA	Analysis of variance
ARC	Agriculture research council
ASN	Ammonium sulphate nitrate
BET	Brunauer–Emmett–Teller
BI	Biomass index
CEC	Cation exchange capacity
cm	Centimetre
CRF	Controlled release fertilizer source
CV	Conventional fertilizer source
DBH	Diameter at breast height
Ep	Potential evapotranspiration
ERD	Effective rooting depth
FC	Field capacity
g	Grams
GLD	Ground line diameter
GR	Growth rate
ha	Hectare
ht	Height
ICFR	Institute for Commercial Forestry Research
K	Potassium
kg	Kilogram
km	Kilometre
l	Litre
LAI	Leaf area index
LAN	Limestone ammonium nitrate
MAI	Mean annual increment
MAP	Mean annual precipitation / Mono ammonium phosphate
mg	Milligram
mm	Millimetre
MMP	Mean monthly precipitation
N	Nitrogen
OC	Organic carbon
P	Phosphorus
PAI	Plant area index
PAR	Photosynthetically active radiation
REW	Relative extractable water
SA	South Africa
SAWS	South African weather service
SC	Southern Cape
SLA	Specific leaf area
sp	Species
spha	Stems per hectare
SWC	Soil water content
WC	Western Cape
WP	Wilting point

Chapter 1: Introduction

1.1 Background

The application of fertilizer in plantation forestry has become a common practice in plantation silviculture over the past decades. The two historical reasons which have led to fertilization have been; to correct nutrient imbalances in the soil and to improve the productivity of a stand established on a marginal site (Evans and Turnbull, 2004). Over time, that has changed and major companies today fertilize all their stands at establishment and/or during the rotation. A fertilizing operation is only justified if a stand yields a significantly higher financial return at the end of rotation to not only offset the costs involved with fertilizing but result in a higher profit. Therefore, it makes sense to desire the maximum potential a fertilizer application can provide.

The important role that research and technology implementation plays in the South African forestry industry is clearly evident from Figure 1.1, which presents the change in plantation area versus the change in plantation production from 1980 to 2009. From 1984 to 1999 the production from industrial plantations was changing proportional to the plantation area. Since 2000, the increase in production became exponential and can be attributed to increases in the degree of intensification of silvilcultural practices within the industry. Over the 29 year period the plantation area increased by a mere 9.8 % but the production from plantations increased by 59 % (Godsmark, 2010). There is no single factor that can be accredited for this change, but advances in genetics, silviculture and good site species matching played a significant role (Dyer, 2007).

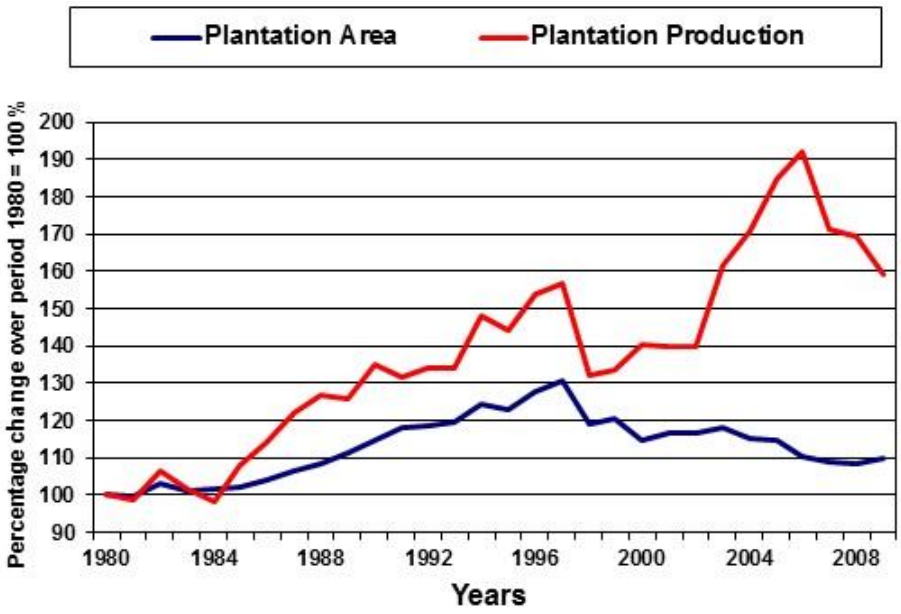


Figure 1.1: Plantation production and area change over the period 1980 till 2009 (Godsmark, 2010)

Boden (1997) suggested that tree growth could be attributed to the inherent site productivity and on more marginal land, the benefit of intensive silviculture practices are minimal. However, it should be kept in mind that it is not sustainable to remove nutrients from the site, without the employment of nutrition management practices. If one were to accept this idea, the question needs to be asked, what role then does intensive silviculture play?

Even though researchers have only recently been able to understand the productivity limits of some of our major site types, it is generally accepted that the current production levels have not yet reached these inherent limits (Dyer, 2007). There is still an opportunity to improve silvicultural practices at the research and operational level.

Tree growth in the early stages of stand development is largely dependent on the silvicultural practices applied (Boden, 1997) and once the site has been 'captured' by the target crop, site productivity, or more specifically plant available water becomes the major driver of production, as most sites in South Africa are water limited (Boden, 1997). The ideal time to improve production then, especially on more water stressed sites, is to augment the available soil nutrients during the high nutrient demanding exponential growth period, before water limitations start to affect growth (du Toit, 2008). Figure 1.2 presents the four main areas which can be manipulated by forestry

professionals in order to maximise growth and their relative size of influence in a *Eucalyptus* spp. site.

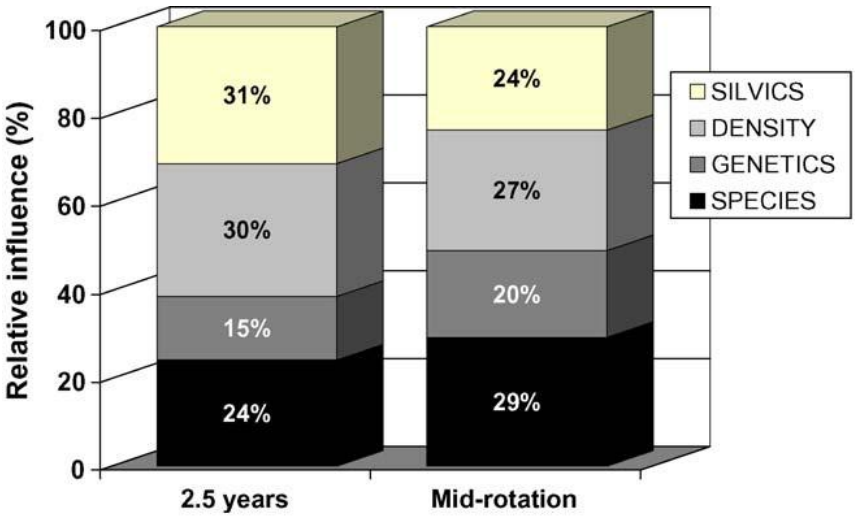


Figure 1.2: Changes in the relative contribution of the four main factors to stand productivity gains over time in a *Eucalyptus* trial series (du Toit *et al.*, 2010)

Volume growth and wood density have been known to increase with improvements in nutrient availability during the early years of eucalypt stands (du Toit *et al.*, 2010). This observation has drawn the attention of major pulp producers as faster growth and increased wood density are both beneficial for increased pulp yields (du Toit *et al.*, 2010).

1.2 Research problem

Conventional forms of nitrogen (N), phosphorus (P) and potassium (K) fertilizer, such as limestone ammonium nitrate (LAN), single/double/triple superphosphate, potassium chloride (KCl), and to a lesser extent, potassium nitrate (KNO_3) are widely used in South African plantation forestry. These sources have been extensively tested with many commercial species, through the works of Donald (1974, 1987), Morris (1980), Carlson and Soko (1999) and many other researchers to optimize the timing and rate of application and the best ratio combination of the three nutrients to achieve the maximum yield response possible. The magnitude of the response to fertilizer treatments is dependent on variables such as soil properties, water availability, tree species, timing and rate of application, weed status and others.

The constraint with conventional forms of fertilizer is that it can be leached out of the soil system relatively quick, especially N (Rothstein, 2005), and so the availability and

potentially tree growth response is rather short in comparison with the rotation lengths of the forestry industry (Crous *et al.*, 2008). It follows that the current mean annual increment (MAI) and volumes the industry is achieving can potentially be improved upon. A possible solution for this could be the introduction of coated membrane-type controlled release forms of N, P and K.

Controlled release fertilizer sources have been tested and used extensively in the agriculture and horticulture sectors of many countries for many years now (Trenkel, 1997), but they are a relatively recent area of interest in plantation forestry. The main reason being issues relating to the cost effectiveness of controlled and slow release fertilizer products.

Previous fertilizer experiments in South Africa exhibited only a type 1 response (du Toit *et al.*, 2010), an advancement in the stand's development stage with the only real benefit a decrease in the time taken to reach canopy closure (Snowdon, 2002). The role of extended nutrient availability using CRF's needs to be tested on tree growth compared to CV sources.

1.3 Research objective

The aim of this study was to investigate whether the use of controlled release fertilizer sources are more beneficial in a plantation environment than current conventional sources, on re-established *P. radiata, E. grandis x urophylla* and *E. dunnii* transplants. The effect of the fertilizer source on the early survival, growth (height, biomass index [BI] and volume growth), foliar nutrient concentration and leaf area index (LAI) development were the main focus points in assessing any differences between treatments. The primary objective of the analysis was to determine if statistically significant differences could be detected between the two fertilizer sources, with regards to the focus points mentioned above. Furthermore, the study was designed to enable the determination of the best nutrient element combination in controlled release and conventional formulation, not only as a ratio, but also the optimal quantity of each element needed to realize the highest yield attainable on the study sites.

1.4 Study hypothesis

The first hypothesis is related to the growth responses to each fertilizer source.

$H1_0$ There are no differences in height (ht), biomass index (BI) or volume growth between different controlled release treatments or selected treatments receiving comparable quantities of conventional and controlled release fertilizers.

$H1_a$ There are significant differences in height, biomass index and volume growth between different controlled release treatments or selected treatments receiving comparable quantities of conventional and controlled release fertilizers.

Hypothesis two investigates the mechanism of tree growth response, namely nutrient uptake, specifically nutrient accretion into tree foliage after planting.

$H2_0$: The uptake of N, P or K into the foliage of *P. radiata, E. grandis x urophylla* or *E. dunnii* transplants is similar when transplants are fertilized with conventional or controlled release fertilizers at establishment.

$H2_a$: The uptake of N, P or K into foliage of *P. radiata, E. grandis x urophylla* or *E. dunnii* transplants is significantly different when either conventional or controlled release fertilizers are applied at establishment.

Hypothesis three investigates the longevity of the response to fertilization.

$H3_o$: The longevity of the response to controlled release fertilizers is similar to (or smaller than) the response to conventional forms.

$H3_a$: The longevity of the response to controlled release fertilizer is greater than the response to conventional forms

1.5 Research questions

To be able to test the first hypotheses, the following research questions will be answered:

i. Are there any significant differences in growth between controlled release treatments?
ii. Are there any significant differences in growth between comparable controlled and conventional treatments?

In order to be able to test hypothesis two, the following questions need to be addressed:

i. Is there a good correlation between LAI development, foliar nutrient content, foliar biomass and biomass/volume growth, i.e. do the trees with the largest leaf areas/canopy sizes and foliar nutrients also have the highest growth response?
ii. Are there any significant differences in leaf area between the treatments?
iii. Are there any significant differences in foliar nutrient contents between treatments?

Research questions relevant to hypothesis 3 are listed below:

i. What was the growth rate of controlled release treatments versus conventional forms over the measurement period?
ii. Was the nature of the growth response to treatments applied type 1, 2 or 3?
iii. Can treatment differences (growth or changes in growth rate) be attributed to the presence or absence of water or nutrient stress?

1.6 Brief chapter overview

Chapter 2: Literature review

The relevant literature to the study is summarized here, with a large emphasis being placed on past South African research, which forms the basis for current industry fertilizer recommendations.

Chapter 3: Materials and methods

A description of the four study sites, experimental designs, data collection techniques and statistical analysis methods used are described in full detail.

Results and Discussion

Results were split into two sections; section A presents the winter rainfall area and section B the summer rainfall area. There were three factors which contributed to the decision of separating this trial from the Mtunzini, Flatcrown and Woolstone trials; 1) the trial is older than the three eucalypt trials, 2) It has a different statistical design with more factors and more treatments, and 3) In the first year of the trial, a large

proportion of the trees were diagnosed to be infected with *Fusarium circinatum*, which had a significant influence on the trial growth data.

Chapters 4 and 6: Results and Discussion A

Presentation and discussion of the results relevant to the Coetzenburg trial site are presented in these two chapters.

Chapters 5 and 7: Results and Discussion B

The early results and findings of the Mtunzini, Flatcrown and Woolstone trials are presented and discussed here. Mtunzini and Flatcrown results (survival, volume growth, leaf area index, foliar analysis, foliar nutrient content and crown area data) are presented together as their trial characteristics are exactly the same. The Woolstone trial is the youngest and only early survival and height growth data are shown.

Chapter 8: Conclusion

In chapter 8, the findings of the study are concluded, with a short overview of how the study contributed to the current fertilizer knowledge base in South Africa. Recommendations are made for possible future research which addresses the delimitations of the study.

Chapter 2: Literature review

2.1 Early fertilization in pines

The first recorded fertilizer trial on *P. radiata* was established in 1957 on Lottering plantation in the Southern Cape (Schönau, 1983). The majority of the research had taken place in a 20 year period stretching from 1957 to 1977 and in almost all of the trials a positive result was found resulting from fertilizer application, especially P (Donald *et al.*, 1987). The details of the reviewed *Pinus sp.* establishment trials in South Africa are summarized in Table 2.1. The listed N, P and K rates are those at which the optimum response was found or where only one treatment was applied and a response obtained. The rates are the actual elemental amounts per ha or per treatment unit (seedling).

The collection of pine fertilizer research in the winter rainfall region is smaller than with the collection of work done in the all year round rainfall and the summer rainfall areas (Carlson, 2001), but the observed results and emerging trends are very similar. From the South Western Cape up to Limpopo in the North, the main response resulted from the application of P, which is not surprising given the low availability and deficiency of P in soils found in South African forestry areas (Schönau, 1983).

The most complete review of establishment trials in the summer rainfall region of South Africa, including Swaziland, was prepared by Carlson (2001). In this report, results from a total of 71 trials, including trials which received fertilizer within one year of establishment, were synthesized into a database summarizing the objectives, treatments and results obtained. It is important to keep in mind that these results are based on a subset of the full set of trials. Poorly responding trials were never reported, while others were abandoned due to various possible reasons such as poor survival, weed infestation or pest and disease outbreaks. For these reasons, estimates of responses should be seen as conservative estimates and even biased.

In many of the trials, the initial response to the application of fertilizer tends to fade over time with control plots “catching up” to treated plots. In the first year after planting, there is an 81.25 % chance that seedlings will respond. In year five this percentage had dropped to 64.15 %, which was still a significant positive response.

Table 2.1: Summary of the South African fertilizer application at establishment trials on *Pinus* species that were reviewed

Trial location	Species	Best performing/single level Treatment			Response variable	% increase over control	Reference
		N	P	K			
Lottering, SC	*P. radiata*	0	169 g/tree	0			Schönau, 1983
Elgin (F12), WC	*P. radiata*	115 kg/ha	32 kg/ha	65 kg/ha	MAI (11 years)	7.50	Donald and Glen, 1974
Elgin (F5), WC	*P. pinaster*	34 kg/ha	19 kg/ha	47 kg/ha	MAI (11 years)	5.00	Donald and Glen, 1974
Tokai, WC	*P. radiata*	0	15 kg ha	0			
Tokai, WC	*P. radiata*	Unknown	30 kg ha	0	MAI (14 years)	63.00	Theron and Ellis, undated
Jamestown, WC	*P. radiata*	Unknown	15 kg ha	0	MAI (7 years)	2.87	Donald *et al.,* 1987
Jonkershoek, WC	*P. radiata*	Unknown	30 kg ha	0	MAI (8 years)	18.07	Donald *et al.,* 1987
Highlands, WC	*P. radiata*	Unknown	15 kg ha	0	Biomass index (4 years)	481.48	Donald *et al.,* 1987
Steenbras, WC	*P. radiata*	0	30 kg ha	0	Mean height (m) (4 years)	23.81	Donald *et al.,* 1987
Ruiterbos, SC	*P. radiata*	45kg ha	37.35 kg ha + 40 kg $MnSO_4$	0	MAI (12 years)	595.29	Donald *et al.,* 1987
Keurboomsrivier, SC	*P. elliottii*	0	5 kg ha + weeding	0	MAI (7.5 years)	118.34	Donald *et al.,* 1987
Kruisfontein, SC	*P. radiata* + *P. pinaster*	45 kg ha	56 kg ha	45 kg ha	MAI (15 years)	231.31	Donald *et al.,* 1987
Usutu, Swaziland	*P. patula*	0	72 kg ha	29 kg ha	Biomass index (28 months)	133.33	Donald *et al.,* 1987
Gilboa, KZN midlands	*P. patula*	30 kg ha	45 kg ha	60 kg ha	MAI (3.5 years)	67.23	Donald *et al.,* 1987
Graskop, Mpumalanga	*P. patula*	10 kg ha	15 kg ha	10 kg ha	Mean height(m) (1.25 years)	10.99	Carlson and Soko, 1999
Driekop, Mpumalanga	*P. patula*		20 g/tree		Mean height (cm) (1 year)	31.00	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	15.00	
	P. taeda		20 g/tree		Mean height (cm) (1 year)	10.20	
					collar diameter (cm)(1 year)	9.30	
	P. elliottii		20 g/tree		Mean height (cm) (1 year)	6.70	
					collar diameter (cm)(1 year)	20.00	

Table 2.1 continued

Trial location	Species	Best performing/single level Treatment			Response variable	% increase over control	Reference
		N	P	K			
Mossbank, KZN	*P. patula*	13 g/tree	19 g/tree	13 g/tree	Mean height (cm) (1 year)	6.33	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	31.60	
Bergvliet, Mpumalanga			20 g/tree		Mean height (cm) (1 year)	5.70	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	4.20	
Longridge, Mpumalanga			20 g/tree		Mean height (cm) (1 year)	8.88	
					collar diameter (cm)(1 year)	14.10	
London, Mpumalanga		13 g/tree	19 g/tree	13 g/tree	Mean height (cm) (1 year)	12.00	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	7.50	
Mac Mac, Mpumalanga	*P. patula*	12 g/tree	25 g/tree	12 g/tree	Mean height (cm) (1 year)	22.00	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	25.40	
			25 g/tree		Mean height (cm) (1 year)	16.80	
					collar diameter (cm)(1 year)	17.90	
Blyde, Mpumalanga	*P. patula*	12 g/tree	25 g/tree	12 g/tree	Mean height (cm) (1 year)	0.51	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	-9.32	
			20 g/tree		Mean height (cm) (1 year)	8.08	
					collar diameter (cm)(1 year)	4.24	
Clan, KZN	*P. patula*	15 g/tree	20 g/tree	15 g/tree	Mean height (cm) (1 year)	3.91	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	3.40	
			20 g/tree		Mean height (cm) (1 year)	10.70	
					collar diameter (cm)(1 year)	3.16	
Driekop, Mpumalanga	*P. taeda*		20 g/tree		Mean height (cm) (1 year)	21.20	Rolando *et al.*, 2007
					collar diameter (cm)(1 year)	17.50	

By year nine, the response to treatment were reported as low as 33.33 % (Carlson, 2001).

Possible reasons why trees do not respond to fertilizer applications are (Carlson, 2001):

i. In areas with fertile soils, few, if any nutrients may have been strongly growth limiting on the site type in question.
ii. The nutrients applied were not the limiting resource.
iii. Small plot sizes in historic trials.
iv. Incorrect quantities and forms of fertilizer were applied.
v. Timing and placement were incorrect.
vi. Vulnerability to other factors such as diseases or stress was increased, thus reducing growth.

The common aspects in all the trials reviewed are:

i. Conventional sources of N cause an increase in seedling mortality as the application rate rises.
ii. The highest responses when fertilizing *P. radiata* were found on the poorest of sites.
iii. N and K applications in the absence of P often yield little or no response and can even result in a decline in the growth rate.
iv. The magnitude and longevity of a fertilizer response is site dependent.
v. Good weed control practices increased the magnitude of the response in fertilized trees significantly.
vi. Adequate soil water was necessary to obtain a response.
vii. The use of good seedling stock with healthy developed root systems helped the tree to take up the additional nutrients.
viii. Placement and timing of application is just as important as the fertilizer source and application rates.

2.2 Release mechanisms for slow and controlled-release fertilizer (CRF)

The way in which different variations of slow and CRF release their nutrients is an important aspect to consider when developing a strategy to match up the right type of fertilizer and crop. The fertilizers are classified in terms of their release mechanism

and thus a good understanding thereof will aid in ensuring that the target crop is provided with sufficient nutrients at the right time during its development (Morgan *et al.,* 2009). Slow and CRF can be divided into four categories.

i. Organic

The organic group of fertilizers includes materials such as animal byproducts, biosolids and various combinations of composted plant materials. These products release nutrients by means of microbial decomposition or mineralization of organic matter and their rate of release are impacted mostly by the temperature and moisture content of the soil and the quality of the product (Morgan *et al.*, 2009). Higher temperatures and moisture contents lead to higher rates of release, but rates are also affected by the extent of the microbial population. It is extremely difficult to accurately estimate how fast these fertilizers will release their nutrients.

ii. Inorganic

Inorganic slow release fertilizers include material such as the mineral phosphates such as apatite and inorganic K fertilizer sources derived from compounds such as biotite. These are typically sparingly soluble minerals and nutrients become available gradually over time as weathering and other chemical reactions take place in the soil.

iii. Synthetic organic

The most common example of a synthetic organic fertilizer is urea formaldehyde. It is formed through a reaction of urea and formaldehyde in the presence of a catalyst (Rose, 2002). The rate of release of this group is dependent on the chain length of the polymers that are formed during the reaction. Longer polymer chains are less soluble and take longer to breakdown and become available to plants than shorter chains (Morgan *et al.*, 2009). The release mechanism is a multi-step process, with the first step being the breaking of the chain and the second being the bacterial

decomposition of the polymers into plant available nutrients (Morgan *et al.*, 2009), usually N.

iv. Coated

CRF's or coated fertilizers are essentially water soluble fertilizers that are covered with a semi-impermeable membrane. This membrane can be made of sulphur, polymers, resin or a polyurethane coating (Morgan *et al.*, 2009; Rose, 2002). The characteristics (composition and thickness) of the coating control the rate at which water diffuses into the water soluble fertilizer core and in some cases the rate of diffusion from the core into the soil. Soil temperature is the most influential environmental factor as it affects the rate of diffusion into and out of the fertilizer core (Morgan *et al.*, 2009).

Apart from the above factors there are others that introduce variation into the rate of release mechanism of slow and CRF as mentioned by Rose (2002). The packaging and storage needs to be as such to avoid prolonged exposure to moisture, as portions of the fertilizer can take up moisture and release nutrients sooner than what was intended. The age of the fertilizer is likely to play a role in its performance as older coatings may not react in the same way as fresher ones. Improper handling and abrasion with soil particles could lead to surface damage of the coatings and accelerate the rate of nutrient release.

2.3 Controlled and slow release sources of N, P and K

Controlled-release fertilizers (CRF) are not used in forestry on a large scale due to uncertainties about their cost-effectiveness, but are currently predominantly used in tree nursery environments and agriculture (Elliot and Fox, 2006). Studies have been conducted, mostly in the North and South America, Tasmania and a small number of South African trials, which tested the effectiveness of its use on varying stand ages, species, climatic and soil conditions. Results and trends emerging from international and domestic studies which have focused on controlled and slow release fertilizer sources are discussed further below.

A pot trial, testing the CRF Osmocote, applied to four conifers, *Picea pungens*, *Picea glauca*, *Abies fraseri* and *Pinus strobes* was established to investigate its effect on

plant growth (Klooster *et al.*, 2010). Containers with a capacity of 11.2 L were used with three application rates of 0.25, 0.5 and 1 g N tree^{-1} respectively. A positive growth response in height and root collar diameter was found in both the 0.5 and 1 g tree^{-1} application levels, but increasing the dosage from 0.5 to 1 g N per tree did not increase the growth response significantly. The foliar N concentrations increased with increasing dosage but resulted in no additions in growth. This is an indication that any additions above 0.5 g N were most probably utilized as luxury consumption by the plants.

The effect of four different CRF's, classified by their relative release rates (fast release, moderate release, slow release and slow release enriched with micronutrients) were investigated on the growth of Ponderosa pine (*Pinus ponderosa*) seedlings at establishment (Fan *et al*., 2002). Four levels (0, 5, 15 and 30 g tree^{-1}) were applied and the effects monitored over a three year period. After three years it was found that fertilizer treatments produced larger seedlings than the control, with fast release and slow release enriched treatments outperforming moderate and slow release (Fan *et al.*, 2002). The lower doses, 5 and 15 g per tree, generally performed better than the highest dose of 30 g per tree, with the single best performing treatment being the 15 g of slow release enriched with micronutrients (diameters 20.8 % larger and heights 30.17 % higher than control). One possible explanation could be that the slower release rate allowed conditions for higher nutrient availability during the three growing seasons. This however is not evident from the foliar nutrient concentrations over the monitoring period (Fan *et al.*, 2002). The 30% height response obtained from the 15 g slow release enriched treatment is in line with height responses recorded in other similar field experiments (Carlson and Preisig, 1981; Van den Driessche, 1988) in north-western North America (Fan *et al.*, 2002).

In a study conducted by Jacobs *et al.* (2005), the effectiveness of the CRF Osmocote on the establishment of three hardwood species, white ash (*Fraxinus Americana*), yellow poplar (*Liriodendron tulipifera*) and black walnut (*Juglans nigra*) was tested. Osmocote was applied at six different rates (0, 15, 30, 45, 60 and 75 g seedling^{-1}) directly into the root zone at establishment. This method seemingly had no significant impact on seedling mortality as survival was ≥ 90% for all treatments. There were differences between the three species with yellow poplar having the

lowest survival (85%), with black walnut (97%) and white ash (100%) performing similarly well. Growth was significantly affected by fertilizer application during both the first and second growing seasons. Seedling growth increased as the application rates increased up to 60 g per seedling rate and then declined in the 75 g rate. Interesting to note was the significant differences in growth between the three species, indicative of a possible species x fertilizer interaction.

When compared to black walnut, the mean first year height growth of yellow poplar and white ash was 300 and 543 % larger, respectively and the root collar diameter growth was 233 and 200 % greater respectively. The improved growth response of yellow poplar and white ash over black walnut can be attributed to nutrient accumulation in the seedlings. N uptake in yellow poplar and white ash was 79 % and 93 % greater than in black walnut, while P uptake was more modest with increases of 28 % and 22 % respectively. There was no significant fertilizer rate x species interaction indicating that all three species responded similarly to all treatments. These results clearly reinforce the idea that CRF can provide additional growth responses over broadcast forms and placement directly in or adjacent to the planting hole where it is most accessible to the seedling could potentially yield the best results.

The effectiveness of CRF's on tree growth has been tested of different species and at varying rates of application, but the effectiveness of different CRF sources is not well documented. Mikkelsen *et al.* (1994) applied six different CRF sources (*Isobutylidene Diurea* (IBDU), Osmocote, Oxamide, Prokote plus, sulphur coated urea and Ureaform) to pots of *Euonymus patens* plants. Two rates were applied, 3.8 g N pot^{-1} or 7.6 g N pot^{-1} respectively, with one half of the dose applied at transplanting and the other half placed on the surface of the pot 15 weeks later. An additional two treatments received no N at planting but instead received daily doses of NH_4NO_3 as fertigation, supplying either 20 or 40 mg N daily. The general trend was that the coated sources resulted in higher yields than the non-coated forms, with Prokote plus and Osmocote performing the best, while NH_4NO_3 and Ureaform were identified as the weakest performers. Increasing the application level caused an increase in both the tissue N concentration and plant biomass production. Coated sources were more effective in raising the tissue N concentrations than the non-coated.

A study by Haase *et al.* (2006) investigated the benefits of supplementing the seedling growing medium of three stock sizes, styro-8 (130 cm^3 cavity), styro-15 (250 cm^3 cavity) and styro-20 (336 cm^3 cavity) of container grown Douglas fir (*Pseudotsuga menziesii*) with additions of CRF, in conjunction with conventional fertilizer treatments. All seedlings were fertilized with conventional fertilizer through overhead irrigation but four treatments had one of four CRF's (Apex #1, Apex #2, Forestcote and Osmocote) incorporated directly into the growing medium at rates of 7, 13, 18 g per seedling cavity for the three stock sizes. The seedlings were grown for 11 months in the nursery and then planted in two different field sites. Four years after planting, seedlings which received the additional CRF fertilizers had greater height, basal stem diameters and stem volume with increases of 19 %, 21 % and 73 % respectively, compared to conventionally treated seedlings. Differences between growing stock sizes were investigated. Larger stock sizes resulted in greater seedling growth, which can be attributed to larger nutrient reserves within the plant and a more developed root system.

Elliot and Fox (2006) tested the effect of Ureaform, a slow release source of N, on the soil N dynamics of a mid-rotation stand of *P. taeda*. They found that the plots treated with Ureaform displayed significantly greater concentrations of total-extractable N at every post-treatment sampling date and that the plant available N fraction was in all cases prolonged over the control and conventional urea plots. An interesting result was that in the third month post-treatment, both the control and conventional plots had shown negative N-mineralization rates (immobilization) while the controlled-release plot had a positive mineralization rate of 6.8 mg N kg $soil^{-1}$.

Smith *et al.* (1971) tested the response of *P. elliottii* seedlings germinated from seed, 1year old seedlings transplanted to pots, and 1 year old seedlings planted in the field to urea formaldehyde and Ammonium nitrate. The soils used in the pots represented the forests of the lower coastal plains in Florida where positive responses to fertilizer applications are seen. In the young seedlings germinated from seed, plant heights were repressed however the diameter growth responses resulting from the urea formaldehyde were very good. In the year old seedlings good responses were seen in both height and diameter of the Ammonium nitrate control plots and the Ureaform plots, but only Ureaform was able to maintain the responses at the highest levels of application (180 kg N ha^{-1}). In all cases Ureaform outperformed Ammonium nitrate.

In Chile a CRF product Basacote which is an NPK blend, was tested against the traditional conventional NPK blend applied during establishment phases of *E. nitens.* Basacote is coated with an elastic polymer coating which is more resistant to physical damage and frost (Anonymous (a), undated). The application rates of six month and nine month release Basacote were extremely small (7, 10 and 15 g product/tree) compared to the NPK blend (20, 80 and 110 g product/tree) but still showed significant differences up to seven months of age (Anonymous (a), undated). By 30 months however, no treatment differences were detectable. It is highly likely that the chosen application rates of Basacote were too small to begin with and a sufficient amount of nutrients was not able to accumulate in the foliage. The experiment was replicated in Tasmania on a newly established *P. radiata* stand. The same application rates were applied and significant differences were only found up to six months post application (Anonymous (a), undated).

In other studies conducted by Walker (1999, 2001) and Hensley and Aldridge (1990) similar results to the ones discussed above were found and can be summarized as follows:

i. CRF's and slow release fertilizers provide an additional response over conventional sources tested, although the response only lasts past the early stages of stand growth in a limited number of cases.
ii. These responses are witnessed throughout the spectrum of application rates.
iii. Mortality is lower with controlled-release treatments (provided no pathogen/disease attack).
iv. Nutrients are available to the plants for longer periods of time and in higher concentrations.
v. The longevity of the response is much better, eliminating the early "rise and fall" in soil nutrient concentrations of conventional sources.
vi. Application rates of CRF need to be high enough to sustain growth differences observed in the first stage of stand development.

There is only one recorded slow release fertilizer trial on *P. radiata* in the Western Cape (Theron and Ellis, undated), where N was tested as Ureaform tablets and P as superphosphate. Unfortunately the survival of the trial was so poor due to

competition from the fynbos regrowth that it had to be abandoned before any noteworthy results could be recorded.

Slow release fertilizer research was mainly done on *E. grandis* in the summer rainfall region. The description and results of these trials are discussed below.

Trial T55 of the Wattle Research Institute (1984) , the response of *E. grandis* to LAN (28 % N) and urea formaldehyde was tested on a site with a sandy Fernwood soil situated near Kwambonambi on the north coast of Kwa-Zulu Natal province. LAN and Ureafom were applied at rates of 0, 50 and 100 g per seedling. An additional factor tested was the placement of the fertilizer, spot, ring or slot applied. The best treatment was 50 g LAN applied in a ring. Poor growth was observed in the Ureaform plots and it was suggested that this was due to the very low soil organic matter content and most probably coupled with low microbial activity not allowing sufficient release of N. A noteworthy trend that emerged was that there was an increase in growth with increase in application rate of Ureaform when it was applied in a ring around the tree. Perhaps if applied rates were increased, Ureafom would have performed better. The data for growth responses beyond one year in this trial were not published.

Trial C68 established by the ICFR on a sandy soil in Kwambonambi, tested the efficacy of the slow release formulation MULTICOTE® and conventional LAN on the growth of *E. grandis* seedlings. In addition, the effect of splitting the application (half at planting, half at six months) was also investigated. LAN was applied at a rate of 35 kg N ha^{-1} and MULTICOTE® at 25, 50 and 75 kg N ha^{-1}. At 11 months after establishment, height measurements indicated that there was no significant difference (p<0.05) between any of the treatments. The only significant difference that was found was between the foliar N concentrations of the MULTICOTE® treatments and the control, with the control having the significantly lower concentration (Noble, 1992b).

Trial C69, established directly adjacent to C68, tested the efficacy of 5 different fertilizer sources and 2 different application rates, 28 and 56 kg N ha^{-1} respectively. The five sources are as follows (Noble, 1992b):

i. Urea formaldehyde

ii. HUMAC
iii. HUMAC + 10% oxi-Humate
iv. HUMAC + 20% oxi-Humate
v. AGROFERT

Two controls, an application of 35 kg ha^{-1} LAN (28 %) and no fertilizer application were also incorporated into the trial. Both levels of Ureaform and the LAN application were the only treatments that showed no significant difference to the control plot with zero fertilizer in terms of height growth. The best performing treatment was AGROFERT applied at 56 kg ha^{-1}. The lack of response to Ureaform can be attributed to the low microbial activity of the Zululand soils (Noble, 1992b), and thus coated forms of fertilizer that are not dependent on microbial breakdown would possibly lead to greater growth responses on these sandy sites (Noble, 1992b).

2.4 Leaching of applied N and K:

Nitrogen exists in the soil in organic and inorganic forms and can transform between forms through microbial activity. N is primarily taken up by plants in two forms namely ammonium (NH_4^+) and nitrate (NO_3^-). Organic N in the soil is converted to ammonium by the work of microbes through a process known as mineralization. This process is most affected by soil moisture and soil temperature. The conversion of ammonium to nitrate is done through the process of nitrification, which is also a biological process controlled by soil bacterial activity and like mineralization it is most accelerated in well aerated, warm and moist soils (Duckworth and Cresser, 1991). Ammonium is positively charged and therefore held close to the surface of soil particles through electrostatic forces. Nitrate on the other hand is negatively charged and water soluble, it is able to move through the soil profile away from the rooting zone and leach out of the soil system. The processes are graphically displayed in Figure 2.1.

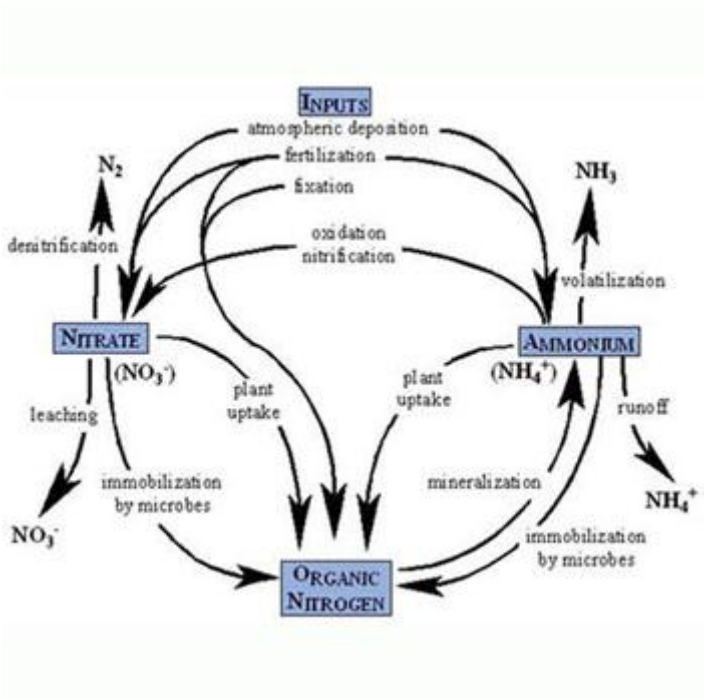


Figure 2.1: The nitrogen cycle (Anonymous (b), undated).

Nitrogen retention in forest soils are affected by factors such as soil temperature, neutral soluble salt concentrations and N pollutant concentrations amongst others (Duckworth and Cresser, 1991). The low pH of forest soils often inhibit the action of microbes in the process of nitrification but the process can still be stimulated by conditions of increased N availability or decreased crop N demand (Duckworth and Cresser, 1991). Where N is the major limiting nutrient to substrate turnover, soil microbes will compete vigorously for any available N resulting in net immobilisation rates in the soil. In an acid soil in maritime climate, N inputs from atmospheric deposition may be offset by the effect that sodium salts have on the ammonium ion i.e. preventing adsorption by keeping it in a mobile form (Duckworth and Cresser, 1991). Soils with more humified horizons have a marked ability to retain more N added to the system and display increased mobilisation of organic N which stresses the importance of soil humus to N soil fluxes. Soil carbon also plays a role in N retention. An increase in soil carbon stimulates heterotrophic soil microbes to immobilise more plant available N. This N then becomes available once more through the turnover of these microbes (Duckworth and Cresser, 1991).

The longevity of the response of applied N from conventional sources is in most cases short lived. A rapid initial response occurs which peaks early and declines with

time (Minogue *et al.*, 2005), resulting in growth responses not realizing their full potential. Researchers have hypothesized that N leaching rates would increase proportionally with the rate of N application into the soil. It was found in a study by Flint *et al.* (2008) on an acidic sandy loam, which examined the N leaching rates of a Douglas-fir stand after the application of Urea that the hypothesized relationship did hold true. Six months after fertilization, 26 % of the applied N was accounted for in the overstory of the trees and 27 % in the top two layers of the soil (Flint *et al.*, 2008). The fertilized plots leached 4.2 kg N ha^{-1} more than that of the control plots which received no fertilizer, but this only relates to a 2 % loss of the total 224 kg N ha^{-1} applied (Flint *et al.*, 2008).

Minogue *et al.* (2005) monitored the soil N levels after fertilization of three pine species namely; *P. elliottii, P. taeda* and *P. palustris* at two, five and 11 years of age on moderately well to excessively drained sandy soils. What they found was that the results were variable between the three different age brackets. In the two year old stand, soluble nitrate concentration at 30 cm and 120 cm soil depth peaked at six and 12 weeks respectively and the same results were found in the 11 year old stand (Minogue *et al.*, 2005). For the five year old stand, *P. taeda* did not show any elevated levels of soluble N but *P. elliottii* and *P. palustris* did show increased N levels at 9-11 weeks, indicating a difference in soil N fluxes between the species (Minogue *et al.*, 2005). The most interesting result was the longevity of the response between the sources of N (mineral and broiler litter). In the two year old stands, the response lasted for 37 weeks. In the 11 year old stand, the N concentration for the mineral and broiler source returned to baseline levels after 18 and 23 weeks respectively.

Soil and climatic conditions have an effect on the rate of leaching as is shown by Mortensen *et al.* (1998) where they tested rates of nitrate leaching at establishment of *Salix viminalis* on two different sites and at two different levels of N application (0 or 75 kg N ha^{-1}). The first site was coarse sand with an average of 963 mm annual precipitation over the three year reporting period. The leaching rates were 130, 9 and 4 kg N ha^{-1} in each of the three years. On the second site, a loamy sand soil with 710 mm average annual precipitation, the leaching rates were 142, 61 and 0 kg N ha^{-1} in each of the three years respectively. The large leaching rates for the first year were due to an abnormally high mineral N fraction in the soil at time of planting. The

0 kg N ha^{-1} leaching rate found on the second site in the third year was due to a low precipitation for that year coupled with poor percolation into the soil. The difference in leaching rates between the fertilized and control treatments in the first period was 32 kg N ha^{-1} (average over both sites) and only 1-2 kg ha^{-1} in the following two periods. From this study it could be concluded that there were differences in the rates of leaching of N between different soil types and climatic conditions, and the percentage loss relative to that which was applied is variable and not easy to predict. Also important to note was that increased temperature and moisture in clear felled stands, coupled with reduced vegetation cover, led to high rates of N leaching.

K is present in soils in an array of forms that can range from cations in the soil solution to a constituent of solid un-weathered primary minerals (Morris, 1980). K availability for uptake by plants varies between the different forms of K and is replenished by the exchangeable fraction of K that has been adsorbed onto the surface of soil particles by electrostatic forces (Morris, 1980).

Pedersen *et al.* (2006) tested the leaching versus input rates of N, K and Mg of different application rates on Nordmann fir (*Abies nordmanniana*) on four different sites. For K it was found that there is a linear relationship between leaching, application rate and atmospheric deposition on three of the four sites. The fourth site did not show a linear relationship which was attributed to its clayey texture and high CEC, caused by a majority of calcium proportionate to the low levels of K. In no instance did the leaching rate ever exceed the total input into the system on any of the four sites. The leaching response of K was very site specific and was affected by soil properties such as texture, pH, CEC and climatic conditions (mostly precipitation) which influences percolation rates.

2.5 Response to P application and soil characteristics

Soil characteristics play a very important part in fertilization as it is one of the most determinant factors of the degree of response that can be expected when fertilizer is applied to a stand. Soil characteristics such as parent material, soil texture, drainage class, pH and soil P retention capacity are briefly discussed below.

The parent material of a soil is mostly responsible for soil characteristics such as particle sizes, pH, chemical status, texture, drainage capacity and some other properties which interact with nutrients in the soil. Knowing the parent material of the

site can assist the practitioner to better predict the type of soil chemical and physical properties that are characteristic of the site. This in turn can assist the practioner to better determine the dose of P fertilizer that should be applied.

Phosphorus in soils is associated with individual soil particles or conglomerates, the finer the soil particles the higher the degree of association with phosphate (Busman *et al.*, 2009). In the event of erosion, more fine particles than coarse particles are removed from the site, causing a higher fraction of P to be removed from the soil and deposited in a different location (Busman *et al.*, 2009). In areas with high runoff, applied P has the potential to be removed from the site with heavy precipitation since P experiences minimal to no vertical movement in the soil (Cornforth, undated).

The drainage of a soil is related to the texture of the soil, a sandy soil has better drainage than a clay soil. In the Southern United States it was found that the degree of the response to P application is highest when the drainage is poor and lowest in a well-drained soil (Dickens *et al.*, 2009). The reason for this being the case, is the varying degree of phosphate reactive surfaces, P retention capacity (discussed later) and soil water with the varying texture classes.

In low soil pH conditions (pH below 5.5) phosphate ions will react with Al and Fe ions and form solid compounds which are generally unavailable to the plant for uptake (Busman *et al.*, 2009). In high pH conditions (pH above 7.3), Ca is the ion which reacts with phosphate and will form a precipitate of compounds such as octocalcium phosphate and hydroxyapatite (Busman *et al.*, 2009). The most adequate pH range for the highest uptake of phosphate by the plant is between 6 and 7 (Busman *et al.*, 2009). The soil phosphate retention capacity is a measure of the maximum soluble P that can be “sorbed” onto the surface of soil particles and is expressed as mg kg^{-1} of soil (Turner *et al.*, 2002). The higher the soil P retention capacity, the higher the amount of P fertilizer that is required by the soil for a positive response to be seen in the growing crop (Cornforth, undated).

2.6 Phosphorus application and its effect on nitrogen

N and P are the two nutrients which most commonly are limiting to tree growth in forest soils (Graciano *et al.*, 2006). These two nutrients are closely associated with

each other and often have to be applied simultaneously to elicit optimal responses. In fact, numerous previous experiments have shown this relationship, those responses to N application depends on P availability and in some extreme cases P deficiency growth can actually be reduced by N fertilization (Graciano *et al.*, 2006). A positive growth response by trees to P application is often the case when P is applied to stands as plantations are usually established in areas of high rainfall with low P availability (Graciano *et al.*, 2006).

In an experiment conducted by Graciano *et al.* (2006), the effect that P availability has on N absorption of young trees was investigated. Three month old *E. grandis* seedlings were transplanted into pots (one seedling per pot) which were filled with three different soil types (deep red sandy soil, dark brown loamy sand and silt clay loam) and were watered on a daily basis. One week after transplant, the seedlings received an application of either N (1, 2 or 4 g of urea) or P (6, 12 or 24 g of triple superphosphate) per pot. Samples and measurements were taken on three different occasions namely 44, 72 and 84 days after transplant and subsequent analysis was done. A positive response to P application was found across all three soil types and at all levels of application. Plants fertilized with P had a significantly different root/shoot ratio compared to plants just receiving N, as those plants partitioned more nutrients to shoot growth than to development of larger root systems. With the N application some surprising observations were made. It was found that N fertilization only improved the N concentration of the foliage, but produced no significant response in terms of growth (across all three soils, which are N deficient). Important to note is that the N uptake by the plants was higher when P was applied than when N was applied without P across all treatments.

What can be concluded from this experiment and many more like it, is that despite a naturally N deficiency in the soils used here, application of N on its own did not improve N uptake by the plants. P application on the other hand caused more N to be taken up by the plant and increased the foliar nutrient concentrations of not only N and P but other nutrients such as sulphur.

This experiment provides valuable data for foresters for understanding how these two macronutrients interact with one another and cements the idea that, to see the most significant response, the availability of N and P to the plant must be balanced.

Decisions can be made as to what and when fertilizer will be applied not only to younger plants but to more mature standing crops as well.

2.7 Organic matter and microbial and enzyme activity

The effect of fertilization and more specifically P fertilization in forest soils does not only influence growth, foliar nutrient content and nutrient status of the soil. Other soil properties such as microbial activity, changes in dissolved organic matter and soil enzyme activity are also affected by the addition of P fertilizers (Wang *et al.*, 2008). The soil dissolved organic carbon, total soil N and P are not significantly changed by the addition of fertilizers, and however, the effects are predominantly seen in the size of the plant available fraction of N and P (Wang *et al.*, 2008). In a study done by Wang *et al*. (2008), it was found that P fertilization significantly increased, on average 80 % more than the control plot, the organic P concentration in the soil of a four month old *E. dunnii* stand. When only N was applied the organic P concentration in the soil decreased by an average of 29 % relative to the control.

P fertilization tends to lead to a decrease in the soil available N, as with the addition of P, more N is taken up by the plant leading to a lowered N availability in the soil (Wang *et al.*, 2008). This lowered plant available N acts as a trigger for soil microbes to release N that was previously immobilized in the soil microbial pool leading to a decrease in the microbial biomass N.

In the same study by Wang *et al*. (2008), the activity of the enzyme acid phosphatase, the enzyme responsible for releasing “sorbed” phosphate groups from soil particles was determined under application of P. It was found that with the addition of P and the subsequent increase in the dissolved organic P fraction of the soil, the activity of phosphatase was reduced markedly but in comparison the activity of the soil enzyme invertase was increased.

2.8 The fate of P applied to soils

P has three major pools in the soil namely; the soluble P, the active P fraction and the fixed P pool (Busman *et al.*, 2009). The soluble portion is the part that is readily available to the plant for uptake and the plants will only take up that portion if it’s in the orthophosphate form (Busman *et al.*, 2009). The active P pool consists of both organic and inorganic P that is present in the soil in the solid phase. The soluble P

pool is small, so most of the plants are dependent on the active P pool to replenish the soluble P pool when it gets depleted (Busman *et al.*, 2009). Extremely insoluble inorganic compounds and organic compounds which do not mineralize easily make up the fixed P pool in the soil (Busman *et al.*, 2009). These phosphate compounds can remain in the soil for long periods of time without becoming available for plant uptake. When P is applied to the soil, there are a few possible pathways that it can follow.

P fertilizers are generally quite soluble and in a form which is readily available to the plant for uptake (Busman *et al.*, 2009). In solution, the maximum uptake of P occurs at a pH of ± 4 (Haynes, 1982). As soon as the fertilizer has made contact with the soil, it undergoes a series of reactions which are dependent on the soil characteristics. These will render some of the P unavailable to the plant. The water in the soil will start to dissolve the fertilizer particle and release phosphate into the soil solution, the phosphate ion can then move away from the particle through the movement of water in the soil (Busman *et al.*, 2009). During this movement, the phosphate will either be taken up by the plant, react with other elements along the way or be sorbed onto the surface of soil particles.

In low soil pH conditions, phosphate will react with Al and/or Fe, and in high pH conditions it will react with Ca to form precipitates which are insoluble and temporary unavailable to the plant (Cornforth, undated). Over time, further reactions with Al, Fe and Ca can form solid compounds such as variscite (Al), strengite (Fe) and apatite (Ca) which form part of the fixed P pool (Busman *et al.*, 2009). Phosphate can be adsorbed onto the surfaces of soil particles where it is temporarily taken out of soil solution. The extent of adsorption is dependent on the characteristics of the adsorbing surface in question and phosphate ions can be fully absorbed into the particle over time and slowly released again through the process of diffusion (Cornforth, undated). The relationship of the adsorbed P and the P in soil solution is directly proportional (Figure 2.2).

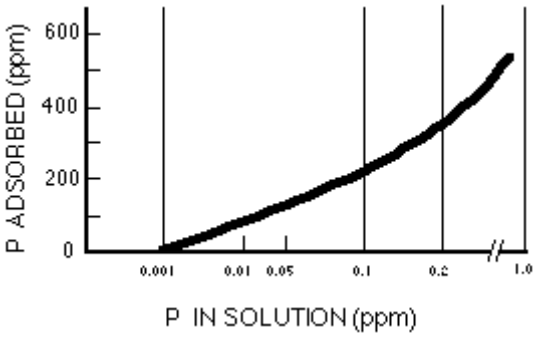


Figure 2.2: Relationship between adsorbed and soluble P (Busman *et al*., 2009)

The specific P sorption of soil is a very important characteristic when trying to determine the P fertilizer requirement of a target crop. It is however not easy to establish which soil parameters are the most important when P sorption is concerned and this is due to a considerable degree of correlation between them (Syers *et al.*, 1971). The removal/neutralisation of one parameter, such as aluminium oxide, is likely to expose reactive sites that previously might have been covered (Juo and Fox, 1977). In spite of this, it is still possible to identify a few general soil parameters and how they influence specific P sorption in soils, as found by Syers *et al.*, (1971) and Juo and Fox, 1977:

i. Parent material - Soils derived from basic igneous rocks have a higher P requirement than those derived from acidic parent materials.

ii. Reactive surfaces - A high degree of reactive surfaces have a high P requirement.

iii. Brunauer–Emmett–Teller (BET)-surface area – The higher the BET surface area the higher the P requirement.

iv. Type of clay – Well-structured clays are able to adsorb less P than disordered clay types.

v. Al and Fe – Al parameters (like exchangeable Al for example) are in most cases better correlated to specific P sorption than Fe. The chemical composition of Al in the soil plays a role in controlling both phosphate solubility and uptake by the plant.

The microbial pool in the soil is responsible for immobilizing a proportion of the applied P in its own biomass and releases it again in both organic and inorganic forms when there is a turnover of the microbes in the pool (Anonymous (c), undated).

P is a nutrient which can remain in the soil system for long periods of time in unavailable forms to the plant. Often most of the P fertilizers applied to stands do not make it into the trees but either precipitate with Fe, Al or Ca, are immobilized by microbes or are adsorbed to charged surfaces of soil particles.

2.9 Longevity of P fertilizer response

P fertilizers often yield a positive response in growth as mentioned earlier due to it being one of the most common limiting nutrients in forest environments. To be able to report on how long this response lasts is imperative information needed for scheduling future applications. The longevity of the response is investigated further below with the reference to two particular cases.

Case 1 is a study on the residual response of P fertilization on *P. radiata* over a 50 year period. The study site is in New South Wales, Australia, on highly weathered, coarse textured sandy to sandy loam soils (Turner *et al.*, 2002). Rock phosphate and superphosphate were applied in 1948 during the first rotation and the residual effects reported 50 years later in 1998, the end of the second rotation (Turner *et al.*, 2002). Growth results indicated the tree height, basal area and volume growth did not differ between the two phosphate treatments, but they were significantly larger than the control, over the 33 year period of the second rotation. The MAI increased from 9.3 m^3 ha year in the control, to 14.8 m^3 ha year mean in the phosphate treatments. Similar responses, like the 50 year longevity seen here, were observed on soils which have sedimentary origins or originate from volcanic ash (Turner *et al.*, 2002).

Case 2 is a study done by Crous *et al.* (2008) in Swaziland on *P. patula*, at Usutu plantation, on Gabbro derived soils. The fertilizer was applied in the third rotation of the stand in a factorial of P x K to set up the foundation for the fourth rotation trial which will test the residual effect of the previous rotation's application. The results showed that in plots which received both P and K application, the residual effect was significant on the quadratic mean DBH, mean tree height and mean plot volume over the three year measuring period, meaning that the longevity of the response lasted

for at least three years into the second rotation. When P was applied on its own to a plot in the third rotation, no residual effect was observed in any of the plots of the forth rotation. The longevity of the response lasted only for a short period towards the end of first rotation.

Gaining a positive response to P application in forest soils is highly dependent on soil characteristics. Different forest soil types affect reactions taking place in the soil, making P either available or unavailable to the plant for uptake. The longevity of a response is another element dependent on the soil. Sandy to loamy sand soil is the soil texture that produces some of the longest residual effects, up to 50 years (Turner *et al.*, 2002) and possibly longer. P fertilization can greatly change the production capacity of a site and should not only be applied in cases of P deficiency but is also beneficial in cases where N is limiting, as P is able to enhance the response of N fertilization on N limited sites.

2.10 Measurement and analysis of young/small pine species

In cases where a fertilizer response is achieved as a result of its application, a selection of measurement techniques can be used to quantify such a response. The analysis of fertilizer research plots with young/small trees posed a problem to the researcher as few of the conventional volume calculations and analysis methods could be used. When working with fertilizer trials at establishment, the two most frequently asked questions are: (a) what growth response was observed in response to the treatments, (b) how survival and stand uniformity was affected.

In forestry, the growth index that is of most interest is the utilizable volume growth, but it is difficult to accurately determine it at a young age. To overcome this problem the use of surrogate measures such as biomass or volume indices (King *et al.*, 2008; McKeand *et al.*, 2000) and plot volume indices (Marx *et al.*, 1977) are used. The question that needs to be asked is whether these surrogate measures are an accurate enough estimation of volume, biomass and growth.

In studies done by international researchers, Hensley and Aldridge (1990), Fan *et al.* (2002), Klooster *et al*. (2010) and local researchers, Noble (1992a), McInnes (1993) and Rolando *et al*. (2007), on fertilizer treatments at establishment of young trees, height and diameter growth are used separately as measures of treatment responses. Height and diameter analyzed individually are often not sound variables

to measure treatment responses as the response is often not reflected solely in either of those two growth indices. Often small or non-significant responses are found in many trials, reflecting a false positive or false negative response (type I and type II errors). Baker *et al*. (1974) proposed that the use of tree weight/biomass or volume would be a better indication of fertilizer response as it would include secondary effects on fertilized trees such as the production of additional foliage.

In a study conducted by Ruehle *et al.* (1984) on two and three year old pine seedlings, they tested the correlation between non-destructive growth indices and above ground tree weight or biomass. Three models (linear, non-linear and logarithmic) were used in the study to determine the strength of the correlation. The measurements of root collar diameter and height to calculate a biomass index was used. In order to compare the effectiveness of each model, the R-squared values obtained were used in the analysis of various data sets of young pines measured on different sites. They found that the linear and non-linear models performed equally well across the board but had a considerable amount of variation when they compared the residual values. The logarithmic model performed the best (having the highest R-squared value) and dealt with the residual variation problem quite well. Furnival's index was then calculated for the linear and logarithmic model for each of the data sets used across the variety of sites to determine the goodness of fit for both models. The logarithmic model outperformed the linear model in all of the sites.

To conclude, both D^2H and log (D^2H) show strong enough positive correlations with above ground tree weight/biomass and can thus be used to reduce the likelihood of type I or II errorswhen investigating treatment responses on young trees.

One standard method used in assessing the effects of treatments on seedling mortality was to transform the plot survival percentages. Amishev and Fox (2006) tested the effects of fertilization and weed control on four pine species, namely: *P. taeda, P. virginiana, P. strobus* and *P. echinata*. The survival count data of each plot was converted to a percentage value and then transformed using an arcsine function before subjected to statistical analysis using Anova techniques. Rolando and Little (2005) used the same methodology on *P. elliottii*, while McKeand *et al*. (2000) used an arccosine function instead.

Another useful comparison is that of trial results across different sites and different *Pinus* spp. Rolando *et al.* (2007) compared the results of nine pine fertilizer at establishment trials across different sites in KwaZulu-Natal and Mpumalanga in South Africa. The relative differences between the treatment responses (change in growth) and survival rates were compared to the control and expressed as a percentage (Equation 1). For example if the control yielded a biomass index of two and a particular treatment an index of 2.5, the increase would be calculated to be 25%. The formula was as follows:

$$Treatment\ response = \frac{(treatment\ value - control\ value)}{control\ value} \times 100 \quad (1)$$

This method allows for specific comparisons to be made across a variety of sites and with different species.

2.11 LAI determination

LAI can be defined as the "total one-sided area of leaf tissue per unit of ground surface" and any changes in canopy LAI can result in changes in stand productivity (Bréda, 2003). LAI is directly related to light capture and the photosynthetic potential of a forest stand. An increase in LAI can result in an increase in light capture, but this relationship will decrease at higher LAI values proportional to the light extinction characteristics of the tree canopy. LAI is also a driver of many important functions such as radiation extinction, interception of precipitation and gaseous exchange (Bréda, 2003) and therefore it is important to have an accurate measure thereof. LAI varies both spatially within the stand and temporally. Temporal variation includes changes in branch phenology, stand development, needle expansion and needle senescence (Vose *et al.*, 1994). LAI is also influenced by site quality (nutrition, soil water holding capacity, soil depth, etc.), climate (precipitation, PAR, temperature, etc.) and climatic variability (droughts, flood events, etc.). Species/genus, laws of light extinction, site quality and climate conditions set the upper limit of LAI and climatic and seasonal variation results in the fluctuation of LAI within these limits (Vose *et al.*, 1994). Species with the greatest shade tolerance usually have the greatest maximum LAI. Beets and Pollock (1987) reported on maximum LAI (all surface) values in *P. radiata* in New Zealand to be between 22.1 and 31.1, which is

approximate to a projected leaf area of 7 and 9,8 m^2/m^2 respectively, peaking at an age of six years. In young stands before canopy closure, the majority of the foliage is present in the lower canopy positions rather than mid to high positions, which result in the LAI distribution to be downward skewed (Vose *et al.*, 1994).

LAI can be measured either directly, through litter fall collection, destructive sampling or point contact sampling, or indirectly by means of optical techniques and models (Chen *et al.*, 1997). Direct measurements relate only to foliage so they provide the most accurate measures of LAI, but are extremely time consuming and costly. There are errors associated with direct measurements such as variance within the stand and errors in the estimation of the foliage area: mass ratio used to scale up from the foliage sub sample to the tree and finally the stand (Chen *et al.*, 1997). Indirect optical measurements estimate LAI through the transmission of radiation through the stand canopy making use of the radiative transfer theory (Bréda, 2003). The accuracy of this method is dependent on the following assumptions being met: 1) leaves are randomly distributed within the canopy and 2) individual leaf size is relatively small when compared with canopy size 3) leaves have a set angular distribution and 4) be randomly distributed azimuthally and in space (Bréda, 2003; Dovey and du Toit, 2006). There is however two problems often encountered with the use of this method. Firstly the under canopy measurements of the radiation interception include interception by non-foliage elements such as branches and stems. For this, PAI (plant area index) is more commonly used in literature than LAI when this method is used with no correction factors to eliminate the woody proportion from the measurements (Bréda, 2003). Secondly, indirect methods have a tendency to underestimate LAI in coniferous stands (Gower and Norman, 1991). This is mostly due to the first assumption being violated, as clumping of foliage within the stand is common (Bréda, 2003).

2.12 Foliar analysis

Foliar analysis has been widely used in forestry in the past and can easily diagnose a nutrient problem at any particular point in time. There are three established methods widely used by researchers namely; critical level approach, diagnosis and recommendation integrated system (DRIS) and vector analysis. These are based on

the following assumptions (Linder, 1995): 1) Optimal growth and plant vitality can only be achieved if nutrients are present in their correct proportions; 2) The proportions of elements relative to N are just as important as their individual concentrations; and 3) To optimise biomass production in a given climate all essential nutrients should be applied at a rate which meets the nutrient demand of the crop, as is affected by mineralization and fixation rates of the soil. To achieve meaningful foliar analysis especially for use in comparative studies, it is imperative to standardize the sampling procedures to avoid errors in the data caused by seasonal and temporal variation. The application merits and shortfalls of each method are discussed.

2.12.1 Critical level approach

In the critical level approach foliar material would be collected from the top third of the crown and its percentage nutrient concentrations analysed. The concentrations of each nutrient are then compared with the critical level of that nutrient for the particular species in question. The critical level can be defined as “the foliar nutrient concentration at which yield attains 90% of the possible maximum” (Ulrich and Hills, 1967) and differs for each nutrient element and between various species.

The first problem with the critical level approach relates to phloem mobility or rather immobility of some nutrients (Gregoire and Fisher, 2004). For example, Comerford (1981) found that the K concentration varied five-fold between lower and upper crown positions. It is therefore important that the relative sampling position in the crown be chosen as to give the most accurate results. An additional form of variation in nutrient concentrations is seasonal changes and needle/leaf age. Nutrient concentrations peak early in the growing season and decline as the season progresses and soil reserves are depleted (Gregoire and Fisher, 2004). Current-year foliage concentrations vary more significantly than older foliage as they are still accumulating dry weight during the season, thus the timing of sampling must be chosen appropriately (Gregoire and Fisher, 2004).

For pines, sampling should be done late in the growing season, i.e. around late July-August in the winter rainfall region, in the upper third of the canopy on one-year old needle tufts. For eucalypts, sampling should ideally take place in late summer/early autumn, on the first fully extended leaves of a live branch in the upper third of the

canopy (Dell *et al.*, 1995) The second problem with this approach is that only one element can be interpreted at a time and vital elemental interactions are missed (Svenson and Kimberly, 1988)

The critical level approach can provide the researcher with a snapshot in time of the plant's current nutrient status but falls short in providing information on the rate of fertilizer needed to correct the deficiencies and the level of response that can be expected (Gregoire and Fisher, 2004).

2.12.1 DRIS

DRIS provides an alternative approach. It provides the researcher with a mechanism of defining optimum nutrient balance for a specific species in a specific location and the simultaneous comparison of optimum nutrient conditions (Needham *et al*., 1990). DRIS therefore solves the second problem of the critical level approach by providing the researcher with of addressing nutrient interactions by using ratios of foliar concentrations to calculate indices that can be used to further diagnose the plant nutritional status (Svenson and Kimberly, 1988). DRIS norms can be defined as the ''average foliar nutrient pairs or ratios for high yielding stands'' (Gregoire and Fisher, 2004). The system is mainly based on the comparison of calculated nutrient indices with data obtained from chemical foliar analysis and already established DRIS norms. These indices cannot only be ranked in the level of importance but also provide an initial indication as to the amount of nutrient addition required by the plant (Gregoire and Fisher, 2004). Users have found that DRIS however is subject to the same variability to sampling timing and location as experienced for the critical level approach (Benton Jones, 1993) and as a result leads to indices that can be misleading and incorrect.

2.12.3 Vector Analysis

Vector analysis is a diagnostic technique that allows the researcher to compare plant growth, foliar nutrient content and foliar nutrient concentration with each other for individual trees and nutrients (Haase and Rose, 1995). In this way the growth responses of the trees to the fertilizer treatments can be assesed in a way that yields more descriptive information on the physiological level. This information is then

presented in a graphical format termed a vector nomogram. One of the major advantages of this approach is that the vector interpretations and comparisons are based on treated and untreated trees grown under the same site conditions and silvicultural regime (Gregoire and Fisher, 2004)

Foliage can be sampled around the same time as critical level foliar analysis. The vector method algebraically compares treatment responses within an experimental design to a reference treatment, usually an untreated control. All calculations are normalized to 100 for ease of interpretation. The vectors for the x and y axes are calculated using the following two equations (Haase and Rose, 1995) (see section 3.6.5):

$$Vector\ x-axis = \frac{Nutrient\ content\ of\ treatment}{Nutrient\ content\ of\ control} \times 100 \quad (2)$$

$$Vector\ y-axis = \frac{Nutrient\ concentration\ of\ treatment}{Nutrient\ concentration\ of\ control} \times 100 \quad (3)$$

This allows for relative nutrient comparisons between individual plots and individual nutrients. The nutrient content is calculated according to the following formula (Haase and Rose, 1995):

$$Nutrient\ content = foliar\ nutrient\ concentration \times unit\ dry\ weight \quad (4)$$

The unit dry weight can be anything from foliar dry weight to whole plant dry weight, but should be kept constant for the analysis. For this study, foliar dry weight will be used as it is highly correlated with long term growth responses (Haase and Rose, 1995). After the normalization is complete, the responses, or vectors, can be plotted on a vector nomogram.

The directional shifts of the vectors will be used to interpret and diagnose the nutritional responses of each treatment. The magnitude and direction of each vector indicates the degree of response obtained. Possible interpretations and diagnosis are presented in Table 2.2.

Critical level foliar analysis is good for determining nutrient deficiency, sufficiency or toxic levels at a particular point in time and while DRIS allows the study of nutrient balances and interactions, it is more informative to understand how the nutrient levels responded to the different nutrient additions over time.

Table 2.2: Directional shifts (adapted from Haase and Rose, 1995)

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

2.13 Biomass growth and nutrient accretion

The accretion of nutrients into the biomass is important to the internal and external nutrient cycle (Morris, 1992). Measuring how much nutrients accumulated in the total foliar biomass provides aid in explaining the growth patterns observed out in field. Silvicultural treatments that increase the availability of growth resources (slash management, fertilization, etc.) can affect stand growth dynamics in several ways. This usually leads to one or more of the following outcomes; 1) increased leaf area; 2) increased photosynthetic efficiency; and 3) changes in allocation of carbon to plant parts (du Toit and Dovey, 2005). Cromer *et al.* (1993a) and Leuning *et al.* (1991) emphasized that optimum plant nutrition in young stands is critical because of its potentially large impact on early growth through its effect on early development of leaf area and photosynthetic efficiency.

It is essential to measure the degree of nutrient accretion or uptake by the trees, especially N, over the monitored growing period. Cromer *et al.* (1993b) found that 80% of the total N uptake by young *Eucalyptus* trees in both fertilized and control plots was present in the foliage and for every 1 kg of N present in the foliage equated to an above ground production of 220 kg dry matter each year, irrespective of the treatment applied.

Chapter 3 Materials and Methods

3.1 Introduction

This chapter provides a detailed description of the selected study sites, trial designs, treatments applied, measurements carried out and the statistical techniques that were used to analyse the data.

3.2 Description of study sites

This study was conducted on four study sites, one located in the Western Cape Province and the other three in the KwaZulu-Natal Province of South Africa. In this trial series, the CRF was tested with four different commercial forestry species, growing in three distinct climatic zones with varying soil conditions. The sites and their climatic zones of the four sites are shown in Table 3.1 and Figure 3.1.

Table 3.1: Site names and their climatic zones

Site number	Site name	Climate zone
1	Coetzenburg	Temperate Coastal
2	Mtunzini	Sub-tropical coastal
3	Flatcrown	Sub-tropical coastal
4	Woolstone	Temperate interior

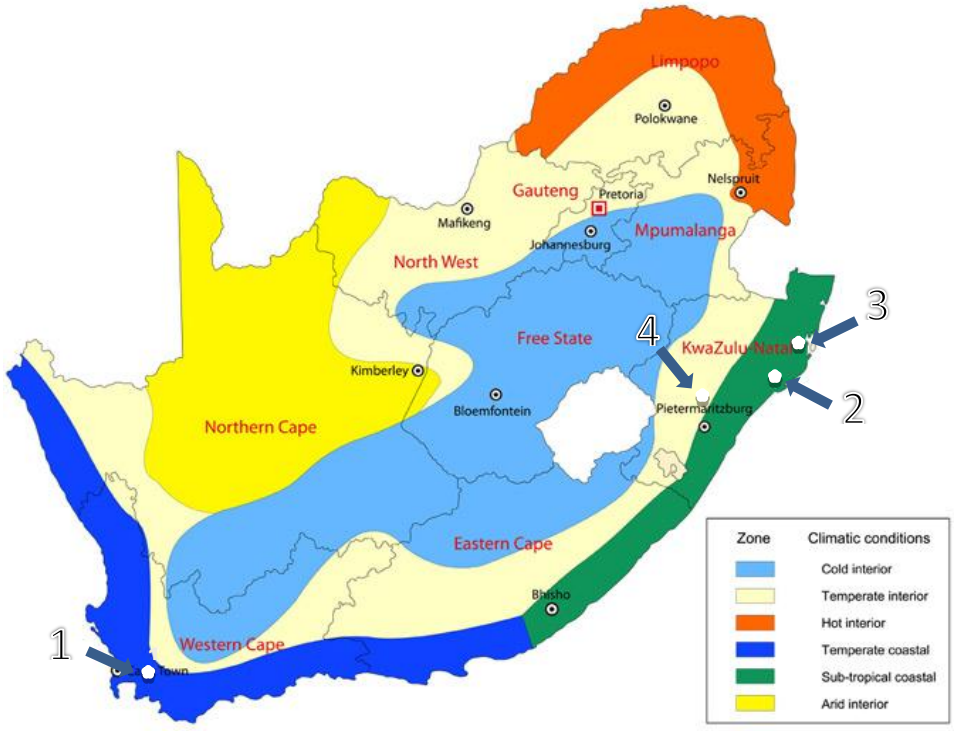


Figure 3.1: The locations of the four trial sites in different climatic zones of SA (Adapted from Anonymous, 2013).

The Coetzenburg site is located in Stellenbosch, situated approximately 40 km South East of Cape Town, on the mountain land of the University of Stellenbosch. The trial site was previously stocked with several *Pinus spp* which burnt down in 2009 and the site was overgrown with fynbos vegetation following the event that prevailed around the trial site (Figure 3.2).

Figure 3.2: A portion of the Coetzenburg site after planting. The fynbos vegetation is visible.

The climate can be classified as temperate with well-defined wet periods in the winter months (from May/June until August) and hot, dry summer months (November/December until March/April). Figure 3.3 shows the mean daily temperature, mean monthly precipitation (MMP) and the moisture growing season, defined as the period where precipitation is greater than 0.3 x potential evaporation (E_p) (FAO, 1978). Mean daily temperatures vary between 12 °C and 21 °C from winter to summer months. MMP figures reach a low of 8 mm in December and a high of 100 mm in June and July. The active moisture growing season on the site lasts five months, starting in May and ending in September. The site is dominated by fine and coarse sand fractions with a soil depth of approximately 1 m.

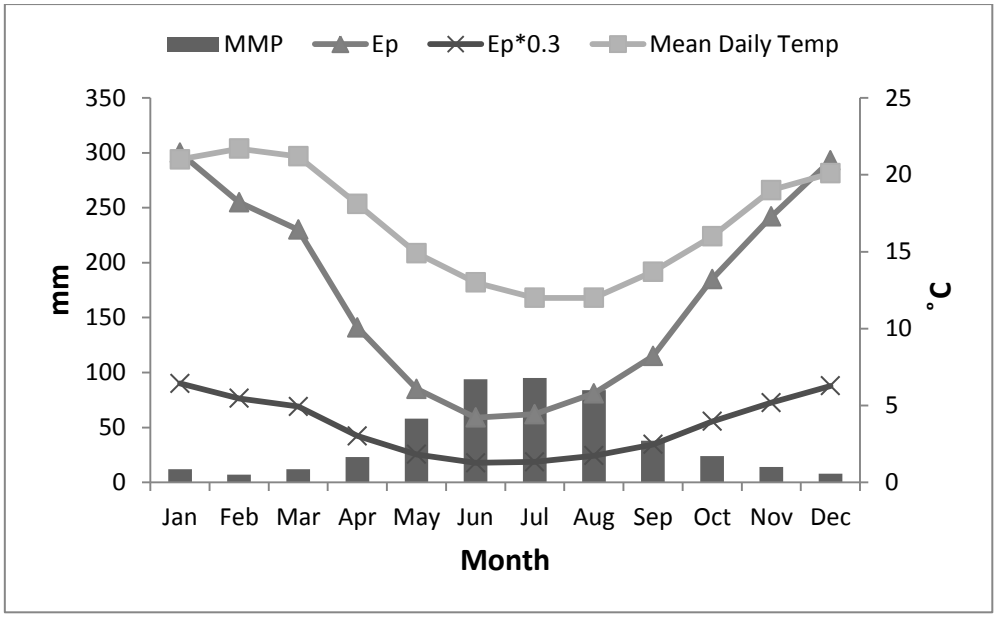


Figure 3.3: Mean monthly precipitation (MMP), mean daily temperatures, potential evaporation (Ep) and moisture growing season gradient line (Ep x 0.3) of the Coetzenburg study site.

The Mtunzini (Figure 3.6 and 3.7) and Flatcrown (Figure 3.8) sites are respectively located in compartments A009 and A035 on Mondi's Mtunzini and Kwambonambi plantations along the coastline of north-eastern KwaZulu-Natal. Both locations fall within the summer rainfall region of South Africa with a typical warm, humid sub-tropical climate. The Mtunzini site is situated 2 km south west of the town of Mtunzini and wad previously under sugar cane production. According to the SA soil classification system, the dominant soil in compartment A009 is a grey Fernwood family, with a sub-domination form being a Hutton family. Both of these soil forms have very sandy topsoil with medium and fine sand the dominant texture classes. The organic carbon (OC) content in the weakly structured, orthic topsoil horizon is less than 0.5 %. The depth of the soil profile typically exceeds 1.5 m on the site. Table 3.2 shows the typical soil properties. Figure 3.4 indicates the mean climatic values for temperature, precipitation, potential evaporation and the moisture growing threshold. The site is warm, with mean temperatures varying between 17.5 °C and 26 °C throughout the year. The site commonly receives in excess of 1 150 mm of precipitation annually, with 70% of it falling between October and March. Although there is a reduction in precipitation during the winter months, the site receives sufficient moisture to result in an all year round moisture growing season. The climatic information of the four sites was summarized (Table 3.3).

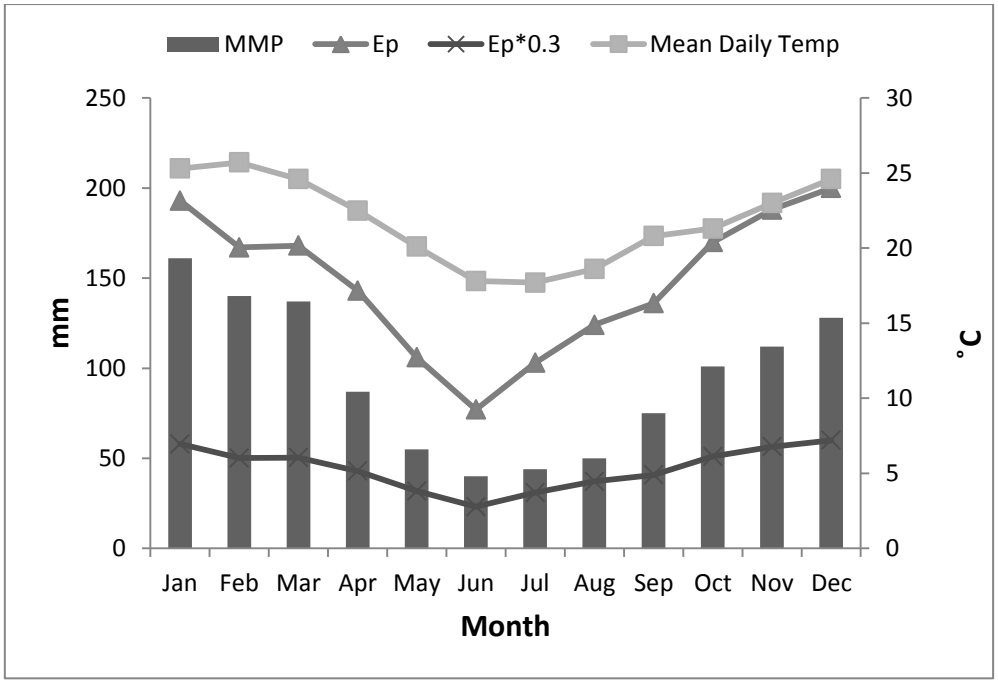


Figure 3.4: Mean monthly precipitation (MMP), mean daily temperatures, potential evaporation (Ep) and moisture growing season gradient line (Ep x 0.3) of the Mtunzini study site.

Table 3.2: Summary of the major soil properties on the four study sites

Soil information	Coetzenburg	Mtunzini	Flatcrown	Woolstone
Family		Fernwood	Fernwood	Inanda
pH (KCl)		4.5	4.2	4.4
P Bray II (PPM)		20	5	3
Exchangeable Na (cmol (+)/kg)		0.09	0.1	0.16
Exchangeable K (cmol (+)/kg)		0.04	0.05	0.39
Exchangeable Ca (cmol (+)/kg)		0.77	0.46	1.08
Exchangeable Mg (cmol (+)/kg)		0.31	0.41	0.96
Organic carbon (%)		0.3	0.41	2.67
Clay (%)	13	4	6	49
Silt (%)	7	5	4	16
Fine Sand (%)	34	50	50	24
Medium Sand (%)	9	39	38	5
Course Sand (%)	37	2	2	6

- Only textural analysis performed on Coetzenburg site

Fernwood is the dominant soil form at the Flatcrown site, with characteristic lightly coloured A and E horizons. The OC content of the soil is less than 0.5 % with an average topsoil sand fraction of >90 %. The soil depth at Flatcrown is greater than 2 m. Detailed soil properties and typical climatic patterns of the site follow (Table 3.2 and Figure 3.5). Flatcrown is slightly warmer and drier than Mtunzini. Mean daily

temperatures range from 18 °C to 26 °C with a MAP of 1 100 mm. Similarly to Mtunzini 70 % of the MAP is received between October and March. Even though the site is drier and warmer than Flatcrown, it also has an all year round moisture growing season.

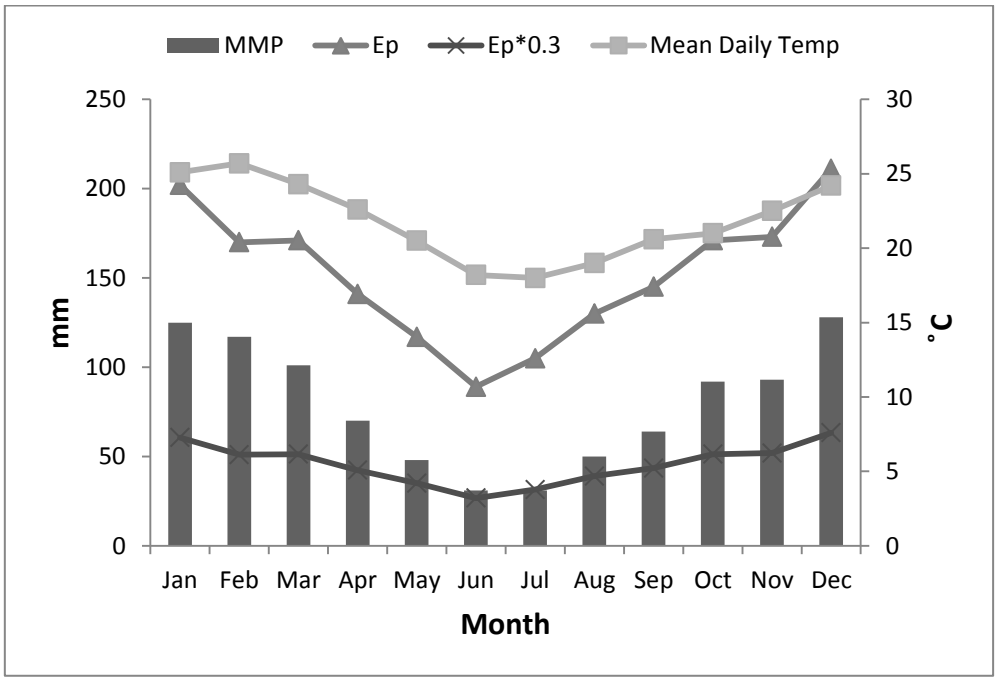


Figure 3.5: Mean monthly precipitation (MMP), mean daily temperatures, potential evaporation (Ep) and moisture growing season gradient line (Ep x 0.3) of the Flatcrown study site.

Figure 3.6: A photo of the Mtunzini site three days after planting

Figure 3.7: The Mtunzini site with the Coastal forest patch on the compartment border

Figure 3.8: The Flatcrown site at Kwambonambi. The indigenous forest patch can be seen in the background

The fourth site is located approximately 15 km north west of Greytown on compartment H003 (Figure 3.10) of Mondi's Woolstone plantation which forms part of the Holmesdale estate. The site was previously stocked with *E. grandis*. The soil on the site is characterised by red apedal soils of the Inanda form with a moderately high to high (35 – 65 %) clay percentage in the soil column. The OC content of the soil is approximately 3 % on average, but sampled topsoil areas are as high as 10 % (Appendix 1D). Refer to Table 3.2 for soil characteristics of the site. The study site is situated in the summer rainfall region with a MAP of 850 mm. The temperate climate of the region and the altitude of the site result in mean daily temperature range of between 13 °C and 24 °C. The active moisture growing season for the site starts in September and lasts until late March/early April (Figure 3.9).

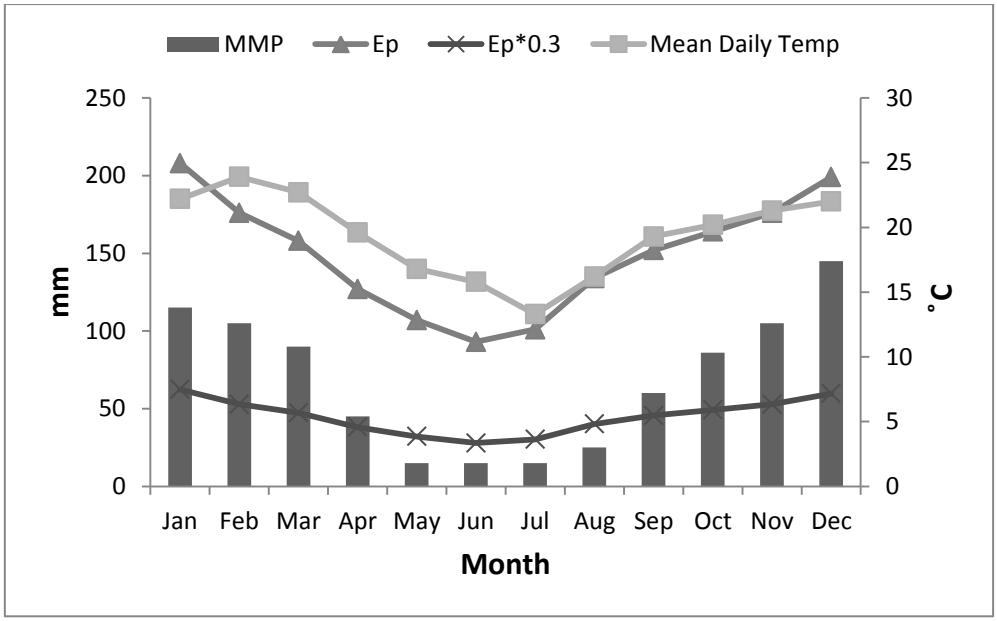


Figure 3.9: Mean monthly precipitation (MMP), mean daily temperatures, potential evaporation (Ep) and moisture growing season gradient line (Ep x 0.3) of the Woolstone study site.

Table 3.3: long term climatic averages of the four trial sites

Climate information	Coetzenburg	Mtunzini	Flatcrown	Woolstone
Mean Annual Rainfall (mm)	616	1132	1064	885
Mean Annual Temperature (°C)	17.5	22	22	19
Mean maximum of warmest month (°C)	28	28	28	31
Mean minimum of coldest month (°C)	8	14	14	6
Mean Annual Min Temperature (°C)	12	17.5	17.5	13
Altitude (m.a.s.l.)	215	45	80	1117
Moisture growing season	May-Sep.	All year	All year	Sep. - Apr.

Figure 3.10: The Woolstone site on the day of treatment application.

3.3 Trial design and Treatments

3.3.1 Coetzenburg

The Coetzenburg trial was designed as a factorial combination with the three factors (N, P and K) applied in different levels. The trial design was a 3 x 2 x 3 + 6, with three levels of N, two levels of P and three levels of K in factorial combination. Six additional treatments were used to make some direct comparisons between the controlled release fertilizer and the conventional forms. This design allowed us to test for differences between the 18 CRF treatments, differences between CRF and CV sources and to evaluate the performance of *P. elliottii* x *caribaea* compared to *P. radiata*. This equates to 120 plots for the entire experiment. The plots were laid out in a rectangle with a 6 x 5 configuration (30 trees per plot) with an espacement of 3 m x 3 m. The controlled release sources for N and K were coated Urea (42 % N) and KNO_3 (35 % K) respectively. P was not tested in a controlled release form due to unavailability of the product. The conventional sources of N, P and K were Limestone Ammonium Nitrate (LAN, 27 % N), double supers (19.6 % P) and KNO_3

(38 % K). Each treatment was assigned a corresponding treatment number with the controlled release treatments receiving numbers 1 through to 18 and the additional treatments, numbers 19 to 24. The additional treatments were as follows:

i. Control plot with no fertilizer application, treatment 24.

ii. Plot with *P. elliottii* x *caribaea* hybrid fertilized, treatment 22.

iii. Plot with *P. elliottii* x *caribaea* hybrid unfertilized, treatment 23.

iv. Comparison of controlled vs. conventional fertilization at the following treatment levels:

   a. N3P1K0 – Comparison with conventional N application as LAN, treatment 19.

   b. N1P1K2 – Comparison with conventional K application as KNO_3, treatment 20.

   c. N3P2K2 – Comparison with conventional NPK application at the highest treatment levels, treatment 21.

The experimental design is summarised in Table 3.4. The application details of all 24 treatments are summarised in Table 3.5.

Table 3.4: Coetzenburg experimental design summary

	Coetzenburg trial site
Species	*P. radiata* & *P. elliottii* x *P. caribaea*
Experimental design	Factorial 3 x 2 x 3 + 6
Number of replications	5
Number of plots	120
Plot size	270 m^2
Espacement	3 m x 3 m (1111 spha)
Total area used	3.25 ha
Date established	24 June 2010

3.3.2 Mtunzini, Flatcrown and Woolstone

The three *Eucalyptus* trials at Mtunzini, Flatcrown and Woolstone plantations were designed differently to the Coetzenburg trial. With previous trials (using conventional

fertilizer sources) in these areas very rarely shows any significant responses to the application to K (Noble, 1992a) only N and P were tested. Fewer factors with fewer treatments meant that with the reduced number of plots per replication, more replications per site could be laid out and therefore increase the statistical power of the trial. Four levels of coated N, with a mixture of two (25 %) and eight (75 %) month release and two levels of P (conventional) were tested in a factorial combination with one additional all-conventional treatment at Mtunzini and Flatcrown for a design of 4 x 2 + 1 and two additional treatments, one all-conventional and one all-controlled release, at Woolstone for a 4 x 2 + 2 design. Summary of the trial designs are shown in Table 3.6. The additional treatments were as follows:

i. Treatment CV11, conventional LAN and MAP application simulating the elemental nutrient contents of N and P provided by treatment number 4. See Table 3.7
ii. Treatment CRF 7-3-0, controlled release fertilizer treatment MULTICOTE® 7-3-0 which contains a mixture of Urea and MAP, both coated.

3.3.3 Fertilizer placement

On the Coetzenburg and Woolstone site, two narrow bands 25-30 cm were made on either side of the tree, approximately 40-45 cm in length and 10 cm deep, for the placement of both the CRF and CV sources. On the Mtunzini and Flatcrown site, a different approach was used for the CRF source. Three holes, 15-20 cm in diameter and 10 cm in depth, were made around the tree for the application. The CV source for Mtunzini and Flatcrown was placed as at Coetzenburg and Woolstone.

Table 3.5: Application details of all 24 treatments tested at Coetzenburg

Treatment	Code	Species	N level	Applied grams of product	Grams of element	P level	Applied grams of product	Grams of element	K level	Applied grams of product	Grams of element
1	CRF110	*P. radiata*	1	14	6	1	107	15	0	N/A	0
2	CRF210	*P. radiata*	2	48	20	1	107	15	0	N/A	0
3	CRF310	*P. radiata*	3	95	40	1	107	15	0	N/A	0
4	CRF111	*P. radiata*	1	7	6	1	107	15	1	26	9
5	CRF211	*P. radiata*	2	41	20	1	107	15	1	26	9
6	CRF311	*P. radiata*	3	88	40	1	107	15	1	26	9
7	CRF112	*P. radiata*	1	0	6	1	107	15	2	51	18
8	CRF212	*P. radiata*	2	34	20	1	107	15	2	51	18
9	CRF312	*P. radiata*	3	81	40	1	107	15	2	51	18
10	CRF120	*P. radiata*	1	14	6	2	214	30	0	N/A	0
11	CRF220	*P. radiata*	2	48	20	2	214	30	0	N/A	0
12	CRF320	*P. radiata*	3	95	40	2	214	30	0	N/A	0
13	CRF121	*P. radiata*	1	7	6	2	214	30	1	26	9
14	CRF221	*P. radiata*	2	41	20	2	214	30	1	26	9
15	CRF321	*P. radiata*	3	88	40	2	214	30	1	26	9
16	CRF122	*P. radiata*	1	0	6	2	214	30	2	51	18
17	CRF222	*P. radiata*	2	34	20	2	214	30	2	51	18
18	CRF322	*P. radiata*	3	81	40	2	214	30	2	51	18
19	CV310	*P. radiata*	3	148	40	1	77	15	0	0	0
20	CV112	*P. radiata*	1	0	6	1	77	15	2	47	18
21	CV322	*P. radiata*	3	126	40	2	153	30	2	47	18
22	CVH322	*P. elliottii x caribaea*	3	81	40	2	214	30	2	51	18
23	Control	*P. radiata*	0	N/A	0	0	N/A	0	0	N/A	0
24	CVH000	*P. elliottii x caribaea*	0	N/A	0	0	N/A	0	0	N/A	0

Table 3.6: Zululand and Midlands trials experimental design summary

	Mtunzini	Flatcrown	Woolstone
	E. grandis x urophylla	*E. grandis x urophylla*	*E. dunnii*
Species			
Clone number	GU 608	GU 608	n/a
Experimental design	Factorial 4 x 2 + 1	Factorial 4 x 2 + 1	Factorial 4 x 2 + 2
Number of replications	9	9	9
Number of plots	81	81	90
Plot size	294 m^2	294 m^2	315 m^2
Espacement	3 x 2 m	3 x 2 m	3 x 2 m
Total trial area	2.38 ha	2.38 ha	2.84 ha
Date established	11/07/2012	12/07/2012	5/12/2012

The controlled release sources of N applied were the same as the Coetzenburg trial but the application rates were substantially. The conventional source of N used was the same (LAN, 25 % active) but the P source was uncoated MAP (12 % N and 26% P active) rather than Double supers. Application rates are summarised in Table 3.7.

Table 3.7: Quantity of CRF applied at the Zululand and Midlands trial sites

Treatment code	Species	N level	Applied grams of product	Grams of element	P level	Applied grams of product	Grams of element
Control	*E. grandis x urophylla + E. dunnii*	0	N/A	0	0	N/A	0
CV01	*E. grandis x urophylla + E. dunnii*	0	N/A	0	1	143	20
CRF10	*E. grandis x urophylla + E. dunnii*	1	95	40	0	N/A	0
CRF11	*E. grandis x urophylla + E. dunnii*	1	95	40	1	143	20
CRF20	*E. grandis x urophylla + E. dunnii*	2	180	80	0	N/A	0
CRF21	*E. grandis x urophylla + E. dunnii*	2	180	80	1	143	20
CRF30	*E. grandis x urophylla + E. dunnii*	3	285	120	0	N/A	0
CRF31	*E. grandis x urophylla + E. dunnii*	3	285	120	1	143	20
CV11	*E. grandis x urophylla + E. dunnii*	1	148	40	1	185	20
CRF7-3-0	*E. dunnii*	N/A	410	29	N/A	410	12.3

3.4 Soil sampling

After the trial plots had been laid out on each site, a number of locations within the trial site boundary were chosen as soil sampling sites. This was done by dividing the trial site into four quadrants and taking the centre of each quadrant as the sample point. The sample points for the Flatcrown site are shown as an example in Figure 3.11.

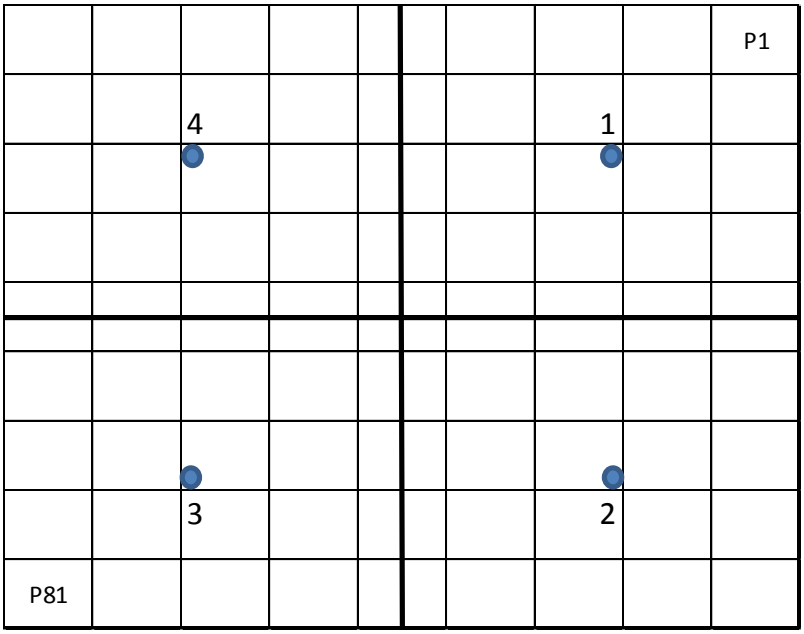


Figure 3.11: Flatcrown soil sampling points.

Following identification of the sample points, a 1.8 m long auger was used to take three soil samples at each point. The first sample was taken at a depth of between 0 cm – 20 cm, the second at 20 cm – 40 cm and the third at 40 cm – 60 cm. The samples were collected in air tight plastic bags. The sample labels were constructed as alphanumeric characters using the following guidelines.

Table 3.8: Guidelines used to label individual soil samples taken at each trial site

Site	Mtunzini	Flatcrown	Woolstone	Coetzenburg
Character	A	B	C	D
Sample point	1	2	3	4
Character	1	2	3	4
Sample depth	0-20 cm	20-40 cm	40-60 cm	
Character	1	2	3	

For example, sample A12, identifies a sample taken on the Mtunzini site, at sampling point number 1 and at a depth of 20 - 40 cm. The 42 (Only two locations in Coetzenburg trial sampled for textural analysis) samples were sent to Bemlab commercial laboratories for standard chemical and five fraction textural analyses. For full analysis results of each individual sample see **Appendix 1A – 1D**. Refer to Table 3.8 for identification of individual samples.

3.5 Soil analysis techniques

The above mentioned soil samples were air dried and sieved through a 2 mm sieve for determination of stone fraction percentage. The bulk density of the sieved soil was determined by weighing 60 cm^3 of soil at 20 °C and expressed as $kg.m^3$. Soil pH was determined with a 1 M KCl solution. Exchangeable cations (K, Ca, Mg and Na) were extracted at pH = 7 with a 0.2 M ammonium acetate solution. The extracts were analysed with a Varian ICP-OES optical emission spectrometer (Raath, 2013). Organic carbon content was determined using the Walkley-Black method (The Non-affiliated Soil Analyses Work Committee, 1990). Extractable acidity was extracted with a 1 M KCL solution determined through titration with 0.05 M NaOH (Raath, 2013). Available soil P was determined through extraction with Bray II solution (0.03 M NH_4F in 0.1 M HCL) and total P extracted with a 1:1 mixture of 1 N HNO_3 and HCL at 80 °C for 30 minutes and determined with a Varian ICP-OES optical emission spectrometer (Raath, 2013). Total N content of the soil was determined through total combustion using a Leco Truspec CN analyser (Raath, 2013). Chemical dispersion is performed with sodium hexametaphosphate and three sand fractions identified through sieving as described by the Non-affiliated Soil Analyses Work Committee (1990). Silt and clay particle sizes were determined through sedimentation rates at 20 °C using an ASTM E100 (152H-TP) hydrometer (Raath, 2013)

3.6 Measurements

Three groups of measurement techniques were applied at each site, selected according to their applicability or logistical feasibility.The first group consists of Coetzenburg, second Mtunzini and Flatcrown and the third Woolstone. A numerical superscript, either 1, 2 or 3 is placed behind each technique's heading to denote which trial(s) it is relevant to.

3.6.1 Biomass index[1]

An estimation of biomass was used for the Coetzenburg site as volume estimation was not the most feasible measure for statistical treatment comparison for small young aged trees. The methodology employed by Donald *et al.* (1987) was used.

To estimate the biomass growth of the trees over the two year monitoring period, ground line diameters and tree heights of each tree were measured. Diameters were measured in cm with a digital calliper and the measurements were taken on two axes, approximately 1-2 cm above the ground to maintain a degree of consistency. Tree height in cm was measured with a metal measuring pole marked with 1 cm increments. The same callipers were used for all three measurement exercises.

A biomass index was determined for each tree measured (Equation 5);

$$Biomass\ index = {D_{gl}}^2 \times tree\ height\ (m) \quad (5)$$

Where, D_{gl} = Ground line diameter in cm

3.6.2 Volume estimation[2]

The accurate estimation of volume in young trees is often difficult to achieve given that the majority of commercially developed volume equations calculate utilizable volume. The volume of the *E. grandis* x *urophylla* hybrids at one year of age was determined through the use of the equation developed by Hardiyanto and Tridasa (2000) as shown in Equation 6.

$$Volume = 0.25 \times \pi \times dbh^2 \times h \times f \quad (6)$$

dbh = diameter at breast height (m)

h = tree height (m)

f = 0.65 (form factor)

The ANOVA analysis was performed on the estimated mean volumes per hectare of each treatment.

3.6.3 Foliar sampling[1,2]

Post fertilization foliar samples were collected in early August 2011 and middle April 2013 for the Coetzenburg *Pinus spp,* and Mtunzini and Flatcrown *Eucalyptus spp* trials respectively. For the Coetzenburg tial, three out of the five replications were sampled. Six trees out of each plot throughout replicates numbers one, three and five were selected for sampling. One year old needles were collected from two

second order branches in the upper third of the crown from each of the selected trees.

The needles collected from the six sample trees were bulked to form a single representative plot sample and sealed in a bag marked with the corresponding plot number. In the laboratory, mean fascicle length was determined from 30 fascicles for each plot.

The oven dry weight of 100 needles was recorded for each plot sample. All the samples were then packaged in clearly marked brown paper bags and sent to Bemlab for full chemical analysis.

For the two Zululand *Eucalyptus* trials, six replications were sampled at Mtunzini and three at Flatcrown. One sample tree for each row of the inner plot was selected. The trees were selected systematically across a diagonal line, for e.g. tree 1 of inner row 1, tree 2 of inner row 2, etc. Two representative branches were sampled, one from the upper half of the canopy and one from the lower half. All the leaves from the five trees were bulked as a single plot sample, labelled and stored in a cold storage container.

For each individual plot, 60 g of fresh leaves were weighed out, scanned using a photoelectric digital scanner for leaf area determination and oven dried to a constant weight. From this a SLA $m^2.kg^{-1}$ per plot was determined for use in the estimation of total foliar nutrient content in 3.6.7.

3.6.4 Foliar analysis techniques

The bulked foliar samples of each plot were analysed for nutrient concentrations according to the techniques described by Campbell and Plank (1998). After selection of the best condition leaf material, the samples were washed with a Teepol solution, rinsed with de-ionised water and oven dried overnight at 70 °C (Raath, 2013). The dried leaf samples were milled and then ashed at 480 °C. The ash was mixed with a 1:1 HCl (32 %) solution for extraction through filter paper (Campbell and Plank, 1998). The cation and micronutrient content of the filtrate was determined using a Varian ICP-OES optical emission spectrometer (Raath, 2013). The total N content of the milled leaves was measured through total combustion in a Leco N-analyser (Raath, 2013).

3.6.5 Vector analysis[1,2]

The trees response to the fertilizer treatments was analyzed using the vector analysis technique. The lab results of the nutrient concentrations of the elements tested for in the samples collected in Section 3.6.2 were used in further vector analysis calculations. First, the nutrient content for each of the macronutrients per treatment was determined by calculating the product of the nutrient concentration (percentage value derived from the lab results) and the unit dry weight (mean weight in grams of 100 needles or 60 fully extended *Eucalyptus* leaves of the relevant treatment). The nutrient concentration, nutrient content and unit dry weight of the control treatment was used as the reference point for the calculation of relative nutrient concentration, relative nutrient content and relative unit dry weight of the other treatments. All calculations were done using Microsoft (MS) Excel 2010.

The MS Excel spreadsheet was imported into the software program Sigmaplot, version 12.5, for plotting of the vector nomograms. Relative nutrient content was used as the response variable as it incorporates both nutrient concentration and unit dry weight. Diagnosis of the vectors was done according to the possible shifts and interpretations shown in Table 2.2.

3.6.6 LAI determination[2]

The PAI of each treatment was measured using a LICOR LAI-2000 plant canopy analyser. Six replications at Mtunzini and three at Flatcrown were measured. At Mtunzini, two LAI-2000 sensors were used, which were synchronized and cross-calibrated with one another, in remote mode setting. The first sensor was set up in an elevated position outside of the compartment, not directly facing the sun, to record above sky conditions automatically at 15 second intervals. The second sensor was used to record below canopy light conditions for the whole plot. A 90 degree lens cap was chosen as it is better suited for use in small plot areas. At Flatcrown, the two sensors were used in paired mode due to the inconsistent sky conditions on the measurement day, with the above sensor mounted on top of a 6 m long aluminium pole and hoisted above the canopy. The same lens cap was used on both sites. At Flatcrown, care had to be taken to ensure that both the above-canopy and below-canopy fish eye lenses were facing the same direction when logging readings. On both sites, the first measurement was always taken on the left hand side corner

of the plot, with the operator facing away from the sun. A total of twenty readings were taken on each plot, which consisted of four readings in each of the inner plot rows. Above and below canopy readings were combined to calculate gap fraction from which PAI was derived with the aid of computer software provided with the instrument. In cases where below canopy readings were greater than above readings, the transmission value was set to one.

The calculated PAI values were then adjusted to an estimated LAI through the use of the extrapolation of the regression equation for LAI of *E. grandis* at two years of age developed by Dovey and du Toit (2006).

3.6.7 Soil water availability[1]

In South African conditions, water availability is a major driver for growth. Determining the soil water content and relative extractable water (REW) (Granier *et al.*, 2000) is important for establishing periods during which trees are experiencing water stress. For this purpose, the HyMo water balance model, developed by Rötzer *et al.* (2004) was used. The choice to use HyMo was motivated by two factors: 1) it's simple and readily available input parameters; and 2) its reliable and robust output across various sites as shown in Rötzer *et al.* (2004) and Fischer (2011).

The basic inputs required by HyMo are meteorological data such as temperature, precipitation, solar radiation, humidity and wind speed (Rötzer *et al.,* 2004). Latitude, longitude and altitude cover the geographical inputs needed, while land cover and edaphic data such as effective rooting depth (ERD), wilting point (WP), field capacity (FC), crop species and crop age are also needed (Rötzer *et al.,* 2004). The model and its input parameters are described in detail in Rötzer *et al.* (2004).

The daily soil water content (SWC) from the 1 June 2010 till 1 July 2013, a 37 month period, was modelled using the HyMo model. The REW was calculated using equation (1) of Granier *et al.* (2000), which relates REW as an index from 0 to 1. Granier *et al.* (2000) proposed that drought stress ensues when the REW drops below 0.4 or 40% of the maximum extractable water and this threshold was tested for *Pinus* species.

3.6.8 Foliar nutrient content[2]

The foliar nutrient content on an area basis of each treatment was estimated using the following procedure. The estimated LAI was converted to a leaf mass by dividing with the SLA and scaled up to a hectare basis. The nutrient content was calculated as the product of leaf mass and foliar nutrient concentration

3.6.9 Crown area determination[2]

In addition to LICOR PAI readings, crown diameters of the same plots were measured at Mtunzini. A three metre long aluminium rod was used. Two measurements were taken, one along the contour line and the second perpendicular to the first. These two measurements were then used to determine an individual crown area in m^2 and summed for the 25 trees of the inner plot. The plot crown area was scaled up to a crown area per ha by dividing the crown area per plot by the quotient of plot size (m^2) and the area of one ha (m^2). For this to be accurate, two considerations were taken into account. The first was mortality. Where trees were missing inside the inner plot, a zero value was assigned to them. The second consideration was crown overlap (Figure 3.12).

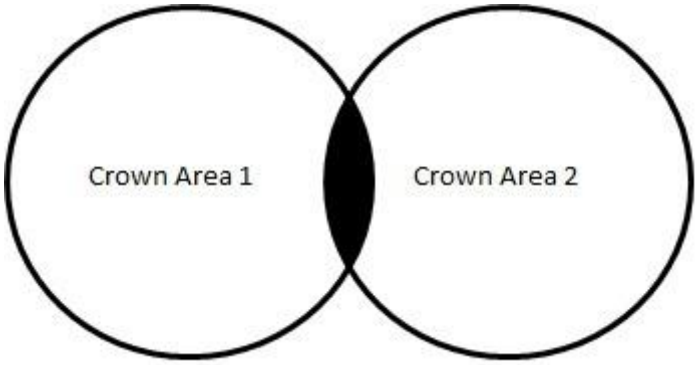


Figure 3.12: Crown overlap consideration in a number of plots at Mtunzini when calculating crown area.

Crown overlap occurred when the sum of the radii of directly adjacent neighbouring trees exceeded the planting distance between them. Radius was taken as half of the measured diameter. In cases where overlap did occur, the larger of the two radii (m) was adjusted down by multiplying it by the quotient of the planting distance (m) in that direction divided by the sum of the two radii in question. The smaller of the two

radii remained unadjusted. The mean radii of the trees were then calculated by adding the four radii (measured and adjusted where applicable) and dividing by four. This mean radius was used in the formula for the area of a circle to estimate crown area.

3.7. Statistical analysis[1,2,3]

The analysis procedures and statistical techniques used for the various data sets are described below. Only treatment differences of $p<0.05$ are reported. All analyses were done with the use of the statistical program Statistica 11.

3.7.1 Coetzenburg

3.7.1.1 Survival

A survival count per plot was taken four weeks after treatment application. The total number of dead trees per plot were converted to a plot mortality percentage by dividing by 30 (plot size of 6 x 5 trees) and multiplying by 100. The data was then analysed on a plot level using an analysis of variance (ANOVA) technique, described in Section 3.7.4.

After testing the assumptions of an ANOVA, it was found that the residuals of the data were not normally distributed and the variances were heteroscedastic. A Kruskal-Wallis non-parametric test (Section 3.7.5) was performed.

3.7.1.2 Biomass index

The GLD - ht pairs of 12, 18 and 30 months were used to calculate a biomass index value per tree. This value was summed and divided by the number of living individuals in each plot. Unfortunately the influence of *F. circinatum* on the growth was evident from the large variation in growth between plots of the same treatment. For this reason, a subset of the data was used in the final analysis to account for the effects of *F. circinatum.*

Trees which were classified as infection level 0 (Table 3.9) for the period between 12 and 30 months were identified. The least amount of level 0 trees for a single plot, 6,

was used as the general standard for all plots. A new mean BI of the largest 6 trees per plot (all non-infected) was calculated for each plot and used as the response variable in the ANOVA procedure. This subset will be referred to as the healthy tree sub-set (Nel, 2013).

3.7.2 Mtunzini and Flatcrown

3.7.2.1 Survival

The mortalities of the individual plots were determined seven weeks after treatment application. A plot mortality percentage was calculated as in Section 3.7.1.1, but on this occasion dividing by 49 (7 x 7 plot size). A Kruskal-Wallis test was performed on the data

3.7.2.2 Volume growth

A rudimentary individual tree volume was calculated by using the equation highlighted in Section 3.6.2. The measured heights and diameters at 12 months of age were used as the input variables. The resultant individual tree volumes were averaged over the entire plot and scaled up to a per hectare value as an estimation of the volume growth over the first growth year. The estimated volume per hectare was analysed for treatment differences using a two-way factorial ANOVA.

3.7.3 Woolstone

3.7.3.1 Survival

A survival count was done 8 weeks after treatment application. A plot mortality percentage was calculated per plot, based upon stocking levels calculated for each plot to account for inconsistent planting densities. A Kruskal-Wallis test was performed on the resulting dataset.

3.7.3.2 Height growth

The measured heights at seven months were used as the response variable. Due to the unbalanced number of experimental units in some plots as a result of the inconsistency of planting distances within rows a set number of 15 trees (five trees for each row of the inner plot) per plot were used to calculate the plot means. The mean height data was then analysed on a plot level using the ANOVA statistical technique.

3.7.4. Analysis of variance

The ANOVA technique is an extension of the T-test. It is used when the means of three or more groups are compared with one another to determine if there are differences between them. The between-treatment variation of the treatment groups is compared to the group's within-treatment variation (Clewer and Scarisbrick, 2001). For the test of variance to be valid, the observations of each treatment need be independent of one another, originate from a normally distributed population and share equal variances with each other (Clewer and Scarisbrick, 2001).

3.7.5 Kruskal-Wallis one-way ANOVA

The Kruskal-Wallis test is the non-parametric equivalent of the one-way ANOVA. It compares the median of populations of three or more sample groups, but the actual data is replaced by its rank. This test does not assume normally distributed data or equal variances, but does assume that the population groups are random, independent from one another and that their distributions are identically shaped (Clewer and Scarisbrick, 2001).

Chapter 4: Results A

4.1 Early survival

The survival on the Coetzenburg site was recorded up until 133 days (time of first height measurement) after treatment application. The non-parametric Kruskal-Wallis test gave no differences between the 18 CRF treatments or CRF and CV sources were. Plot mortalities were not affected by increases in application of N, P and K or their various factor interactions. The only significant difference on the site was between the two species, *P. radiata* and *P. elliottii* x *caribaea* hybrid. The fertilized and unfertilized hybrid treatments had a mean mortality of 9 and 2 % respectively. CRF111 was the best surviving CRF treatment with a mean mortality of 27 %, while CV310 with a mean of 33 % had the lowest mortality of the CV treatments. The control (24 %) treatment however performed better than both CRF111 and CV310. Survival of the trial at 133 days post treatment application was 60 %. The ten best overall surviving treatments are shown in Figure 4.1.

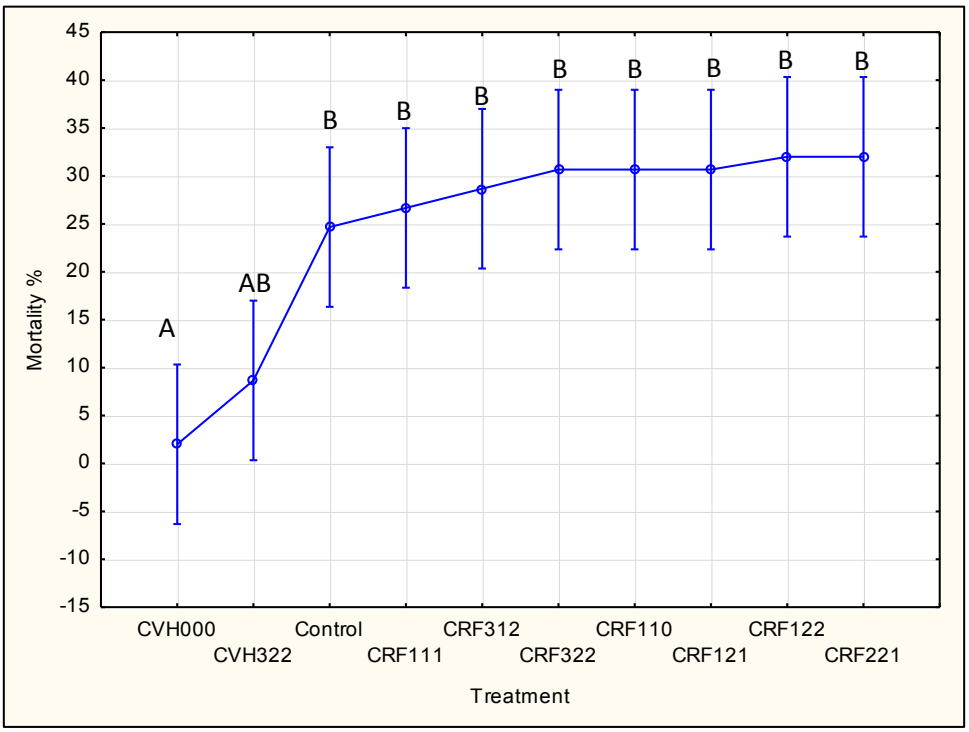


Figure 4.1: The top ten surviving treatments on the Coetzenburg site with 95 % confidence intervals. Different letters indicate significance (p<0.05). Refer to treatment codes in Table 3.5.

4.2 Foliar analysis

The laboratory analysis results of the *P. radiata* samples collected as described in Section 3.6.3 are further discussed here. Refer to **Appendix 2A** for the full lab analysis report.

4.2.1. Critical levels

The foliar concentrations 12 months after fertilizer treatment application were assessed according to the critical values determined by Boardman *et al.* (1997). The two *P. elliottii* x *caribaea* treatments were excluded from the critical value analysis due to the unavailability of published critical nutrient values. The results can be seen in Table 4.1.

The chemical analysis showed that K, Ca, Na, Mn, Fe, Cu and Zn were all present in adequate concentrations, and are thus unlikely to pose a growth limitation The nutrient concentrations were subjected to an ANOVA (Table 4.2).

N in all *P. radiata* treatments were at the higher end of the adequate range and treatments CRF110 and CRF311 found to contain excessively high N levels. P concentrations were marginal in the majority of treatments with only five treatments (CRF111, CRF122, CV112, CV310 and CV322) having adequate foliar concentrations. P was not present in a controlled release form and the source of P in the CRF and CV sources were silphos and double superphosphate respectively. Silphos is a non-coated concentrated superphosphate containing 14 % P used in the manufacturing of the CRF fertilizer blends. Deficiencies were only found for Mg in treatments CRF222, CRF311, CRF312, CV112 and the control with the rest of the treatments displaying marginal levels. With a range of 0.06-0.10 Mg clearly seems to be a limitation on this site. Refer to **Appendix 2B** for graphical representations of the N x P x K interactions for the significant nutrients.

Table 4.1: Foliar nutrient concentrations one year after treatment application assessed according to the critical values determined by Boardman *et al*. (1997).

Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
	%					mg kg^{-1}					
Control	2.42	0.12	1.06	0.20	**0.06**	422	139	206	4	64	18
CRF110	2.62	0.14	1.03	0.26	0.07	460	260	220	3	30	17
CRF111	2.43	0.15	1.15	0.16	0.07	320	230	170	3	28	19
CRF112	2.45	0.13	1.08	0.19	0.07	224	260	163	4	36	22
CRF120	2.41	0.14	0.97	0.24	0.10	209	431	158	4	29	24
CRF121	2.46	0.14	1.01	0.17	0.08	289	309	194	4	32	18
CRF122	2.45	0.18	1.05	0.19	0.07	201	313	160	4	49	15
CRF210	2.42	0.12	0.87	0.18	0.09	285	249	181	3	22	14
CRF211	2.47	0.14	1.00	0.18	0.07	290	282	185	3	18	17
CRF212	2.54	0.13	0.94	0.23	0.09	344	345	205	4	24	16
CRF220	2.50	0.13	0.83	0.22	0.09	398	285	205	3	16	18
CRF221	2.56	0.14	0.90	0.19	0.07	371	239	175	3	21	15
CRF222	2.52	0.13	1.09	0.18	**0.06**	407	231	198	3	22	16
CRF310	2.54	0.12	0.80	0.17	0.08	437	156	225	3	14	11
CRF311	2.62	0.13	1.03	0.19	**0.06**	275	288	176	3	25	13
CRF312	2.51	0.13	0.90	0.13	**0.06**	608	206	230	3	17	16
CRF320	2.56	0.13	0.77	0.21	0.08	412	234	195	3	20	13
CRF321	2.36	0.13	0.91	0.21	0.08	416	286	186	3	22	13
CRF322	2.46	0.12	0.92	0.20	0.07	312	321	184	3	20	12
CV112	2.38	0.16	1.07	0.21	**0.06**	470	270	230	3	62	17
CV310	2.50	0.15	0.99	0.19	0.07	375	147	174	3	33	19
CV322	2.42	0.15	1.04	0.23	0.07	379	198	175	4	38	15
Deficient	0.5-1	0.06	<0.25	<0.06	<0.07	<20	<5	<35	<2	<6	5-12
Marginal	1-1.2	0.09-0.14	<0.35	0.06-0.07	0.07-0.1	20-30	5-20	40-80	2.1-2.3	11-13	10-16
Adequate	1.6-2.4	0.177-0.344	0.36-1.8	0.08-0.45	0.11-0.8	40-500	20-400	70-200	2.4-9	14-16	16-70
Toxic	>2.6	n/a	>1.9	n/a	n/a	>3000	n/a	n/a	n/a	n/a	>170

*Non shaded cells = Adequate values; Shaded cells = Marginal concentrations

Bold values = Deficient concentrations; red values = Toxic (or excessively high) levels; n/a = not available/not applicable

Table 4.2: Significant ANOVA results of Coetzenburg foliar nutrient concentration analysis. Significant effects shown in red.

Analysis of variance results of Foliar nutrient concentration						
Coetzenburg nutrient concentration significant differences						
			P			
Effect	SS	Degree Of freedom	MS	F	p	Comments. Refer to Appendix 2B
N level	0.004311	2	0.002156	13.857	0.000034	P concentrations decreased with increasing N
N level * P level * K level	0.001722	4	0.000431	2.768	0.041939	
			K			
N level	0.2426	2	0.1213	14.011	0.000032	K concentrations increases with K application, but decreases at higher levels of N
K level	0.17685	2	0.08842	10.214	0.000307	
N level * P level * K level	0.01384	4	0.00346	0.4	0.807544	
			Na			
N level	143448	2	71724	5.0434	0.011724	Na concentrations increases with increasing N application
N level * P level * K level	142525	4	35631	2.5055	0.05916	
			Cu			
N level	8.9259	2	4.463	10.955	0.000192	Cu concentrations decreases with increasing N application
N level * P level * K level	0.5185	4	0.1296	0.318	0.863929	
			Zn			
N level	2340.48	2	1170.24	39.619	0.00000	Zn concentrations increases with K application, but decreases at higher levels of N
K level	357.37	2	178.69	6.05	0.005432	
N level * K level	478.74	4	119.69	4.052	0.008183	
N level * P level * K level	191.56	4	47.89	1.621	0.19007	
			B			
N level	336.26	2	168.13	4.0333	0.02627	B concentrations decreases with increasing N application
N level * P level * K level	48.44	4	12.11	0.2905	0.88219	

4.2.2. Vector analysis

After assessment of the nutrient values across replications 1, 3 and 5, in terms of the accepted critical values of Boardman *et al.* (1997), an investigation into the relative effect of the macronutrients (N, P, K, Ca and Mg) was performed on each treatment

The vector analysis technique was used as described in Section 2.12.3. It was found that the magnitude of the vectors and therefore their influence on the majority of the

treatments were in most cases negligible. Results may have been unreliable and influenced by asymptomatic *F. circinatum* infections at the time of sampling should be stressed. For each of the five macronutrients, only those treatments which represented noteworthy responses were presented graphically on the vector nomograms. A summary of the interpretation and possible diagnosis of the significant vectors (when the magnitude is at least 1.5 times that of the control) for all the treatments, excluding the control, which serves as the reference point and the *P. elliottii x caribaea* treatments, which have different needle architecture, length and weight, are given in Table 4.3.

Refer to **Appendix 2C** for a summary of all the calculated vectors and graphical representations of the significant vector nomograms.

Table 4.3: A summary of the macronutrient vector responses across all replications that were deemed to be of a sufficiently large magnitude to warrant discussion and interpretation

	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium	
Treatment	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**
CRF110							Luxury	Non-toxic		
CRF120							Luxury	Non- toxic	Luxury	Non-toxic
CRF222	Deficiency	Limiting	Deficiency	Limiting	Excess	Antagonistic				
CRF310									Luxury	Non-toxic
CRF322					Excess	Antagonistic				
CV112			Luxury	Non-toxic						
CV322	Sufficiency	Non-limiting	Deficiency	Limiting	Sufficiency	Non-limiting	Deficiency	Limiting	Deficiency	Limiting

4.3 Disease incidence

During the period between the survival count and first ht measurement (six months) it was noted that a few individual trees were exhibiting symptoms characteristic of *Fusarium* infection. These individuals were monitored closely in the weeks to follow, but over time the tree health deteriorated and symptoms were being observed in multiple plots across all five replications. Sample branches were cut from three diseased trees and sent to the Stellenbosch Disease Clinic for identification of the pathogen. Results were conclusive that all three samples had tested positive for *Fusarium circinatum*.

Following the second ht measurement and first GLD measurement, where a BI could be calculated, it was clear that *F. circinatum* was having a significant effect on plant growth. A rudimentary numerically based visual assessment of disease incidence and severity was developed (Table 4.4; Figure 4.2), with the primary purpose of quantifying the extent of the infection for use as a covariate in the analysis procedures. Only in circumstances where the covariate was significant was it included in the analysis procedure. A disease incidence percentage (number of diseased trees / number of living trees in plot) was then calculated per plot. Trees with both level 1 and 2 descriptions were bulked in the calculation procedure.

Table 4.4: Levels of disease severity and their descriptions

Level	Description
0	Tree does not display any visual signs of foliage discolouration, wilt of the growing tips or resin on stem or branches. Photo A
1	Clear foliage discolouration on a single branch ("flagging") or group of branches, a degree of foliage loss, wilting growing tip or resin on stem/branches. Less than 30% of tree affected. Photo B and C
2	More than 30% of tree affected with level 1 symptoms or whole tree chlorotic. Photo D

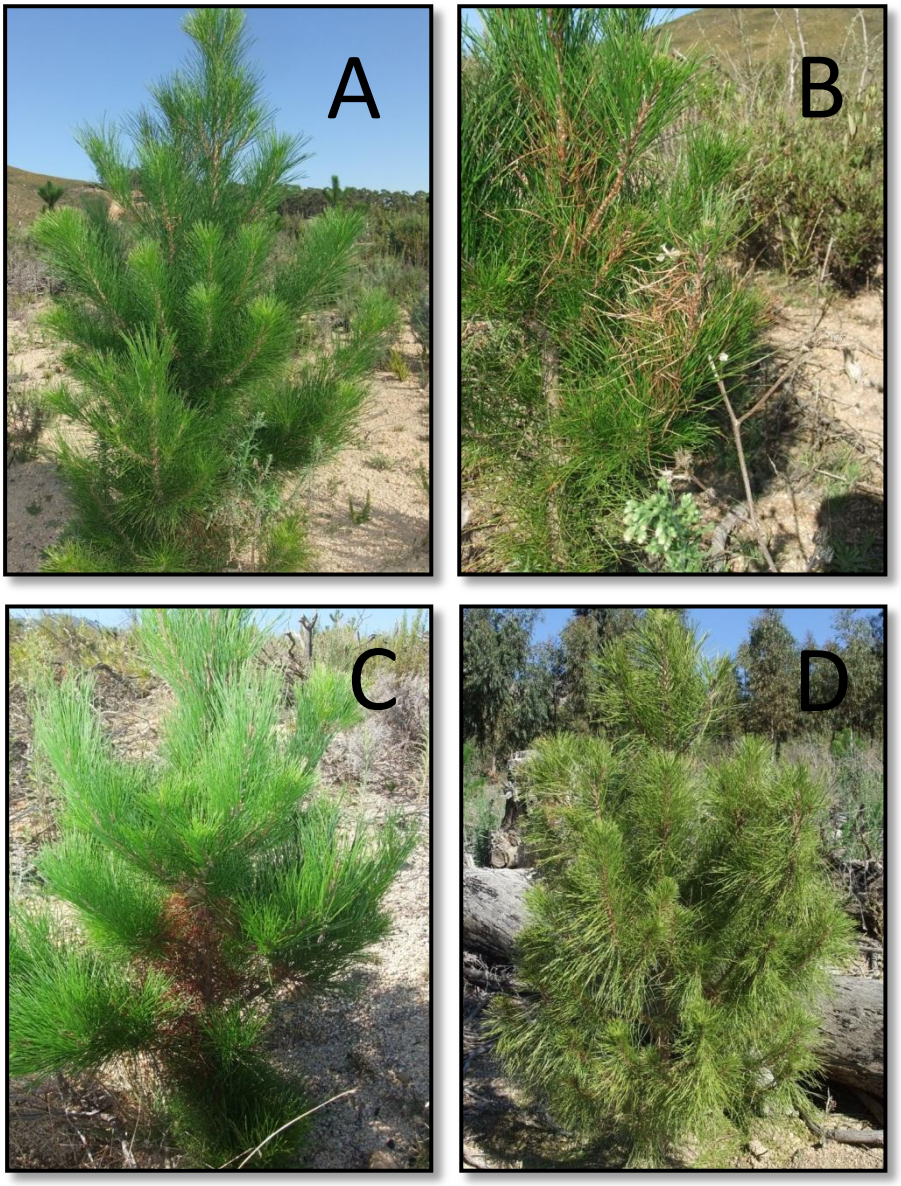


Figure 4.2: Visual symptoms used for the diagnosis of the *Fusarium circinatum* infections.

Table 4.5: Spread of trees classified in each disease level category

	Disease incidence 10/04/12	Disease incidence 14/02/13	% change
Total assessed	1764	1673	- 5.16
Level 0	1192	1318	+ 11.53
Level 1	515	353	- 29.4
Level 2	57	2	- 71.43

Table 4.6: Non-parametric results of *F. circinatum* disease incidence analysis across all treatments on the Coetzenburg site. Different letters indicate significant differences ($p<0.05$)

Kruskal-Wallis ANOVA by Ranks: H (23, N= 120) =35.31468 *p* =.0484*		
Treatment	**Sum of Ranks**	**Mean Rank**
CVH000	29.0000	5.80000 A
CVH322	76.0000	15.20000 A
Control	218.5000	43.70000 B
CRF322	233.5000	46.70000 B
CRF210	239.5000	47.90000 B
CRF310	254.0000	50.80000 B
CRF312	260.5000	52.10000 B
CV322	266.5000	53.30000 B
CRF220	271.5000	54.30000 B
CRF320	299.5000	59.90000 B
CV310	330.0000	66.00000 B
CRF120	335.5000	67.10000 B
CRF311	338.0000	67.60000 B
CV112	340.5000	68.10000 B
CRF212	341.0000	68.20000 B
CRF112	343.0000	68.60000 B
CRF222	356.5000	71.30000 B
CRF110	369.5000	73.90000 B
CRF221	374.5000	74.90000 B
CRF122	378.5000	75.70000 B
CRF121	391.0000	78.20000 B
CRF211	397.5000	79.50000 B
CRF321	404.5000	80.90000 B
CRF111	411.5000	82.30000 B

A significant P-value (p=0.0484) indicated that there were differences among treatments. The *P. elliottii x caribaea* treatments, CVH000 and CVH322, was statistically different to all other treatments. CVH000 and CVH322 had the lowest disease incidence with the control treatment displaying the least mean disease incidence of the *P. radiata* treatments. The observation that the hybrid control had a lower disease incidence than its fertilized counterpart, and that the same was true for the *P. radiata* control, suggests a likely fertilizer x disease interaction, however an investigation into the effect of different levels of N, P and K fertilizer application on the disease incidence percentage proved inconclusive with no significant differences between varying levels of application.

4.4. Soil water availability

For the first three months the SWC was erratic with three distinct intermittent peaks and drops (Figure 4.3). September 2010 was a very dry month and the REW was well below the 0.4 water stress inducing threshold (Figure 4.4). An uncharacteristically high SWC was modelled from October 2010 to the start of January 2011, where the SWC eventually reaches the lower limit of water availability by the end of the latter month. The trend did not change significantly until the onset of the wet season in late May 2011. The results for the period that followed was as expected. A clear seasonal pattern was observed with clear dry and wet periods in the summer and winter months respectively. The odd sporadic rainfall event in the spring and autumn months brought temporary stress relief to the trees. These results are similar to the seasonal trends found in Fischer (2011) for the Boland region, which forms part of the winter rainfall zone.

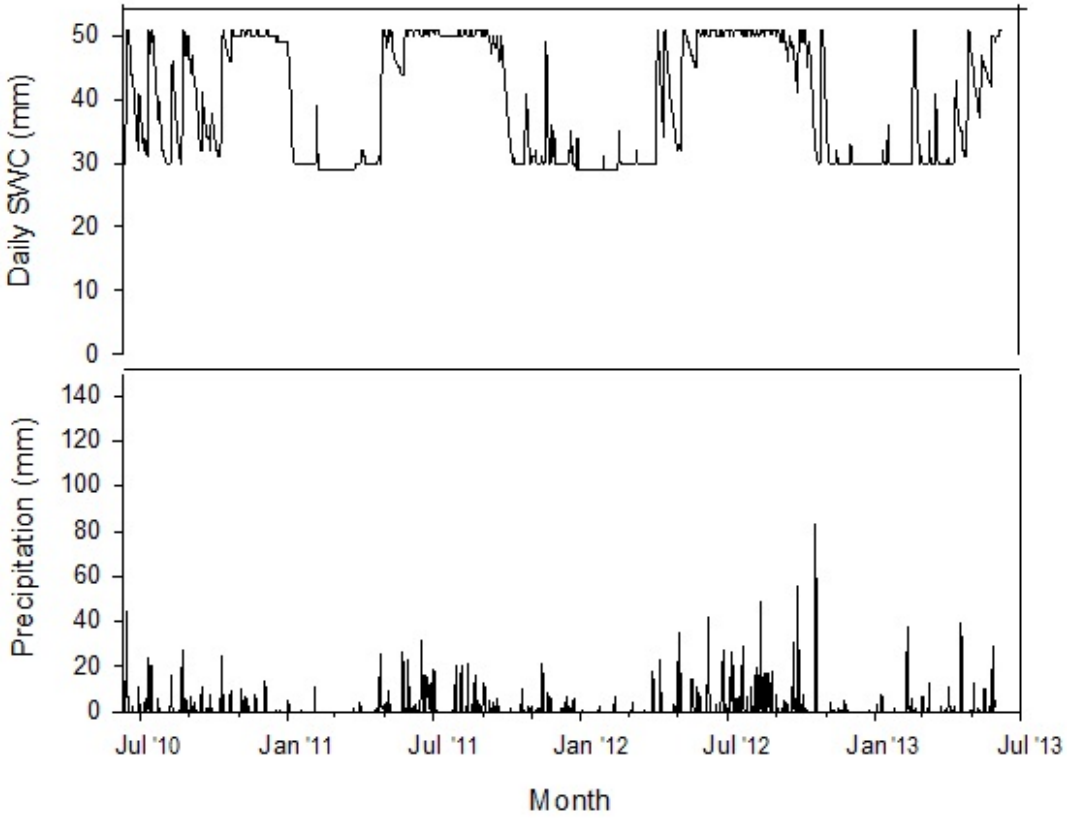


Figure 4.3: Coetzenburg modelled daily SWC vs. daily precipitation from 1 June 2010 till 1 July 2013.

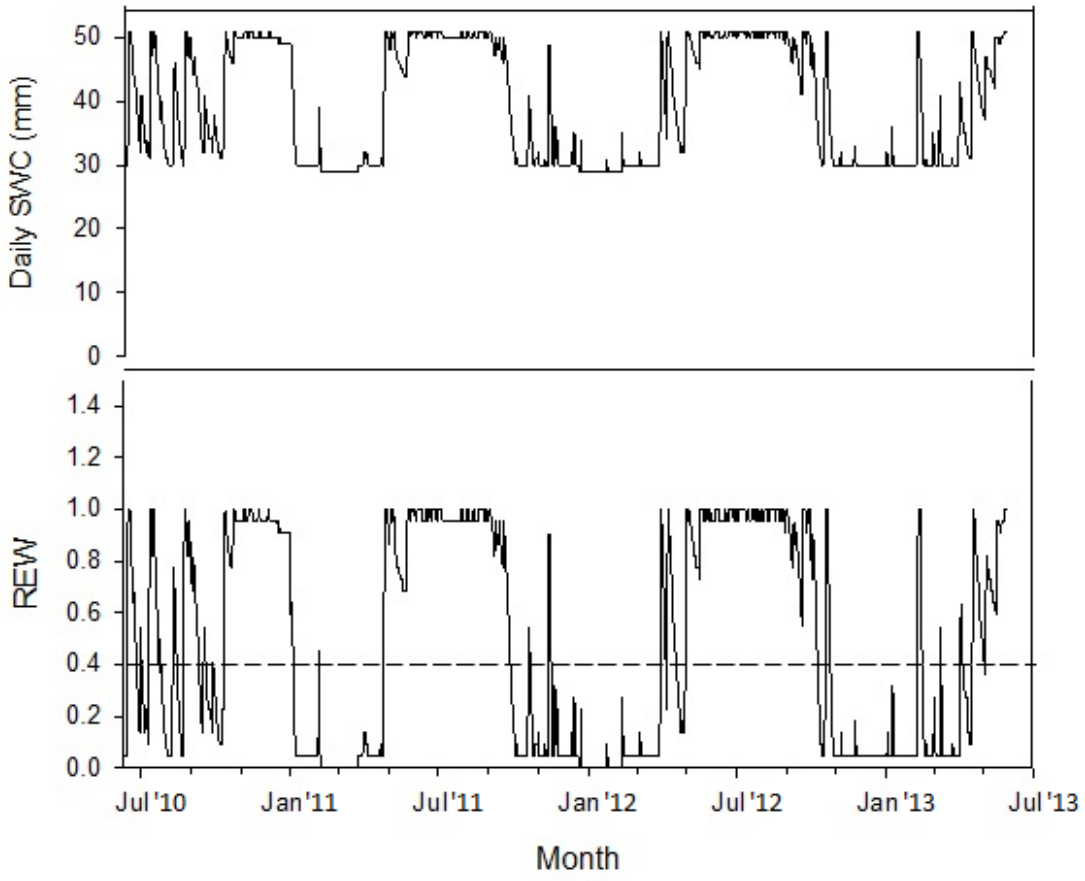


Figure 4.4: Coetzenburg modelled daily SWC vs. daily REW for the period 1 June 2010 to 1 July 2013.

4.5. Biomass index growth

The results (non-significant output not shown) of the full ANOVA analysis showed that there was no significant (p<0.05) interaction between N x P (p=0.8207), N x K (p=0.7319), P x K (p=0.5197) and N x P x K (p=0.624). The effects of the main factors N (p=0.6038), P (p=0.6608) and K (p=0.5033) were non-significant (p<0.05) on the BI growth across all three measurement periods. The fourth factor, time, which is the repeated measure in the analysis was significant (p=0.000). This is to be expected, as the BI equation contains a squared term, which would result in an exponential increase in the BI value over time (Figure 4.5).

The trees that did not show signs of *F. circinatum* infection (the healthy subset) were analysed separately to gauge the effect of fertilization in the absence of disease influences. The results of the healthy trees data subset that was prepared as described in Section 3.7.1.2 was more conclusive (Table 4.7). There was a

significant interaction between N x K (p<0.01) and N x P x K (p<0.01). Figure 4.6 and Figure 4.7 show these interactions for the mean BI over 12, 18 and 32 months.

Table 4.7: ANOVA output of the healthy tree subset for the CRF factorial treatments. Significant effects shown in red.

Repeated measures ANOVA: CRF Factorial treatments					
Effect	**SS**	**Degree Of freedom**	**MS**	**F**	**p**
Intercept	2025473	1	2025473	1590,859	0,000000
N	5916	2	2958	2,323	0,098963
P	1096	1	1096	0,861	0,353977
K	2313	2	1156	0,908	0,403833
N*P	3258	2	1629	1,280	0,279007
N*K	18873	4	4718	3,706	0,005497
P*K	6535	2	3268	2,566	0,077780
N*P*K	27111	4	6778	5,323	0,000330
Error	664608	522	1273		
TIME	2547649	2	1273825	1367,096	0,000000
TIME*N	10871	4	2718	2,917	0,020469
TIME*P	1476	2	738	0,792	0,453274
TIME*K	4235	4	1059	1,136	0,337906
TIME*N*P	3072	4	768	0,824	0,509824
TIME*N*K	26668	8	3333	3,578	0,000418
TIME*P*K	6378	4	1595	1,711	0,145186
TIME*N*P*K	40457	8	5057	5,427	0,000001
Error	972772,3	1044	931,7743		

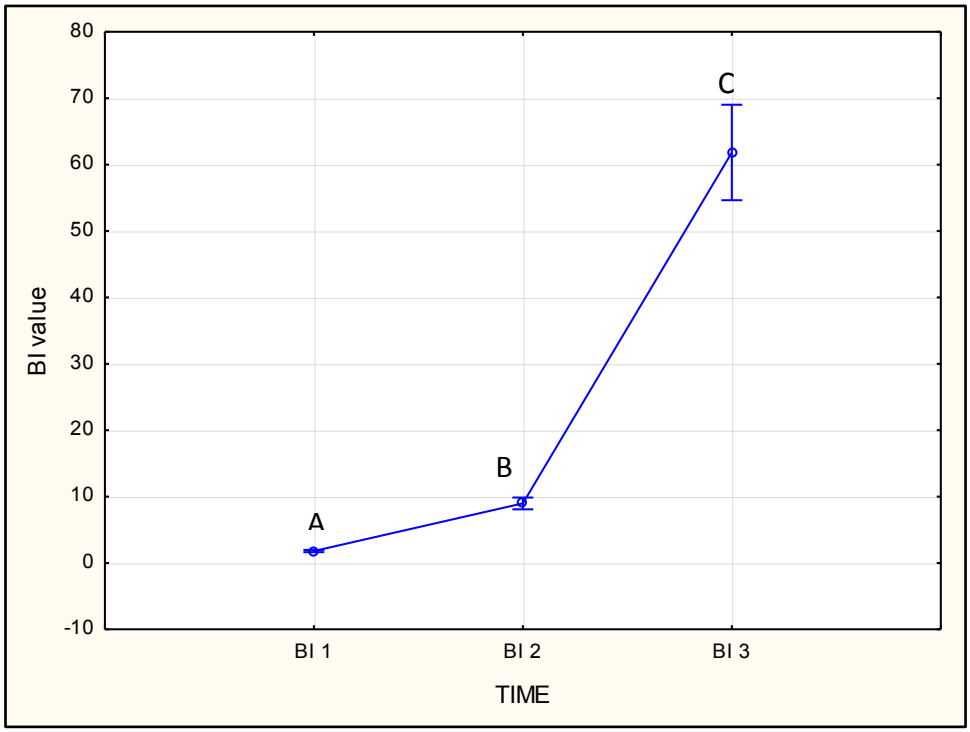


Figure 4.5: The trend of increase in mean BI across CRF treatments over time Period 1 = summer (December 2010) through to winter (July 2011), period 2 = winter (July 2011) through to summer (December 2011) and Period 3 = A full rotation of the four seasons (December 2011 to February 2013).

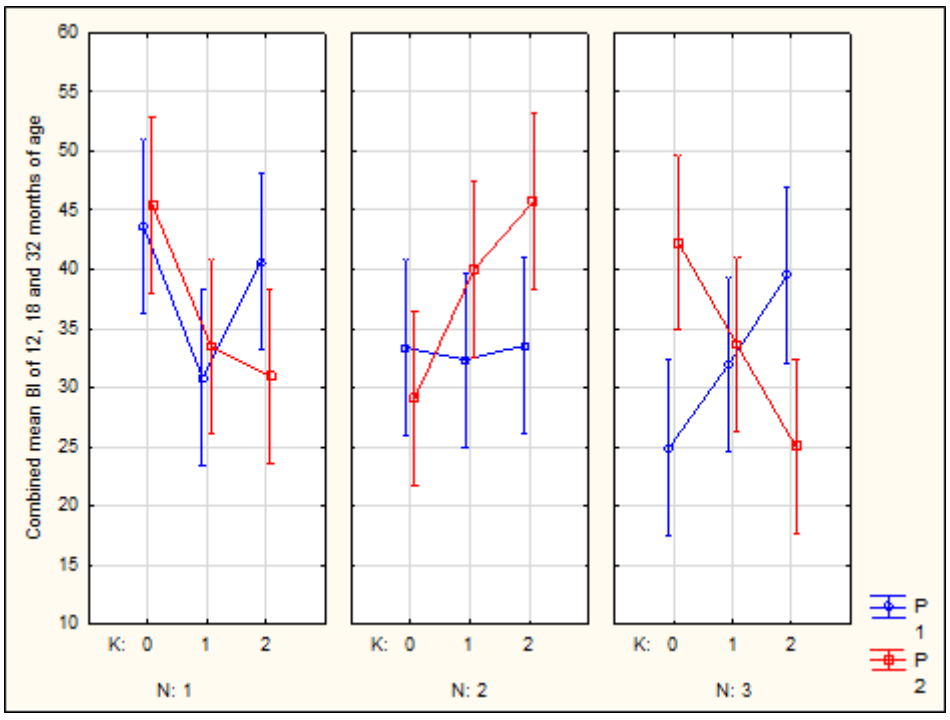


Figure 4.6: Significant N x P x K interaction for the healthy tree subset of the Coetzenburg BI data.

The N x P x K interaction (Figure 4.6) is discussed in regard to the three N levels. For level 1 N application, there is a decrease in growth with an increasing K application for both levels of P applied, with the exception of level 2 K in combination with level 1 P. For level 2 applications of N, the growth across all K application levels is the same with level 1 P applied and growth sharply increases with increasing applications of K in combination with level 2 P. It appears that a balanced N:P:K ratio is needed with treatment N2P2K2 yielding the best results. At the highest level of N application, the relationship between increasing levels of K in combination with the two levels of P show inverse trends. BI growth increases with an increase in K application in combination with level 1 P and decreases in combination with level 2 P.

Figure 4.7 shows the growth of the *P. elliottii* x *caribaea* hybrid compared to *P. radiata* in control and fertilized treatments. From this limited comparison, it appears that *P. radiata* is more responsive to fertilizer application than the *P. elliottii x caribaea* hybrid.

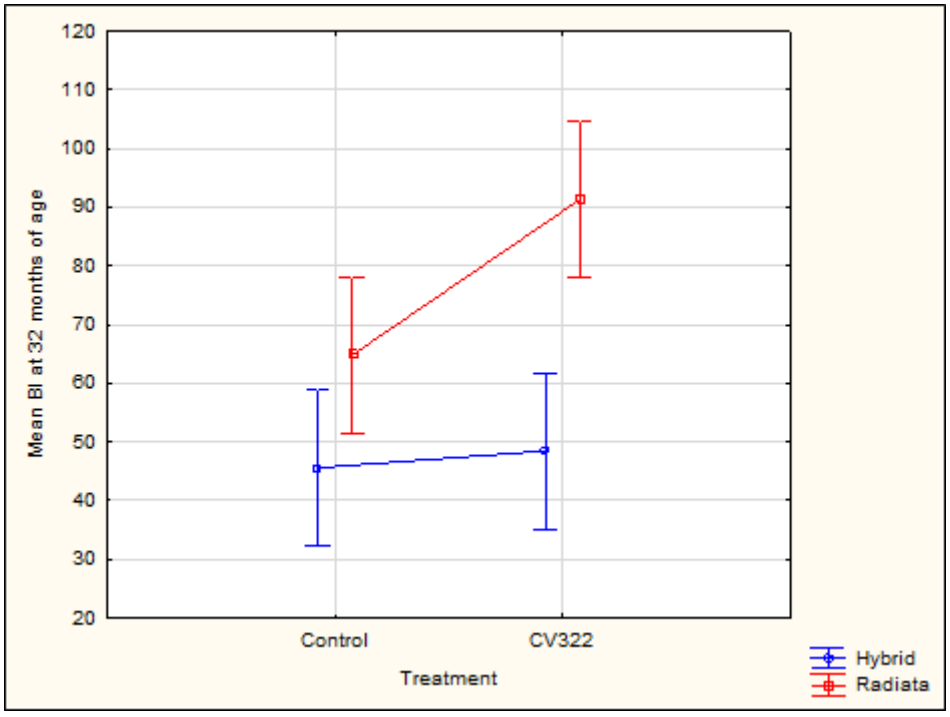


Figure 4.7: The growth response to fertilizer application of *P. elliottii x caribaea* hybrid compared to *P. radiata*.

Figures 4.8, 4.9 and 4.10 show the responses in respect of N, P and K, of the three CRF treatments (CRF112, CRF310 and CRF322), as identified for use as direct comparisons with their CV counterparts, as mentioned in Section 3.3.1.

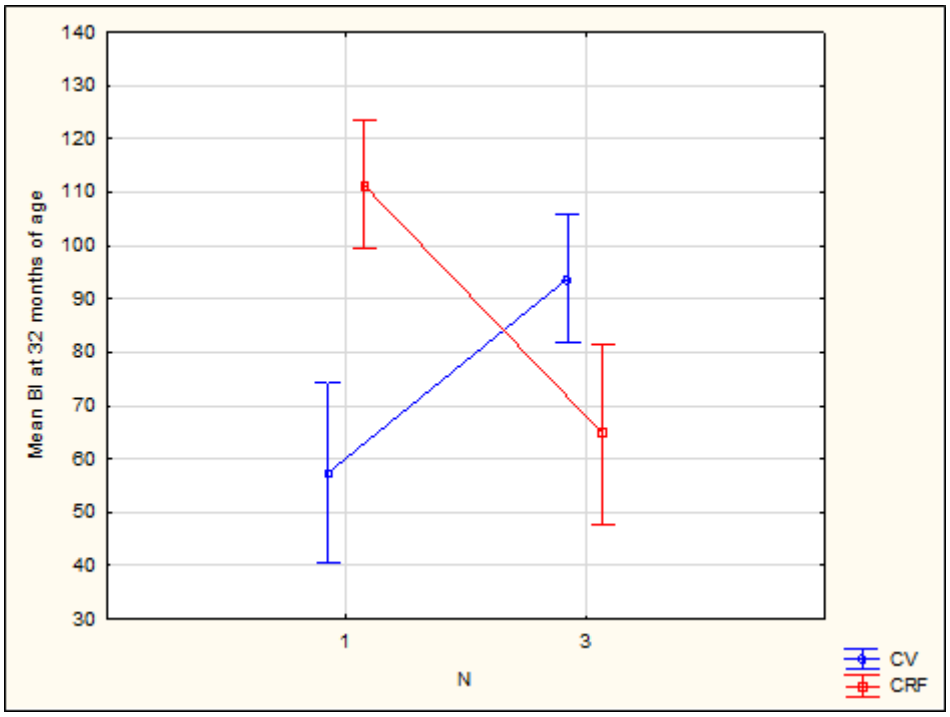


Figure 4.8: The growth response of the direct comparison treatments to comparable levels of N application from the two different fertilizer sources. Trees responded to higher levels of N when applied in the CV form but similar responses are seen with lower applications of N in the CRF form.

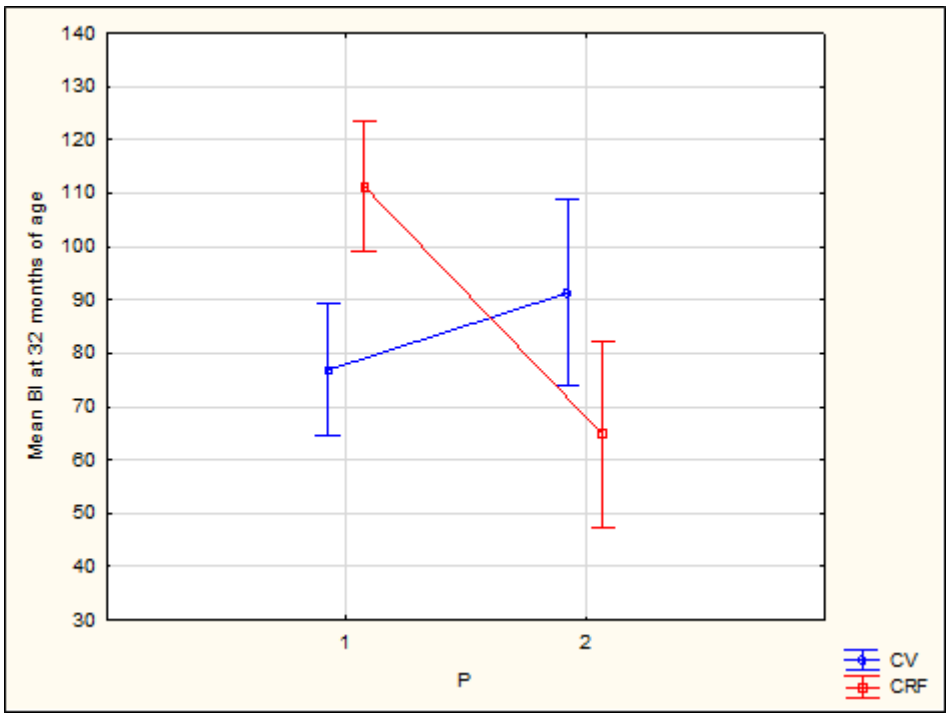


Figure 4.9: The growth response of the direct comparison treatments to comparable levels of P application from the two different fertilizer sources. Trees respond better to low levels of silphos over higher levels of double superphosphate.

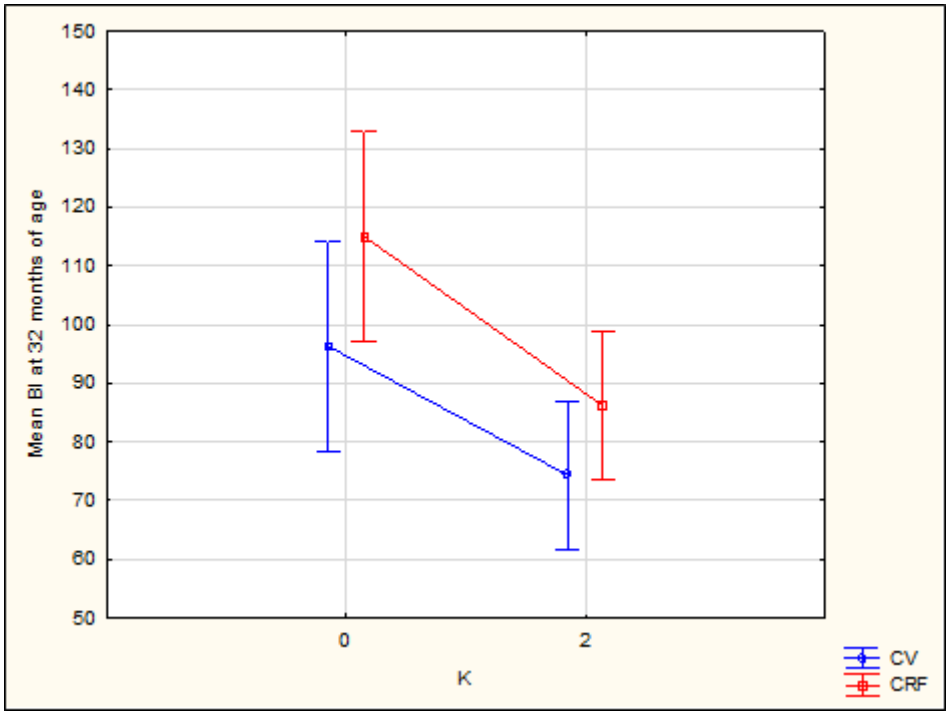


Figure 4.10: The growth response of the direct comparison treatments to comparable levels of K application from the two different fertilizer sources.

The top three CRF treatments overall were CRF222, CRF120 and CRF110 with each having a combined mean BI that reached approximately 45. These three were not statistically different from one another but were different to both the hybrid treatments (CVH000 BI=18, CVH322 BI=19.3), CV112 (BI=23.1), CRF322 (BI=25), CRF310 (BI=25.4) and the control (BI=25) treatment. Of the three CRF treatments chosen for comparison with the equivalent CV sources, none performed statistically better (p<0.05) than their CV counterparts. Only CRF112 (BI=39) had a higher combined mean BI than its CV112 (BI=23.1) equivalent.

The percentage differences in ht and GLD of CRF110, CRF120 and CRF222 over the control at 32 months are shown in Table 4.8. The results are similar to those found by the study conducted by Fan *et al*. (2002) discussed in Section 2.3.

Table 4.8: Percentage increase in ht and GLD of treatments CRF110, CRF120 and CRF222 over the control at 32 months of age

	% Difference over control	
Treatment	**ht**	**GLD**
CRF110	16.1	17.5
CRF120	14.36	20
CRF222	19.5	20.2

Chapter 5: Results B

5.1 Early survival

Mean seedling mortality was lowest on the Flatcrown site (4 % mortality) and acceptably low according to industry standards, on the Mtunzini and Woolstone sites, with a mean mortality of 11 % and 6 % respectively. The effect of site and treatment were investigated on the mean mortality of the seedlings. A significant (p<0.05) site effect was found between Mtunzini and the other two sites (Table 5.1). The significantly higher mortality at Mtunzini was not directly caused by site conditions, but of a weevil outbreak in the stand 4 – 5 weeks after treatment application. Across all three sites, there were no significant differences in the mortality rate between the CRF treatment combinations, the CV treatment or the control.

No significant interaction was found between the two factors (fertilizer N and P) on mortality rates across any of the sites. This allowed for the main effects on mean mortality to be interpreted separately. The influence of an increasing N level on mortality was non-significant on all sites, while an increasing P level was significant on the Flatcrown site only (Table 5.1). An increase in the level of application from 0 to 20 g P per tree resulted in a non-significant increase in the mean treatment mortality from 2.75 % to 4.75 % (Figure 5.1).

The situation at Woolstone was not any different from the other two sites. There were no significant trends in mortality with levels ranging from 4 to 9% across all treatments.

5.2 Foliar analysis

5.2.1 Critical levels

The *E. grandis* x *urophylla* foliar samples were subjected to full chemical analysis as described in Section 3.6.3. The published critical values for *E. grandis x urophylla* were used as described by Dell *et al.* (1995). Refer to Table 5.2 and Table 5.3 for the critical level results.

Table 5.1: Statistical results of mean mortality percentage between site, treatment and main effect of experimental factors

Effect	Non-parametric test P-value
Comparison of Mean Mortality between sites	
Site	>0.001**
Comparison between Treatments at each site	
Mtunzini	0.666
Flatcrown	0.1157
Woolstone	0.5794
Influence of main effects on mortality at each site	
Mtunzini	
N level	0.46495
P level	0.44273
Flatcrown	
N level	0.84983
P level	0.00402*
Woolstone	
N level	0.67555
P level	0.18133

** $p<0.001$ *$p<0.05$

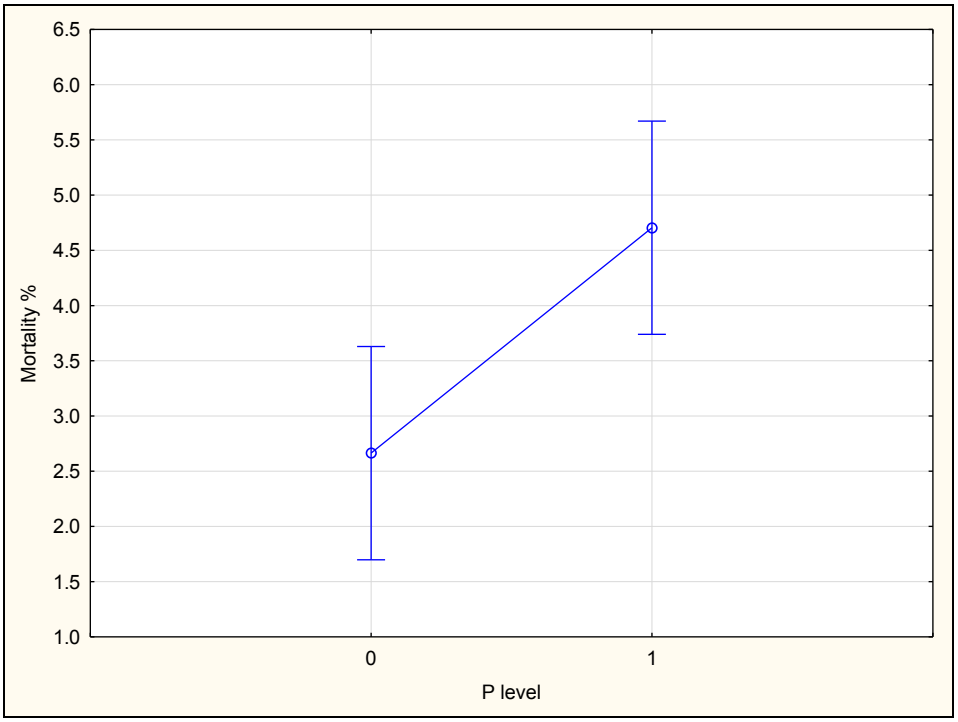


Figure 5.1: Significant P level effect on the mean mortality of treatment plots on the Flatcrown site.

Table 5.2: Mtunzini foliar nutrient concentrations nine months after treatment application assessed according to the critical values determined by Dell *et al.* (1995)

Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
	%					mg/kg					
Control	1.85	0.24	0.83	0.93	0.35	4395	189	105	7	17	31
CRF10	1.81	0.23	0.72	0.97	0.34	3886	221	101	7	16	30
CRF11	1.78	0.23	0.80	0.97	0.33	3755	172	100	6	15	31
CRF20	2.02	0.21	0.73	0.91	0.32	4044	171	99	7	16	30
CRF21	1.82	0.23	0.76	0.94	0.32	3706	242	98	6	15	32
CRF30	2.00	0.19	0.74	1.02	0.33	3829	211	102	6	15	32
CRF31	1.97	0.20	0.70	1.01	0.33	3568	216	99	5	15	33
CV01	1.81	0.26	0.94	0.91	0.35	4170	160	95	8	19	30
CV11	1.83	0.25	0.78	0.97	0.35	3890	195	99	7	18	30
Deficient	0.8-1.1	0.08-0.1	0.2-0.6	n/a	0.02-0.04	n/a	n/a	n/a	n/a	n/a	8-12
Marginal	1.11-1.8	0.1-0.15	0.6-0.9	<0.21	0.04-0.1	n/a	n/a	n/a	n/a	n/a	12-13
Adequate	1.8-2.9	0.15-0.26	0.9-1.5	0.21-0.75	0.11-0.36	3000-4200	134-2316	40-100	3.5-13.4	13-29	13-30
Toxic	n/a	n/a	n/a	n/a	n/a	>10000	n/a	n/a	n/a	n/a	n/a

*Non shaded cells = Adequate values; Shaded cells = Marginal concentrations

n/a = not available/applicable

Table 5.3: Flatcrown foliar nutrient concentrations nine months after treatment application assessed according to the critical values determined by Dell *et al.* (1995)

Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
	%					mg/kg					
Control	2.48	0.17	1.09	0.98	0.29	2528	349	163	10	18	28
CRF10	2.46	0.16	0.90	1.08	0.30	2245	350	161	9	18	29
CRF11	2.37	0.17	0.92	0.95	0.28	2376	289	172	8	17	31
CRF20	2.53	0.17	1.07	1.00	0.25	2408	365	156	9	20	30
CRF21	2.73	0.19	4.00	0.88	0.30	3075	367	306	10	31	35
CRF30	2.92	0.17	1.11	0.93	0.27	1957	315	177	9	23	35
CRF31	2.80	0.16	1.05	0.98	0.26	2026	311	164	8	17	34
CV01	2.16	0.18	0.93	0.96	0.30	2675	328	165	9	18	27
CV11	2.57	0.16	0.92	0.96	0.27	2066	360	168	9	17	31
Deficient	0.8-1.1	0.08-0.1	0.2-0.6	n/a	0.02-0.04	n/a	n/a	n/a	n/a	n/a	8-12
Marginal	1.1-1.8	0.1-0.15	0.6-0.9	<0.21	0.04-0.1	n/a	n/a	n/a	n/a	n/a	12-13
Adequate	1.8-2.9	0.15-0.26	0.9-1.5	0.21-0.75	0.1-0.36	3000-4200	134-2316	40-100	3.5-13.4	13-29	13-30
Toxic	n/a	n/a	n/a	n/a	n/a	>10000	n/a	n/a	n/a	n/a	n/a

*Non shaded cells = Adequate values; Shaded cells = Marginal concentrations

n/a = not available/applicable

On the Mtunzini site all elements for all treatments were at adequate concentrations except for N and K (Table 5.2). The N concentration for CRF11 was just outside the adequate range. The 0.02 % difference between marginal and adequate can be deemed negligible. The concentration of K for all treatments except CRF31 was marginal but had minimal negative effects on the growth as CRF31. On the Flatcrown site, all the nutrient concentrations fell well within their adequate ranges (Table 5.3).

ANOVA of the macro and micronutrient values of Mtunzini and Flatcrown resulted in significant nutrient differences for some elements and treatments (Table 5.4.) Refer to Figures 5.2 to 5.8 for the effect of N and P fertilizer treatments on the foliar concentrations of the four (P, K, Mg, Fe) significant nutrient concentration responses at Mtunzini and three significant nutrient concentration responses at Flatcrown (N, Fe, Cu).

At Mtunzini, significant responses were found for P, K, Mg and Fe concentrations. The application of N had the most significant effect on foliar nutrient concentration values. Reductions in foliar P, K and Mg concentrations were found with increases in N application. Fe concentrations increased significantly with N applications up to 80 g per tree. There was no significant difference in foliar nutrient concentrations between comparable CV and CRF treatments.

At Flatcrown, the foliar N concentration increased with higher N applications with no additive P effect. Treatments with no N application were still well within the adequate range of Dell *et al.* (1995). The Fe concentrations decreased from N level 0 to 1, then subsequently increased from level 1 to 3 with P having an additive effect at N levels 0 and 3. The CV11 treatment had a significantly higher Fe concentration, with nearly double the foliar Fe than its CRF11 counterpart. N application had the opposite effect on foliar Cu concentrations than it did on Fe concentrations. Increases in Cu concentration were found from level 0 to 1, for N application in combination with level 1 P, and from level 0 to 2 for N applied singly. CV11 had lower non-significant foliar Cu concentrations than CRF11.

Table 5.4: Foliar nutrient concentration ANOVA results for both Mtunzini and Flatcrown. Nutrients with significant differences shown in red.

Analysis of variance results of Foliar nutrient concentration					
Mtunzini nutrient concentration significant differences					
		P			
Effect	SS	Degree Of freedom	MS	F	p
N level	0.021373	3	0.007124	22.119	0.000000
P level	0.002269	1	0.002269	7.044	0.011357
N level * P level	0.000273	3	0.000091	0.282	0.837750
		K			
N level	0.21803	3	0.07268	7.423	0.000458
P level	0.03000	1	0.03000	3.064	0.087694
N level * P level	0.03137	3	0.01046	1.068	0.373494
		Mg			
N level	0.008675	3	0.002892	7.14	0.000596
P level	0.000000	1	0.000000	0.00	1.000000
N level * P level	0.000317	3	0.000106	0.26	0.853311
		Fe			
N level	862.0	3	287.3	3.772	0.017860
P level	40.3	1	40.3	0.529	0.471087
N level * P level	147.0	3	49.0	0.643	0.591787
Flatcrown nutrient concentration significant differences					
		N			
Effect	SS	Degree Of freedom	MS	F	p
N level	1.0268	3	0.3423	9.652	0.000710
P level	0.0408	1	0.0408	1.152	0.299140
N level * P level	0.2040	3	0.0680	1.918	0.167433
		Fe			
N level	11233.3	3	3744.4	17.902	0.000023
P level	2521.5	1	2521.5	12.055	0.003144
N level * P level	2476.5	3	825.5	3.947	0.027746
		Cu			
N level	5.458	3	1.819	4.367	0.019911
P level	0.042	1	0.042	0.100	0.755918
N level * P level	2.792	3	0.931	2.233	0.123791

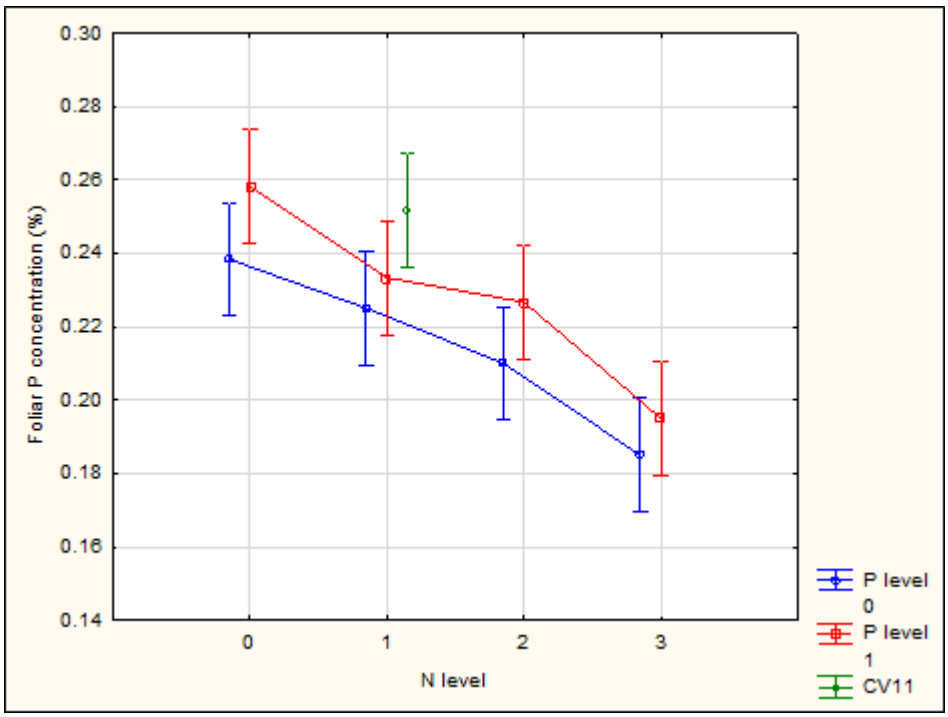


Figure 5.2: Foliar P concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Mtunzini.

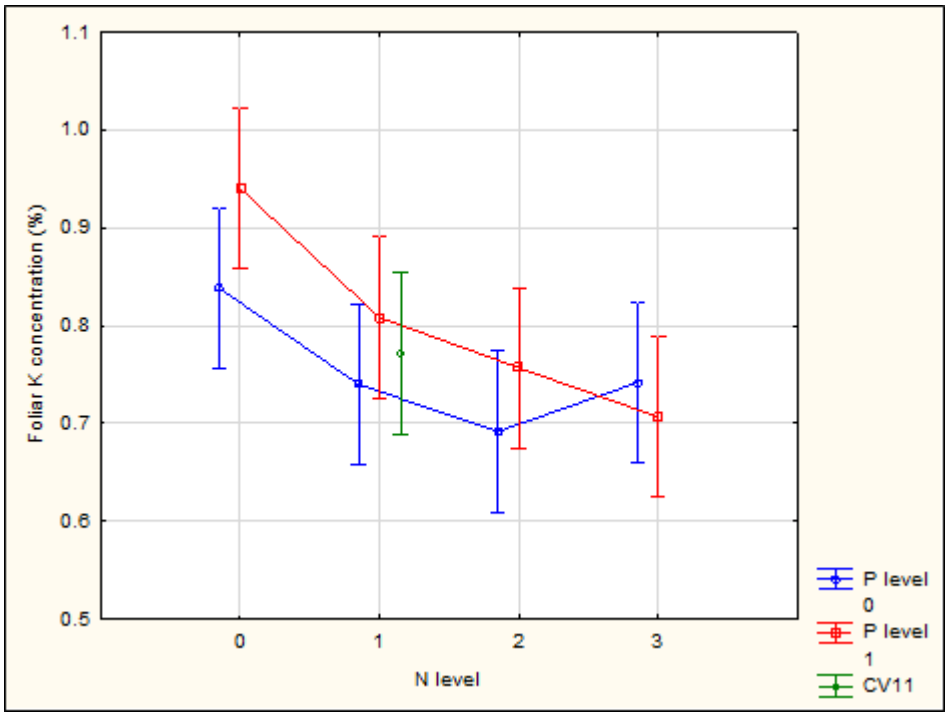


Figure 5.3: Foliar K concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Mtunzini.

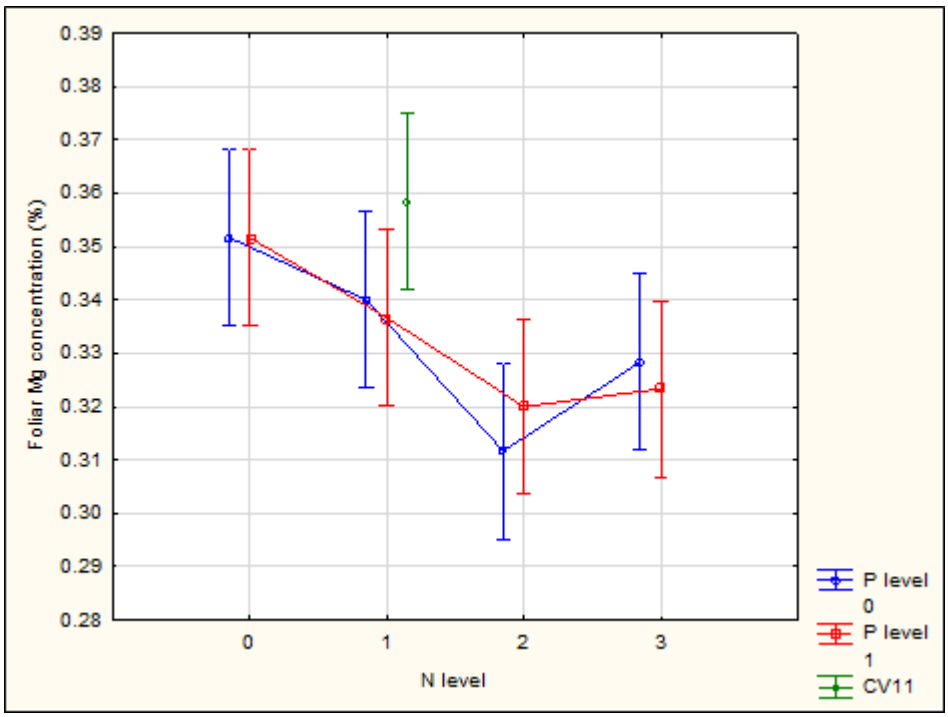


Figure 5.4: Foliar Mg concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Mtunzini.

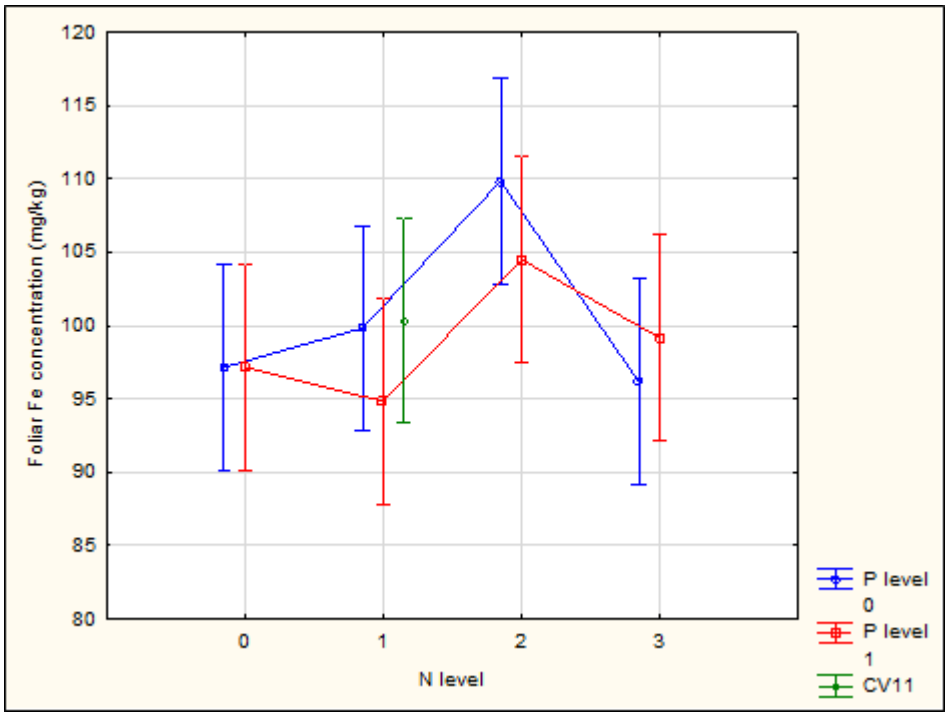


Figure 5.5: Foliar Fe concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Mtunzini.

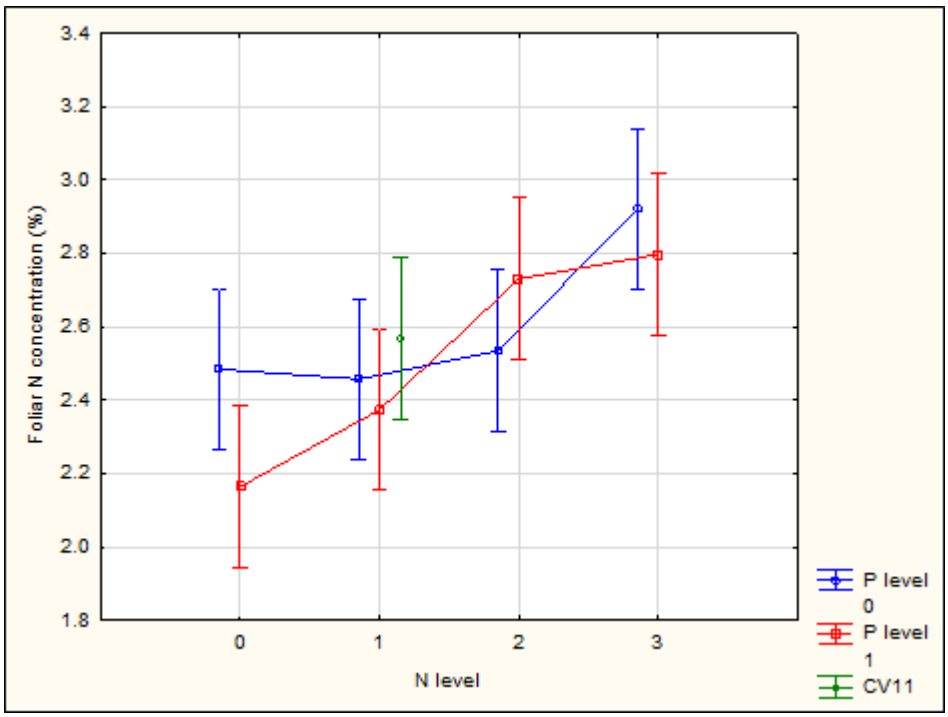


Figure 5.6: Foliar N concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Flatcrown.

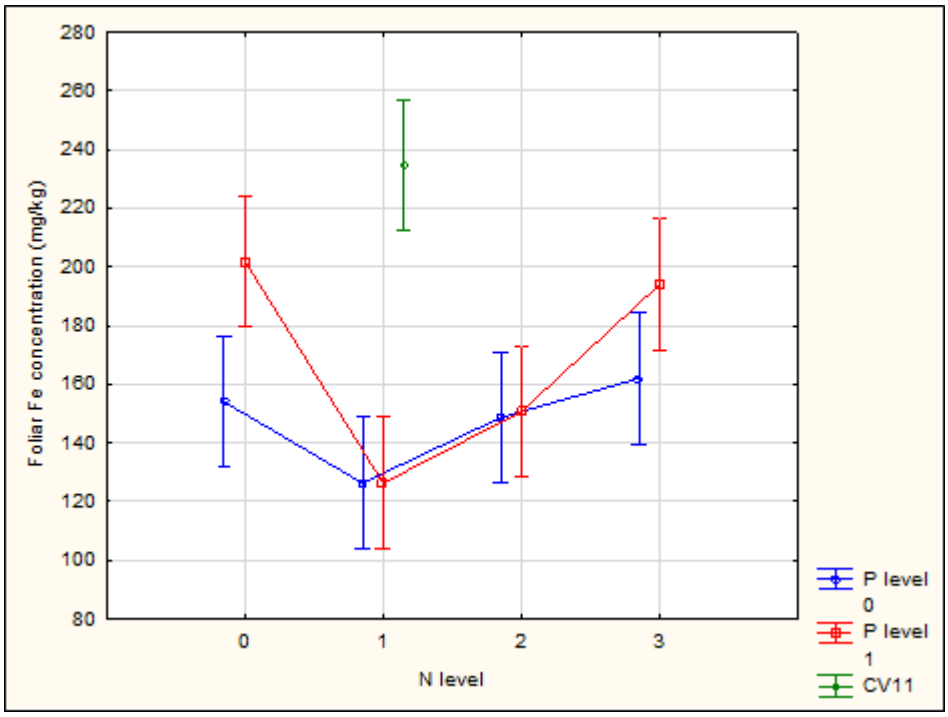


Figure 5.7: Foliar Fe concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Flatcrown.

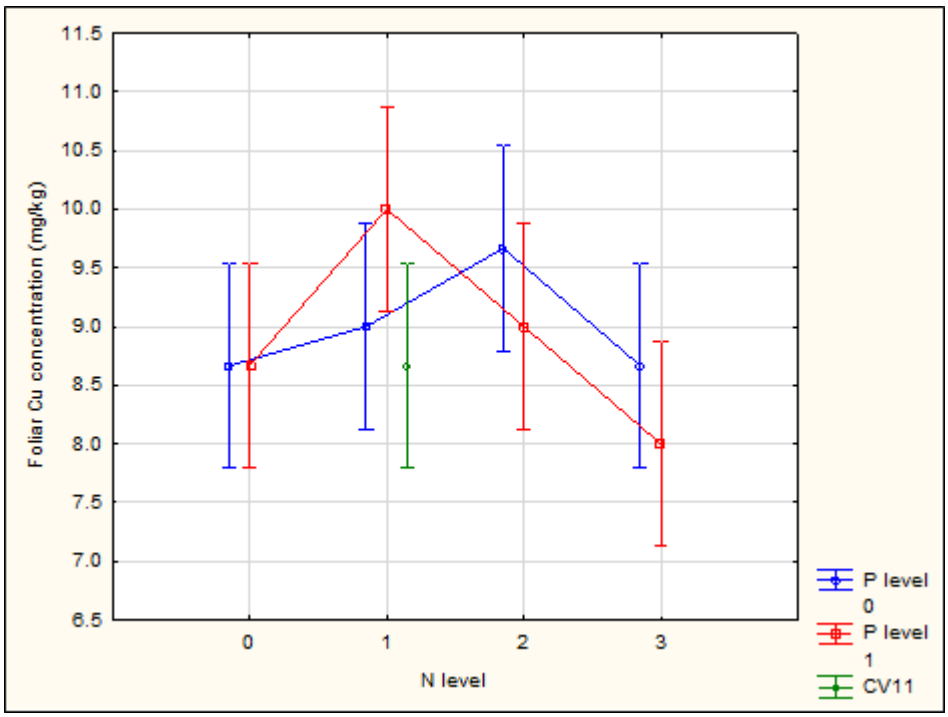


Figure 5.8: Foliar Cu concentrations of the CRF factorial treatment combinations as well as the additional CV11 treatment at Flatcrown.

5.2.2 Vector analysis

All nine treatments on both Mtunzini and Flatcrown had notable vectors for N, P, K, Ca and Mg (Table 5.5; Table 5.6). Refer to **Appendix 3B** for the vector nomograms for both sites.

All of the responses were either of the type A, B or C (Table 2.2). Majority of the responses showed either a deficiency or a dilution effect. Level 1 N application on both sites with the exception of CV11 at Flatcrown (deficiency) all had dilution effects. Level 2 N application exhibited deficiencies all round with the exception of one dilution effect of CRF21 at Mtunzini. Level 3 N application clearly revealed deficiencies at both sites

Table 5.5: Summary of the macronutrient vector responses across all replications at Mtunzini

	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium	
Treatment	Interpretation	Diagnosis	Interpretation	Diagnosis	Interpretation	Diagnosis	Interpretation	Diagnosis	Interpretation	Diagnosis
CRF10	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting
CRF11	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting
CRF20	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting
CRF21	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting
CRF30	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting
CRF31	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting
CV01	Dilution	Non-limiting	Deficiency	Limiting	Deficiency	Limiting	Dilution	Non-limiting	Sufficiency	Non-limiting
CV11	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting	Deficiency	Limiting	Deficiency	Limiting

Table 5.6: Summary of the macronutrient vector responses across all replications at Flatcrown

	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium	
Treatment	Interpretation	Diagnosis	Interpretation	Diagnosis	Interpretation	Diagnosis	Interpretation	Diagnosis	Interpretation	Diagnosis
CRF10	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Deficiency	Limiting
CRF11	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting
CRF20	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting
CRF21	Deficiency	Limiting	Deficiency	Limiting	Deficiency	Limiting	Dilution	Non-limiting	Deficiency	Limiting
CRF30	Deficiency	Limiting	Sufficiency	Non-limiting	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting
CRF31	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting
CV01	Dilution	Non-limiting	Deficiency	Limiting	N/A	N/A	Dilution	Non-limiting	Deficiency	Limiting
CV11	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting	Dilution	Non-limiting

The cells demarcated as N/A represent instances where a response in unit dry weight, nutrient concentration and nutrient content did not match an interpretation as set out by Haase and Rose (1995).

5.3 Foliar nutrient content

An investigation into the foliar macronutrient contents at nine months for both sites revealed some significant differences (p<0.05). On the Mtunzini site there were significant treatment differences for all five macronutrients (Table 5.7).

Table 5.7: Analysis of variance results of significant increases in macronutrient foliar content at nine months of age for Mtunzini and Flatcrown. Significant effects shown in red.

Analysis of variance results of Foliar nutrient content					
Mtunzini nutrient content significant differences					
		N			
Effect	SS	Degree Of freedom	MS	F	p
N level	26.1810	3	8.7270	9.6528	0.000064
P level	9.8276	1	9.8276	10.8702	0.002056
N level * P level	3.4327	3	1.1442	1.2656	0.299146
		P			
N level	9.2073	3	3.0691	7.2560	0.000535
P level	5.6604	1	5.6604	13.3824	0.000733
N level * P level	1.7507	3	0.5836	1.3797	0.262881
		K			
N level	113.494	3	37.831	7.5840	0.000395
P level	63.340	1	63.340	12.6976	0.000965
N level * P level	19.847	3	6.616	1.3262	0.279311
		Ca			
N level	289.449	3	96.483	12.4382	0.000007
P level	87.134	1	87.134	11.2329	0.001765
N level * P level	31.935	3	10.645	1.3723	0.265093
		Mg			
N level	26.1810	3	8.7270	9.6528	0.000064
P level	9.8276	1	9.8276	10.8702	0.002056
N level * P level	3.4327	3	1.1442	1.2656	0.299146
Flatcrown nutrient content significant differences					
		N			
Effect	SS	Degree. Of freedom	MS	F	p
N level	9669.2	3	3223.1	4.4181	0.019136
P level	2.1	1	2.1	0.0028	0.958167
N level * P level	3885.1	3	1295.0	1.7752	0.192375
		K			
N level	1641.85	3	547.28	4.7428	0.014950
P level	21.67	1	21.67	0.1878	0.670511
N level * P level	1005.90	3	335.30	2.9057	0.066891

Figures 5.9 to 5.13 illustrate the influence of N and P application on the foliar contents of the five macronutrients at Mtunzini. For all five macronutrients there is a trend of increasing foliar contents with an increase in N application, while P application had an additive effect on nutrient uptake into the foliage.

Treatment combination CRF31 and CRF21 had the highest foliar contents of N, 22.3 kg ha^{-1} and 21.2 kg ha^{-1} respectively, while CV01 and the control treatment had the lowest contents at 5.9 kg ha^{-1}. The mean foliar N content for the site was only 13 kg ha^{-1}. For P, CRF21 had the highest value with 2.6 kg ha^{-1}, more than three times the content of the control. The mean foliar P content on the site was 1.5 kg ha^{-1}. As expected, treatments which included an application of P in combination with N were in the top positions for foliar N content with CRF21 having a significantly higher content than CV01. This is an indication that P accumulation in the foliar biomass of *E. grandis x urophylla* clones is improved when P is applied in conjunction with N. A similar trend was found for K, Ca and Mg content, with trees treated with combination CRF21 containing the highest mass of K, Ca and Mg per hectare at 8.8 kg ha^{-1}, 11 kg ha^{-1} and 3.7 kg ha^{-1} respectively. The macronutrient contents of CV11 were not significantly different to CRF11.

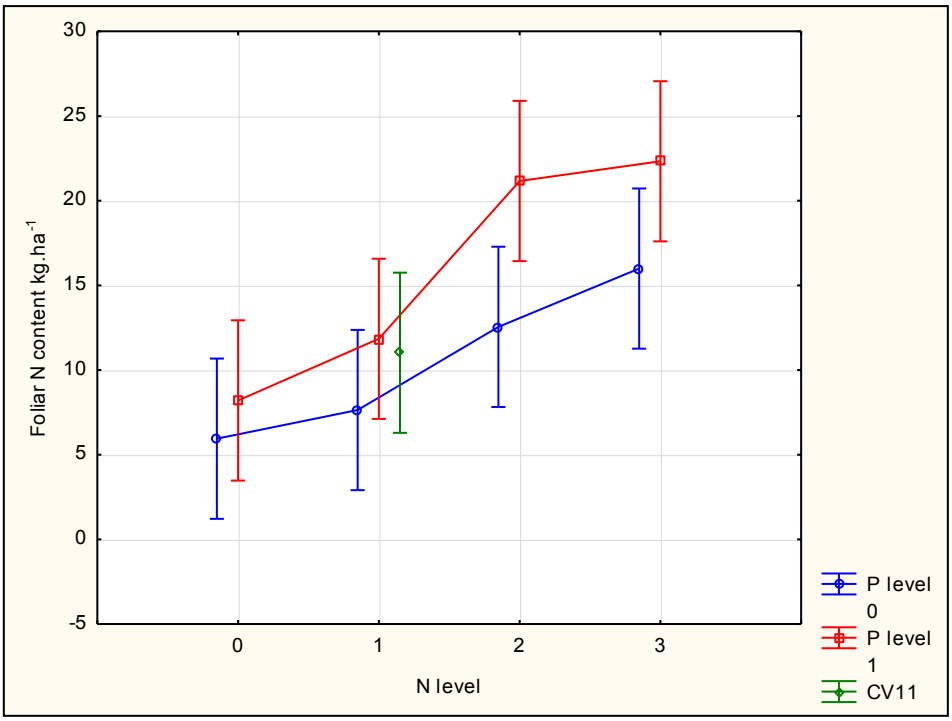


Figure 5.9: Foliar N contents for the eight factorial treatment combinations as well as the CV11 treatment at Mtunzini at nine months of age.

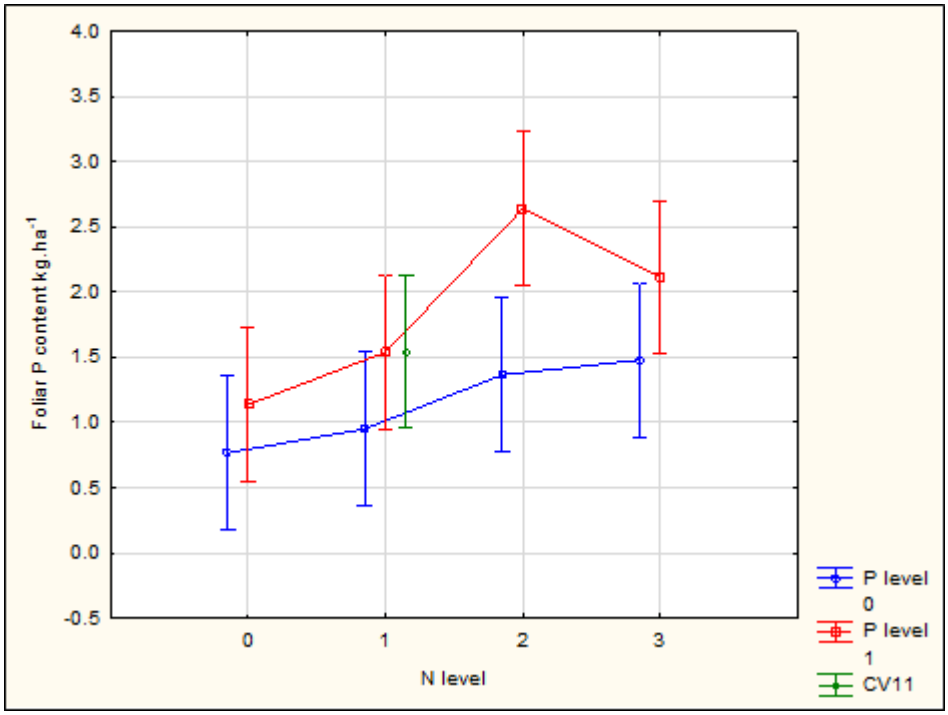


Figure 5.10: Foliar P contents for the eight factorial treatment combinations as well as the CV11 treatment at Mtunzini at nine months of age.

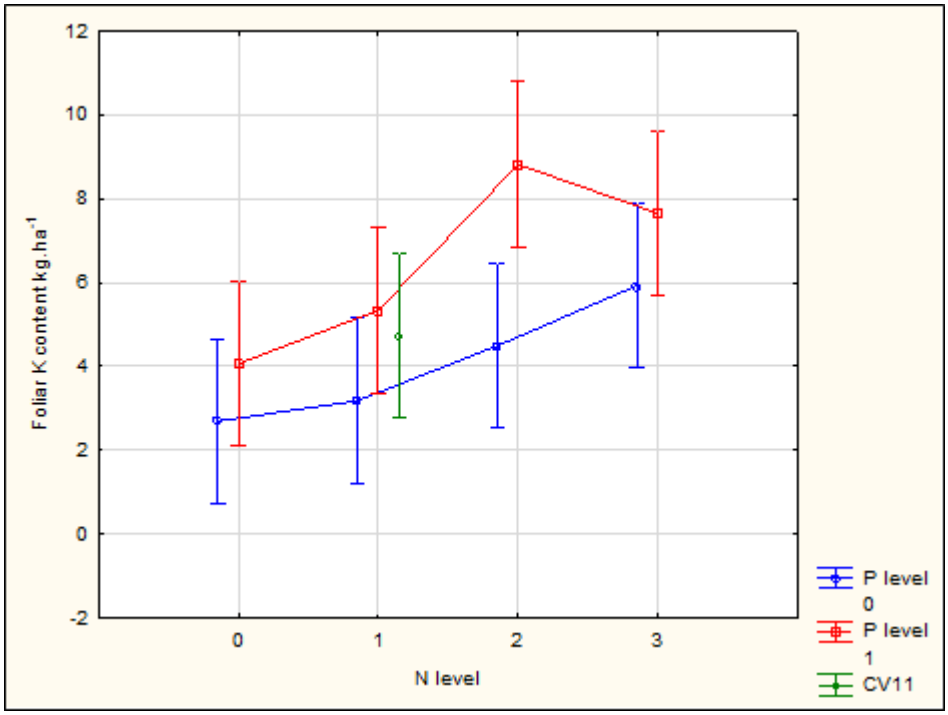


Figure 5.11: Foliar K contents for the eight factorial treatment combinations as well as the CV11 treatment at Mtunzini at nine months of age.

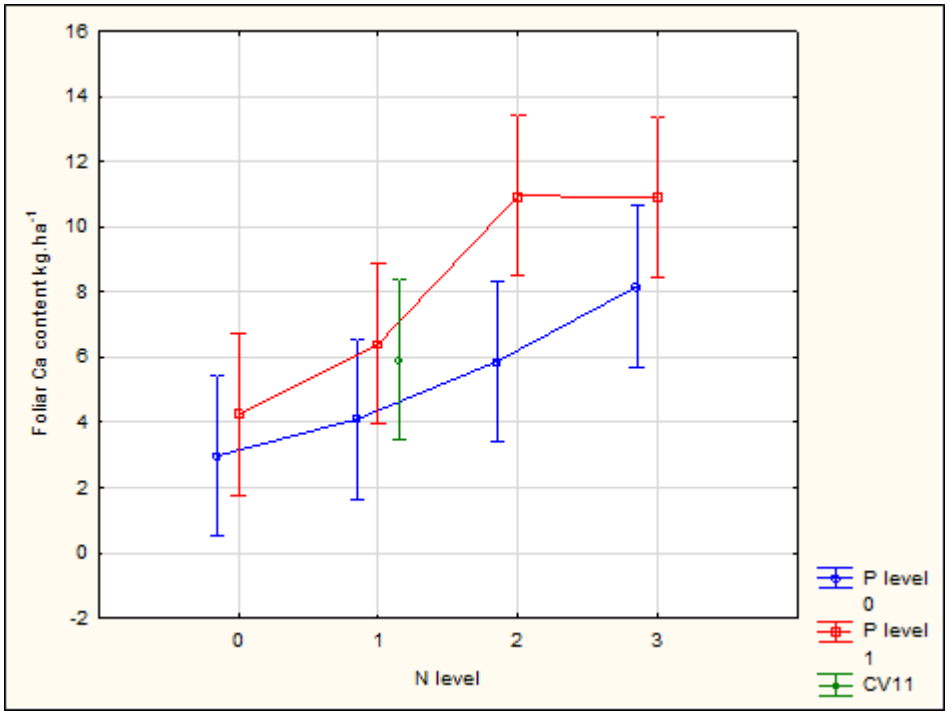


Figure 5.12: Foliar Ca contents for the eight factorial treatment combinations as well as the CV11 treatment at Mtunzini at nine months of age.

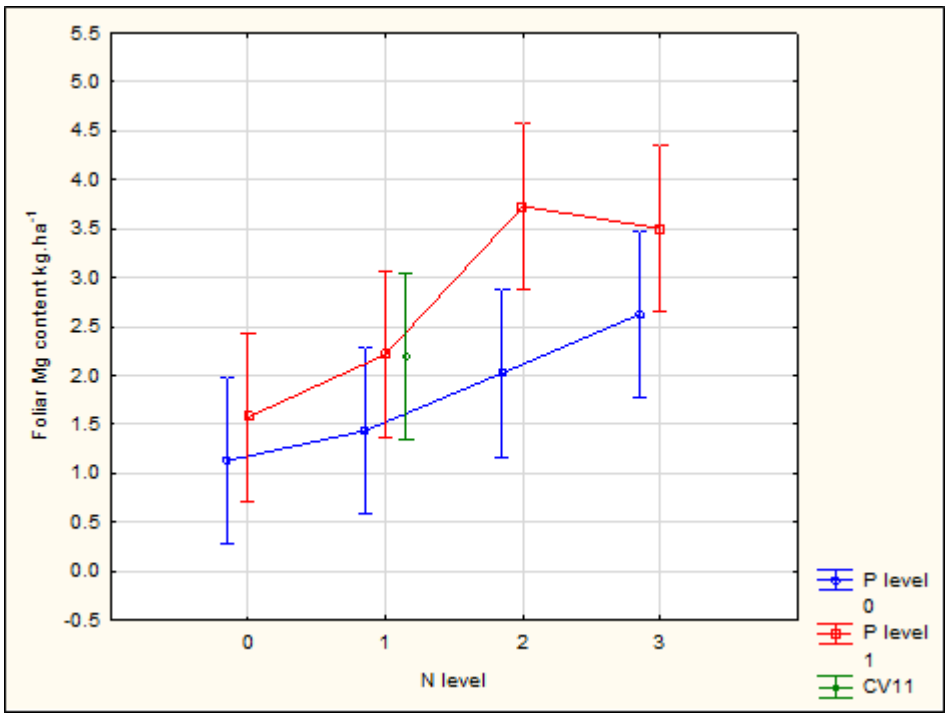


Figure 5.13: Foliar Mg contents for the eight factorial treatment combinations as well as the CV11 treatment at Mtunzini at nine months of age.

On the Flatcrown site, only foliar N and K contents were significantly (p<0.05) different among treatments. The difference in N uptake into the foliage between the

four levels of N in the absence of P was not significant, though there was an increase in foliar N content with increasing N application. The difference in N contents when N was applied in combination with P is clearer. A higher foliar N content was found when applying level 2 and 3 N over level 1 and no N application. The treatment combination with the highest foliar N content, CRF31 accumulated 128.9 kg ha^{-1}, nearly six times the amount accumulated in the equivalent treatment at Mtunzini over the same period of time. The mean foliar N accumulation for the site at nine months was 97.1 kg ha^{-1}, more than seven times the mean of Mtunzini. The control treatment had an N content of 80.9 kg ha^{-1}, which was higher than the CV01 (57.6 kg ha^{-1}) and CRF11 combination treatment (67.6 kg ha^{-1}). P had a negative effect on N uptake at zero and low levels of N application and an additive effect when application rates are increased to 80 g N per tree and above. There was no clear indication as to why CRF11 did not manage to accumulate as much N as its CV11 counterpart or CRF10. A possible reason for this occurrence was that the modest amount of N applied in the CRF form, the longevity of the release period and some influence of P addition at the lower levels of N, could be conducive to unfavourable N/P ratio for optimal N uptake into the foliage The only significant difference for foliar N content was between CRF31 and CV01 (Figure 5.14).

The trend for foliar K content was similar to that of foliar N. N application in the absence of P across all levels had very similar foliar K contents. As with foliar N contents, a slight non-significant positive trend in foliar K content was also seen with higher N applications (Figure 5.15). N applied in the presence of P had a significantly positive effect on K uptake. There was a significant increase in K content from 26.2 kg ha^{-1} for CRF11 to 58.7 kg ha^{-1} in CRF21. The K content of CRF21 was more than six times that of the equivalent treatment at Mtunzini. Although a higher K content was found in the CV11 (43.4 kg ha^{-1}), it was not significantly different to the CRF11 equivalent. The control once again performs better than anticipated with a content of 35.6 kg ha^{-1}. The mean K foliar content for the site was 39.1 kg ha^{-1}, more than 14 times that of Mtunzini.

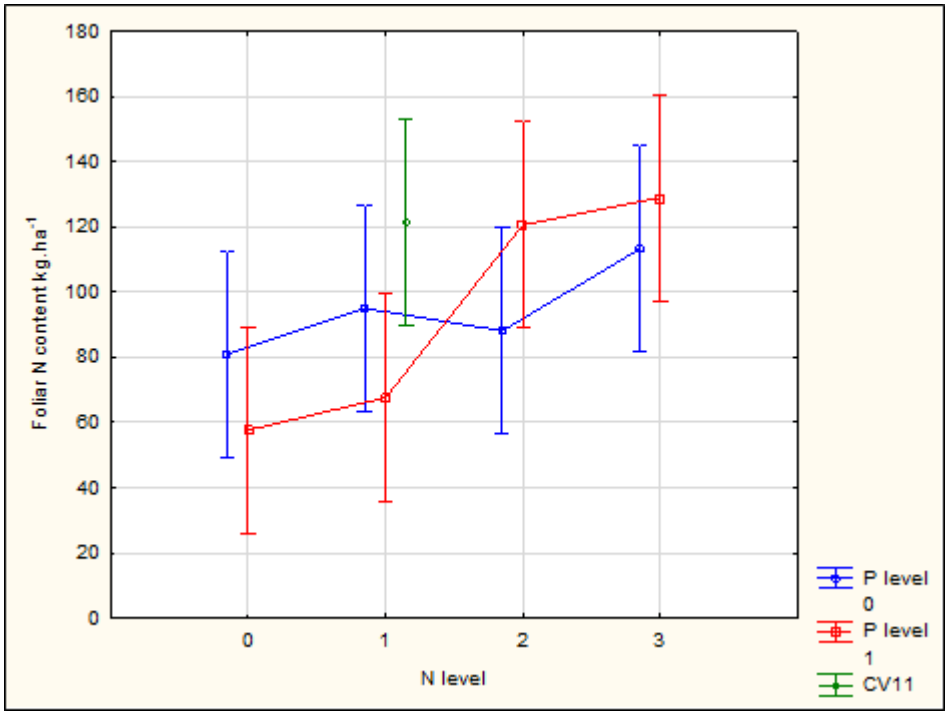


Figure 5.14: Foliar N contents for the eight factorial treatment combinations as well as the CV11 treatment at Flatcrown at nine months of age.

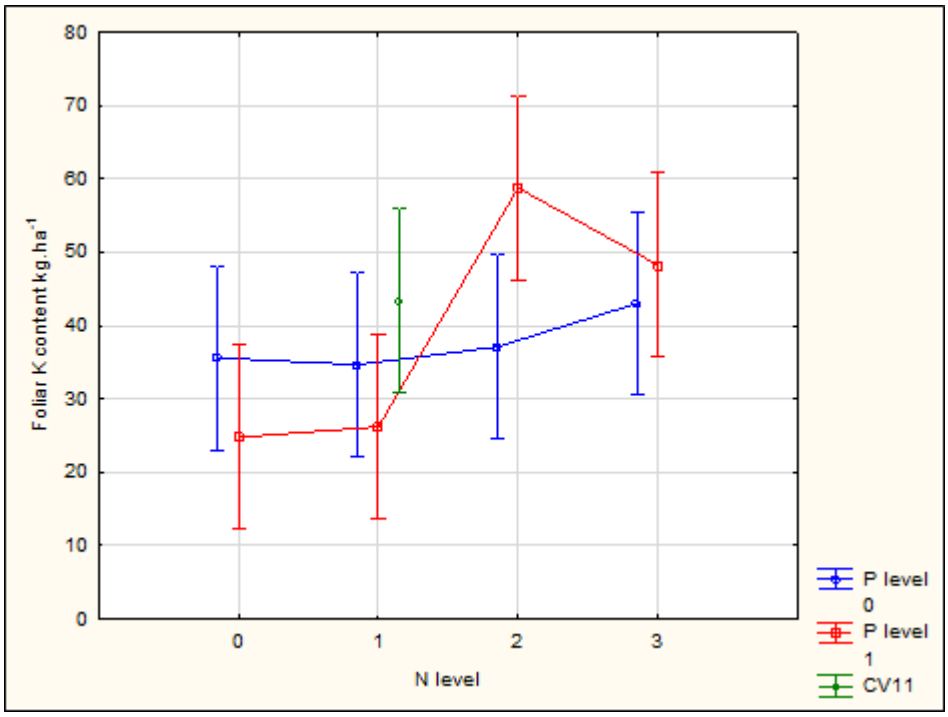


Figure 5.15: Foliar K contents for the eight factorial treatment combinations as well as the CV11 treatment at Flatcrown at nine months of age.

5.4 Estimated LAI

Both the N and P factors had significant (p<0.05) effects on the LAI at Mtunzini, while no significance in LAI development was evident on the Flatcrown site. At Mtunzini there was no significant increase in LAI between N level 0 and 1, or level 2 and 3. At Mtunzini the major response in leaf area was to the application of N with P having an additive effect The marked increase in estimated mean LAI takes place between level 1 and 2 N in the presence of P, a significant increase from 0.27 to just over 0.52 (Figure 5.16). The mean estimated LAI for the conventional treatment was not significantly different to CRF11 with each attaining a value of 0.27.

The estimated mean LAI on the Flatcrown site varied from 1 to 1.8, with no significant treatment differences between any of the factorial combinations or the additional conventional treatment. There are two factors which may have contributed to the lack of significance. Firstly, the overhead sky conditions on the measurement day were inconsistent, resulting in error/variability within treatments being larger than treatment differences. Secondly, with fairly homogenous growth across the site and plots nearing canopy closure, differences between treatments may have been non-existing or indiscernible. Given the presence of the large error bars on the treatment means, the former appears the more feasible explanation (Figure 5.17).

Table 5.8: Results of the analysis of variance analysis of estimated LAI at nine months of age for Mtunzini and Flatcrown

ANOVA results of Estimated LAI analysis					
Mtunzini					
Effect	SS	Degree Of freedom	MS	F	p-value
N level	0,473596	3	0,157865	11,2322	0,000018
P level	0,159571	1	0,159571	11,3535	0,001678
N level*P level	0,073727	3	0,024576	1,7486	0,172567
Flatcrown					
Effect	SS	Degree. Of freedom	MS	F	p-value
N level	1,14101	3	0,38034	2,1634	0,132268
P level	0,02100	1	0,02100	0,1195	0,734111
N level*P level	0,73275	3	0,24425	1,3893	0,282189

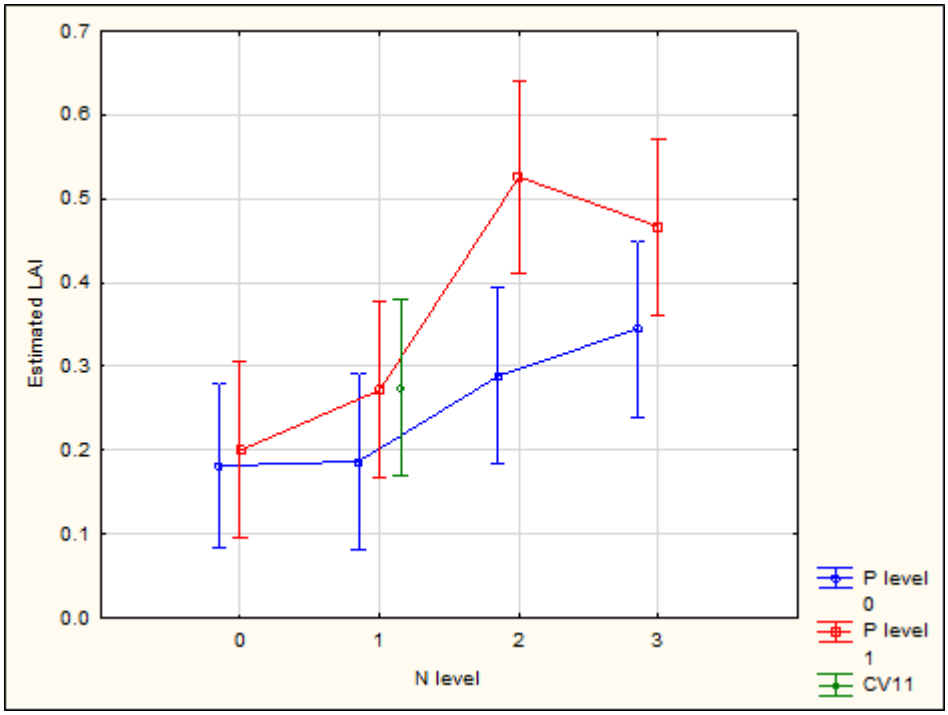


Figure 5.16: Estimated leaf area index for the eight factorial treatment combinations as well as the CV11 treatment at Mtunzini at nine months of age.

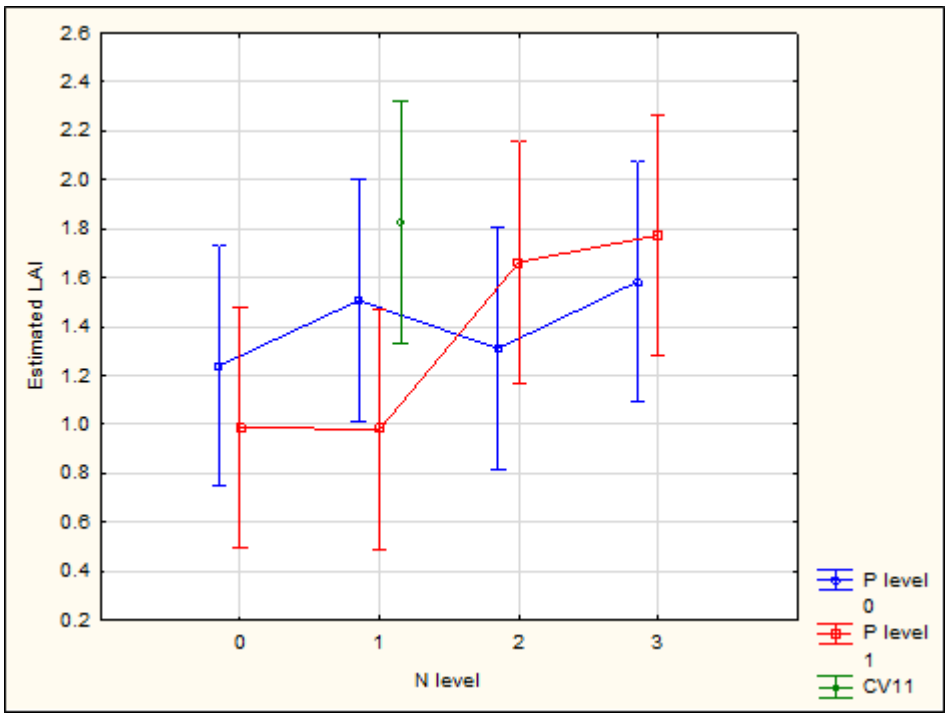


Figure 5.17: Estimated leaf area index for the eight factorial treatment combinations as well as the CV11 treatment at Flatcrown at nine months of age.

5.5 Crown area projections

The results of the crown area analysis showed that on the Mtunzini site there were significant (p<0.05) treatment differences (Table 5.9). The mean crown area per ha

for the site was 4503.13 m^2, with the control treatment and P application in the absence of N exhibiting the smallest crowns of 3579 and 3619 m^2/ha. The response in crown area was primarily due to N application with P yet again having an additive effect.

Table 5.9: ANOVA results of the investigation into crown area per hectare treatment differences on the Mtunzini site

ANOVA results of estimated crown area analysis					
Mtunzini					
Effect	SS	Degree Of freedom	MS	F	p-value
N level	16361038	3	5453679	14.072	0.000002
P level	2912153	1	2912153	7.514	0.009108
N level*P level	1004201	3	334734	0.864	0.467835

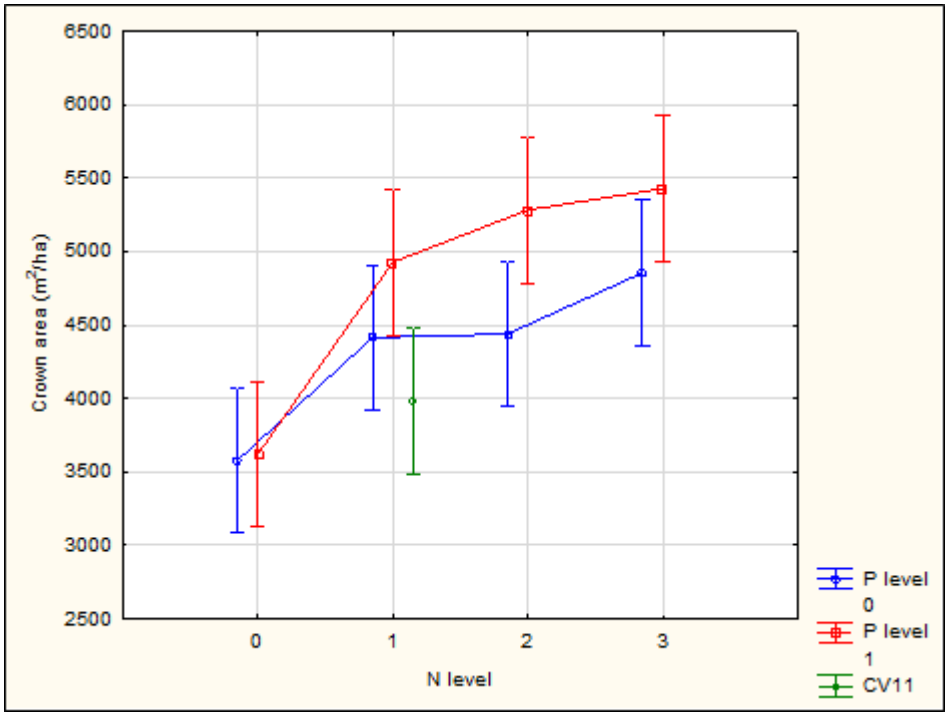


Figure 5.18: Crown area estimation values for the factorial treatment combinations and the additional conventional treatment at Mtunzini.

Level 1 N application, with and without P, increased the crown area by a significant 38 % and insignificant 23 % over the control respectively. The increase from level 1 N application to level 3 N applications, with or without P, only showed an improvement of approximately 10 %. The crown area response of the conventional

treatment was poorer than its CRF11 counterpart achieving a crown area of 3984 m^2/ha.

5.6 Estimated volume growth

On the Mtunzini site, the effects of N and P were significant (p<0.05) with an insignificant interaction. There was a near linear increase in growth with an increasing level of N application with an additive effect from P application. The control treatment achieved a mean volume of approximately 3.5 m^3 ha^{-1}, while the treatment that received only P applications (20 g P per tree) had a mean volume of 3.2 m^3 ha^{-1}, suggestive of a slight non-significant depressive effect on growth by P fertilization applied singly.

Table 5.10: ANOVA results of estimated mean volume on the Mtunzini and Flatcrown site

Effect	SS	Degree Of freedom	MS	F	p
Mtunzini					
Influence and interaction of Main factors					
N level	120.287	3	40.096	20.637	0.000000
P level	19.774	1	19.774	10.177	0.002203
N level*P level	16.720	3	5.573	2.869	0.056460
Testing for any significant treatment differences					
Treatment	162.915	8	20.364	10.854	0.000000
Flatcrown					
Influence and interaction of Main factors					
N level	330.96	3	110.32	9.340	0.000033
P level	25.13	1	25.13	2.128	0.149525
N level*P level	89.57	3	29.86	2.528	0.065154
Testing for any significant treatment differences					
Treatment	479.33	8	59.92	5.059	0.000052

Figure 5.19 shows the significant interaction between the four levels of CRF N applied in either the presence or absence of conventional P for the Mtunzini site. It was evident that the highest levels of application equated to the highest levels of growth. Level 3 N applications in the absence of P were able to attain a mean volume of 6.4 m^3 ha^{-1}. When applied in combination with P, this yield was even further improved with 1.6 m^3 ha^{-1} to reach a maximum yield of 8 m^3 ha^{-1} for the CRF31 treatment on the site.

The mean volume of level 3 N application in combination with P was significantly (p<0.05) higher than level 0 and 1 N in combination with P. The increase in volume between the CV11 and best N and P combination treatment (level 3 N, level 1 P) was approximately 82 %.

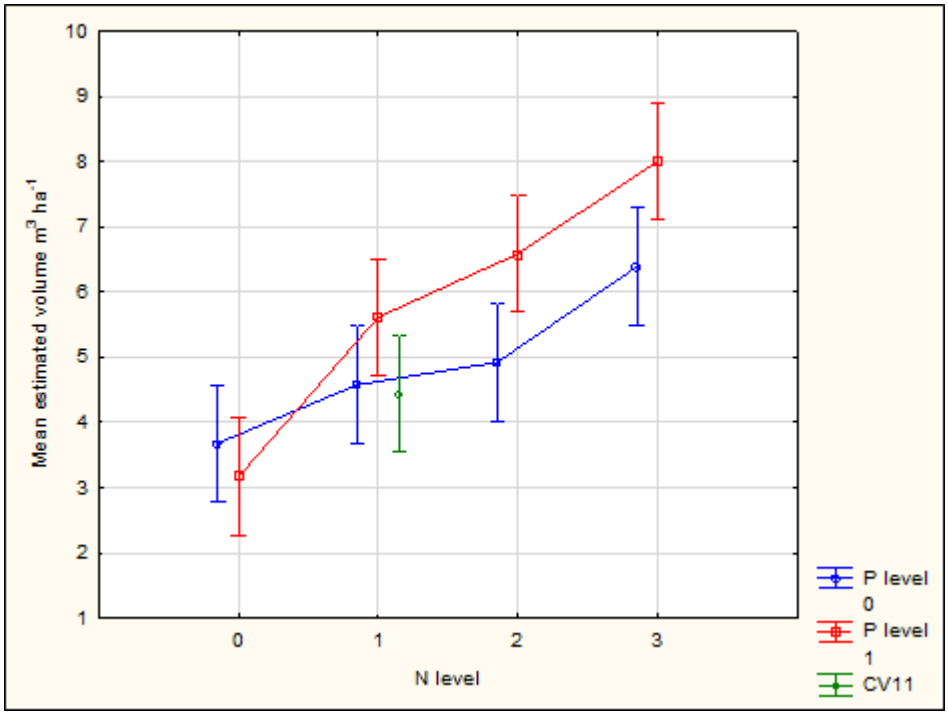


Figure 5.19: The relationship between increasing CRF N applications in the presence or absence of conventional P and the response in volume growth on Mtunzini.

On the Flatcrown site only the effect of N was significant and in contrary to Mtunzini, no additive effect from P application was found. In combination with P, there was a marked increase in the mean estimated volume from level 0 (17.5 m^3 ha^{-1}) to 2 (24.6 m^3 ha^{-1}) N. A slight reduction in the volume growth when the N application is increased from level 2 to 3 was found. When N is applied singly, the mean estimated volume between levels 0 and 1, increased from 17.7 m^3 ha^{-1} to 21.1 m^3 ha^{-1}. Between level 1 and 2, the volume was reduced from 21.1 m^3 ha^{-1} to 20.6 m^3 ha^{-1} and between 2 and 3, increased from 20.6 m^3 ha^{-1} to 21.6 m^3 ha^{-1}. There are no significant differences between any of the four N levels applied in the absence of P.

The interaction of the levels of CRF N and conventional P are shown in Figure 5.20. The peak mean volume for the site (24.6 m^3 ha^{-1}) was found at level 2 N in the presence of P. The conventional treatment performed well on this site, with a mean

estimated volume of 22.9 m^3 ha^{-1}, an improvement of 3.5 m^3 ha^{-1} over the CRF11 treatment.

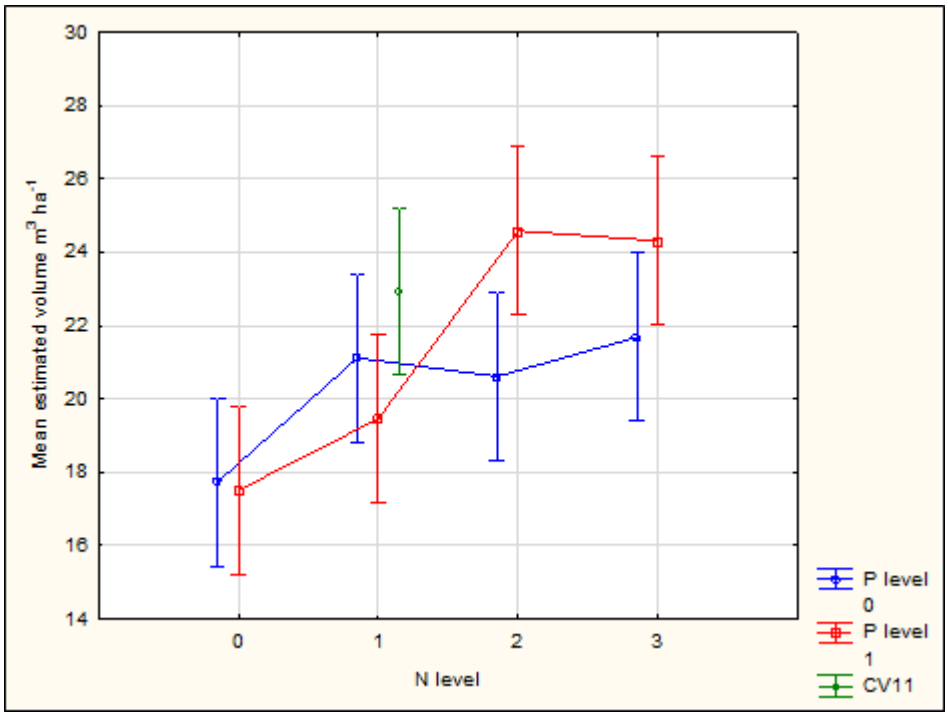


Figure 5.20: The relationship between increasing CRF N applications in the presence or absence of conventional P and the response in volume growth on Flatcrown.

5.7 Mean height growth

The fertilizer response at Woolstone is distinctly different to the two Zululand sites (Table 5.11). There is a significant effect (p<0.05) of P fertilization on this site, while N addition did not have a significant effect on early height growth. With an insignificant interaction between the main factors, the effect of P could be further investigated.

There was a clear noticeable difference in height growth between treatment combinations which received 20 g P per tree and those without (Figure 5.21). Treatments which received P had a mean height of 155.9 cm and those with no P had a mean height of 123.8 cm, a significant difference of 32.1 cm. The interaction between the N and P factor combinations as well as the two additional treatments on the site is shown in Figure 5.21.

Table 5.11: ANOVA results of mean height growth analysis on the Woolstone site

Woolstone					
Influence and interaction of Main factors					
Effect	SS	Degree Of freedom	MS	F	p
N level	1606	3	535	2.049	0.115832
P level	18584	1	18584	71.127	0.000000
N level*P level	106	3	35	0.135	0.938531
Testing for any significant treatment differences					
Treatment	25266	9	2807	11.292	0.000000

The growth trend of increasing applications of N, with or without P, was the same. A non-significant trend with negative height growth response was elicited as N application rates increased. N applications in the presence of P, performed superiorly than equivalent N applications in the absence of P. The best growth was obtained when P was applied in the CV form unaccompanied by N. The difference in height growth between all treatments which received P are however not statistically significant from one another. Treatments which received P were significantly different from those which did not receive any P, with the exception of the level 3 N which performed statistically similar to the control.

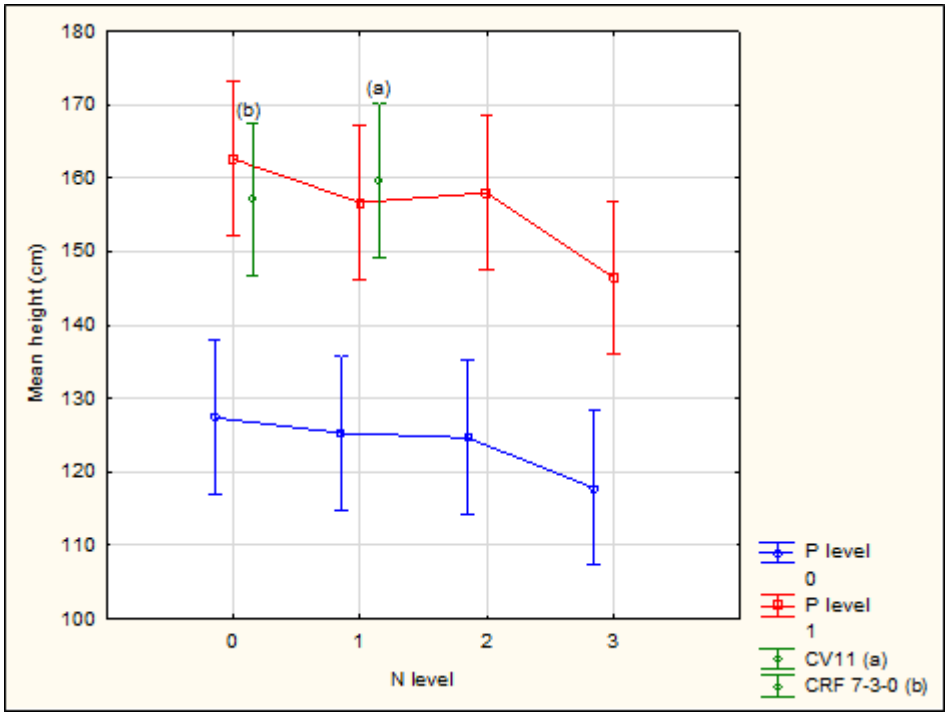


Figure 5.21: The relationship between increasing CRF N applications in the presence or absence of conventional P and the response in mean height growth at 7 months of age on the Woolstone site. The two additional treatments performance are shown relative to the factorial treatments.

The two additional treatments performed well on the site. The height growth of CV11 was statistically similar to the CRF11 equivalent. CRF 7-3-0, contained both N (29 g N per tree) and P (12.3 g N per tree) in a controlled release form and despite the lower application rate, the growth was similar to the best treatment combinations on the site. The treatments which only received N were not significantly different to the control.

Chapter 6: Discussion A

6.1 Early survival

The non-significant effect of fertilizer application on early survival of pine species is similar to results found by Carlson and Soko (1999), Amishev and Fox (2006) and Rolando *et al.* (2007). The poor survival experienced can be ascribed mainly to the infection of seedlings by *F. circinatum*. *Pinus radiata* is particularly susceptible to infection (Gordon *et al.* 1998, Gordon *et al.* 2001, Wingfield *et al.* 2002) while the *P. elliottii x caribaea* hybrid in previous studies demonstrated good resistance to the pathogen (Roux *et al.* 2007). This would explain the differences found between the two taxa. The question remains whether *Fusarium* infection is the sole contributor to mortality, or whether it was masking other outside influences.

Two additional influences could have exerted an additive effect on the poor survival. The first is the relatively late (4 weeks after planting) application of the fertilizer treatments, but excellent survival in both the *P. radiata* and hybrid control treatments indicates that the timing of application was not a contributing factor.

The interspecific competition from weeds could have induced a significant degree of stress on the seedlings. Little and Rolando (2001) indicated that competition from weeds during the establishment phase of pines in the summer rainfall region of South Africa is a significant contributor to early seedling mortality. Although hoeing and herbicide applications were performed on schedule, due to the nature and history of the site, fynbos weed growth may have reduced survival.

The results suggested that a fertilizer x disease interaction occurred, but the mechanism and relationship requires further investigation.

6.2 Foliar analysis

The magnitude of the responses was negligible in most cases, suggesting that the site was not nutrient limited. However, magnitude of the vectors aside, the interpretation and diagnosis among treatments which received the same level of application is highly inconsistent for all five macronutrients.

For level 1 N application, treatment CRF110 shows a toxic level, treatment CRF111 was sufficient non-limiting and CRF112 was deficient. Inconsistencies like these are prevalent throughout the vector analysis results. Whether this was a result due to the *Fusarium* influence is unclear, these results therefore do not give a true indication of the site's nutrient limitations and requirements, or the ability of CRF fertilizers to increase the uptake of nutrients into the above ground foliar biomass. The only consistent trend in the analysis was large vector response magnitude for all macronutrients in the CV322 treatment. CV322 indicates that N and K were not limiting factors, while P, Ca and Mg were limitations on growth. This is consistent with the critical value analysis which indicates marginal to deficient values for P and Mg.

6.3 Disease incidence

Tree mortality reduced sample numbers between first and second measurement dates. There was an increase of 11.53 % in the frequency of trees not displaying any visual signs of the disease, a reduction of 29.4 % for level 1 symptoms and a 71.43 % decrease in level 2 trees. These percentages take into account the amount of trees that died, assuming they died as classified at the first assessment, and those that were reclassified into different levels in the 10 month period between first and second assessments. For example, for level 2, of the 57 trees classified at the first assessment, 50 trees died, and of the 7 that survived, 5 were reclassified as level 1. The true percentage change for level 2 is thus 5/7, which equals the 71.43 % reduction.

Blakeslee *et al.* (1999) investigated the influence of pre-commercial thinning and fertilization on the disease incidence and severity of pitch canker on loblolly pine. The authors found that disease incidence and severity fluctuated substantially between different years. These results are in line with what was observed on the Coetzenburg site between assessments one and two. Cumulative incidence and severity was also higher in treatments which received fertilization.

Fertilization with N alone, or in combination with P and/or K, favoured *F. circinatum* (pitch canker fungus) development on *P. elliottii, P. taeda* and *P. virginiana* (Fraedrich and Witcher, 1982). N appears to be the primary element responsible for

increases in canker severity in the three tree species investigated, with P and K fulfilling secondary additive functions when applied in combination with N (Fraedrich and Witcher, 1982). For the *P. radiata* on this site though, no significant correlation could be found between increasing applications of N, alone or in the presence of P and/or K, and increases in disease incidence. The highest level of applications of CRF and CV sources, CRF322 and CV322, had the 4th and 8th lowest disease incidence of all 24 treatments.

6.4 Biomass index growth

Even though the trees of the healthy tree data subset did not show any visual symptoms of *F. circinatum* it cannot be said with 100 % certainty that their growth was unaffected.

The growth of *P. elliottii x caribaea* in unfertilized plots was not significantly different to the *P. radiata* control, but the latter's growth response to fertilizer application was significantly greater than the former. The fertilized *P. elliottii x caribaea* plots performed poorer than the *P. radiata* control and equivalently fertilized plots. These results show that the *P. elliottii* x *caribaea* hybrid is not a suitable species to be grown on this site given its poor growth performance despite clearly showing superior resistance to *F. circinatum.* However, the hybrid remains an option for the site if nothing else shows good survival.

The three treatments identified as statistically different to the control, CRF110, CRF120 and CRF222 show an improvement over the control of 75 %, 82 % and 83 % respectively. The best CV performer, CV310, however only exhibited a difference of 42 %. In comparison with two CV trials reviewed by Donald *et al.* (1987) which reported early BI results, the improvements over the control seen here were small. The first trial reported by Donald *et al.* (1987) showed a percentage increase of 481.48 % (at 48 months) and the second an increase of 133.33 % (at 28 months) (Table 2.1). At the lowest rates of application of N, P and K, the CRF source performed better than the CV sources.

When directly assessing the two fertilizer sources, increases in the applications of N and P, resulted in significant reductions in growth for the CRF source, while the

opposite situation was found for the CV source. For increases in K, reduction in growth was found for both sources. The CRF fertilizers which allow nutrients to be available to the trees for a longer period of time stimulates new tissue growth which as a consequence could possibly lead to an intensification of the action of the pitch canker fungus and it's inhibiting effects on plant growth. It is likely that greater additional responses to fertilizer application would have been obtained in the absence of disease.

Chapter 7: Discussion B

7.1 Early survival

Claims are made that fertilizer application decreases mortality, but the contradictory results seen here were not surprising. Germishuizen and Smith (2007) reviewed a number of conventional fertilizer trials on eucalypts at establishment in Zululand and found only two instances of a significantly positive response on stand survival. Bennett *et al.* (1996) found similar non-significant effects on survival when they tested fertilizer applications on three eucalypt species across three different sites in Australia. Significantly negative responses to conventional fertilizer were found by du Toit and Oscroft (2003) at rates of 100 g of N applied as LAN and 100 g of ASN (Ammonium Sulphate Nitrate) in a single trial on the Zululand coast.

Noble (1992a) and du Toit and Oscroft (2003) suggested that where conventional fertilizer is applied, the placement thereof is an important consideration, especially at higher rates of application. In trial C.87 of the ICFR, high mortality was found in specific lines of treatment plots that received 100 g of N while less disproportionate mortality was found in plots of the same treatments on four other sites that formed part of the same trial series. Poor fertilizer placement in ICFR trial C.87 is most likely the cause of the higher mortality (du Toit and Oscroft, 2003).

The non-significant mortality results in this trial, even at application rates of 120 g of N per tree and that the higher than expected mortality at Mtunzini was caused by an externality is an indication that CRF fertilizers can be applied more safely at higher rates.

7.2 Foliar analysis

The foliar analysis results were not as discernible between treatments as initially expected. On both Mtunzini and Flatcrown, clear and discernible increases were seen in foliar nutrient content and dry weight but changes in foliar nutrient concentrations were minimal. Past research conducted on the development of diagnosis norms for nutrient deficiencies and optimal foliar nutrient concentrations for eucalypts should be treated with caution, especially after a fertilization event as foliar nutrient concentration fluctuations are minor (Germishuizen and Smith, 2007). Although foliar diagnosis in other commercial species has proven its worth as a

useful analysis tool, for *Eucalyptus*, results have been proven unreliable (Cromer, 1996).

Nutrient concentrations in a plant vary according to leaf age, position in crown, seasonality and nutrient mobility (Gregoire and Fisher, 2004). Eucalypts have a high level of nutrient translocation, which can take place in leaves as young as six months of age (Fife *et al.*, 2008) which leads to nutrient concentrations which may not reflect the true nutritional status of the plant.

Eucalyptus are known to possess the capacity to rapidly take up readily available nutrients in support of new growth expansion (Germishuizen and Smith, 2007). Often nutrients taken up into the plant at planting becomes ever more diluted over time as total tree biomass increases (Noble, 1991). At Mtunzini and Flatcrown there was a definite foliar biomass response to an increased nutrient availability at planting and this can be seen in the estimated LAI values (Section 5.4) and crown area projections (Section 5.5). The mixture of deficiency and dilution vectors found can possibly be explained through the translocation and therefore dilution of foliar nutrient concentrations as the trees grew. The sampling and analysis methods may need review and further development to overcome the shortcomings described here.

Foliar nutrient analysis on *Eucalyptus* was erratic and the variability of these results only further reinforce what has previously been found (Cromer 1996, Bennett *et al*. 1996, Germishuizen and Smith 2007), with studies on eucalypt species.

7.3 Foliar nutrient content

Foliar N and P concentrations of juvenile eucalypts are higher in the younger foliage, at higher positions in the canopy, than older foliage lower down (Cromer *et al.* 1993b). This is an indication of re-translocation of nutrients at a young age. As a result of the chosen sampling strategy, the calculated foliar nutrient contents are more representative of the entire crown area. Laclau *et al.* (2000) found that in clonal eucalypt plantations in the Congo, N and K concentrations are highest in the foliage and 50 % N and 65 % K have already been accumulated within the first two years of growth. Cromer *et al*. (1993b) showed that by as early as 0.66 years after fertilizer application, *E. grandis* had already accumulated 80 % of the total aboveground N in its foliage in both fertilized and non-fertilized trees.

When analysing the results of the foliar N contents of Mtuzini and Flatcrown there is a clear discernible difference in the N supplying capability of the Mtunzini site in comparison with Flatcrown, and this can be seen in the difference in growth rate of the trees (see Section 5.6). This observation is a typical attribute of an ex-agricultural site in South Africa, where historical agriculture practices such as soil cultivation, burning of harvesting residues and intensive fertilization have had adverse effects on the soil fertility (du Toit *et al.*, 2001). CRF N fertilization at its highest rates on the Mtunzini site had a significantly positive effect on the available N for uptake in the soil, and increased the foliar uptake two fold from the optimal conventional treatment for these sites. Not only is it safer to apply larger doses of CRF N over CV N, but higher N uptake into the tree can also be achieved.

For high rates of growth to be achieved, equally high rates of nutrient uptake was needed, especially during the period before canopy closure (Cromer *et al.* 1993b). In the study by Cromer *et al.* (1993b), where N and P was applied at nine intervals during the first three years for a total of 1 536 kg ha^{-1} and 461 kg ha^{-1} respectively, the N content in the foliage of the fertilized plots accumulated to 130 kg ha^{-1} in 1.04 years and continued to increase slowly to 150 kg ha^{-1} by 2.4 years. The control plots accumulated 27 kg ha^{-1} of N in 3.08 years. In addition, Cromer *et al.* (1993b) also suggested that each kg ha^{-1} of N in the foliage was associated with 220 kg of above ground dry matter production per year.

The highest rates of fertilizer application in this study i.e. 200.04 kg ha^{-1} of N and 33.34 kg ha^{-1} of P, resulted in similar accumulation rates on the Flatcrown site. This was achieved at a younger age and with only a single application at planting. The substantially lower foliar N concentrations at Mtunzini could be an indication that an even larger application could be applied to further increase growth. At this point it is not clear which treatment is the most economically viable option on either site. It is clear though, that higher nutrient availability and uptake during the early growth period before canopy closure is crucial to achieving the maximum growth potential of the target crop on the site.

7.4 Estimated volume growth

Results from previous fertilizer trials established on former agricultural lands have been unpredictable due to the atypical nature of these sites. The soils are fraught with poor physical properties, low levels of exchangeable cations and low N mineralization and supply capacity (Germishuizen and Smith, 2007; Noble, 1992a). Preceding agriculture practices such as tillage, burning and excessive fertilization have led to indirect consequences of site nutrient deficiencies for forest managers to deal with. Although trees have shown significant responses to conventional fertilization in the past on ex-agricultural sites (du Toit and Oscroft, 2003; du Toit *et al.*, 2001; Noble, 1992a), the excellent response to controlled-release N fertilization has proven the need for prolonged N availability in the soil for additional growth benefits to be achieved early on in the rotation.

Although there is only a 0.11 % difference in the mean site OC content of the two sites, their responses are evidently dissimilar. However it should be stated that even though the total OC difference is small, differences in labile OC are bound to be larger due to the history of the Mtunzini site. Mtunzini's ability, as an ex-agriculture site, to supply N directly from the soil is significantly lower than Flatcrown. Assuming that the control plot foliar N contents were directly related to the quantity of N that the site can supply on its own, the control plot values in Figures 5.14 and 5.15 should provide a good indication as to the difference in soil fertility of the two sites. The relative difference in growth between the control and the best treatment combination at Mtunzini is 116 %, but it only represents an absolute increase of 4.3 m^3 ha^{-1}. The difference between the control and best treatment combination on Flatcrown is 38.9 % or 6.9 m^3 ha^{-1}. Even though Flatcrown responded relatively poorer than Mtunzini, it had the best absolute increase in volume growth. This is often the case with the most productive sites having the largest responses. Even though both sites were planted with the same hybrid clone, some of the differences on the two sites can possibly be attributed to clone x site interactions. However, these differences are likely to be small and given that the weather conditions on the two sites were similar over the 12 month period, with similar average daily temperatures, 21.68 °C and 21.19 °C, and rainfall 1 234 mm and 1 107 mm for Mtunzini and Flatcrown respectively. The observed differences are mainly site related, with the biggest effect most probably due to the history of the two sites.

One criticism of fertilization at establishment is that the root systems are not adequately developed for optimal nutrient uptake at the time of application. With conventional fertilizer, the common response to this criticism was to delay the timing of, or split the application which incurs additional costs. Controlled-release fertilizers allow the flexibility of blending fertilizers with different release rates to produce a tailor-made product for specific tree nutrient demands. The 75/25 combination of eight and two month release periods allowed at least 25 % of the total application to be available to the plant within the first two months of growth to aid in root system development.

The suppressive effect of P fertilization on both sites did not come as a surprise. The requirement for N on low OC content sites was much higher than P and when P was applied without remedying the N requirement, it may have resulted in an unfavourable N:P ratio for optimum growth. The Mtunzini site had higher amounts of available P in the soil to begin with (Table 3.2) most likely as a result of past agricultural practices when the site was under sugarcane production. The N:P balance in the soil was thus likely to be unfavourable at trial establishment and as a result, P fertilization on its own was found not to be beneficial and the CV01 performed poorer than the control. Trial C.19 (ICFR, 1987) and C.82 (du Toit and Oscroft, 2003) of the ICFR, report similar findings on similar sites with P fertilization performing poorer than the control. To achieve the best growth on sites with low OC content, P should be applied in combination with N.

The growth performance of CV11 at Mtunzini was slightly poorer than CRF11, but at Flatcrown it performed 18 % better. Even though the growth of the CV11 treatment is comparable to CRF11, the benefit that CRF had over CV sources was that additional responses could be obtained with increases in application rates. Du Toit and Oscroft (2003) showed that very few responses were found to applications of N above 50 g per tree on comparable sites in the same region. With pre-enriched organic fertilizers, Agrofert® and Humac®, du Toit *et al.* (2001) found the optimum application at 80 kg/ha or 60 g N per tree. On the Mtunzini site significant responses were found at double (120 g N per tree) that application rate.

7.5 Mean height growth

Soils such as at Woolstone, with substantial OC (2.67 %) and clay (48 %) content, high levels of available N and strong P fixing capacity, require P addition more strongly than N. With an increase in soil OC, an increase in P fixation can be expected due to an escalation of P adsorption by Al and Fe surfaces (Tisdale *et al.*, 1993). As discussed in Section 2.8, the availability of P in soils is dependent on multiple factors. In low soil pH conditions, such as the acidic Inanda soil at Woolstone, which contain high levels of sesquioxides are predisposed to high rates of P sorption (Bainbridge *et al.*, 1995). Highly weathered red or yellow-brown clays, with high OC content in the topsoil were found to be some of the highest P sorbers in the Mistbelt region of the Kwa-Zulu Natal province (Bainbridge *et al.*, 1995). Although these soils are rated as having a high to very high P requirement on the classification system developed by Juo and Fox (1977), there is still considerable variation in P sorption within the same soil form. Bainbridge *et al.* (1995) illustrated that P sorption in soils of the Inanda form varied noticeably even among soils with similar clay contents. P sorption in Inanda soils with similar clay contents to Woolstone varied between 200 and 600 mg of P sorbed per kg of soil (Bainbridge *et al.*, 1995). An inverse relationship between soil OC content and P availability to trees was observed by Tisdale *et al.* (1993) which may indicate an opportunity for additional productivity gains to be had with increases in the dosages of P on P fixing sandstone derived sites.

The results seen here, with a reduction in height growth with increasing applications of N in the absence of P, suggests an adverse N/P ratio in these treatments which had a non-significant depressive effect on the growth. With a baseline available P of only 3 ppm in the soil (Table 3.2), the response to P addition is justified. Although early negative responses to N were found, the N accumulation in the above ground biomass and especially foliage would have been high in the period from May to August. Refer to du Toit and Dovey (2005) for measured nutrient accretion rates. The growing season at Woolstone is in the spring and summer months and the additional N accumulated in the higher N application treatments will aid in supplying the N demand for sustained fast growth. The responses obtained here are similar to results found by du Toit (1998), where conventional N, P and K addition was tested on *E. dunnii* on an Inanda soil form. The most significant responses were to P, with K

application having an additive effect when applied in combination with P. In the same trial positive responses were also found to N application in the presence of P on low tillage sites.

Chapter 8: Conclusion and Recommendations

The findings presented in this study are only preliminary responses to controlled release fertilization on three commercial plantation species in South Africa. The *F. circinatum* outbreak in the *P. radiata* trees introduced a large degree of variation into the trial which the original design could not compensate for in the Coetzenburg site. This compromised the statistical integrity of the data and imposed a severe limitation to the analysis thereof. In terms of resistance to *F. circinatum,* the *P. elliottii x caribaea* hybrid, both fertilized and unfertilized, was significantly better than all other treatments. The attempt made to compensate for this external factor in the BI growth, was to some extent successful in revealing some statistical differences between treatments. These differences were not as expected and the influence of the pitch canker on the growth of the trees was clearly evident. The results of the effectiveness of controlled release fertilization on *P. radiata* in the Western Cape region of South Africa warrants further investigation.

The early results of Mtunzini and Flatcrown show the importance of fertilization on these sandy sites with low OC contents. Fertilization had no effect on stand survival and the results show that it is possible to apply large doses, up to 120 g N per tree, in a controlled release form with no ill-effect on seedling mortality. Mtunzini, the ex-agriculture site (mean OC = 0.3 %), showed significantly positive responses to both N and P application in terms of estimated LAI, foliar nutrient content, crown area projections and estimated volume growth. LAI values ranged from 0.15 (CV01) to 0.52 (CRF21). The conventional treatment CV11 had an estimated LAI value of only 0.28. The foliar N contents ranged from just over 5 kg ha^{-1} in the CV01 and control treatments, to approximately 23 kg ha^{-1} in treatment CRF31. Crown area projections range was estimated at between 36 % and 54 % ground coverage for the same treatments. All of these significant responses culminated in superior volume growth of the treatments with high N in the presence of P. With higher LAI values, larger canopies for radiation interception and significantly greater N uptake into the foliar biomass culminated in the CRF treatments being able to produce more biomass. The control and CV treatments produced one year mean volumes of between 3.1 and 4.4 m^3 ha^{-1}. The top CRF treatments, CRF21 and CRF31, produced mean volumes of 6.6 and 8 m^3 ha^{-1} respectively, with CRF31 mean volume nearly double

that of CV11. The best response overall was achieved with the highest application of controlled release N at 120 g per tree in combination with 20 g of conventional P. The application of 20 g P in the absence of N caused a slight depressive effect on the growth (3.1 m^3 ha^{-1}) with the control (3.4 m^3 ha^{-1}) producing marginally (but not significant) more volume.

Flatcrown (mean OC = 0.41 %) , the more fertile of the two coastal Zululand sites in terms of N supplying potential, still responded significantly to applications of N in foliar N content and estimated volume only. Mean foliar N contents ranged from 57.6 kg ha^{-1} for CV01 to 128.9 kg ha^{-1} for CRF31, a significant difference of 71.3 kg ha^{-1} or 123 %.The control and CV11 had mean foliar N contents of 80.9 and 121.5 kg ha^{-1} respectively. Although the top treatment combination, N level 3 and P level 1, had a mean improvement in estimated volume growth at 12 months of 59 % over the control and only 6 % over CV11, these differences were not significantly different between them or between any of the other treatments. The biggest response in volume growth was found in treatment combinations N level 2 and N level 3 in the presence of P, with 24.6 and 24.3 m^3 ha^{-1} respectively. These two responses were significantly different to the control and the single P treatment only. The conventional treatment, CV11 (22.9 m^3 ha^{-1}), performed well on this site, especially in the early stages where it was the best performer with regards to height growth. However it was not able to sustain the growth rate through the full year. None of the CRF treatment combinations were significantly different to the conventional treatment when volume growth for the first year is compared. The LAI values on the site varied from 1 to 1.8, but no significant treatment differences could be detected.

Early responses on the Woolstone site were primarily to the application of P. Unfortunately CRF N was the primary nutrient that was tested and with only one treatment with CRF P, definite conclusions to the merits of CRF P on this site cannot be made. Although treatments with only N application did not perform well in the early stages of growth, the N accumulated in the biomass of the tree will be crucial to supplying the higher N demand in the oncoming growth season.

No attempt was made in performing an economic analysis at this stage of the study, due to the early nature of the responses and the possibility that the situation may look different towards the end of the rotation. It is recommended that growth

responses need to be monitored up until end of rotation and those values used in the final economic viability study. An additional option could be the projection of the current growth data to rotation end Additional research on the wood properties of the eucalypts growing at different rates and their pulping properties is an avenue worthy of further investigation in the coming years.

Fertilization at re-establishment improved early growth gains of eucalypts on all sites tested with CRF as opposed to CV sources. Early productivity gains to CRF N fertilization are promising and provide additional growth when compared against standard CV applications used widely in the South African forestry industry. Volume growth gains found in this study, at application rates above those reported as optimal in past research on similar sites, are reason to re-evaluate current fertilizer recommendations.

References

Amishev, D.Y. & Fox, T.R. 2006. ***The effect of weed control and fertilization on survival and growth of four pine species in the Virginia piedmont***. *Forest Ecology and Management,* 236(1): 93-101.

Anonymous. Undated (a). ***Basacote fertilizer for forestry plantation establishment***. [Online]. Available: http://serve-ag.com.au/uploads/pdf/Basacote Information [10 May 2013].

Anonymous. Undated (b). ***The nitrogen cycle***. [Online]. Available: www.nps.gov [24 April 2013].

Anonymous. Undated (c) . ***Phosphorus in Soil***. *Lesson 34: Phosphorus Management* , 8-11.

Anonymous. 2013 . ***Product specifications***. [Online]. Available: www.isotherm.co.za/ [25 June 2013].

Baker, J.B., Switzer, G.L. & Nelson, L.E. 1974. ***Biomass production and nitrogen recovery after fertilization of young loblolly pines***. *Soil Science Society of America Journal,* 38(6): 959-961.

Bainbridge, S.H., Miles, N., Praan, R. & Johnston, M.A. 1995. **Phosphorus sorption in Natal soils.** *South African Journal of Plant and Soil*, 12(2): 59-64.

Beets, P.N. & Pollock, D.S. 1987. ***Accumulation and partioning of dry matter in Pinus radiata as related to stand age and thinning***. *New Zealand Journal of Forest Science,* 17: 246-271.

Bennett, L.T., Weston, C.J., Judd, T.S., Attiwill, P.M. & Whiteman, P.H. 1996. ***The effects of fertilizers on early growth and foliar nutrient concentrations of three plantation eucalypts on high quality sites in gippsland, Southeastern Australia***. *Forest Ecology and Management,* 89: 213-226.

Benton Jones, J. 1993. ***Modern interpretation systems for soil and plant analyses in the United States of America*****.** *Australian Journal of Experimental Agriculture,* 33: 1039-1043.

Blakeslee, G.M., Jokela, E.J., Hollis, C.H., Wilson, D.S., Lante, W.D. & Allen, J.E. 1999. ***Pitch canker in young loblolly pines: Influence of precommercial thinning and fertilization on disease incidence and severity***. *South Journal of Applied Forestry,* 23(3): 139-143.

Boardman, R., Cromer, R.N., Lambert, M.J. &Webb, M.J. 1997. ***Forest plantations***, in Reuter, D.J., Robinson,J.B. and Dutkiewicz,C.(eds.). *Plant analysis: An interpretation manual.* 2nd edition. Collingwood: CSIRO.Pages 505-566.

Boden, D. I. 1997. [Online]. ***Some Aspects of Silviculture practices for maintaining and improving site productivity*.** Available: http://agriculture.kzntl.gov.za/publications/production_guidelines/conservation_farmland/cons_farm_7.2.htm [18 April 2013].

Breda, N.J.J. 2003. ***Ground-based measurements of leaf area index: A review of methods, instruments and current controversies***. *Journal of Experimental Botany,* 54(392): 2403-2417.

Busman, L., Lamb, J., Randall, G., Rehm, G. & Schmitt, M. 2009. ***The nature of phosphorus in soils***. [Online]. Available: http://www.extension.umn.edu/ [21 July 2011].

Campbell, C.R. & Plank, C.O., 1998. **Preparation of plant tissue for laboratory analysis**, Y.P. Kalra (Ed) Handbook of reference methods for plant analysis, pp 37-49. CRC Press, Boca Raton.

Carlson, C. 2001. ***A Summary of the Literature Concerning the Fertilization of Pines at Planting in the Summer Rainfall Region of South Africa, and some Current Thoughts on Fertilizer Recommendations***. ICFR Bulletin series. No. 03/2001, *Institute for Commercial Forestry Research, Pietermaritzburg*.

Carlson, C. and Soko, S. 1999. ***An Investigation into the Effects of Timing, Rate and Splitting of Fertilizer Applications made to Pinus Patula at Planting.*** ICFR Bulletin series. No. 02/99, *Institute for Commercial Forestry Research, Pietermaritzburg*.

Carlson, W.C. & Preisig, C.L. 1981. ***Effects of controlled-release fertilizers on the shoot and root development of Douglas-fir seedlings***. *Canadian Journal of Forest Research,* 11: 230-242.

Chen, J.M., Rich, P.M., Gower, T.S., Norman, J.M. & Pulmmer, S. 1997. ***Leaf area index on boreal forests: Theory, techniques and measurements.*** *Journal of Geophysics Research,* 102: 429-444.

Clewer, A.G. & Scarisbrick, D.H. 2001. ***Practical statistics and experimental design for plant and crop science.*** The Atrium, Southern Gate, Chichester, West Sussex, England: John Wiley & Sons Ltd.

Comerford, N.B. 1981. ***Distributional gradients and variability of macroelement concentrations in the crowns of plantation grown Pinus resinosa (ait.)***. *Plant Soil,* 63: 345-353.

Cornforth, I. Undated. ***The fate of phosphorus fertilizers in soil***. Unpublished. Department of Soil Science, Lincoln University.

Cromer, R.N. 1996. ***Silviculture of Eucalypt Plantations in Australia***. in: Attiwill P.A. and Adams M.A. (Eds). Paper presented at Nutrition of Eucalypts. CSIRO, Australia.

Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A. & Brown, M. 1993a. ***Response to nutrients in eucalyptus grandis.1. Biomass accumulation***. *Forest Ecology and Management,* 62: 211-230.

Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A. & Brown, M. 1993b. ***Response to nutrients in eucalyptus grandis. 2. Nitrogen accumulation.*** *Forest Ecology and Management,* 62: 231-243.

Crous, J.W., Morris, A.R. & Scholes, M.C. 2008. ***Growth and foliar nutrient response to recent applications of phosphorus (P) and potassium (K) and to residual P and K fertilizer applied to the previous rotation of Pinus patula at Usutu, Swaziland.*** *Forest Ecology and Management,* 256: 712-721.

Dell, B., Malajczuk, N., Xu, D. & Grove, T.S. 1995. ***Nutrient disorders in plantation eucalypts***. Australian Centre for International Agriculture Research, Canberra, Australia.

Dickens, D. E., McElvany, B. C. & Moorhead, D. J. 2009. ***Phosphorus fertilization at establishment in loblolly and slash pine stands on Atlantic and gulf coastal plain sites***. [Online]. Available: www.forestproductivity.net [21 July 2013].

Donald, D.G.M. & Glen, L.M. 1974. ***The response of Pinus radiata and Pinus pinaster to N, P and K fertilizers applied at planting***. *South African Forestry Journal,* 91: 19-28.

Donald, D.G.M., Lange, P.W., Schutz, C.J. & Morris, A.R. 1987. ***The application of fertilizers to pines in Southern Africa***. *South African Forestry Journal* 141: 53-62.

Dovey, S.B. & du Toit, B. 2006. ***Calibration of LAI-2000 canopy analyser with leaf area index in a young eucalypt stand***. *Trees,* 20: 273-277.

du Toit, B. 1998. ***Initial Responses of E. Dunnii to Fertilization and Timing of Fertilizer Applications on a Highly Leached Sandstone-Derived Soil of the Inanda Form***. Paper published in ICFR Newsletter. August 1998. *Institute for Commercial Forestry Research, Pietermaritzburg*.

du Toit, B., Arbuthnot, A., Oscroft, D. & Job, A.R. 2001. **The effects of remedial fertilizer treatments on growth and pulp properties of *Eucalyptus grandis* stands established on infertile soils of the Zululand coastal plain**. *Southern African Forestry Journal,* 192(1): 9-18.

du Toit, B. and Oscroft, D. 2003. **Growth Response of a Eucalypt Hybrid to Fertilization at Planting Across Five Site Types in Zululand**. ICFR Bulletin series. No. 21/2003. *Institute for Commercial Forestry Research, Pietermaritzburg*.

du Toit, B. 2008. ***Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of Eucalyptus grandis in South Africa***. *Forest Ecology and Management,* 255(7): 2324-2336.

du Toit, B. & Dovey, S.B. 2005. ***Effect of site management on leaf area, early biomass development, and stand growth efficiency of a Eucalyptus grandis plantation in South Africa***. *Canadian Journal of Forest Research,* 35(4): 891-900.

du Toit, B., Smith, C.W., Little, K.M., Boreham, G. & Pallett, R.N. 2010. ***Intensive, site-specific silviculture: Manipulating resource availability at establishment for improved stand productivity. A review of South African research***. *Forest Ecology and Management,* 259(9): 1836-1845.

Duckworth, C.M.S. & Cresser, M.S. 1991. ***Factors influencing nitrogen retention in forest soils***. *Environmental Pollution,* 72: 1-21.

Dyer, C. 2007. Editorial: ***Forestry faces big issues to remain sustainable - a role for forestry research.*** *Southern Hemisphere Forestry Journal,* 69: iii-iv.

Elliot, J.R. and Fox, T.R. 2006. ***Proceedings of the 13th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-92***. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Evans, J. & Turnbull, J.W. 2004. ***Plantation forestry in the tropics: The role, silviculture and use of planted forests for industrial, social, environmental and agroforestry purposes.*** OUP Oxford.

FAO .1978. **Report on the agro-ecological zones project, volume 1:Methodology and results for Africa**, World Soil Resources Report 48, Food and Agricultural Organisation of the United Nations, Rome

Fan, Z., Moore, J.A., Shafii, B., & Osborne, H.L. 2002. ***Three-year response of ponderosa pine seedlings to controlled-release fertilizer applied at planting***. *Western Journal of Applied Forestry,* 17(3): 154-164.

Fife, D.N., Nambiar, E.K.S. & Saur, E. 2008. ***Retranslocation of foliar nutrients in evergreen tree species planted in a mediterranean environment***. *Tree Physiology,* 28: 187-196.

Fischer, P.M. 2011. δ^{13} C ***as indicator of soil water availability and drought stress in Pinus radiata stands in South Africa***. *Unpublished M.Sc thesis.* Stellenbosch, South Africa: University of Stellenbosch.

Flint, C.M., Harrison, R.B., Strahm, B.D. & Adams, A.B. 2008. ***Nitrogen leaching from Douglas-fir forests after urea fertilization***. *Journal of Environmental Quality,* 37: 1781-1788.

Fraedrich, B. R., Witcher, W. 1982***. Influence of fertilization on pitch canker development on three southern pine species***. Plant Disease, 66: 938-940.

Germishuizen, I. and Smith, C.W. 2007. ***Fertilizing Eucalpyts at Establishment in the Summer Rainfall Region of South Africa: A Critical Review***. Paper published at ICFR Bulletin series. No. 11/2007. *Institute for Commercial Forestry Research, Pietermaritzburg*.

Godsmark, R. 2010. ***The South African forestry and forest products industry 2009.*** [Online]. Available: www.forestry.co.za [17 April 2013].

Gordon, T.R., Okamoto, D., Storer, A.J. & Wood, D.L. 1998. ***Susceptibility of Five Landscape pines to pitch canker disease, caused by Fusarium subglutinans f. sp. pini.*** *Hortscience,* 33(5): 868-871.

Gordon, T.R., Storer, A.J. & Wood, D.L. 2001. ***The pitch canker epidemic in California***. *Plant Disease,* 85(11): 1128-1139.

Gower, S.T. & Norman, J.M. 1991. ***Rapid estimation of leaf area index in conifer and broad leaf plantations***. *Ecology,* 72: 1896-1900.

Graciano, C., Goya, J.F., Frangi, J.L. & Guiamet, J.J. 2006. ***Fertilization with phosphorus increases soil nitrogen absorption in young plants of Eucalyptus grandis***. *Forest Ecology and Management,* 236: 202-210.

Granier, A., Loustaub, D. & Bréda, N. 2000. ***A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index*** . *Annals of Forest Science,* 57: 755-765.

Gregoire, N. & Fisher, R.F. 2004. ***Nutritional diagnoses in loblolly pine (Pinus taeda L.) established stands using three different approaches***. *Forest Ecology and Management,* 203: 195-208.

Haase, D.L. & Rose, R. 1995. ***Vector analysis and its use for interpreting plant nutrient shifts in response to silvicultural treatments***. *Forest Science,* 41(1): 54-66.

Haase, D.L., Rose, R. & Trobaugh, J. 2006***. Field performance of three stock sizes of Douglas-fir container seedlings grown with slow-release fertilizer in the nursery growing medium.*** *New Forests,* 3: 11-24.

Hardiyanto, E.B. and Tridasa, A.M. 2000. ***Early Performance of Eucalyptus urophylla x grandis Hybrid on several Sites in Indonesia***. Paper presented at Hybrid Breeding and Genetics of Forest Trees. Noosa, Queensland, Australia. 9-14 April 2000.

Haynes, R.J. 1982. ***Effects of liming on phosphate availability in acid soils***. *Plant and Soil,* 68: 289-308.

Hensley, D.L. & Aldridge, E.G. 1990. ***Pre-plant incorporation of nitrogen fertilizer to spring- and fall-planted bareroot scotch pine***. *Scientia Horticulturae,* 45: 175-180.

ICFR. 1987. ***ICFR Annual Research Report*** (Ed. MacLennan, L). Report published by Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Jacobs, D.F., Salifu, K.F. & Seifert, J.R. 2005. ***Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting***. *Forest Ecology and Management,* 214: 28-39.

Juo, A.S.R. & Fox, R.L. 1977. ***Phosphate sorption characteristics of some bench-mark soils of West Africa***. *Soil Science,* 124(6): 370-376.

King, N.T., Seiler, J.R., Fox, T.R. & Johnsen, K.H. 2008. ***Post-fertilization physiology and growth performance of loblolly pine clones.*** *Tree Physiology,* 28: 703-711.

Klooster, W.S., Cregg, B.M., Fernandez, R.T. & Nzokou, P. 2010. ***Growth and photosynthetic response of pot-in-pot-grown conifers to substrate and controlled-release fertilizer***. *Hortscience,* 45(1): 36-42.

Laclau, J.P., Bouilleta, J.P. & Ranger, J. 2000. ***Dynamics of biomass and nutrient accumulation in a clonal plantation of Eucalyptus in Congo.*** *Forest Ecology and Management,* 128: 181-196.

Leuning, R., Cromer, R.N. & Rance, S. 1991. ***Spatial distributions of foliar nitrogen and phosphorus in crowns of Eucalyptus grandis***. *Oecologia,* 88504-510.

Linder, S. 1995. ***Foliar analysis for detecting and correcting nutrient imbalances in Norway spruce***. *Ecological Bulletins,* 44178-190.

Little, K.M. & Rolando, C.A. 2001. ***The impact of vegetation control on the establishment of pine at four sites in the summer rainfall region of South Africa.*** *The Southern African Forestry Journal,* 192(1): 31-39.

Marx, D.H., Bryan, W.C. & Cordell, C.E. 1977. ***Survival and growth of pine seedlings with Pisolithus finctorius after two years on reforestation sites in North Carolina and Florida.*** *Forest Science,* 23: 363-373.

McInnes, A.C. 1993. ***Fertilization at Planting on the Zululand Coastal Plain***. Paper published in ICFR Annual Research Report. *Institute for Commercial Forestry Research, Pietermaritzburg*.

McKeand, S.E., Grissom, J.E., Handset, J.A., O'Malley, D.M. & Allen, H.L. 2000. ***Responsiveness of diverse provenances of loblolly pine to fertilization - age 4 results***. *Journal of Sustainable Forestry,* 10(1): 87-94.

Mikkelsen, R.L., Williams, H.M. & Behel Jr., A.D. 1994. ***Nitrogen leaching and plant uptake from controlled-release fertilizers***. *Fertilizer Research,* 37: 43-50.

Minogue, P., Osiecka, A., Nowak, J. & Hochmuth, G. 2005. ***Nitrate monitoring following forest fertilization in the Suwannee valley region of North Florida and implications for best management practices***. [Online]. Available: www.sfrc.ufl [10 September 2012].

Morgan, K.T., Cushman, K.E. & Sato, S. 2009. ***Release mechanisms for slow- and controlled-release fertilizers and strategies for their use in vegetable production***. *Horttechnology,* 19(1): 10-12.

Morris, A.R. 1980. ***The Assessment of Soil Potassium Status - A Review***. . Usutu Forest Research Report No.7. Usutu Pulp Company Limited, Mhlambanyatsi, Swaziland.

Morris, A.R. 1992. ***Dry Matter and Nutrients in the Biomass of an Age Series of Pinus patula Plantations in the Usutu Forest, Swaziland***. *South African Forestry Journal,* 163: 5-11.

Mortensen, J., Nielsen, K.H. & Jørgensen, U. 1998. ***Nitrate leaching during establishment of willow (Salix viminalis) on two soil types and at two fertilization levels***. *Biomass and Bioenergy,* 15(6): 457-466.

Needham, T.D., Burger, J.A. & Oderwald, R.G. 1990. ***Relationship between diagnosis and recommendation integrated systems (DRIS) optima and foliar nutrient critical levels***. *Soil Science Society of America Journal,* 54: 883-886.

Nel, D.G. ***Personal communication***. 11 April 2013, Centre for Statistical Consultation, University of Stellenbosch.

Noble, A.D. 1992a. ***Nutrition of Eucalypts on the Zululand Sands***. ICFR Bulletin series. No. 29/1992. *Institute for Commercial Forestry Research, Pietermaritzburg*.

Noble, A.D. 1992b. ***Zululand Sands Project Report no.5***. ICFR Bulletin Series. No. 14/92. *Institute for Commercial Forestry Research, Pietermaritzburg*.

Noble, A.D. 1991. ***Current Advances in the Nutrition of Eucalyptus Grandis on the Zululand Coastal Plain***. ICFR Document. No. 4/91. *Institute for Commercial Forestry Research, Pietermaritzburg*.

The Non-Affiliated Soil Analysis Work Committee, 1990. **Handbook of standard soil testing methods for advisory purposes**. Soil Sci. Soc. South Africa

Pedersen, L.B., Christensen, C.J. & Ingerslev, M. 2006. ***Leaching versus input of nitrogen, potassium and magnesium in different fertilizer regimens in christmas tree stands of Abies nordmanniana in Denmark***. *Scandinavian Journal of Forest Research,* 21: 130-142.

Raath, P. (2013) ***Bemlab leaf and soil analysis.*** Unpublished

Rolando, C.A and Little, K.M. 2005. **The effects of harvest residue management, fertilisation and vegetation management on the re-establishment of *Pinus elliottii* in Mpumalanga.** Paper published in ICFR Bulletin series. No. 21/2003. *Institute for Commercial Forestry Research, Pietermaritzburg.*

Rolando, C.A., Little, K.M. & Campion, J.M. 2007. ***The Impact of Selected Fertilizer Treatments on Survival, Growth and Uniformity of Pines during Re-Establishment.*** ICFR Bulletin Series. 08/2007. *Institute for Commercial Forestry Research, Pietermaritzburg*.

Rose, R. 2002. ***Slow Release Fertilizers 101***. Paper presented at National Proceedings: Forest and Conservation Nursery Associations-1999, 2000 and 2001. Ogden, Utah.

Rothstein, D.E. 2005. ***Nitrogen management in a Fraser fir (Abies fraseri [pursh] poir.) christmas tree plantation: Effects of fertilization on tree performance and nitrogen leaching***. *Forest Science,* 2(51): 175-184.

Rötzer, T., Dittmar, C. & Elling, W. 2004. ***A model for site specific estimation of the available soil water content and the evapotranspiration in forest ecosystems***. *Journal of Environmental Hydrology,* 11: 1-14.

Roux, J. 2007. ***Testing of selected South African Pinus hybrids and families for tolerance to the pitch canker pathogen, Fusarium circinatum***. *New Forests,* 33: 109-123.

Ruehle, J.L., Marx, D.H. & Muse, H.D. 1984. ***Calculated nondestructive indices of growth responses for young pine seedlings***. *Forest Science,* 30(2): 469-474.

Schönau, A.P.G. 1983. ***Fertilization in South African forestry***. *South African Forestry Journal,* 125: 1-19.

Smith, W.H., Underwood, H.G. & Hays, J.T. 1971. ***Ureaforms in the fertilization of young pines***. *Journal of Agricultural and Food Chemistry,* 19(5): 816-821.

Snowdon, P. 2002. ***Modeling type 1 and type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments***. *Forest Ecology and Management,* 163(1–3): 229-244.

Swenson, G.A. & Kimberly, M.O. 1988. ***Can DRIS improve diagnosis of nutrient deficiency in Pinus radiata?*** *New Zealand Journal of Forest Science,* 18(1): 33-42.

Syers, J.K., Evans, J.D., Williams, J.D.H. & Murdock, J.T. 1971. ***Phosphate sorption parameters of representative soils from Rio Grande do sul, Brazil***. *Soil Science,* 112(4): 267-275.

Theron, J.M.& Ellis, F. Undated. ***Summary of Fertilizer Research on Pines in the Western Cape, 1964-1994.*** Faculty of Forestry, University of Stellenbosch, South Africa.

Tisdale, S.L., Nelson, W.L., Beaten, J.D. & Halving, J.L. 1993. ***Elements required in plant nutrition***. Fifth edition. New York: McMillan Publishing Co. Pages 48-49.

Trenkel, M.E. 1997. ***Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient efficiency in agriculture***. Paris, France: International Fertilizer Industry Association (IFA).

Turner, J., Lambert, M.J. & Humphreys, F.R. 2002. ***Continuing growth response to phosphate fertilizers by a Pinus radiata plantation over fifty years***. *Forest Science,* 48(3): 556-568.

Ulrich, A. & Hills, F.J. 1967. ***Principles and practices of plant analysis in: Soil testing and plant analysis part II madison (WI).*** *Soil Science Society of America Journal,* Special publication series (2):

Van den Driessche, R. 1988. ***Response of Douglas-fir (Pseudotsuga menziesii (mirb.) franco.) to some different fertilizers applied at planting***. *New Forests,* 2: 89-110.

Vose, J.M., Dougherty, P.M., Long, J.N., Smith, F.W., Gholz, H.L. & Curran, P.J. 1994. ***Factors influencing the amount and distribution of leaf area in pine stands. in the structure and productivity of pine forests: A synthesis***. *Ecological Bulletins,* 43102-114.

Walker, R.F. 2001. ***Growth and nutritional responses of containerized sugar and jeffrey pine seedlings to controlled release fertilization and induced mycorrhization***. *Forest Ecology and Management,* 149: 163-179.

Walker, R.F. 1999. ***Reforestation of an Eastern Sierra Nevada surface mine with containerized jeffrey pine: Seedling growth and nutritional responses to controlled release fertilization and ectomycorrhizal inoculation***. *Journal of Sustainable Forestry,* 9(3): 127-147.

Wang, Q.K., Wang, S.L. & Liu, Y.X. 2008. ***Responses to N and P fertilization in a young Eucalyptus dunnii plantation: Microbial properties, enzyme activities and dissolved organic matter***. *Applied Soil Ecology,* 40:484-490.

Wattle Research institute. 1984. ***Annual Research Report*** .Report published by Wattle Research Institute, Pietermaritzburg, South Africa.

Wingfield, M.J., Jacobs, A., Coutinho, T.A., Ahumada, R. & Wingfield, B.D. 2002. ***First report of the pitch canker fungus, Fusarium circinatum, on pines in Chile***. *Plant Pathology,* 51: 397.

Appendix 1A

Mtunzini soil chemical and textural properties

Sample no	Depth		pH	Resist.	H^+	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C	Clay	Silt	Fine Sand	Medium Sand	Course Sand	Stone
	(cm)	Soil	(KCl)	(Ohm)	(cmol/kg)	mg/kg		Na	K	Ca	Mg	%	%	%	%	%	%	(Vol %)
A11	0-20	Sand	5.8	2320	0.36	18	26	0.09	0.07	2.08	0.53	0.41	4	4	49.2	40.6	2.2	1
A12	20-40	Sand	4	5460	0.87	60	14	0.07	0.04	0.4	0.17	0.34	4	4	48.7	41.3	2	1
A13	40-60	Sand	4	8390	0.61	45	14	0.07	0.04	0.21	0.15	0.21	4	2	51.7	40.4	1.9	1
A21	0-20	Sand	5.5	1510	0.26	17	28	0.09	0.07	1.76	0.51	0.38	4	4	52.6	37.3	2.1	1
A22	20-40	Sand	4.4	3060	0.66	12	16	0.08	0.04	0.64	0.2	0.27	4	4	49.7	40.6	1.7	1
A23	40-60	Sand	4.1	4680	0.66	3	8	0.07	0.02	0.26	0.12	0.26	4	4	51.4	39	1.6	1
A31	0-20	Sand	5.1	2010	0.26	10	28	0.08	0.07	1.02	0.41	0.27	4	6	48.8	39.7	1.5	1
A32	20-40	Sand	3.9	5280	0.71	29	17	0.07	0.04	0.32	0.16	0.17	4	4	47.1	43.5	1.4	1
A33	40-60	Sand	3.9	3040	0.71	21	9	0.15	0.02	0.19	0.11	0.22	2	6	50.3	40	1.7	1
A41	0-20	Sand	4.8	2460	0.46	16	29	0.12	0.07	1.61	0.52	0.39	4	4	53	37.2	1.8	1
A42	20-40	Sand	3.9	5260	0.97	9	3	0.09	0.01	0.42	0.32	0.34	4	6	51.8	37	1.2	1
A43	40-60	Sand	4.1	5530	0.66	4	9	0.09	0.02	0.32	0.52	0.33	2	8	49.3	38.8	1.9	1

Appendix 1B

Flatcrown soil chemical and textural properties

Sample no	Depth		pH	Resist.	H^+	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C	Clay	Silt	Fine Sand	Medium Sand	Course Sand	Stone
	(cm)	Soil	(KCl)	(Ohm)	(cmol/kg)	mg/kg		Na	K	Ca	Mg	%	%	%	%	%	%	(Vol %)
B11	0-20	Sand	4.4	1760	0.51	8	21	0.14	0.05	0.68	0.53	0.43	4	6	54.5	34	1.5	1
B12	20-40	Sand	4.4	4450	0.41	3	13	0.1	0.03	0.45	0.26	0.33	4	4	53	37	2	1
B13	40-60	Sand	4.4	1800	0.36	2	17	0.16	0.04	0.5	0.23	0.34	4	6	47.7	40.5	1.8	1
B21	0-20	Sand	4.2	1650	0.61	6	30	0.11	0.08	0.71	0.44	0.51	6	2	45.2	45.4	1.4	1
B22	20-40	Sand	4	2900	0.92	4	26	0.11	0.07	0.33	0.21	0.39	6	6	44.6	41.8	1.6	1
B23	40-60	Sand	3.9	3820	1.02	4	24	0.1	0.06	0.23	0.15	0.36	8	6	44	40	2	1
B31	0-20	Sand	4.2	2030	0.82	6	7	0.08	0.02	1.16	0.41	0.67	8	4	55	30.9	2.1	1
B32	20-40	Sand	4	3950	1.17	12	14	0.06	0.04	0.37	0.16	0.38	6	6	52.9	33.2	1.9	1
B33	40-60	Sand	4	4910	0.92	2	13	0.06	0.03	0.19	0.13	0.37	8	4	49	37.3	1.7	1
B41	0-20	Sand	4.4	2150	0.36	6	16	0.08	0.04	0.43	0.22	0.46	4	2	53.8	38.6	1.6	1
B42	20-40	Sand	4.1	2840	0.61	4	23	0.08	0.06	0.27	0.27	0.35	6	2	52.6	37.6	1.8	1
B43	40-60	Sand	4.1	3360	0.77	1	19	0.09	0.05	0.22	0.19	0.32	6	4	50	38.1	1.9	1

Appendix 1C

Woolstone soil chemical and textural properties

Sample no	Depth		pH	Resist.	H^+	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C	Clay	Silt	Fine Sand	Medium Sand	Course Sand	Stone
	(cm)	Soil	(KCl)	(Ohm)	(cmol/kg)	mg/kg		Na	K	Ca	Mg	%	%	%	%	%	%	(Vol %)
C11	0-20	Loam	4	1630	4.18	4	74	0.11	0.19	1.21	1	4.26	48	15	24	5	8	3
C12	20-40	Loam	4	2100	4.58	2	85	0.13	0.22	0.54	0.84	3.98	54	15	23	4	4	3
C13	40-60	Loam	4.4	3820	2.19	1	37	0.17	0.09	0.28	0.68	0.67	71	12	14	1	2	1
C21	0-20	Loam	4.3	5200	2.19	1	17	0.07	0.04	0.27	0.65	1.27	62	13	21	3	2	1
C22	20-40	Loam	4	3850	4.48	1	49	0.04	0.13	0.25	0.53	1.94	35	18	26	12	10	1
C23	40-60	Loam	4.1	4170	3.69	1	27	0.13	0.07	0.21	0.9	2.27	53	14	26	3	4	1
C31	0-20	Loam	4	2040	3.93	2	65	0.1	0.17	0.34	0.6	2.21	31	14	37	8	10	4
C32	20-40	Loam	4.6	4930	1.49	**0**	25	0.16	0.06	0.18	0.53	1.1	49	14	24	4	9	26
C33	40-60	Loam	5	5010	1	**0**	73	0.11	0.19	0.5	0.86	0.86	43	18	21	5	13	24
C41	0-20	Loam	5.4	580	0.75	17	1213	0.36	3.1	6.04	2.19	10.14	33	24	25	8	11	2
C42	20-40	Loam	4.7	1160	2.09	6	119	0.2	0.3	2.72	1.51	2.15	47	20	25	3	6	2
C43	40-60	Loam	4.6	1610	1.79	**0**	24	0.32	0.06	0.46	1.22	1.19	59	18	17	2	4	2

Appendix 1D

Coetzenburg soil textural properties

Sample no	Depth (cm)	Soil	Clay %	Silt %	Fine Sand %	Medium Sand %	Course Sand %
D11	0-20	Loamy Sand	8	6	40.6	10	35.4
D12	20-40	Loamy Sand	6.4	7.6	34.6	9	42.4
D13	40-60	Loamy Sand	10	6	34.5	9.5	40
D21	0-20	Sand	6	6	41.1	10.4	36.5
D22	20-40	Sand	6	4	37	11	42
D23	40-60	Sandy Loam	16	8	25.6	8	42.4

Appendix 2A

Coetzenburg foliar analysis results

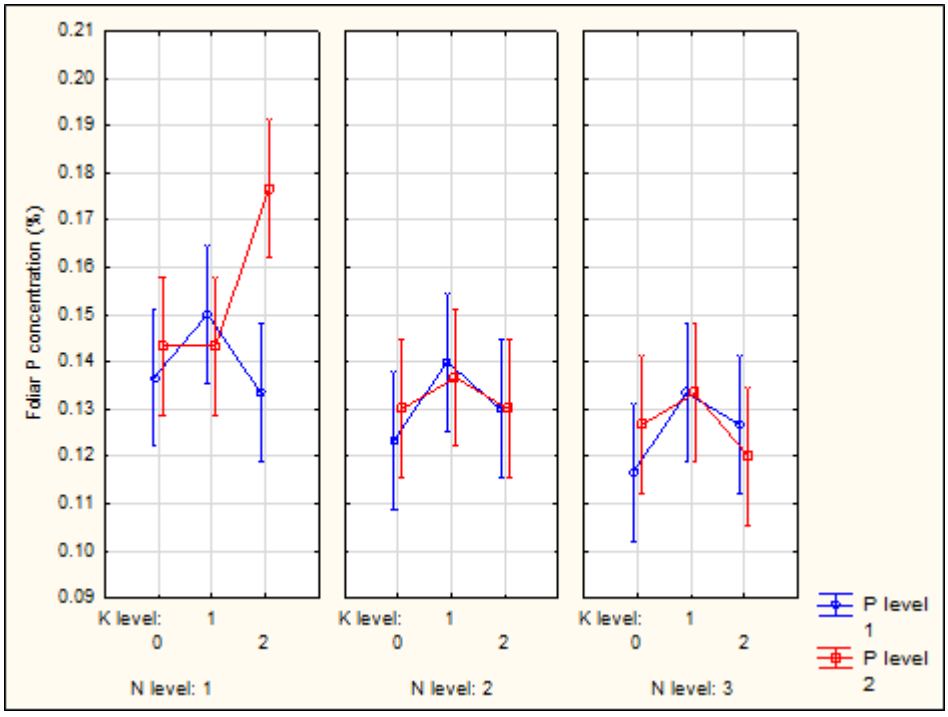
Plot number	Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
		%					mg/kg					
1	CV322	2.38	0.16	1.07	0.27	0.08	250	228	184	4	34	17
2	CRF212	2.62	0.12	0.94	0.25	0.10	270	433	192	4	30	23
3	CRF112	2.44	0.12	1.02	0.22	0.09	191	417	183	4	38	36
4	CRF121	2.61	0.15	1.05	0.21	0.07	234	391	172	4	33	27
5	CRF312	2.48	0.13	0.83	0.17	0.07	571	161	204	3	22	17
6	CRF210	2.20	0.13	0.95	0.21	0.09	242	179	177	4	30	21
7	CRF110	2.95	0.15	0.93	0.15	0.04	425	165	229	4	33	18
8	CRF122	2.37	0.18	1.00	0.17	0.06	251	328	168	4	39	16
9	CRF221	2.72	0.14	0.85	0.20	0.09	244	380	172	3	21	24
10	CVH322	2.16	0.09	0.53	0.15	0.04	819	529	185	2	14	20
11	CRF222	2.61	0.13	0.93	0.18	0.07	387	183	220	4	25	22
12	CV310	2.63	0.13	0.86	0.19	0.08	543	145	240	2	19	18
13	CRF320	2.65	0.14	0.78	0.21	0.08	428	357	210	3	16	23
14	CRF120	2.27	0.13	1.01	0.23	0.09	237	262	175	4	33	28
15	CRF311	2.84	0.13	1.07	0.25	0.06	238	393	194	3	23	19
16	CRF321	2.17	0.12	0.77	0.26	0.10	353	386	188	3	23	14
17	CRF211	2.46	0.13	1.02	0.15	0.07	327	209	208	3	22	12
18	CV112	2.30	0.16	1.07	0.22	0.02	368	159	226	2	82	17
19	CRF310	2.53	0.12	0.71	0.18	0.09	204	139	171	3	20	13
20	Control	2.32	0.11	1.11	0.21	0.05	339	238	221	3	60	23
21	CRF322	2.52	0.12	1.01	0.27	0.09	311	497	216	3	13	15
22	CRF220	2.48	0.14	0.88	0.30	0.13	293	333	177	3	21	23
23	CRF111	2.38	0.15	1.17	0.14	0.06	222	266	160	3	30	17
24	CVH000	2.35	0.10	0.69	0.29	0.04	444	555	138	3	37	23

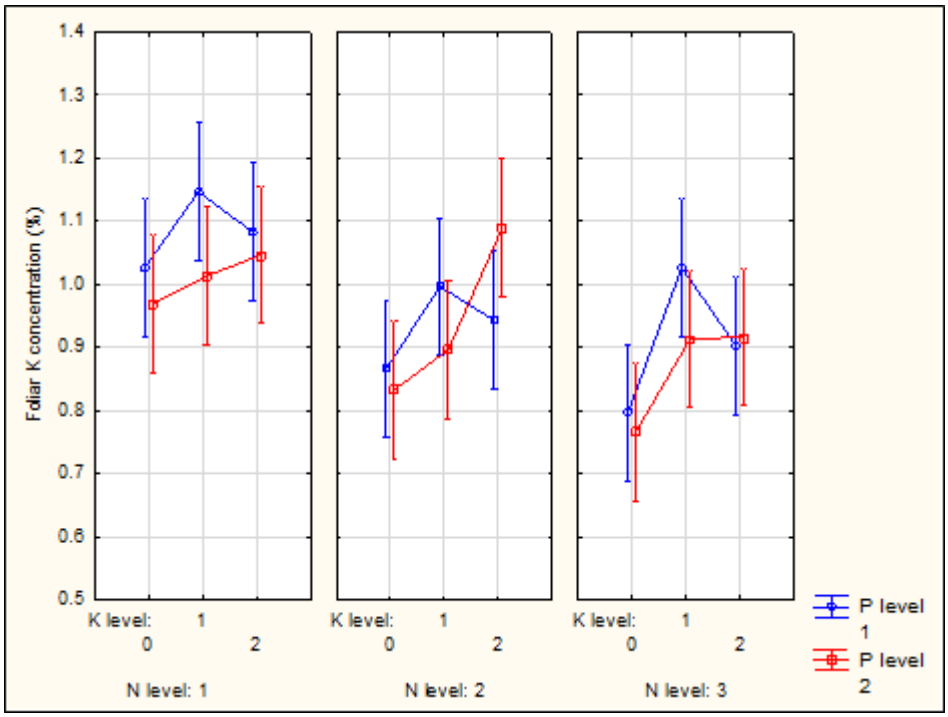
49	CRF211	2.50	0.14	0.95	0.25	0.11	221	453	215	2	15	27
50	CRF310	2.55	0.11	0.87	0.18	0.08	524	213	275	2	9	15
51	CRF222	2.44	0.12	1.19	0.15	0.04	381	267	187	2	18	16
52	CRF312	2.56	0.13	0.98	0.10	0.05	509	362	252	3	15	19
53	CRF122	2.50	0.18	0.97	0.24	0.07	124	345	168	5	60	17
54	CRF111	2.48	0.14	0.99	0.19	0.07	426	232	205	4	30	20
55	CRF120	2.48	0.16	0.94	0.20	0.13	178	475	170	5	29	26
56	CRF121	2.38	0.14	0.98	0.12	0.10	179	228	224	4	34	13
57	CRF212	2.47	0.12	1.00	0.27	0.10	216	468	210	3	26	14
58	CRF210	2.49	0.11	0.77	0.18	0.11	256	419	202	2	21	13
59	CRF110	2.45	0.12	1.14	0.37	0.10	277	470	221	3	25	17
60	CRF311	2.54	0.11	0.87	0.18	0.08	193	254	171	3	29	15
61	CV112	2.43	0.14	1.04	0.17	0.08	255	514	185	4	37	21
62	CRF220	2.53	0.13	0.84	0.20	0.09	262	329	179	2	14	18
63	CVH322	2.34	0.07	0.46	0.12	0.02	725	146	155	1	10	12
64	CRF221	2.44	0.13	0.95	0.15	0.05	426	169	148	3	21	14
65	CRF322	2.42	0.11	0.80	0.10	0.03	335	169	150	2	25	6
66	Control	2.46	0.12	1.11	0.19	0.05	440	101	196	5	64	20
67	CRF320	2.50	0.11	0.84	0.20	0.06	390	160	191	3	30	9
68	CRF112	2.42	0.14	1.08	0.18	0.05	178	129	133	4	32	14
69	CV310	2.42	0.14	1.05	0.23	0.07	354	195	147	4	41	25
70	CVH000	2.29	0.08	0.45	0.16	0.04	490	69	119	3	37	17
71	CV322	2.42	0.14	0.90	0.23	0.08	392	139	145	4	48	15
72	CRF321	2.42	0.13	0.94	0.18	0.06	521	235	189	4	19	11
97	CRF121	2.39	0.14	1.01	0.18	0.07	453	307	186	4	30	14
98	CVH000	2.29	0.11	0.82	0.14	0.04	680	128	185	3	25	12
99	CRF311	2.49	0.16	1.14	0.13	0.05	394	216	162	3	22	6
100	CRF112	2.48	0.14	1.15	0.18	0.06	304	235	174	4	37	15
101	CRF122	2.47	0.17	1.17	0.16	0.08	227	266	143	4	48	12
102	CV322	2.47	0.14	1.16	0.20	0.05	496	227	197	3	32	14

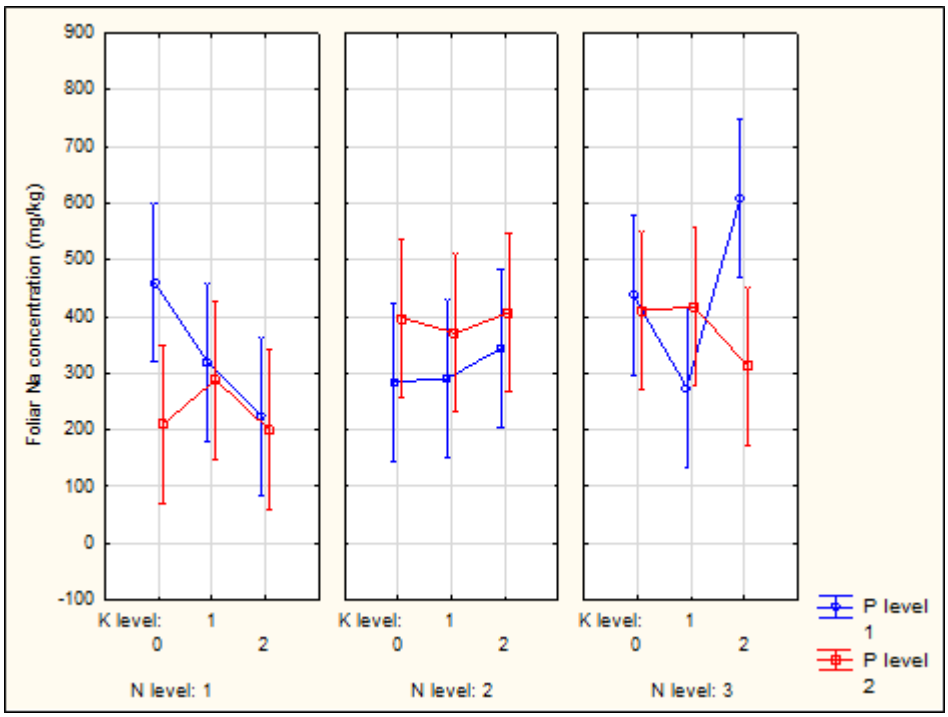
103	CRF120	2.47	0.14	0.96	0.3	0.08	212	555	129	3	25	17
104	CRF322	2.45	0.13	0.94	0.22	0.08	289	297	187	4	23	14
105	CV112	2.42	0.19	1.11	0.23	0.08	787	137	279	4	67	12
106	CRF111	2.44	0.16	1.28	0.16	0.07	311	193	145	3	24	20
107	CRF211	2.46	0.15	1.02	0.14	0.04	323	183	131	3	18	11
108	CV310	2.44	0.17	1.05	0.15	0.06	227	100	134	4	40	13
109	CRF222	2.50	0.14	1.15	0.20	0.07	453	244	187	3	24	11
110	CVH322	2.44	0.08	0.78	0.12	0.05	767	165	147	2	14	5
111	Control	2.47	0.12	0.97	0.19	0.08	488	78	201	4	67	10
112	CRF321	2.49	0.15	1.03	0.20	0.07	375	238	181	2	25	15
113	CRF110	2.46	0.14	1.01	0.26	0.08	679	146	210	3	32	17
114	CRF320	2.54	0.13	0.68	0.23	0.09	418	185	184	3	13	7
115	CRF210	2.56	0.13	0.88	0.15	0.06	357	150	163	3	15	8
116	CRF221	2.52	0.14	0.89	0.21	0.07	442	169	205	3	20	7
117	CRF220	2.49	0.12	0.78	0.17	0.06	638	194	260	3	12	12
118	CRF212	2.52	0.15	0.89	0.18	0.07	546	133	214	4	16	11
119	CRF310	2.55	0.12	0.81	0.16	0.08	584	115	228	3	13	5
120	CRF312	2.50	0.12	0.90	0.12	0.05	743	96	233	3	13	11

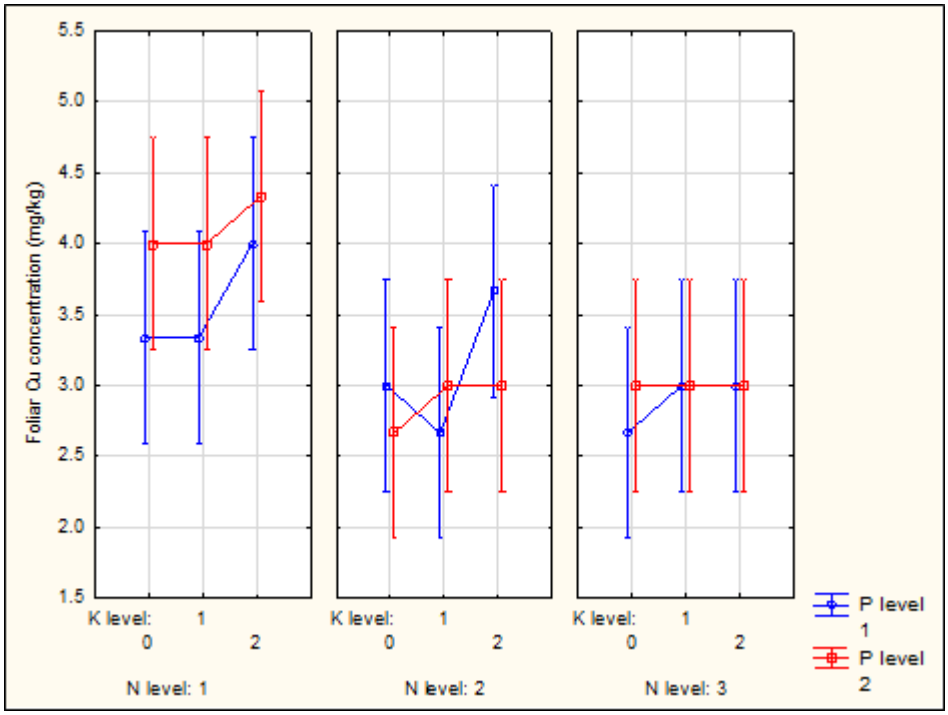
Appendix 2B

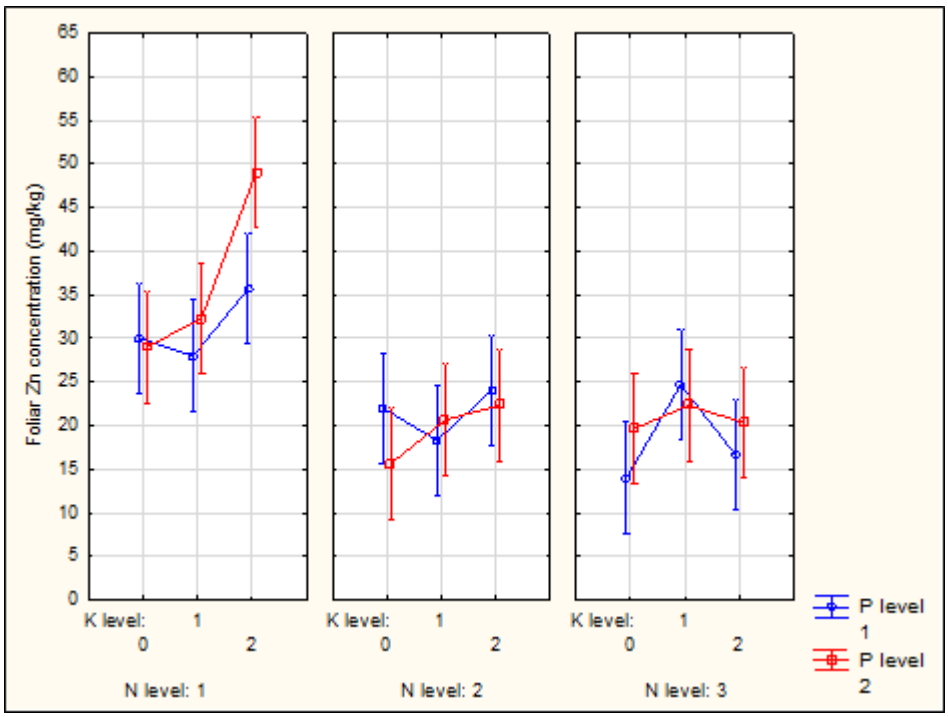
N x P x K interactions of the significant foliar nutrient concentrations

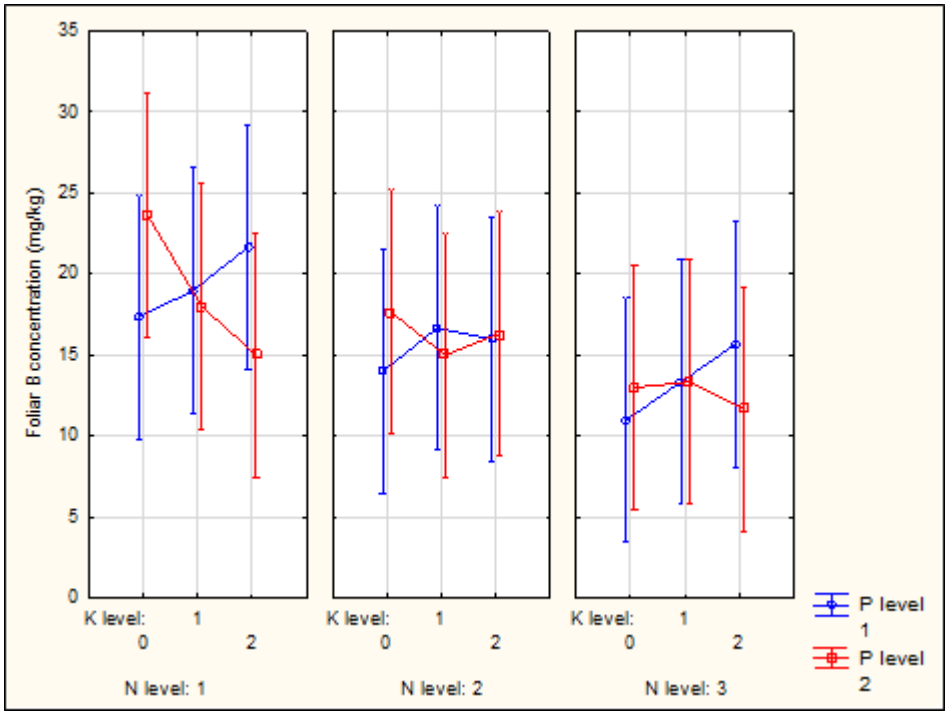





Foliar Na concentration (mg/kg)
900
800
700
600
500
400
300
200
100
0
-100
K level: 1
0 2
N level: 1
N level: 2
N level: 3
P level 1
P level 2


Foliar Cu concentration (mg/kg)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
K level: 1
0 2
N level: 1
N level: 2
N level: 3
P level 1
P level 2





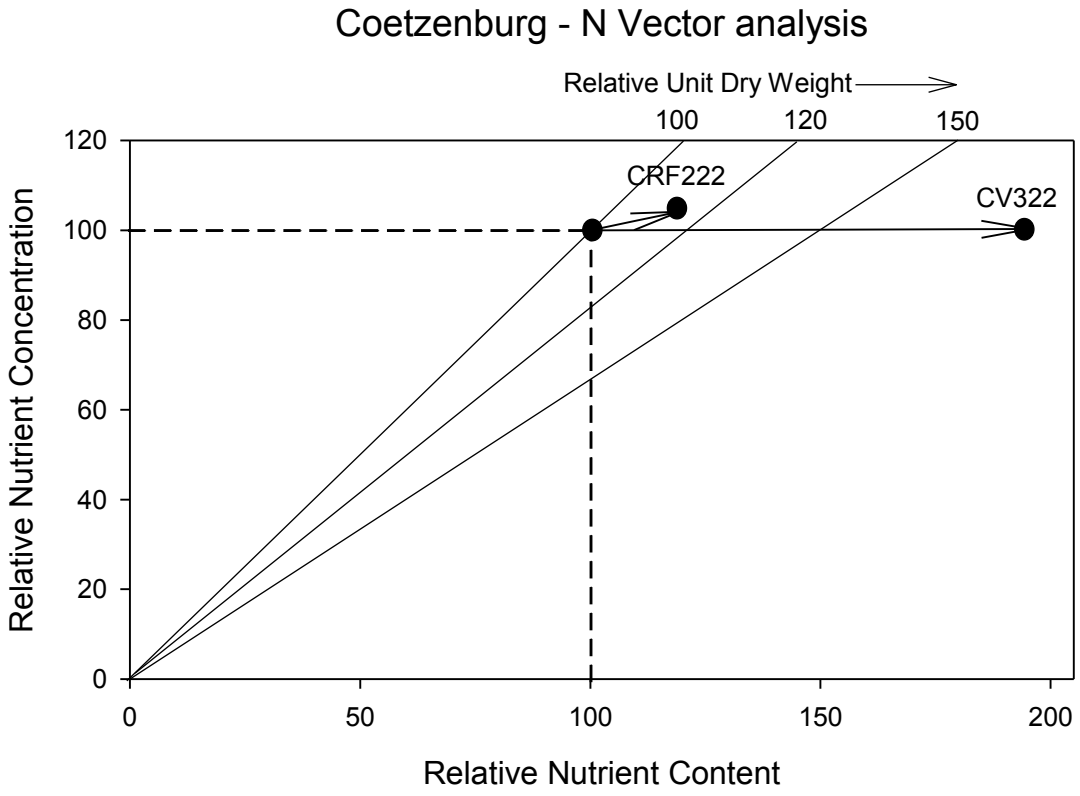
Appendix 2C

Coetzenburg Macronutrient Vector nomograms. Shaded results of each nutrient are shown graphically.

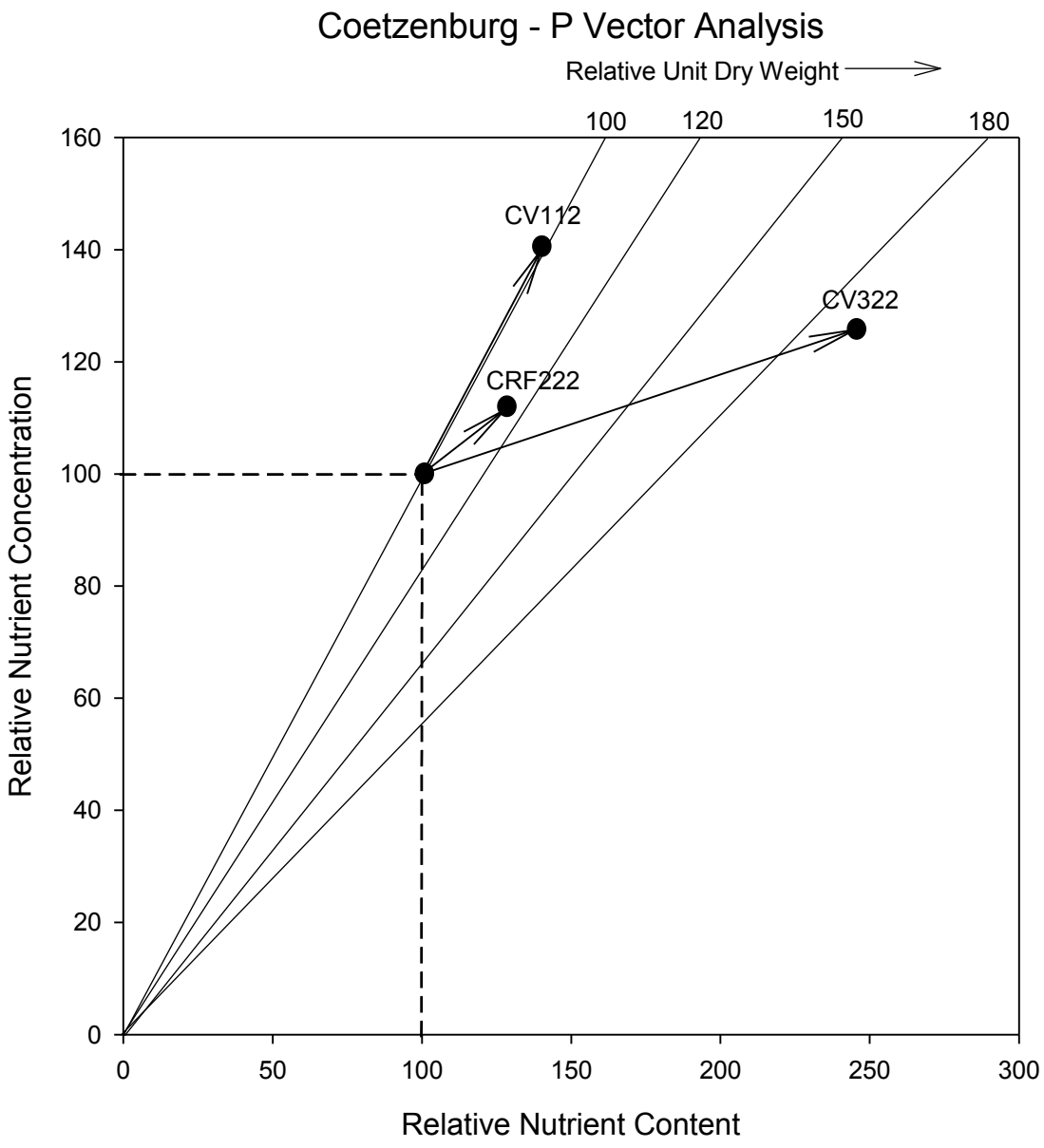
The cells demarcated as N/A represent instances where a response in unit dry weight, nutrient concentration and nutrient content did not match an interpretation as set out by Haase and Rose (1995).

	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium	
Treatment	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**	**Interpretation**	**Diagnosis**
CRF110	Excess	Toxic	Excess	Toxic	Excess	Antagonistic	Luxury	Non-toxic	Excess	Toxic
CRF111	Sufficiency	Non-limiting	Deficiency	Limiting	N/A	N/A	N/A	N/A	Deficiency	Limiting
CRF112	Deficiency	Limiting	Sufficiency	Non-limiting	N/A	N/A	N/A	N/A	Deficiency	Limiting
CRF120	Excess	Toxic	Excess	Toxic	N/A	N/A	Luxury	Non- toxic	Luxury	Non-toxic
CRF121	Excess	Toxic	Excess	Toxic	Excess	Antagonistic	Excess	Antagonistic	Excess	Toxic
CRF122	Deficiency	Limiting	Deficiency	Limiting	Dilution	Non-limiting	Dilution	Non-limiting	Deficiency	Limiting
CRF210	Excess	Toxic	Excess	Toxic	Excess	Toxic	Excess	Antagonistic	Excess	Toxic
CRF211	Deficiency	Limiting	Deficiency	Limiting	N/A	N/A	N/A	N/A	Deficiency	Limiting
CRF212	Excess	Toxic	Excess	Toxic	Excess	Antagonistic	Excess	Toxic	Excess	Toxic
CRF220	N/A	N/A	Excess	Toxic	Excess	Antagonistic	Excess	Toxic	Excess	Toxic
CRF221	N/A	N/A	Excess	Toxic	Excess	Antagonistic	Excess	Antagonistic	Excess	Toxic
CRF222	Deficiency	Limiting	Deficiency	Limiting	Excess	Antagonistic	Excess	Antagonistic	N/A	N/A
CRF310	Deficiency	Limiting	Deficiency	Limiting	N/A	N/A	N/A	N/A	Luxury	Non-toxic
CRF311	N/A	N/A	Excess	Toxic	Excess	Antagonistic	Excess	Antagonistic	Excess	Toxic
CRF312	Excess	Antagonistic	Excess	Toxic	Excess	Antagonistic	Excess	Antagonistic	Excess	Antagonistic
CRF320	Luxury	Non toxic	Luxury	Non toxic	N/A	N/A	Deficiency	Limiting	Deficiency	Limiting
CRF321	Deficiency	Limiting	Deficiency	Limiting	Deficiency	Limiting	Deficiency	Limiting	Deficiency	Limiting
CRF322	Excess	Toxic	Excess	Toxic	Excess	Antagonistic	N/A	N/A	Excess	Toxic
CV112	N/A	N/A	Luxury	Non-toxic	Excess	Antagonistic	Excess	Toxic	N/A	N/A
CV310	N/A	N/A	Luxury	Non toxic	Luxury	Non toxic	N/A	N/A	Luxury	Non toxic

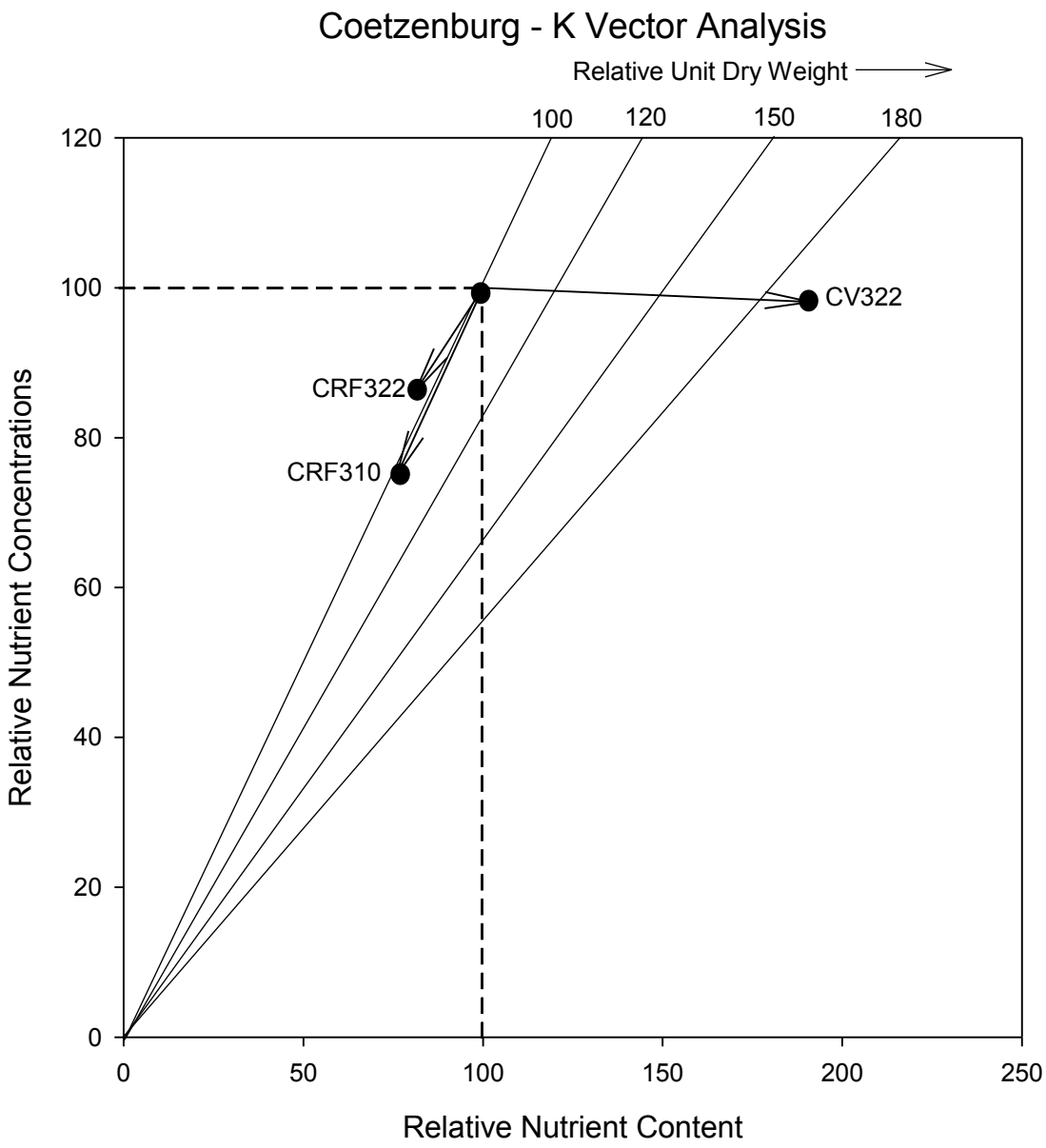
CV322	Sufficiency	Non-limiting	Deficiency	Limiting	Sufficiency	Non-limiting	Deficiency	Limiting	Deficiency	Limiting



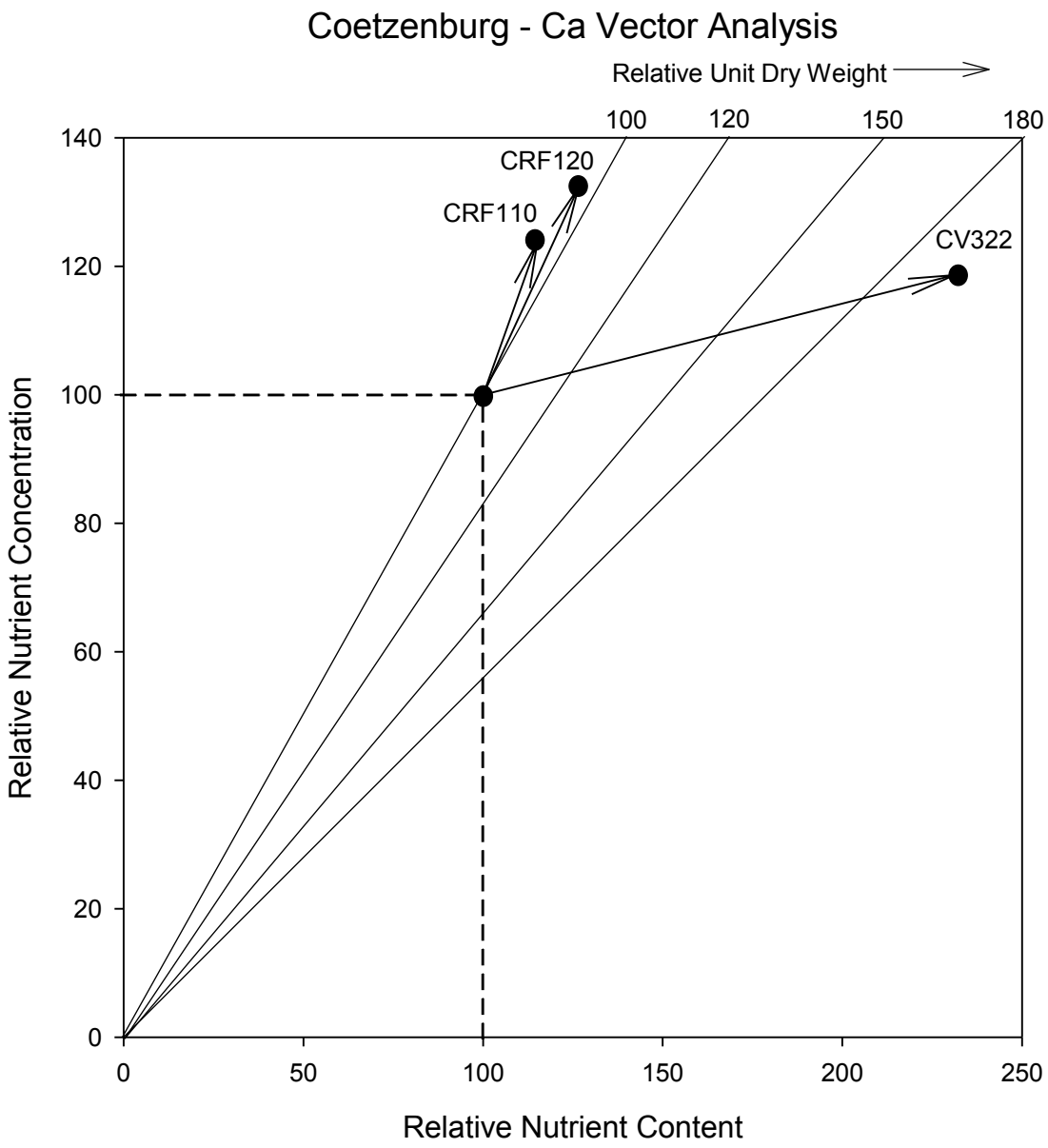
i) Vector nomogram of responses to N of treatments CRF222 and CV322. CRF222 showing a type C shift and CV322 a type B shift.



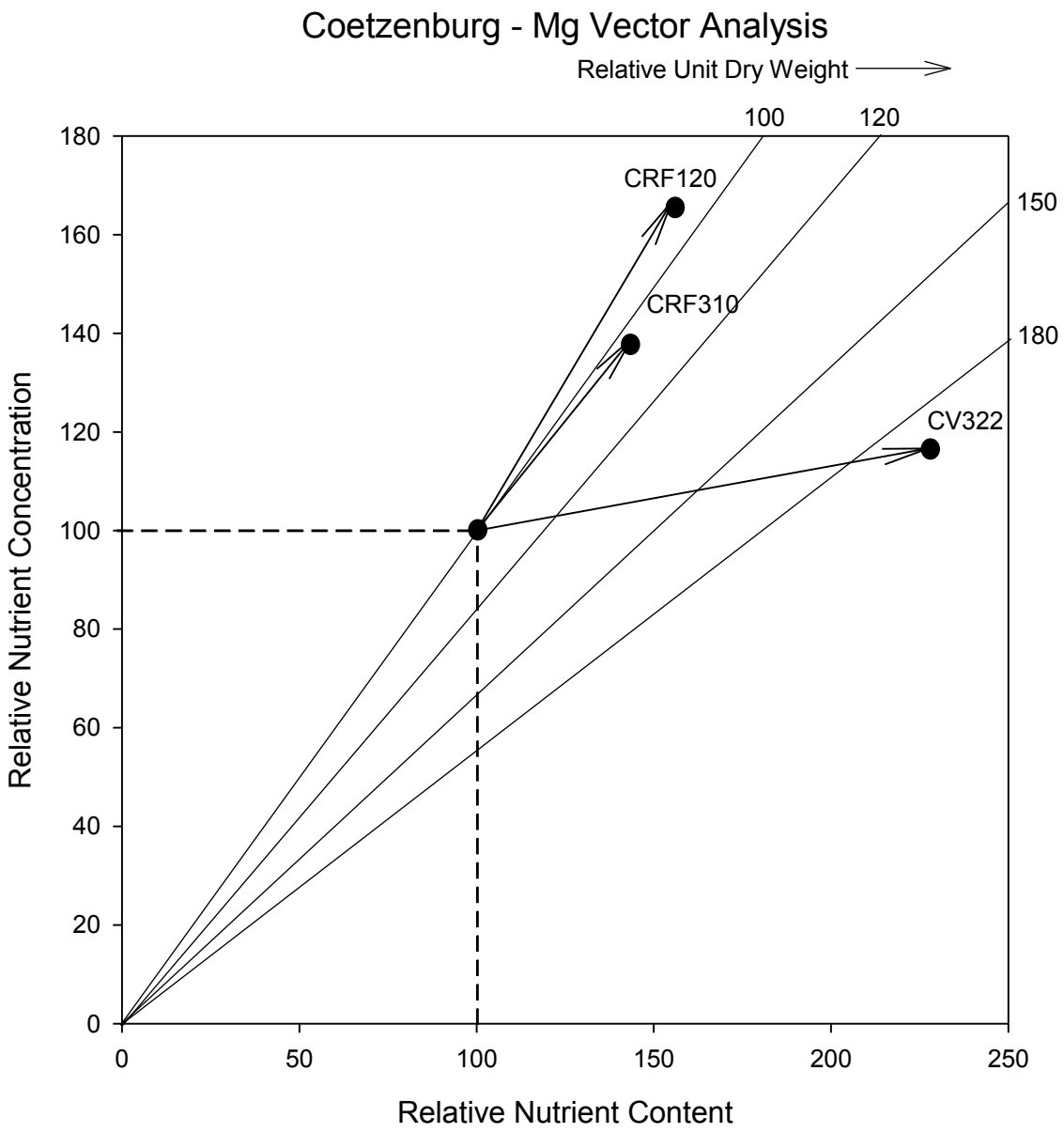
ii) Vector nomogram of responses to P of treatments, CRF222, CV112 and CV322. CRF222 and CV322 showing a type C while CV112 a type D.



iii) Vector nomogram of responses to K application of treatments CRF310, CRF322 and CV322. CRF310 and CRF322 shows a type F shift and CV322 a type B shift.



iv) Vector nomogram of responses to Ca application of treatments CRF110, CRF120 and CV322. A type D shift for CRF110 and CRF120 and a type C shift for CV322.



v) Vector nomogram of responses to Mg application of treatments CRF120, CRF310 and CV322. CRF120 and CRF310 show type D shifts and CV322 and type C shift.

Appendix 3A

Mtunzini and Flatcrown foliar analysis results

i) Mtunzini

Plot	Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
		%					mg/kg					
1	Control	1.75	0.25	0.60	0.91	0.35	2655	154	103	6	16	40
2	CRF31	1.63	0.25	0.75	0.87	0.37	3609	165	98	6	17	34
3	CRF21	1.92	0.24	0.72	0.89	0.30	3967	186	88	5	14	31
4	CRF11	2.21	0.21	0.80	0.83	0.31	3658	192	97	5	16	34
5	CRF10	1.83	0.22	0.63	0.86	0.32	4089	165	94	5	16	28
6	CRF20	2.33	0.23	0.88	0.90	0.34	4170	175	103	7	18	34
7	CRF11	1.73	0.22	0.61	1.05	0.36	3153	165	111	5	14	37
8	CV11	1.81	0.21	0.78	0.87	0.33	3777	137	89	5	15	35
9	CRF20	2.04	0.22	0.74	0.77	0.29	3996	115	93	6	17	29
10	CV01	2.00	0.26	0.92	1.03	0.38	4477	138	96	7	20	30
11	CRF30	2.00	0.21	0.64	0.98	0.33	4290	190	103	5	16	31
12	CV11	2.46	0.24	0.80	0.91	0.37	3952	146	107	7	20	29
13	CRF30	2.20	0.17	0.69	1.04	0.32	2269	154	88	6	14	34
14	CRF31	2.19	0.20	0.73	0.98	0.32	3371	192	92	5	15	35
15	CV01	2.01	0.26	1.08	0.89	0.37	4729	158	96	8	18	30
16	Control	2.04	0.28	0.96	0.93	0.37	5428	146	107	9	20	28
17	CRF21	1.60	0.22	0.64	0.98	0.34	3911	219	94	5	14	33
18	CRF10	1.99	0.23	0.75	0.98	0.34	3830	209	92	9	16	31
22	CRF31	1.96	0.22	0.68	1.22	0.33	3144	216	101	5	14	38
23	CRF11	1.76	0.24	0.86	0.97	0.35	4162	202	103	6	16	28
24	CRF10	2.07	0.21	0.68	1.12	0.39	3721	213	134	7	16	37

28	CV11	1.58	0.30	0.65	1.15	0.38	3439	241	102	7	20	28
29	CRF20	2.41	0.21	0.68	1.06	0.36	4407	232	116	13	17	32
30	CRF30	2.35	0.18	0.8	1.14	0.35	4082	241	103	5	15	32
34	CRF21	1.62	0.22	0.66	1.08	0.34	3482	281	98	9	14	29
35	CV01	1.97	0.24	0.81	0.81	0.32	4397	183	96	7	16	29
36	Control	1.96	0.21	0.79	0.93	0.35	4145	217	123	7	14	33
55	CRF21	1.87	0.27	0.84	1.06	0.33	3200	185	104	6	16	35
56	CV11	1.87	0.25	0.93	0.91	0.33	3812	151	102	7	17	30
57	CRF30	1.93	0.18	0.79	0.99	0.33	3924	259	104	6	16	34
58	CRF11	1.73	0.25	0.88	0.93	0.31	4192	158	91	6	14	27
59	CRF20	2.03	0.20	0.73	0.96	0.29	4423	196	107	5	15	28
60	Control	1.97	0.24	0.88	0.89	0.35	4817	244	103	8	19	25
61	CRF11	1.82	0.24	1.00	1.09	0.34	3950	165	99	6	17	32
62	CRF20	1.75	0.19	0.69	0.89	0.30	3522	140	87	6	15	28
63	CRF10	1.61	0.24	0.76	0.86	0.31	3458	145	90	6	15	25
64	CRF31	1.94	0.18	0.68	1.03	0.33	3935	234	100	4	14	30
65	CRF10	1.78	0.24	0.80	0.97	0.35	4174	248	103	6	17	28
66	CRF21	2.16	0.19	0.74	0.80	0.29	3932	405	109	6	14	28
67	CV01	1.71	0.27	0.94	0.92	0.33	3435	158	82	6	18	34
68	Control	1.57	0.23	0.85	0.91	0.34	4452	141	97	6	17	30
69	CRF31	2.00	0.18	0.68	1.11	0.34	3317	216	104	5	15	32
70	CV01	1.64	0.24	0.90	0.94	0.36	4176	166	92	10	20	27
71	CRF30	1.80	0.18	0.67	1.07	0.33	4366	221	107	5	14	31
72	CV11	1.67	0.23	0.84	1.03	0.36	4278	327	102	7	18	31
73	CRF21	1.73	0.22	0.94	0.83	0.32	3741	177	96	6	16	33
74	CRF11	1.44	0.22	0.62	0.92	0.32	3414	147	98	5	13	30
75	CRF20	1.53	0.22	0.68	0.88	0.31	3744	169	88	5	14	28
76	CV11	1.58	0.24	0.66	0.93	0.34	4082	168	94	6	17	28
77	Control	1.82	0.22	0.95	0.99	0.35	4874	230	99	6	18	27
78	CV01	1.53	0.28	0.99	0.88	0.35	3804	158	107	8	19	31

79	CRF30	1.73	0.19	0.86	0.91	0.31	4045	203	108	6	15	29
80	CRF31	2.07	0.18	0.67	0.87	0.31	4031	270	101	5	14	28
81	CRF10	1.60	0.22	0.67	1.03	0.32	4042	345	93	6	15	29

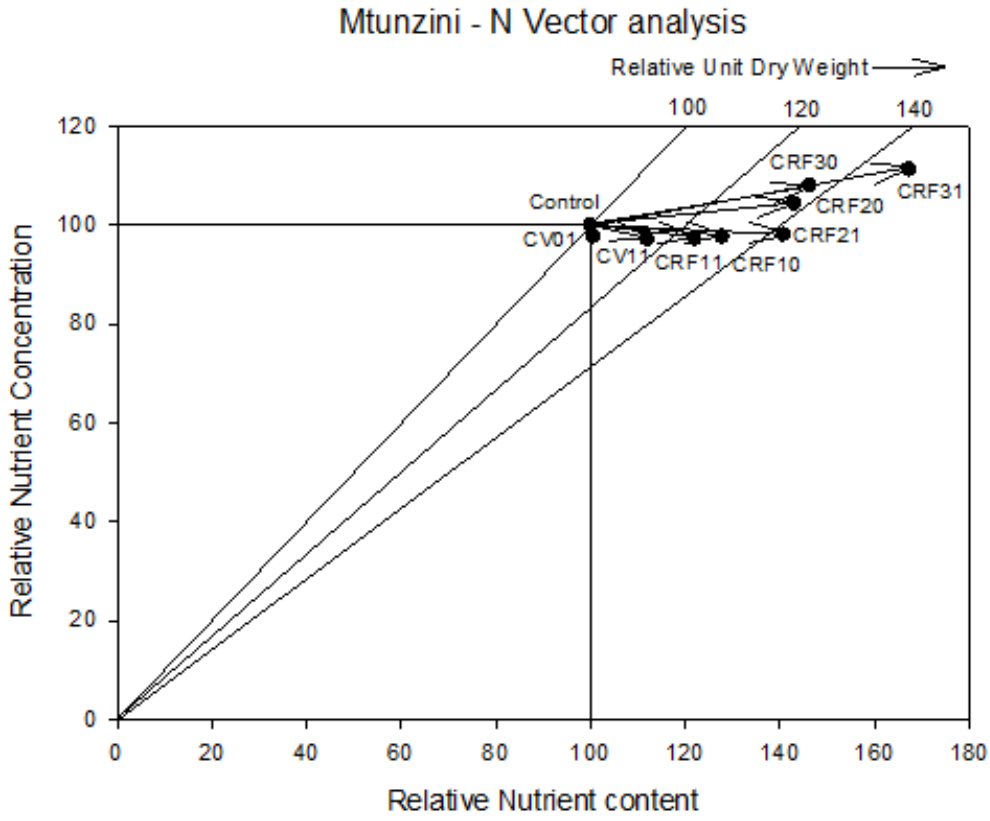
ii) Flatcrown

Plot	Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
		%					mg/kg					
7	CV01	2.08	0.20	0.95	0.91	0.32	3088	251	142	9	18	29
8	CRF11	2.66	0.18	0.85	0.97	0.28	2301	268	137	9	18	35
9	CRF30	3.02	0.18	1.12	0.89	0.27	1973	230	183	8	32	38
16	CRF10	2.53	0.15	0.95	1.12	0.31	2499	328	139	9	17	31
17	CRF21	2.74	0.17	1.09	0.82	0.27	2123	208	109	9	17	30
18	CRF31	2.71	0.15	1.01	1.04	0.25	2198	293	131	9	19	34
25	CRF20	2.76	0.19	1.13	0.93	0.25	2340	325	127	10	19	30
26	Control	2.48	0.18	1.16	0.93	0.29	2507	323	127	10	18	29
27	CV11	2.62	0.17	0.98	0.86	0.27	2316	249	125	10	17	30
31	CRF31	2.98	0.18	0.98	0.86	0.24	1685	299	146	9	17	33
32	Control	2.45	0.18	1.05	1.11	0.29	2392	342	155	10	20	27
33	CRF30	2.90	0.18	1.09	1.07	0.28	1921	383	145	10	20	32
40	CRF20	2.47	0.14	0.91	1.15	0.24	2443	450	163	8	17	31
41	CRF21	2.83	0.21	1.02	0.84	0.26	2243	308	134	9	18	30
42	CRF10	2.67	0.17	0.78	1.08	0.28	1991	387	155	10	19	28
49	CRF11	2.04	0.16	0.98	0.96	0.30	2638	316	170	8	16	27
50	CV01	2.04	0.20	0.96	1.00	0.30	2335	331	162	9	17	25
51	CV11	2.64	0.16	0.94	1.07	0.29	2033	575	154	9	18	31
55	CRF20	2.37	0.18	1.16	0.92	0.27	2441	320	177	9	24	29
56	CRF31	2.70	0.16	1.15	1.04	0.29	2196	340	216	7	16	35
57	CRF10	2.17	0.17	0.96	1.03	0.30	2245	335	189	8	17	29

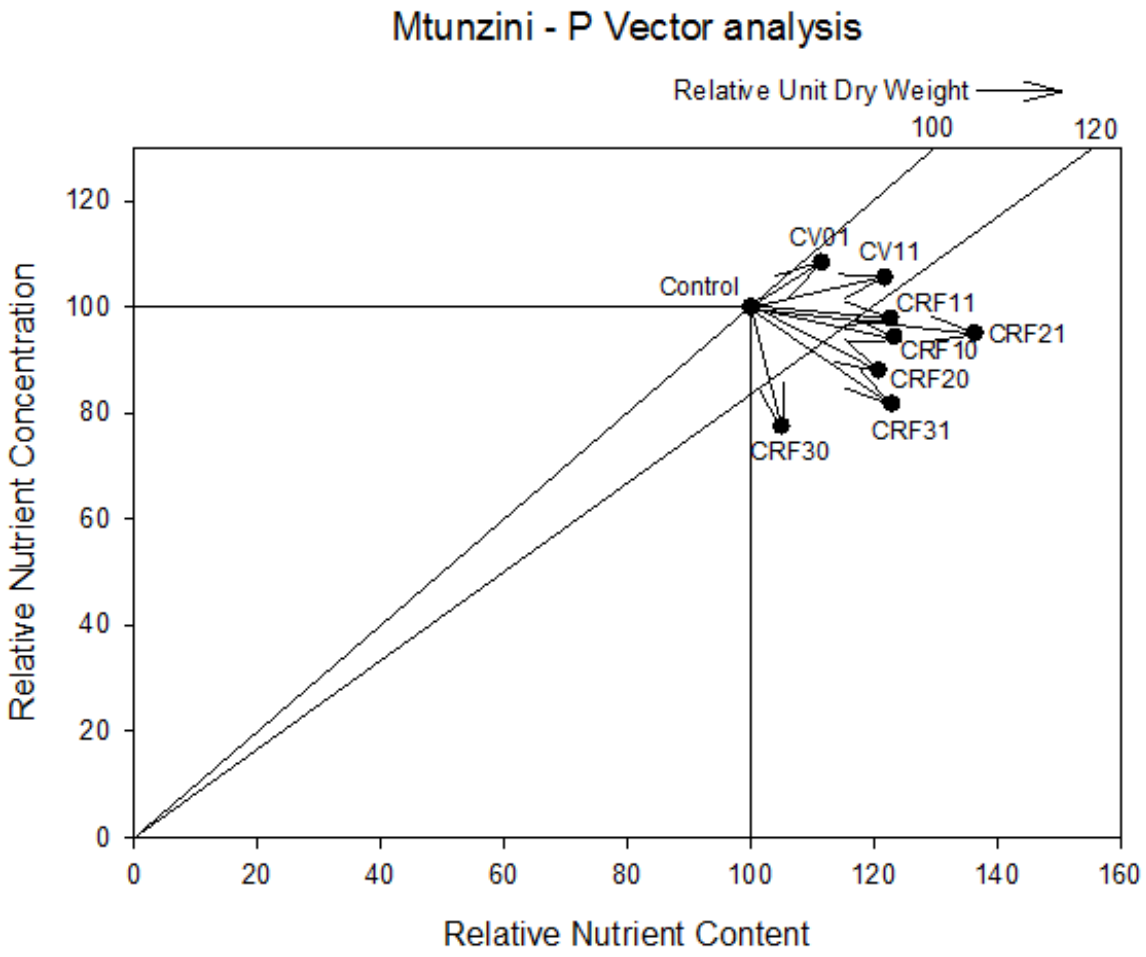
64	CRF11	2.42	0.16	0.93	0.93	0.26	2190	283	208	8	17	31
65	Control	2.52	0.16	1.07	0.91	0.28	2685	381	206	9	17	28
66	CV01	2.37	0.15	0.88	0.97	0.29	2602	403	192	9	19	26
73	CV11	2.44	0.14	0.83	0.94	0.26	1850	255	224	8	15	33
74	CRF30	2.84	0.16	1.12	0.84	0.25	1976	332	204	8	17	34
75	CRF21	2.62	0.20	9.88	0.99	0.37	4860	584	676	12	57	46

Appendix 3B

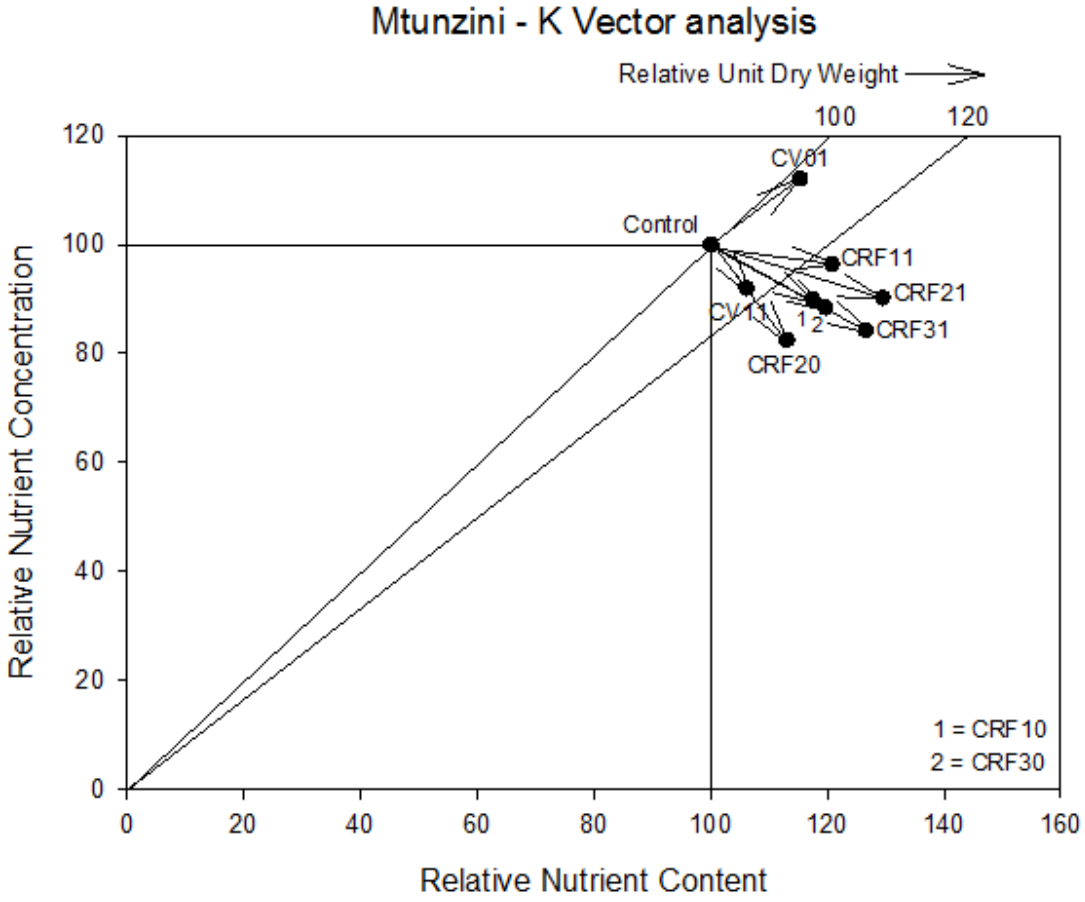
Mtunzini and Flatcrown Macronutrient Vector nomograms



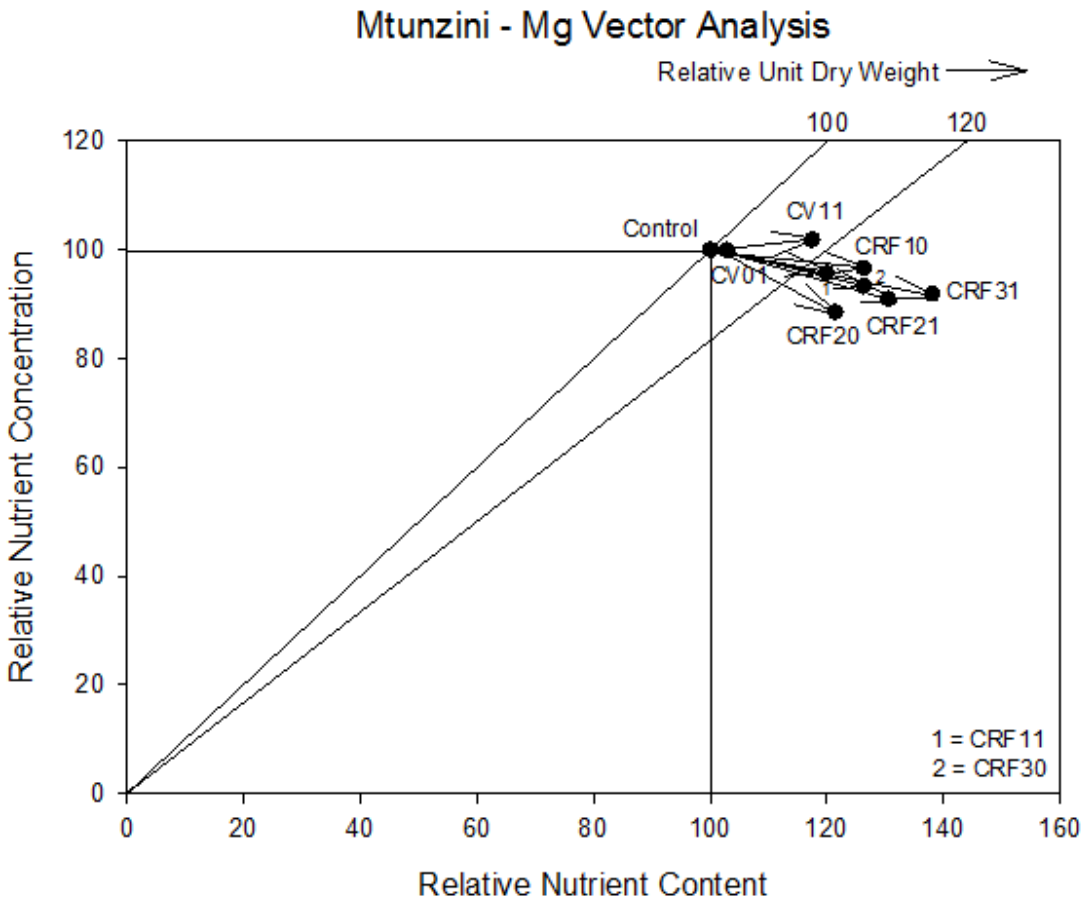
a) Vector nomogram of responses to N of all treatments showing a mixture of type A and C shifts.



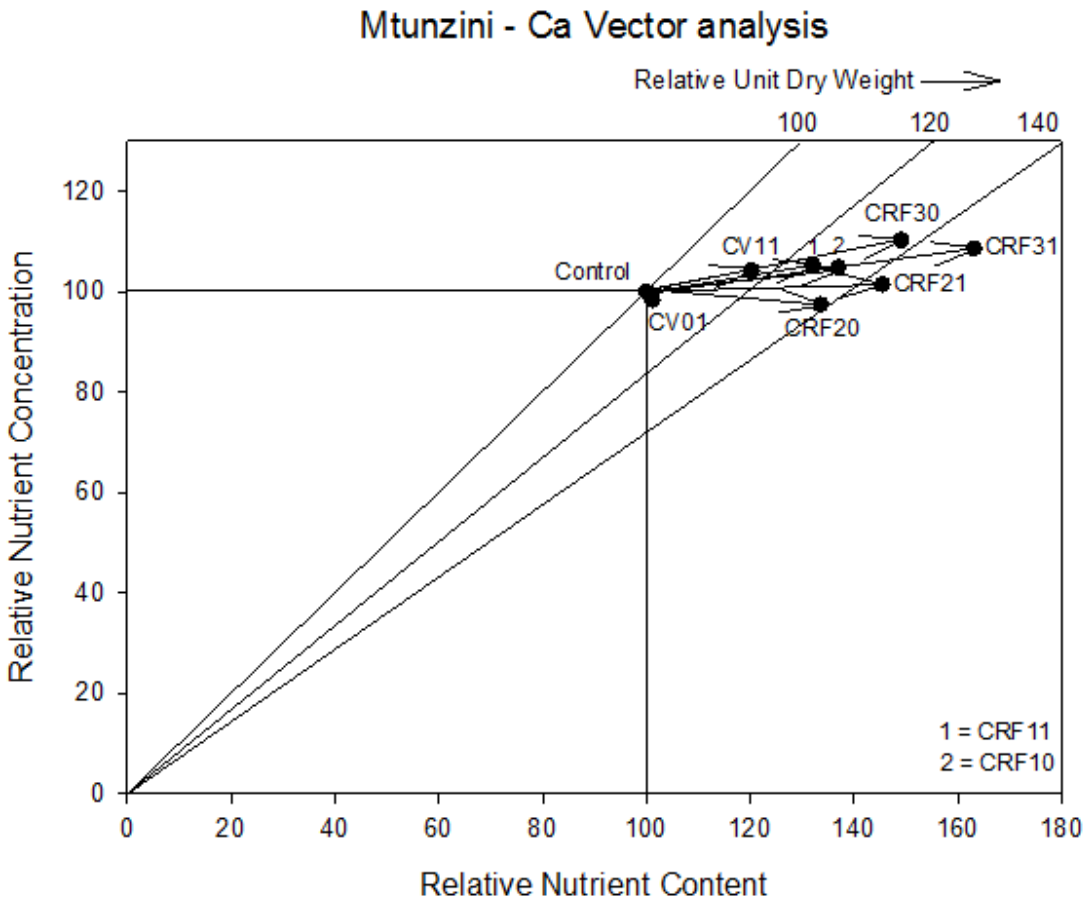
b) Vector nomogram of responses to P of all treatments showing majority of type A shifts.



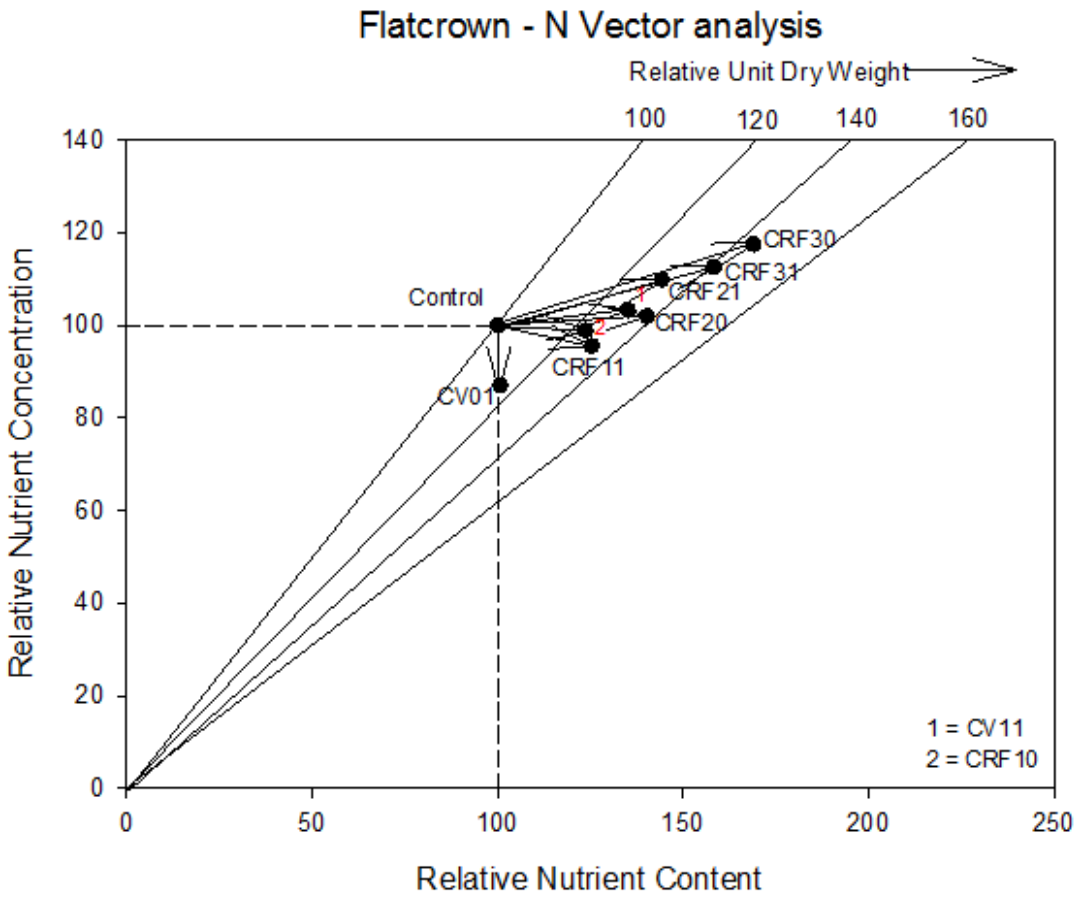
c) Vector nomogram of responses to K of all treatments showing type A responses for all treatments except CV01.



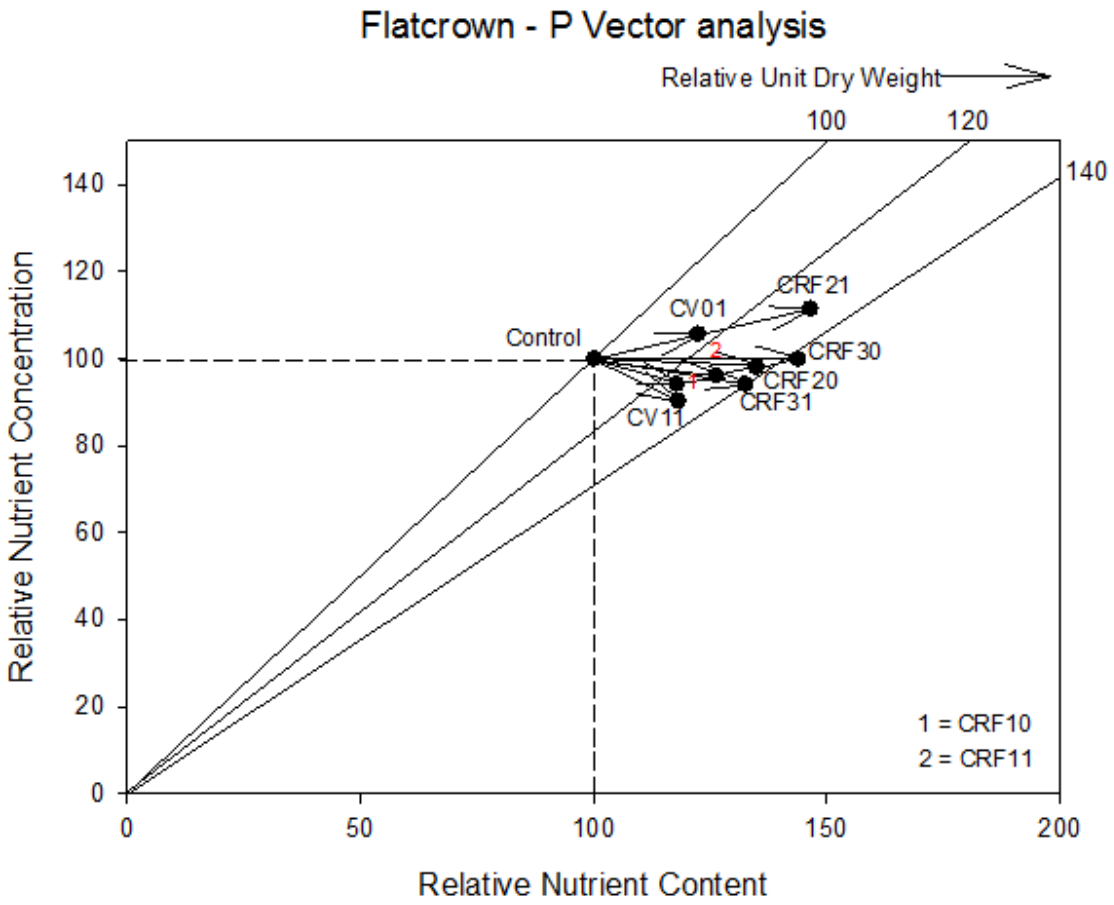
d) Vector nomogram of responses to Mg of all treatments showing type A shifts for all treatments except CV11, type C and CV01 type B.



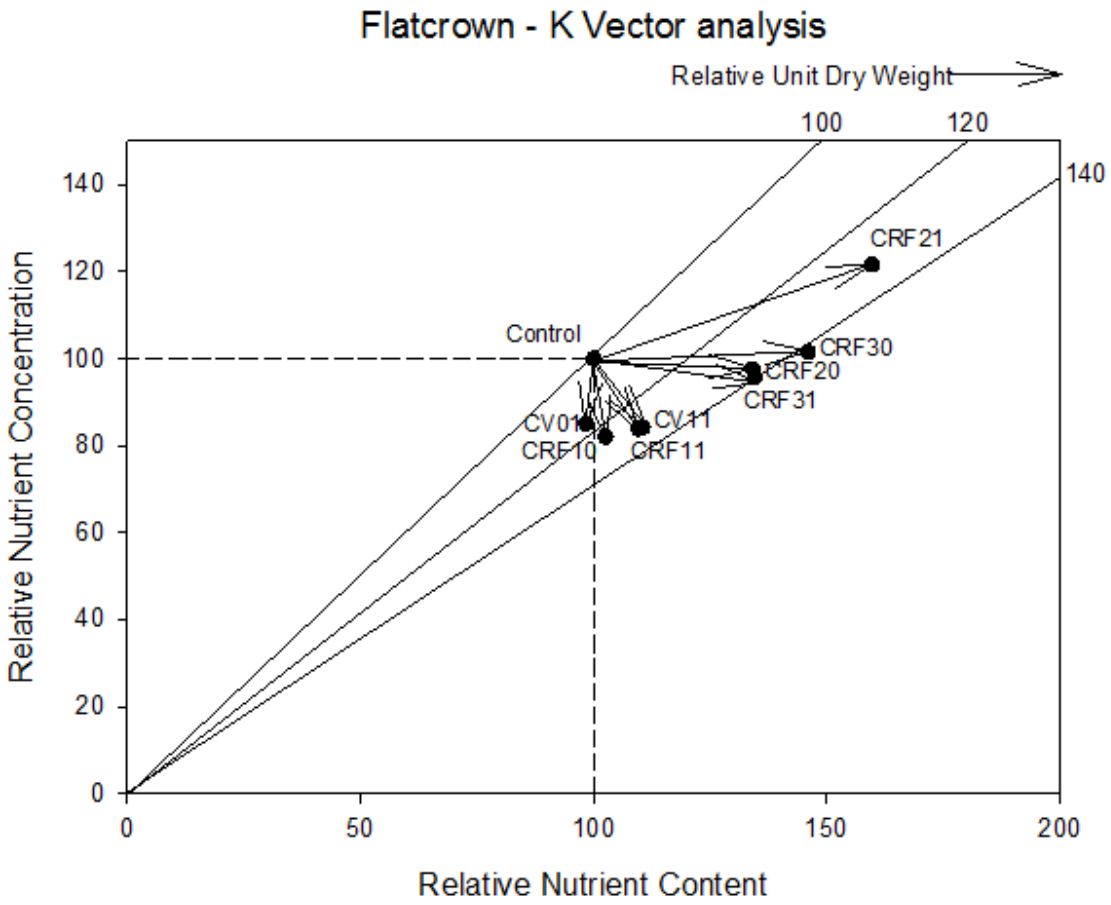
e) Vector nomogram of responses to Ca shows majority of Type C shifts.



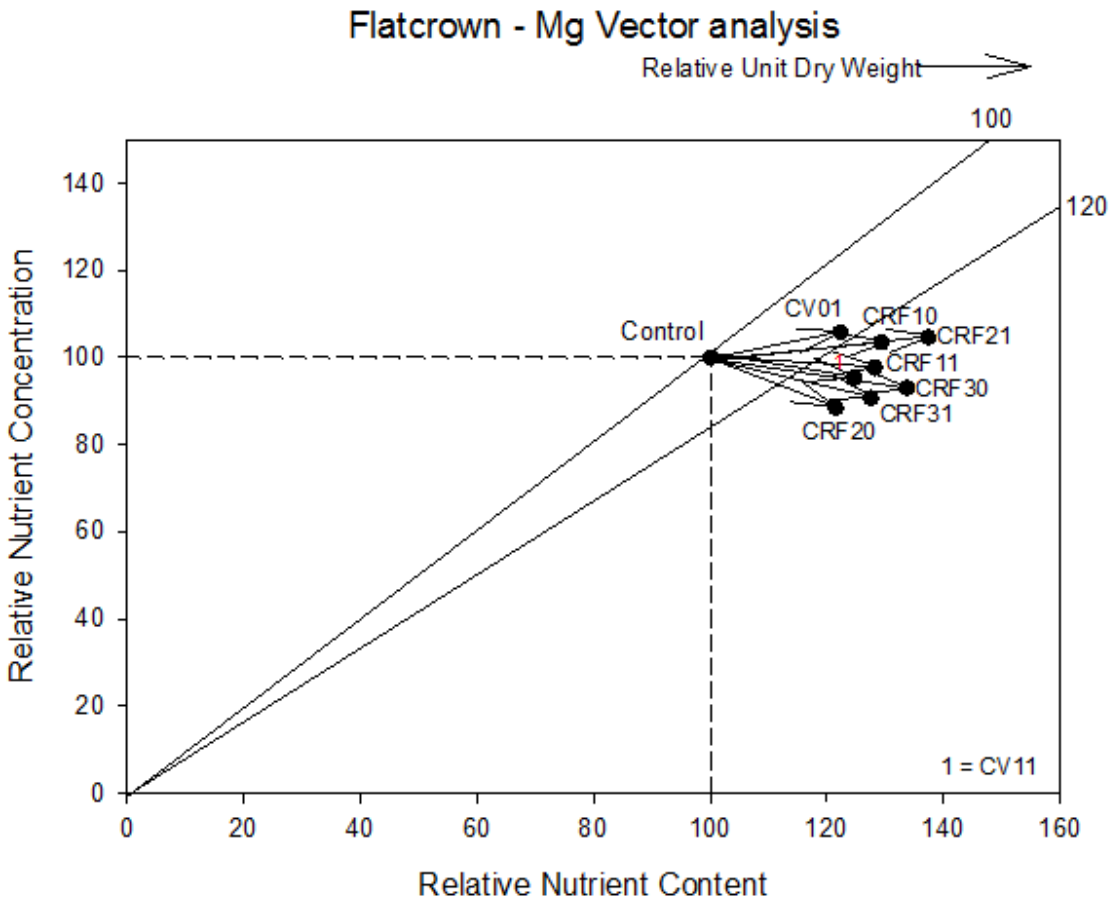
f) Vector nomogram of responses to N of all treatments showing a mixture of Type A and C responses.



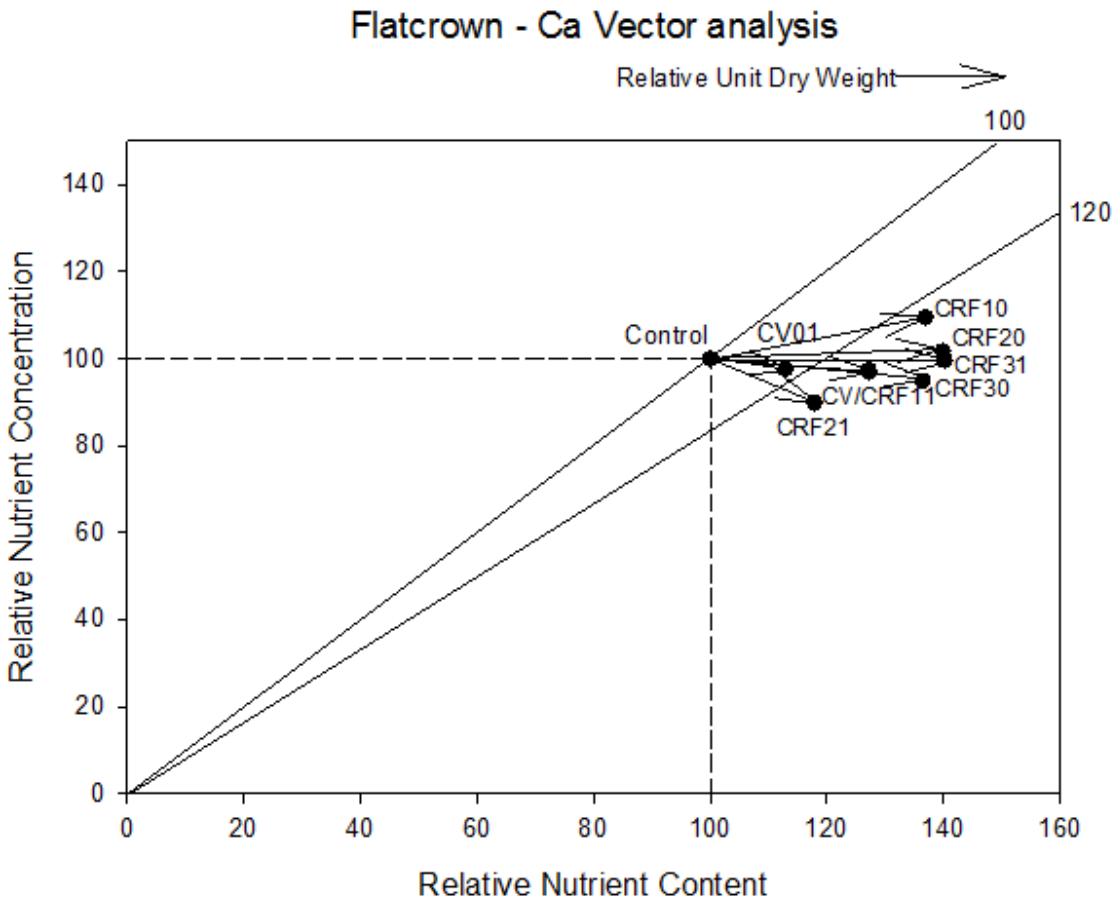
g) Vector nomogram of responses to P indicating a mixture of Type A, B and C responses.



h) Vector nomogram of responses to K of all treatments showing a mixture of Type A and C responses, with CV01 showing a non-typical response.



i) Vector nomogram of responses to Mg of all treatments showing a mixture of Type A and C responses.



j) Vector nomogram of responses to Ca of all treatments showing majority of type A responses.