

**Fertilisation of semi-mature *Pinus elliottii* and *Pinus elliottii* x
caribaea stands on a climatic gradient in the Tsitsikamma and its
effect on system nutrition and stand productivity**

by

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DECLARATION

I declare that the electronic submission of the research reported in this thesis, for the degree of Doctor of Philosophy at the University of Stellenbosch, is my own original research (except where otherwise indicated). This thesis has not been submitted in its entirety or partly for any degree or examination at any other university.

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ABSTRACT

Eight field trials were established in October 2015 to test the effect of different nitrogen and phosphorous combinations on *Pinus elliottii* and *P. elliottii x caribaea* growth. Fertiliser is costly, and the financial return is governed by the degree of the response, application costs and product worth. Commercial pine plantations are commonly fertilised at two stages – at establishment, and at mid-rotation following a final stem reduction. National and international studies are uncertain regarding the economic feasibility and response of semi-mature pine plantations to fertilisation. These uncertainties can be attributed to the substantial edaphic, topographic and climatic variations under which commercial plantations and forests are grown. The formulation of site-specific fertilisation rates could allow commercial and private forest companies to increase the profitability of fertilisation and achieve optimal growth responses. The field studies were established in the Tsitsikamma in the Eastern Cape, across a water-availability gradient and on sandy loam soils with soil pH (KCl) values ranging from 2.9 to 4.0. The field trials were designed to test the interaction of six fertiliser treatment combinations (all in kg ha⁻¹) and consisted of a control treatment of 0 N and 0 P (T0), and then treatments of 0 N and 50 P (T1), 0 N and 100 P (T2), 100 N and 50 P (T3) and 100 N and 100 P (T4), and a maximum application rate of 200 N and 100 P (T5). These application rates were based on the findings of previous softwood fertilisation projects in the Southern Cape, as well as in the Boland region of the Western Cape. Data collection was done at 0, 6, 12, 18 and 24 months after fertilisation. The primary objective of this study was to formulate site-specific fertilisation rates for the semi-mature pine plantations of the Cape forest region. To achieve this, the study was divided into four sub-studies. The first sub-study focused on the effect of water availability on stand growth. It investigated whether the water deficit estimate by Thornthwaite (1948) and Thornthwaite and Mather (1955) could be used as a reliable estimate of soil water availability, relative to other widely accepted (lesser and increasingly complex) estimates of water availability generally used in forestry and other agricultural practices. The second sub-study made use of the Soil Nitrogen Availability Predictor (SNAP) model to predict the N mineralisation rates of all field trials. The predicted N mineralisation rates were then used to determine whether the N mineralisation potential of a soil significantly affects the fertilisation response after 24 months. The third sub-study was a development of the second: the mineralisable N and P, from simple to increasingly complex, was determined in controlled laboratory conditions by means of aerobically and anaerobically incubating soil samples acquired from each field study. The relationships between (a) calculated mineralisation rates,

together with the basal daily N mineralisation rate predicted by the SNAP model and (b) the growth response at 24 months after fertilisation were evaluated. The final sub-study investigated whether canopy N and P contents were significantly affected by fertilisation and whether the application of different N and P fertiliser combinations can address the potential nutrient deficiencies of semi-mature slash plantations in the Tsitsikamma.

Findings: This study shows that Thornthwaite's soil water deficit methodology is an improved and increasingly accurate estimate of plant-available water relative to mean annual precipitation, and (FAO) estimates of aridity index a moisture growing season. The methodology has fewer and more easily obtainable data requirements and paints an accurate picture of soil water availabilities at times of seasonal fluctuations and inconsistent climatic conditions. The water deficit estimate has the potential to identify sites where growth is limited by soil water availability to larger and/or smaller degrees. Soils from slash pine plantations in the Tsitsikamma region have superior water-retention capabilities relative to sites from the Knysna and Boland regions of the Western Cape.

No significant correlations were observed between the predicted annual N mineralisation rate of the SNAP model and the growth responses at 24 months after fertilisation; however, the model predicted the highest annual rates for the least responsive field trial: a N mineralisation rate in the range of 149 (after subtracting the NH_4^+ before incubation from the final NH_4^+ pool) to 238 kg N ha⁻¹ yr.⁻¹ (final pool only) was predicted for field trial A, and this field trial exhibited the poorest growth response to added fertiliser over the experimental period. In addition, field trial A had a higher soil pH, and a significant interaction was observed between the N mineralisation potentials of each site and the soil pH ($p = 0.040$).

Significant Pearson correlations were observed between the total N, anaerobic N and aerobic P estimates and the growth response at 24 months after fertilisation. Field trials with higher total N contents were less responsive to increased N applications in the presence of P. The opposite was observed for increased P applications: sites with higher total N contents were increasingly responsive to higher applications of P. Sites with inherently higher anaerobic N mineralisation rates exhibited weaker growth responses to increased N application in the presence of P. Sites with higher P mineralisation rates were less responsive to P fertilisation. The anaerobically incubated N mineralisation rates were superior to the aerobic rates in this study, although the predicted basal N mineralisation rate of the SNAP model (which relies on an estimate of aerobic N) correlated with the volume responses at 24 months after fertilisation.

Canopy N and P contents differed significantly between sites ($p < 0.001$). The N contents were significantly affected by fertilisation, at a confidence level of 90% ($p = 0.059$), and the N contents increased according to the highest fertilisation rates (T0 to T5). Significant treatment differences were observed for the canopy P content ($p = 0.014$) after 24 months, with the highest P content observed for the highest application of phosphorus (T2), in the absence of a N source. Plant nutrient availability appeared to be primarily driven by site-specific edaphic and topographic conditions and, to some extent, by the higher N and P fertiliser combinations. The field trials were established on highly acidic soils. This finding, together with the documented volume responses, suggests that stand growth in the Tsitsikamma can be improved with moderate N and P fertiliser application rates. It also calls for further testing of micronutrient and lime additions, as low pH conditions and sub-optimal foliar micronutrient levels were associated with lower stand growth responses.

OPSOMMING

Agt veldproewe is in Oktober 2015 uitgelê met die doel om die uitwerking van verskillende stikstof- en fosfaatkombinasies op die groeitempo van *Pinus elliottii* en *P. elliottii x caribaea* plantasies te bestudeer. Kunsmistoedienings is 'n noemenswaardige uitgawe van boskultuur en die winsgewendheid berus op die groeireaksie, toedieningskoste en die kunsmismengsel. Kommersiële denneplantasies word tipies op twee groeifases bemes: tydens vestiging en kort na 'n finale uitdunning op middeljarige ouderdom. Die winsgewendheid en uitwerking van kunsmis op die groeitempo van middeljarige denneplantasies varieer en die bevindings van nasionale en internasionale studies verskil beduidend. Die beduidende verskille kan toegeskryf word aan die reeks edafiese, topografiese en klimaatstoestande waarop plantasies gevestig word. Die formulering van groeiplek-spesifieke bemestingsvlakke stel kommersiële en private maatskappye in staat om kostes te sny en optimale groeireaksies te behaal. Die veldproewe is geleë in die Tsitsikamma in die Oos-Kaap, oor 'n reënvalgradiënt en op sanderige leemgronde met pH (KCl) waardes van ongeveer 2.9 tot 4.0. Die proewe het elk ses kunsmisvlakke getoets (in kg ha^{-1}): 0 N en 0 P (T0), 0 N en 50 P (T1), 0 N en 100 P (T2), 100 N en 50 P (T3), 100 N en 100 P (T4), en 'n finale behandeling van 200 N en 100 P (T5). Die kunsmismengsels en vlakke van bemesting is gebaseer op vorige bemestingseksperimente in Suid- en Wes-Kaapland. Opmetings om die groeireaksie te bepaal, is op 0, 6, 12, 18 en 24 maande ná behandeling geneem. Die primêre doelwit van die studie was om groeiplek-spesifieke kunsmistoedienings te formuleer vir denne-opstande in die Kaapse plantasiegebiede. Die navorsing is opgedeel in vier subprojekte. Die eerste projek het ondersoek of grondwatertekort (bereken deur die Thornthwaite (1948; 1953) metode) 'n beter skatting is van grondwaterbeskikbaarheid relatief tot die algemene (en toenemend komplekse) skattings wat in die bosbou- en landboubedrywe gebruik word. Tweedens is die *SNAP* model (*Soil Nitrogen Availability Predictor*) gebruik om die N-mineralisasievermoë van elke veldproef te bereken. Dié waarde is gebruik om vas te stel of die N-mineralisasievermoë die groeireaksie 24 maande ná behandeling affekteer. Die derde subprojek was 'n uitvloeisel van die tweede – N- en P-mineralisasietempo's is in gekontroleerde laboratoriumtoestande bereken deur inkubasies van grondmonsters vanaf elke proef. Die bogenoemde mineralisasietempo's, insluitend die basale mineralisasietempo van die *SNAP*-model, is met behulp van regressiewe tegnieke vergelyk met die groeireaksie van elke proef tot en met 24 maande ná behandeling. Die finale subprojek het ondersoek of N- en P-inhoud in die kroondak beduidend beïnvloed word deur

kunsmistoedienings in die Tsitsikamma en terselfdertyd of die toedienings enige voedingstofgebrekke oor die studietypderk kon ophef.

Bevinding: Die studie het vasgestel dat die Thornthwaite-grondwater-tekortmetodiek 'n verbeterde en akkurate skatting is van plant beskikbare waterinhoud relatief tot die gemiddelde reënval, asook die (FAO) indekse van ariditeit en vog-groeiseisoen. Die metodiek het minder datavereistes en skets 'n verbeterde algehele beeld van grondwaterbeskikbaarheid tydens seisoenale en uiterste klimaatsveranderinge. Die metodiek het die potensiaal om groeiplekke te identifiseer waar hoër en laer vlakke van grondwater beskikbaar is en boomgroei kan beïnvloed. Die gronde van die Tsitsikamma het hoër vlakke van beskikbare grondwater relatief tot verskeie plantasiegebiede in Suid- en Wes-Kaapland.

Die groeireaksies 24 maande ná bemesting is nie beduidend beïnvloed deur die jaarlikse N-mineralisasievermoë wat deur die *SNAP*-model voorspel is nie, alhoewel die model 'n jaarlikse mineralisasie van 149 en 238 kg N ha⁻¹ jr⁻¹ (aanvanklike NH₄⁺-konsentrasie uitgesluit en ingesluit) voorspel het in proef A en dié proef ook die swakste groeireaksie tot gevoegde bemesting oor die eksperimentele tydperk getoon het. Daarbenewens het proef A die hoogste pH gehad en 'n beduidende interaksie is waargeneem tussen die N-mineralisasievermoë en die grond-pH ($p = 0.040$). Die bevinding het bewys dat die N-mineralisasievermoë van 'n grond 'n beduidende faktor is wat ingereken kan word met die beplanning van jaarlikse bemestingsveldtogte.

Beduidende Pearson-korrelasies is waargeneem tussen die totale N-inhoud, anaerobiese N en aërobiese P-mineralisasietempo's, en die groeireaksie 24 maande ná bemesting. Proewe met 'n hoër N-inhoud het laer groeireaksies op N-toedienings getoon in die teenwoordigheid van P. Daarbenewens is die teenoorgestelde waargeneem vir toenemende P-toedienings: proewe met hoër totale N-inhoud het beter groeireaksies getoon met toenemende P-toedienings. Proewe met hoër anaerobiese N-mineralisasietempo's het swakker groeireaksies op verhoogde N-toedienings in die teenwoordigheid van P getoon. In dié studie was die anaërobiese skattings van N beter as die aërobiese skattings, alhoewel die voorspelde basale N-mineralisasietempo van die *SNAP*-model (wat van die aërobiese N-skatting gebruik maak) ook beduidend gekorreleer het met die groeireaksies op bemesting.

Die kroondak N-inhoud is matig beduidend beïnvloed deur die kunsmisbehandelings ($p = 0.059$). Die N-inhoud het beduidend toegeneem volgens die toenemende hoeveelhede kunsmis wat in die studie gebruik is (T0 tot T5). Beduidende verskille in kroondak P-inhoud

is ná 24 maande ($p = 0.014$) tussen die behandelings waargeneem. Die hoogste kroondak P-inhoud is waargeneem vir die hoogste P-behandeling (T2) in die afwesigheid van N. Dit het voorgekom asof blaarvoedingstatus gedryf word deur groeiplek-spesifieke edafiese en topografiese toestande en in 'n mate deur die hoër N- en P-kunsmisbehandelings. Hierdie bevinding, saam met die groeireaksies wat in al die proewe waargeneem is, dui daarop dat verbeterde groeireaksies in die Tsitsikamma behaal kan word met matige N- en P-toedienings. Dit is noodsaaklik om verdere eksperimente uit te voer op bekalking en spoorelemente in die streek, omdat suur grond en sub-optimale vlakke van spoorelemente in die naalde geassosieer is met die swakste opstandgroeï in die reeks proewe.

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TERMS AND ABBREVIATIONS

- AI = Aridity index
- ASW = Available soil water
- B = Boron
- Ca = Calcium
- CAD = Soil water storage capacity
- Cu = Copper
- DBH = Diameter at breast height
- ET_r = Real evapotranspiration
- ET_p = Potential evapotranspiration
- Fe = Iron
- h_n = Angle at time of sunrise
- I = Heat index
- ICP-OES = Inductively coupled plasma optical emission spectrometry
- IRR = Internal rate of return
- K = Potassium
- LAI = Leaf area index
- LUE = Light-use efficiency
- MAP = Mean annual precipitation
- MAT = Mean annual temperature
- Mg = Magnesium
- MGS = Moisture growing season
- Mn = Manganese
- N = Nitrogen
- Na = Sodium
- NDA = Day number of year
- NEG ACUM = Negative accumulation
- OER = Optimum economic rotation
- P = Phosphorous
- RFWC = Relative field water content
- SLA = Specific leaf area
- SNAP = Soil nitrogen availability predictor

- STUF = Soil temperature under forest
- SWUF = Soil water under forest
- T_n = Mean monthly air temperature
- WC = Water content
- WD = Water deficit
- W_{LL} = In-field lower limit water content
- W_{UL} = In-field upper limit water content
- Zn = Zinc

CHAPTER 1

INTRODUCTION AND STUDY OBJECTIVES

1.1 Introduction

Commercial plantation forestry is an economically driven sub-division of the South African agricultural sector that relies on the integration of technology, proficient planning and biological production to achieve sustainable and optimal resource use for selected timber species. In South Africa, exotic timber species are favoured over indigenous species, due to the demand of national and international markets, desired timber properties and the increased resource-use efficiency.

The productivity of these monoculture plantation species is strongly affected by environmental factors such as water availability and evaporative demand, ambient temperature, edaphic properties and how well the species is matched to a site. The implementation of different fertiliser regimes has enabled private and commercial forest companies to increase stand productivities and timber yields. Fertilisation generally occurs at two stages in a softwood plantation's rotation age, viz. at establishment and at mid-rotation. The notion of applying fertiliser to semi-mature pine stands is not accepted without disinclination; the long-term financial returns (at rotation age) and the cost-effectiveness of fertilisation vary markedly due to stand variability and different growing conditions. Fertiliser is costly, and the financial return is governed by the degree of the response, application costs and product worth (Jokela, 2004). Fertilisation at establishment supplies the seedlings with nutrients during a growth stage when the nutrient demand is at its peak and the seedling is most susceptible to external factors. The nutritional demand placed on the soil, up to canopy closure, can potentially outweigh the soil's ability to meet this demand. Semi-mature pine plantations tend to have a reduced growth rate after canopy closure is reached. This loss of productivity could likely be attributed to the soil no longer being able to meet the nutritional demand of the stand, provided the competition for light and water is not limiting. Mid-rotation fertilisation can temporarily supplement the soil with the necessary nutrients to increase site productivity and crop yield up to rotation age.

1.2 Commercial pine plantations in the Western Cape

South African commercial plantations cover approximately 1.3 million hectares of land area and have an investment value of around \$2.6 billion. The forestry industry produces an annual sustainable timber volume of 20 million tons, and softwood plantations account for approximately 51% of all the intensively managed forest plantations (Godsmark, 2014).

In 2011, 9.1% and 18.1% of the total afforested area (51.1%) in the Western and Eastern Cape respectively were pine plantations (Godsmark, 2013). In 2011 and 2012, pulp, paper and saw log primary production plant timber intakes consisted of 73% pulpwood and 20% sawtimber (Godsmark, 2014). The South African forestry industry operates on a relatively small land area and therefore relies on intensive forest management practices to remain sustainable, economically competitive and, at the same time, to meet the demands of national and international markets.

1.3 Fertilisation in pines

National and international studies have shown that the response to fertilisation across different age classes is affected by the edaphic and climatic conditions at each growing site. Fertiliser and water additions to a semi-mature *Pinus taeda* stand, grown on a well-drained sandy soil, can increase volume increment and leaf area development (Albaugh, Allen, Dougherty, Kress & King, 1998). After four years, fertilisation increased stem volume increment, total biomass production and leaf area index by 152%, 99% and 101% respectively. In addition, the treatments increased stem volume growth efficiency (growth per unit leaf area index (LAI)) by 21% and total biomass production efficiency by 91%.

Jokela and Stearns-Smith (1993) studied the effects of single and split N and P fertilisations to 14- to 17-year-old *P. elliotii* and *P. taeda* stands in the Coastal Plain of the southwestern United States. The authors observed positive basal area and stand volume responses, relative to the control treatments, at eight years after fertiliser application. In addition, basal area and volume increases of 43% and 39% respectively were observed. Payn, De Ronde & Grey (1988) studied the effects of phosphate fertilisation on semi-mature (16-20 years) *P. radiata* stands in the Western Cape. The authors found a highly significant response for the potential volume increases at 35 years of age. Increases ranged between 44 m³ ha⁻¹ and 130 m³ ha⁻¹ and relied on site conditions. The authors suggested an economically viable application rate of 35 to 60 kg P ha⁻¹ fertiliser on P-deficient sites planted with *P. radiata*. In agreement with Payn *et al.* (1988), Scott and Bliss (2012) found that greater P fertilisation rates do not necessarily lead to

improved growth responses in 27-year-old *P. taeda*. The higher P fertilisation rates were not as effective, possibly due to induced N limitations.

The fertilisation of semi-mature pine plantations has the potential to optimise the productivity and volume output of pine stands. The irregular growth responses reported in the literature accentuate the potential opportunities to study and make positive contributions to the current fertiliser regimes of commercial softwood plantations in the Western and Eastern Cape, South Africa.

1.4 A need for improved pine fertilisation regimes in South Africa

New afforestation decreased from approximately 45 000 ha in 1992 to nearly 0 ha in 2012 (Godsmark, 2014). The environmental concerns regarding the excessive use of soil water by plantations, and several economic and social constraints have made it necessary for private and commercial companies to explore new means of increasing biomass and timber production on a relatively small (and shrinking) afforested area. Mid-rotation fertilisation has the potential to increase sawtimber yield in pine plantations. However, new approaches must be explored whereby edaphic and climatic variation are incorporated into the decision-making process. In addition, the inherent costliness of fertilisation furthermore accentuates the importance of incorporating these variables into the decision support system to optimise fertiliser regimes. Site-specific fertiliser recommendations would reduce the costliness of fertilisation and ensure an optimal growth response by utilising the edaphic and climatic conditions more effectively.

1.5 Approach of the study

This thesis describes the scientific approach and steps taken to formulate site-specific fertiliser recommendations for *P. elliottii* and *P. elliottii x caribaea* plantations in the Western and Eastern Cape, South Africa. Several trials were established in the Tsitsikamma region, with each trial testing a series of N and P fertiliser combinations for a range of different edaphic and climatic conditions. The study primarily compares the effect of different fertiliser combinations, ranging from conservative to increased application rates, on the nutritional status, growth and canopy development of pine stands. Chemical and physical analyses were done on foliage and soil samples from each site to observe and assess the potential effects of fertiliser on stand nutrition. The effect of different soil N and P availabilities and the annual N mineralisation rates were additionally incorporated as part of the assessment. Changes in tree diameter, height and canopy development were used to assess the degree of the responses. Data

collection commenced several months before fertilisation and continued up to 24 months after fertilisation.

1.5.1 Objectives

The main objective of the study was to investigate the effects of N and P fertilisation on *P. elliottii* and *P. elliottii x caribaea* stand nutrition and development. Several growth predictors, viz. soil water availability, soil N and P mineralisation rates, canopy N content, foliar nutrient concentrations and the predicted basal and annual N mineralisation rates of the SNAP model (of each field trial) were used to assess the responses. The results from this study were used to identify afforested areas that have the potential to respond positively to fertilisation and, lastly, these findings were used to formulate site-specific fertiliser recommendations for the Eastern and Western Cape pine afforested regions.

1.5.2 Research questions

Four simplified research questions were developed for this project, and each research question represents one of the main chapters of this thesis.

1. Can the water deficit (WD) estimate of Thornthwaite (1948) be used to characterise the soil moisture regimes of several sites in the Cape Forest Region, and can this estimate be used to identify soils for a variety of land uses that could potentially be less or more responsive to fertilisation, relative to more commonly used agrometeorological estimates such as mean annual temperature (MAT), the aridity index (AI) and moisture growing season (MGS)?
2. Is there a relationship between the early growth responses of semi-mature slash pine stands to fertilisation and the predicted annual N mineralisation rates of the soil Nitrogen Availability Predictor (SNAP) model, and can the SNAP model be used to identify sites more responsive to fertilisation?
3. Can more simplified estimates of soil N and P availability (i.e. estimates that do not require modelling) be correlated with the early growth responses of semi-mature slash pine stands to fertilisation?
4. What is the effect of fertilisation in semi-mature slash pine stands on canopy N and P contents, and did fertilisation address the nutritional deficiencies of the tested stands within the 24-month monitoring period?

1.6 Thesis structure

The thesis consists of a general literature review (Chapter 2), followed by the site descriptions, analytical approaches and laboratory procedures implemented throughout this project (Chapter 3). The main body of the thesis is a compilation of four sub-studies and is represented by four chapters (Chapters 4 to 7). Each chapter was prepared for peer-reviewed publications and will be near completion or under review by the time of the submission of this manuscript. Chapters 4 to 7 make use of the same numerical datasets (growth responses); however, some chapters incorporate additional analytical and numerical datasets that conform to the set objectives for the respective chapter. Additional methodological descriptions and approaches are described in the respective chapters to avoid repetition and confusion. Chapter 8 comprises the conclusion, recommendations and future work of this project.

CHAPTER 2

GENERAL LITERATURE REVIEW

2.1 Introduction

Stand productivity is controlled and limited by a range of processes and factors, such as the nutrient supply-demand capability and fertiliser properties of the soil (Crane, 1984). Biological and stand factors such as age, development stage (Crane, 1984), initial basal area, site index (Duzan, Allen & Ballard, 1982), genotype (Allen, Fox & Campbell, 2005), light-use efficiency, dry matter allocation, pest occurrence and size-density relationships equally affect the responsiveness to fertilisation (Campion, 2008; Jokela, 2004). The application of fertiliser to pine plantation stands has been shown to increase site productivity, but application is costly and gives rise to its own challenges regarding reliable application rates and application methods. *Pinus elliottii* and *P. taeda* stands place a substantial nutrient demand on the soil during initial canopy development (Jokela, 2004). The increased soil nutrient demand could have a considerable effect on the growth responses to fertilisation in soils where the quantity and intensity of nutrient release from various soil nutrient pools into the soil solution and the exchange inadequately meet demand. Semi-mature pine stands that have reached canopy closure have a reduced growth rate; the growth reduction could likely result from the soil not being able to meet the nutritional demand of the stand after several years of growth, along with competition for light and water. Mid-rotation fertilisation can temporarily supplement the soil with additional nutrients to meet the demand on the stand, thus effectively increasing stand productivity and growth.

The identification of several site-specific growth predictors and criteria that could aid in identifying and evaluating the potential responsiveness of a site to fertilisation, and incorporating these criteria into the decision-making process, create the opportunity to optimally increase the productivity of a species and reduce the rotation length. This can greatly improve on existing fertiliser regimes by reducing the cost of fertilisation and increasing the profitability of softwood plantation forestry in South Africa.

2.2 Pine fertilisation

The fertilisation of softwood plantations is well researched in South Africa. This section describes the documented changes in stand nutrition and canopy development following the application of N and P fertiliser to several pine species and a range of growing conditions. The responses of *P. taeda* to fertiliser are central to most of the reviewed literature. Xiao et al. (2003) found that *P. taeda* and *P. elliottii* follow closely related growth strategies after intensive silvicultural management operations, thus the responses of *P. taeda* to fertiliser application can to an extent be indirectly correlated to the potential responses of *P. elliottii*.

2.3 Soil properties

2.3.1 N and P availability

Wienand and Stock (1995) studied the effects and duration of phosphorous fertiliser additions on the N and P cycling in *P. elliottii* plantations in the Southern Cape, South Africa. Fertiliser application occurred at different ages and intensities, viz. at establishment (0 years), at 10 years of age and at a combination of both intervals. The authors found that the application of 30 to 60 kg ha⁻¹ superphosphate on 8-, 20- and 25-year-old *P. elliottii* stands significantly increased the soil P availability in the eight- and 20-year-old stands. Plots treated with fertiliser at establishment and 10 years of age showed significant increases in soil P availability (as indicated by triacid digestion) at 25 years of age. Soil N availability decreased significantly in all plots. The authors attributed the decrease to the immobilisation of inorganic N by the microbial populations in the soil due to the phosphate additions. Similar to Wienand and Stock (1995), Lopez-Zamora, Duryea, Wild, Comerford and Neary (2001) found that fertiliser increased the soil P availability at 24 months after application. The authors studied the effects of pine needle removal and fertiliser application on the growth and P availability of a 13-year-old *P. elliottii* stand. Plots were treated with 280 kg ha⁻¹ diammonium phosphate (DAP) for two consecutive years. Fertilisation significantly affected the P availability of the soils, and the treated plots had higher P availabilities relative to the unfertilised plots. Scott and Bliss (2012) reported similar findings; however, these authors studied considerably higher application rates relative to those studied by Lopez-Zamora *et al.* (2001). The former authors observed that exceedingly high P applications (up to 324 kg ha⁻¹) to *P. taeda* stands did not increase the available P; however, the reduced application rates of 81 and 162 kg ha⁻¹ increased soil P availability in the second rotation. The increases were evident for a highly weathered loamy soil. The findings of Wienand and Stock (1995), Lopez-Zamora *et al.* (2001) and Scott and

Bliss (2012) show that reduced or moderate P applications can increase soil P availability, although high rates of fertiliser application can have little or a negative effect on soil P availability.

Ring, Jacobson and Högbom (2011) studied the long-term effects of N fertiliser applications on the soil chemical properties in *P. sylvestris* stands in Sweden. The authors tested moderate to high application rates of 450, 900 and 1 800 kg N ha⁻¹. Soil sampling commenced in the 0 to 20 cm topsoil mineral layer. Fertilisation significantly decreased the soil C:N ratio. The decreases were attributed to the high N additions. Nitrogen, exchangeable Mg and P increased, and exchangeable K decreased in the mineral soil layer. These authors concluded that the effects of fertiliser applications on soil chemical properties were greater for increased fertiliser application rates.

2.3.2 *N mineralisation*

Nitrogen mineralisation refers to the microbial release of NH_4^+ from organic matter in and on the soil, and it relies on the quality of the organic substrate, microbial populations and ambient conditions such as temperature, moisture and soil pH (Pajuste & Frey, 2003). Forest management practices and genotype contribute significantly to the N cycling in forest systems (Arslan, Güleriyüz & Kirmizi, 2010; Lee & Jose, 2006). Lee and Jose (2006) found that the N mineralisation responses elicited from fertilisation and irrigation were significantly affected by the feedback mechanisms of different species, and that the relationship between N mineralisation and forest productivity is essential in the forest environment. Nitrogen mineralisation rates can fluctuate due to different elevation gradients, vegetation types and seasonal changes (Knoepp & Swank, 1998).

In line with the abovementioned statement by Knoepp and Swank (1998), Lee and Jose (2006) reported N mineralisation rates of 75 kg N ha⁻¹ year⁻¹ for a seven-year-old *P. taeda* stand in Florida, USA, grown on a siliceous sandy loam soil. The experiment tested a range of N fertiliser and irrigation treatments, and mineralisation rates were determined by means of the buried bag incubation technique. Pulito *et al.* (2015) reported higher mineralisation rates in Eucalypt stands and found that the N mineralisation rate of a soil can affect the degree to which trees respond to N fertilisation. Pulito *et al.* (2015) made N fertiliser applications of 240 kg ha⁻¹ (maximum application rate) to *Eucalyptus grandis* and *E. grandis x urophylla* stands in Brazil, 16 to 18 months after establishment. Soils were largely oxisols and quartzipsamments and had organic matter and clay contents of 15 to 55 g kg⁻¹ and 8 to 67%

respectively. Potentially mineralisable N and N mineralisation rates were determined by means of quarterly in situ anaerobic incubations, and rates varied from 140 to 400 kg ha⁻¹ and 100 to 200 kg ha⁻¹ respectively. Sites with a high N mineralisation rate had a low response to N fertiliser additions throughout the early growth period, and this effect was most noticeable on sandy soils. Environmental factors such as temperature, initial moisture and pH can significantly affect soil N mineralisation rates (Pajuste & Frey, 2003). The former authors studied the N mineralisation rates of podzol soils in Norway spruce and Scots pine stands in Estonia for an incubation period of one (summer) and five months (winter). Pajuste and Frey (2003) reported lower annual net N mineralisation rates of 29.2 and 23.6 kg ha⁻¹ for the two periods respectively. The lower N mineralisation rates reported in this study, relative to the above-mentioned studies, could likely be attributed to the lower temperatures at the time of incubation (winter). The differences could also be ascribed to genotypic and soil differences. Harrison and Maynard (2014) assessed and compared the N mineralisation rates of fertilised and unfertilised pine and spruce forest soils under controlled conditions, using exchange membranes and soil extractions. Both forests were treated with N fertiliser for a period of 14 years, either periodically (every six years) or annually. Aerobic incubation periods of one, two, four, six, eight, 10 and 12 weeks were chosen for the experiment, and incubations were divided into small and large pots. After the 12-week incubation period, the control treatments for the pine forest soils had respective mean (standard error) NH₄⁺ mineralisation rates of 1.6 (0.2) mg kg⁻¹ and 1.7 (0.5) mg kg⁻¹. Sites periodically fertilised had respective mineralisation rates of 39.0 (11.4) mg kg⁻¹ and 38.7 (12.2) mg kg⁻¹. Annual fertilisation had mineralisation rates of 60.4 (10.9) mg kg⁻¹ and 63.5 (12.1) mg kg⁻¹ respectively.

The positive effect of increased N availability from fertiliser application could be attributed to a soil C limitation, more specifically the moment the microbial demand for carbon exceeds the supply (Liu, Van Groenigen, Dijkstra & Hungate, 2017). This limitation would stimulate microbial biomass to increase the production of extracellular enzymes to break down the soil organic matter (Drake, Darby, Giasson, Kramer, Phillips & Finzi, 2013) and gain energy from carbon priming (Liu *et al.*, 2017). Microbial C priming can simultaneously release soil N due to the low C:N ratio of the soil organic matter (Schimel & Weintraub, 2003). The increased N mineralisation could also be attributed to the release of native soil N, initially immobilised by microbes, back into the environment following microbial death (remineralisation) (Redin *et al.*, 2014).

2.3.3 Soil depth and incubation time

Studies of N availability are done in the upper mineral soil, at a depth of 0 to 10 cm or 0 to 15 cm from the soil surface. The upper mineral soil layer is favoured more due to the mineral layer producing more than half of the N mineralised in the soil, and because mineralisation decreases with soil depth (Binkley & Hart, 1989). Buck (2013) studied the importance of placement depth regarding the use of soil N, P and sulphur ion exchange resin capsules in low-fertility soils. The author tested six N, P and S fertiliser treatments. Resin capsules were removed and substituted every 90 days, and final sampling occurred approximately 240 days later. The author found that a soil depth of 5 to 10 cm was the best capsule placement depth for the estimation of NH_4^+ after the incubation period. For the estimation of NO_3^- , the depth was not significant, but resin capsules correlated more strongly with the N applications and less with the 398 day incubation period. Bicarbonate-extractable P was significant for P fertiliser applications at all the tested depths (0 to 5, 5 to 10 and 10 to 15 cm) and incubation periods. The only exception was found for the two shallowest depths, of 0 to 5 and 5 to 10 cm, at the final sampling (240 days), and resin capsule P only correlated with P applications at 398 days after application.

Laboratory incubation times for N mineralisation studies are subjective and range from seven to 30 days or several months. The net production of inorganic N does not increase linearly with incubation time; this is due to the variations in the balance between N mineralisation and immobilisation, and the dynamics of the microbial populations within the soil (Binkley & Hart, 1989). Ion exchange resin bags are used under laboratory or field conditions as assays of P availability. In-field incubation periods range from one month to a year (Binkley & Hart, 1989). Buck (2013) used similar incubation times to test the effect of resin bag placement depth on N, P and S availability after several fertiliser treatments were added to a low-fertility soil, and incubation periods ranged between three and approximately eight months.

2.4 Responses to fertilisation

2.4.1 Foliar nutrient levels

Fertiliser applications of 280 kg ha⁻¹ diammonium phosphate (DAP) can increase needlefall N concentrations (Lopez-Zamora *et al.*, 2001). Barron-Gafford, Will, Burkes, Shiver and Teskey (2003) proposed that the amount of foliage in *P. elliotii* and *P. taeda* stands following high levels of fertilisation was an adequate estimator of growth. The experiment tested the effect of

fertilisation and different planting densities on foliar nutrient concentrations and stem growth. Three sites were selected, each site with a different soil type. At two years of age, the stands received 56.1 kg ha⁻¹ of N, P and K. At four years of age, the stands were treated with 67.3 kg N, P and K ha⁻¹ and a supplementary 45 kg N ha⁻¹ (NH₄NO₃). Micronutrients were applied in the same period. At five years of age, stands received a further 45 kg N ha⁻¹ (NH₄NO₃). The average soil N concentrations were similar for all stands (sampled at a depth of 30 cm). Foliar N and P concentrations were higher in the *P. taeda* stands after fertilisation, and foliar N decreased from 11.2 mg g⁻¹ to 9.1 mg g⁻¹ in the *P. elliotii* stands with increasing stand density. This suggests that the competition for resources was growth limiting in stands planted at higher densities. Stands planted at higher densities had higher levels of foliar biomass and foliar N contents (Shelton, 1984). In addition, the foliar K concentrations were significantly higher for the fertilised *P. elliotii* plots. Carlson, Fox, Allen, Albaugh, Rubilar and Stape (2014) found that N, P and K applications to mid-rotation *P. taeda* stands, aged between nine and 25 years, could increase foliar P concentrations. Plots treated with N and P fertiliser had increased foliar K concentrations relative to the control plots. Soil conditions varied significantly, as trials were located at various points in the South-Eastern parts of the United States. The effect of different soil and stand conditions on foliar nutrient levels is evident, as shown in the findings of Barron-Gafford *et al.* (2003) and Carlson *et al.* (2014).

2.4.2 Canopy development and volume responses

Fertiliser application to *P. taeda* can significantly increase absorbed photosynthetically active radiation (APAR) and light-use efficiency (LUE) (Campoe *et al.*, 2013). Campoe *et al.* (2013) studied the effects of fertilisation, irrigation and a combination of both on nine-year-old *P. taeda* stands, two years after the implementation of treatment. Responses were measured at tree level and the trees were selected per size class. The stand, located on an infertile siliceous sandy soil, had an average precipitation of approximately 1 210 mm year⁻¹. Fertiliser application was done in such a way that optimum stand nutrition was maintained for the experimental period. Tree size had a significant effect on the results obtained; fertilisation increased the above-ground net primary production (ANPP) of the top 20% trees twofold (8.6 kg tree⁻¹ year⁻¹). Of the 20% increase in ANPP, 29% was from higher APAR rates and 71% from higher LUE. The increases in ANPP, APAR and LUE were measured relative to the top 20% of the largest trees in the control treatments. The findings of Campoe *et al.* (2013) were similar to the findings of Albaugh, Allen, Dougherty and Johnsen (2004).

Chikumbu (2011) applied a range of fertiliser combinations in the Boland region of the Western Cape, South Africa. The experiment tested three factorial combinations of different levels of N and P fertiliser across a water gradient on *P. radiata* stands: 0, 100 and 200 kg N ha⁻¹ and 0, 50 and 100 kg P ha⁻¹. Stands were semi-mature and received a final thinning before fertilisation commenced. Chikumbu (2011) reported a significant response of LAI increment to the single effect of N and P fertilisations at one year and to P at two years after fertilisation. In addition, there were no significant interactions for the effect of supplementary N and P additions and moisture gradient on LAI, basal area, volume increment and growth efficiency. The largest responses were attributed to the additive effects of N and P applications. Nitrogen additions to an 11-year-old *P. radiata* plantation can increase the LAI and facilitate a positive growth response (Carlyle, 1998). Carlyle (1998) regulated the nitrogen uptake and water status of the stand by means of residue management, thinning and N and P fertilisation. Nitrogen uptake and the resulting positive LAI and growth responses were highly correlated with the stand density (thinning status) of the plantation; LAI and volume increases were significantly smaller for the unthinned stands after the three-year monitoring period. Fertiliser and water additions to a well-drained sandy soil can increase leaf area development and volume increment (Albaugh *et al.*, 1998). The experiment tested four fertiliser and irrigation treatment combinations on 8-year-old *P. taeda* stands. After four years, the plots treated with fertiliser showed increases in stem volume, total biomass production and a peak leaf area index (LAI) of 152%, 99% and 101% respectively. Furthermore, fertilised plots showed increases of 21% in stem volume growth efficiency (growth per unit LAI), and total biomass production efficiency increased by 91%.

Jokela and Martin (2000) found that the increases in LAI units in young *P. taeda* (seven years) and *P. elliottii* (nine years) stands following fertilisation produced nearly 3 and 3.1 times more stemwood biomass per year, relative to 14- and 16-year-old stands of the same species respectively. The application of K and a mixture of P and K at establishment can increase *P. patula* volume by 27 m³ ha⁻¹ and 25.2 m³ ha⁻¹ at seven years of age respectively (Crous, Morris & Scholes, 2007). Crous *et al.* (2007) authors applied single applications of K and combined applications of P and K to a fourth rotation *P. patula* crop in Swaziland in an attempt to increase yield. Ramírez Alzate, Rubilar, Montes, Allen, Fox and Sanfuentes (2016) reported volume increases of 25 m³ ha⁻¹ and 50 m³ ha⁻¹ for more than six years following the application of fertiliser to semi-mature *P. radiata* stands.

Scott and Bliss (2012) studied the effects of P fertiliser applications on soil P availability and long-term growth in a 27-year-old *P. taeda* stand. Phosphorous fertiliser application rates of 0, 81, 162 and 324 kg ha⁻¹ were tested on a highly weathered loamy soil. The authors found that plots treated with lower application rates responded more optimally; total biomass increased by 39% relative to unfertilised plots. The higher fertilisation rates were not as effective, possibly due to induced N limitations. Carlson *et al.* (2014) reported similar findings; these researchers found that applications of urea and diammonium phosphate (DAP) to semi-mature *P. taeda* stands (aged nine to 25 years) increased mean growth by 3.71 m³ ha⁻¹ year⁻¹ up to eight years after fertilisation. The fertilisation of 14- to 17-year-old *P. elliottii* and *P. taeda* stands can lead to increased basal area and stand volumes, eight years after the initial treatment applications (Jokela & Stearns-Smith, 1993). Basal area increased by 43% and volume by 39% relative to the control treatments. The authors tested the effectiveness of single and split fertiliser treatments; both fertilisers supplied the selected sites with approximately 224 kg N ha⁻¹ and 56 kg P ha⁻¹. Single treatments were applied as a single dose at the time of fertilisation. Split treatments were applied in two timeframes: the first treatment contained 56 kg N ha⁻¹ and 56 kg P ha⁻¹. The second treatment (two years later) contained 168 kg N ha⁻¹. Jokela & Stearns-Smith (1993) observed no significant difference in the degree or duration of the responses for the single and split N fertiliser treatments; this shows that delaying N applications for approximately two years did not reduce the observed growth response.

Payn *et al.* (1988) studied the effects of phosphate fertilisation on semi-mature (16 to 20 year) *P. radiata* stands in the Western Cape. The authors observed a highly significant response for the volume increase at 35 years of age. Increases ranged between 44 m³ ha⁻¹ and 130 m³ ha⁻¹ and relied on site conditions. The authors suggested an economically viable application rate of 35 to 60 kg P ha⁻¹ fertiliser on P-deficient sites planted with *P. radiata*.

2.4.3 *Specific leaf area*

The specific leaf area affects the canopy expansion and growth of vegetation by means of its influence on the total leaf area per plant (Kumar, Singh & Boote, 2012). Additionally, the light-use efficiency and light interception of a tree hinges on the total leaf area. The storage of additional carbohydrates, under elevated CO₂ conditions, or the reallocation of biomass to thicker leaves, increases leaf mass and decreases the specific leaf area (Kimball, Kobayashi & Bindi, 2002). The effect of increased nutrient availability on the specific leaf area (SLA) of pine plantations and forests varies significantly. Several studies have shown that high nutrient

availability can increase (Niinemets, Ellsworth, Lukjanova & Tobias, 2001; Raison, Myers & Benson, 1992) or decrease (Murthy & Dougherty, 1997; Niinemets *et al.*, 2001; Will, 2005) the specific leaf area of a pine forest. The high degree of variation could be attributed to the complex relationship between sunlight (photosynthesis) and forest nutrition in conifers, as the plasticity of foliar morphological properties (i.e. needle length and thickness) could be affected by nutrient availability (Niinemets *et al.*, 2001).

Will (2005) studied the effects of annual fertilisations on increased nutrient availability and needle morphology in the absence of the influence of light. Factorial combinations of fertiliser and interspecific competition controls were implemented at stand level for a five- and 12-year-old *P. taeda* stand. Competition control and stand age did not affect fascicle morphology; however, annual fertilisations increased fascicle length (5%), the number of needles per fascicle (4%) and total leaf area (18%), and decreased the specific needle area by 4%. This revealed that the extent of the morphological changes in pine needles (for *P. taeda*) are small relative to the changes in total canopy leaf area following increased nutrient availability.

Evidence suggests that the effect of stand age, needle age, crown position and seasonal variation significantly affects the SLA within certain pine species. Choonsig, Nam-Gyu, Hye-Yeon & Kwang-Soo (2013) found that the fertilisation of a mature *P. resinosa* stand did not significantly affect the specific leaf area, leaf area and dry mass of the canopy. The authors applied respective N:P:K and P:K fertiliser rates of 113:150:37 kg ha⁻¹ and 150:37 kg ha⁻¹ respectively and observed significant changes in dry needle mass and leaf area; however, the changes were a product of needle age and time of sampling. Beets and Lane (1987) reported similar findings to Choonsig *et al.* (2013). Beets and Lane (1987) suggested that stand age and leaf age could have accounted for the significant SLA variations in the studied *P. radiata* canopies. The findings were limited to stands with no substantial moisture and nutrient limitations. In addition to stand and needle age, the crown position can significantly affect the SLA of a pine forest (Xiao, Janssens, Yuste & Cuelemans, 2006). Xiao *et al.* (2006) investigated the SLA variation in a 73-year-old *P. sylvestris* stand and found the SLA of current-year needles to be higher than that of the one-year-old needles. The SLA increased significantly from the top to bottom of the crown and was significantly higher near the interior of the crown relative to the edge.

2.4.4 Stand density

The fertilisation of *P. taeda* stands, planted at increased densities, can yield larger leaf area indices (LAI) due to the increased efficiency of the canopy in intercepting radiation (Will, Narahari, Shiver & Teskey, 2005). Fertiliser was applied at establishment (56 kg ha⁻¹ N) and at one year of age (56 kg ha⁻¹ N) in stands planted at densities ranging from 740 to 4 440 trees ha⁻¹. Stem growth rates increased non-proportionally from 13.0 to 32.5 m³ ha⁻¹ y⁻¹ with planting density, thus suggesting that competition induced growth limitations. Annual intercepted photosynthetically active radiation (IPAR), LAI and foliar N content increased from 863 to 2 345 MJ m⁻² y⁻¹, 2.5 to 4.9 and 67 to 122 kg ha⁻¹ respectively as planting density increased from 740 to 4 440 trees ha⁻¹ (Will *et al.*, 2005). In addition, Will *et al.* (2005) authors found that stem growth correlated best with the annual IPAR and attributed the increase to the even distribution of foliage in higher density stands. The foliage of stands planted at higher densities has an increased proficiency to intercept light.

2.4.5 Litter dynamics

Phosphorous fertilisation can affect litterfall rates, litter accumulation (mass) and decomposition (Wienand & Stock, 1995). Wienand and Stock (1995) made phosphate additions to eight-, 20- and 25-year-old *P. elliotii* plantations in age sequence. All three stands were planted on highly acidic low P-available soils, and pH values ranged from 3.6 to 4.0 (0.01 M CaCl₂). The eight- and 20-year-old stands were treated with treatments of 30 and 60 kg superphosphate ha⁻¹ respectively at establishment. The 25-year-old stand received two treatments of 56 kg ha⁻¹ at establishment and an additional 50 kg ha⁻¹ after ten years. Fertilisation significantly increased litterfall rates, litter mass and the age at which litterfall rates peaked. The 25-year-old stand exhibited decreased litter decomposition rates. The authors attributed the decreases to the re-translocation of N in the foliage. Similarly, the re-translocation of P in the foliage decreased in the fertilised stands and was attributed to the decreased P-use efficiency of the trees.

2.5 Wood properties

Fertiliser application at establishment and mid-rotation can potentially affect wood properties. Love-Myers, Clark, Schimleck, Jokela and Daniels (2009) studied the wood density (specific gravity) responses of *P. elliotii* and *P. taeda* after mid-rotation fertilisations. The trial was located on the Coastal Plains of Georgia and Florida in the USA. Three fertiliser applications

were tested: a control treatment that received no fertiliser, combined with weed control at establishment and brush control at mid-rotation; a treatment that received 45 kg N ha⁻¹ and 56 kg P ha⁻¹ applications, combined with weed control at planting and 224 kg N ha⁻¹ and 45 kg ha⁻¹ applications paired with mid-rotation brush control; and a final treatment that received 56 kg P ha⁻¹ combined with weed control at establishment and 224 kg N ha⁻¹ and 45 kg P ha⁻¹ combined with brush control at mid-rotation. The authors found that that the fertilisation of semi-mature plots in the absence N at establishment had a potentially negative effect on the early wood specific gravity and increased the average tree ring width. Lastly, the *P. elliottii* and *P. taeda* stands treated with and without N fertiliser at planting had lower latewood specific gravities at two to three years after fertilisation. This effect was temporary, as the latewood specific gravity slowly returned to the levels of the control. The temporary effects of mid-rotation fertilisation in this study were similar to the findings of Ross, Buckner, Core and Woods (1979). The fertilisation of a thinned semi-mature *P. taeda* stand can decrease the latewood specific gravity (Finto, Schimleck, Daniels & Clark, 2011). Finto *et al.* (2011) observed these decreases after N applications of 112, 224 and 336 kg ha⁻¹, combined with 28 kg P ha⁻¹. In addition, they found that whole ring width, the early and latewood width and the ratio of earlywood to latewood were not affected in both the thinned and unthinned stands. The effects of fertilisation on growth and wood properties continued for two to three years and relied on whether the site had received a thinning and the quantity of fertiliser applied.

Finto, Jordan, Daniels, Schimleck, Clark and Hall (2009) studied the effects of mid-rotation fertilisation on the wood properties of *P. taeda*. The experiment largely tested N fertiliser application rates of 0, 112, 224 and 336 kg ha⁻¹, including a lesser amount of 28 kg P ha⁻¹ with each treatment. The authors reported decreased stiffness, air-dry densities and tracheid wall thickness and increased tracheid radial diameters for application rates of 336 kg ha⁻¹, relative to the control and 112 kg ha⁻¹ treatments. In addition, microfibril angle (MFA), cell tangential diameter and tracheid perimeters showed little response to fertilisation. Trees treated with application rates of 112 and 336 kg ha⁻¹ did not show any significant differences.

2.6 Financial feasibility

The economic benefits of mid-rotation fertilisation in softwood plantations, particularly for saw timber management plans, are well documented. The benefits stem from a reduction in the length of the compound interest over the investment period (Campion, 2008), effectively reducing the rotation age.

The economic feasibility can be evaluated by accurately determining changes in stand density, diameter, volume (Martin, Bailey & Jokela, 1991), costs incurred at fertilisation and product worth (Jokela & Stearns-Smith, 1993). Martin *et al.* (1991) estimated the optimum economic rotation (OER) ages for *P. elliotii* plantations, using a model to calculate the maximum internal rate of return (IRR) for different soil conditions and treatment combinations. The model projected the IRR into the future from establishment age for several scenarios. These authors found that, in most conditions, mid-rotation fertilisation decreased the OER ages and increased the internal rate of return. In addition, the annualised marginal rate of return for responses from N and P fertiliser additions at 25 years of age were greater than 20%. The marginal one-rotation rate of return for all scenarios treated with N and P fertiliser was 14% or greater. Martin *et al.* (1991) concluded that the responses calculated by the models were less than what was observed in existing plantations, and that mid-rotation fertilisation can be economically beneficial to *P. elliotii* plantations. In addition, N and P fertilisations in a five-year-old *P. radiata* stand produced an IRR of 15% at 15 years of age (Donald, 1987). Payn *et al.* (1988) found contrasting results following the application of various levels of P to two trials in a 17.5-year-old *P. radiata* stand. The authors performed an economic analysis on both trials after six and 10 years. The volume increase after six years was not enough to offset the incurred costs and it was thus deemed that the fertilisation was not economically viable. The second trial, however, reported an IRR of 26% to 58% after 10 years. The responses depended on the level of P applied.

CHAPTER 3

SITE DESCRIPTION AND EXPERIMENTAL DESIGN

3.1 Study Sites

Eight study sites were selected in the Tsitsikamma region of the southwestern and Eastern Cape, South Africa (Figure 3.1). The sites were identified and selected per a set of criteria developed during the initial planning stages of the project. These criteria included: edaphic properties, geographic location, tree species and stand age.



Figure 3.1: Field trials in the Tsitsikamma

3.1.1 Site description

Three soil groups were identified and chosen from soil maps as being representative of the dominant soil types in the Lottering and Witsbos plantations managed by MTO Forestry. The company manages and processes softwood plantations, largely in the Western Cape. *Pinus elliottii* and *P. elliottii x caribaea* were chosen as the experimental species. The soil properties, age, genotype and geographic location of each field trial from west to east are shown in Table

3.1. Each field trial was assigned a new identity based on the annual N mineralisation rate of each site. This sequence was maintained throughout this thesis for uniformity and ease of interpretation.

Table 3.1: Site characterisation based on respective genotype, age at trial establishment (2015), current trees per hectare, location and soil properties. Soil forms are classified into soil families according to the South African classification system (Soil Classification Working Group, 1991) and broad soil groups proposed by Fey (2010).

Plantation	Compartment number	ID	Genotype	Age (years)	MAP (mm)	Stand density (trees ha ⁻¹)	Coordinates (degrees, minutes and seconds)	Altitude (m)	Soil family	Broad soil group
Lottering	D8b	C	<i>P. elliottii</i>	14	1 010	409	33°58'48'' S 23°44'58'' E	± 233	Tukulu	Cumulic
Lottering	C33d	G	<i>P. elliottii</i>	14	1 010	486	33°59'16'' S 23°46'29'' E	± 227	Longlands/ Wasbank	Plinthic
Lottering	R28	E	<i>P. elliottii</i>	13	1 010	416	34°00'01'' S 23°50'22'' E	± 219	Lamotte	Podzolic
Lottering	L46b	H	<i>P. elliottii</i>	13	1 010	446	33°59'39'' S 23°57'24'' E	± 218	Avalon	Plinthic
Lottering	L22a	F	<i>P. elliottii</i>	14	1 010	396	34°00'23'' S 23°55'29'' E	± 213	Lamotte	Podzolic
Lottering	L67	D	<i>P. elliottii</i> <i>x caribaea</i>	15	1 010	444	34°00'30'' S 23°58'23'' E	± 231	Kroonstad	Plinthic
Witelsbos	B57b	B	<i>P. elliottii</i> <i>x caribaea</i>	13	1 090	533	34°02'48'' S 24°08'06'' E	± 162	Avalon	Plinthic
Witelsbos	H6	A	<i>P. elliottii</i>	13	1 090	484	34°01'32'' S 24°24'35'' E	± 261	Longlands	Plinthic

3.1.2 Soil characterisation

All soils were classified as sandy loam soils. Sites A and B had lower carbon contents (Table 3.2) and higher sand contents (Table 3.3) relative to the other sites. Each site consisted of two replications – six treatments or plots replicated twice. Replications were analysed separately for a comprehensive site analysis.

Table 3.2: Chemical soil analysis of each field study per replication (0-10 cm topsoil).

Site	Replication	Soil type	Total C %	Total N %	P (Bray II) mg kg ⁻¹	K mg kg ⁻¹	Na mg kg ⁻¹	K cmol c kg ⁻¹	Ca cmol c kg ⁻¹	Mg cmol c kg ⁻¹	pH (KCl)
A	1	SaLm	1.46	0.03	5	16	0.14	0.04	1.00	0.7	4.0
	2	SaLm	1.66	0.04	6	32	0.11	0.08	0.99	0.7	3.9
B	1	SaLm	0.89	0.04	36	19	0.11	0.05	0.89	0.5	3.8
	2	SaLm	1.40	0.03	3	43	0.16	0.11	1.65	0.9	3.9
C	1	SaLm	2.46	0.07	6	33	0.18	0.08	2.04	1.1	3.7
	2	SaLm	2.67	0.07	2	32	0.25	0.08	2.00	1.1	3.8
D	1	SaLm	2.06	0.11	44	23	0.17	0.06	1.91	1.1	3.7
	2	SaLm	2.50	0.05	7	28	0.16	0.07	1.69	0.9	3.8
E	1	SaLm	2.33	0.05	5	43	0.18	0.11	1.13	0.8	3.5
	2	SaLm	3.01	0.08	13	39	0.29	0.10	5.15	1.8	3.9
F	1	SaLm	2.45	0.04	15	21	0.13	0.05	0.43	0.4	3.2
	2	SaLm	2.77	0.04	19	32	0.15	0.08	0.99	0.6	3.5
G	1	SaLm	3.36	0.13	5	36	0.19	0.09	0.44	0.7	2.9
	2	SaLm	2.76	0.10	5	36	0.18	0.09	1.67	1.0	3.8
H	1	SaLm	2.58	0.05	19	29	0.10	0.08	0.80	0.5	3.2
	2	SaLm	2.53	0.09	17	36	0.09	0.09	0.74	0.4	3.3

Table 3.3: Physical soil properties for each trial site (0-10 cm topsoil).

Site	Replication	Clay	Silt	Sand	Classification
		%			
A	1	14	22	64	SaLm
	2	14	20	66	SaLm
B	1	12	12	76	SaLm
	2	12	14	74	SaLm
C	1	18	38	44	SaLm
	2	22	40	38	SaLm
D	1	18	40	42	SaLm
	2	18	38	44	SaLm
E	1	16	42	42	SaLm
	2	20	28	52	SaLm
F	1	18	40	42	SaLm
	2	18	40	42	SaLm
G	1	16	46	38	SaLm
	2	16	42	42	SaLm
H	1	20	40	40	SaLm
	2	18	40	42	SaLm

3.1.3 Climate

3.1.3.1 Rainfall

Both plantations have similar rainfall; Lottering plantation has a mean annual rainfall of approximately 1 010 mm and Witelsbos plantation receives slightly more rainfall, with an average annual rainfall of 1 090 mm. The reported figures are based on climatic data monitored for the last 45 years (Figure 3.2) at the plantation (33°58'48'' S and 23°44'58'' E). This small difference, coupled with several other edaphic and site conditions, was used to establish whether the rainfall for the two-year monitoring period significantly affected the documented fertiliser responses. October is the wettest month of the year for both plantations, with average monthly rainfalls of 105 mm and 85 mm, respectively (Figure 3.3). In addition, both plantations receive the highest rainfall in the months of August to November.

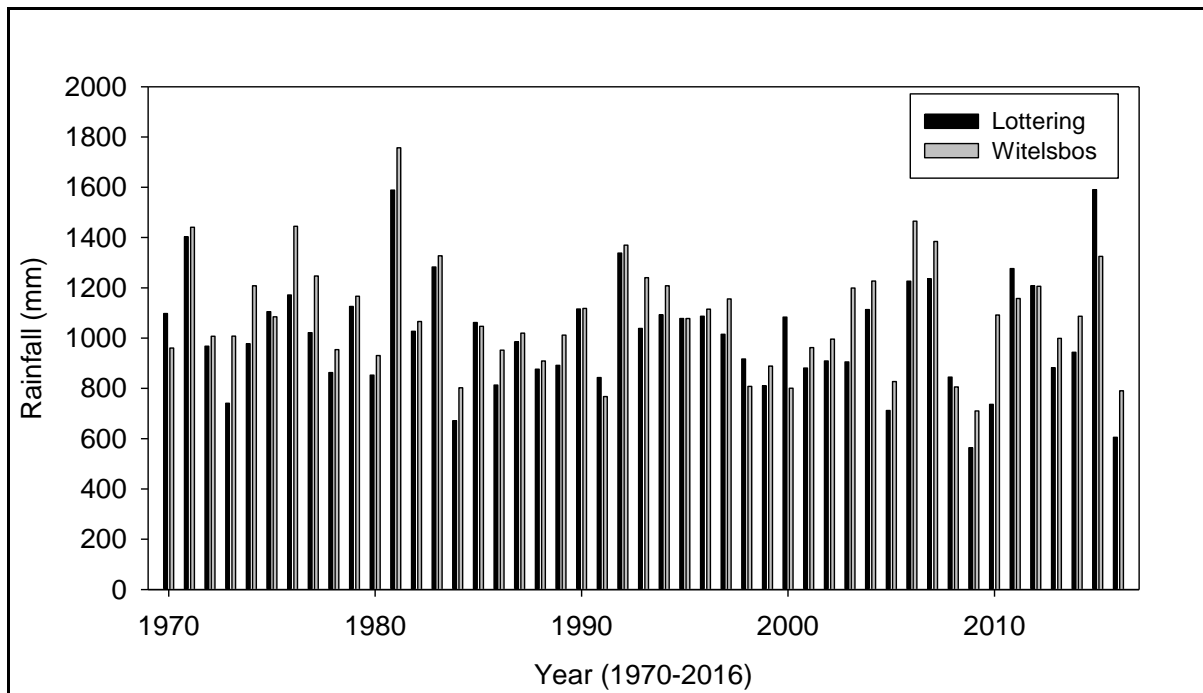


Figure 3.2: Total annual rainfall for Lottering and Witelsbos plantations (45 years).

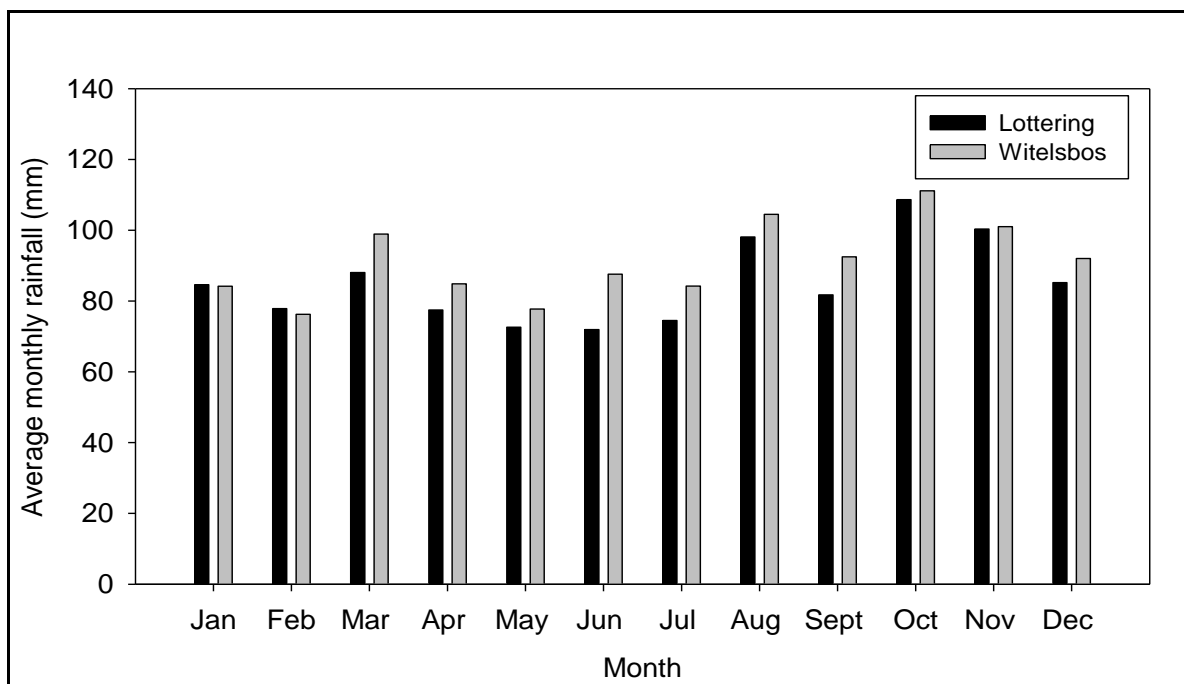


Figure 3.3: Average monthly precipitation for Lottering and Witelsbos plantations (45 years).

3.1.3.2 Temperature

Average maximum monthly temperatures are highest from November to March and range from 22.2°C to 23.7°C. The average minimum monthly temperatures are lowest from June to September and range from 10.5°C to 11.4°C (Figure 3.4). Figures and values are based on data

monitored for 32 years by the Storms River Mouth weather station (34°0'58'' S and 23°51'14'' E).

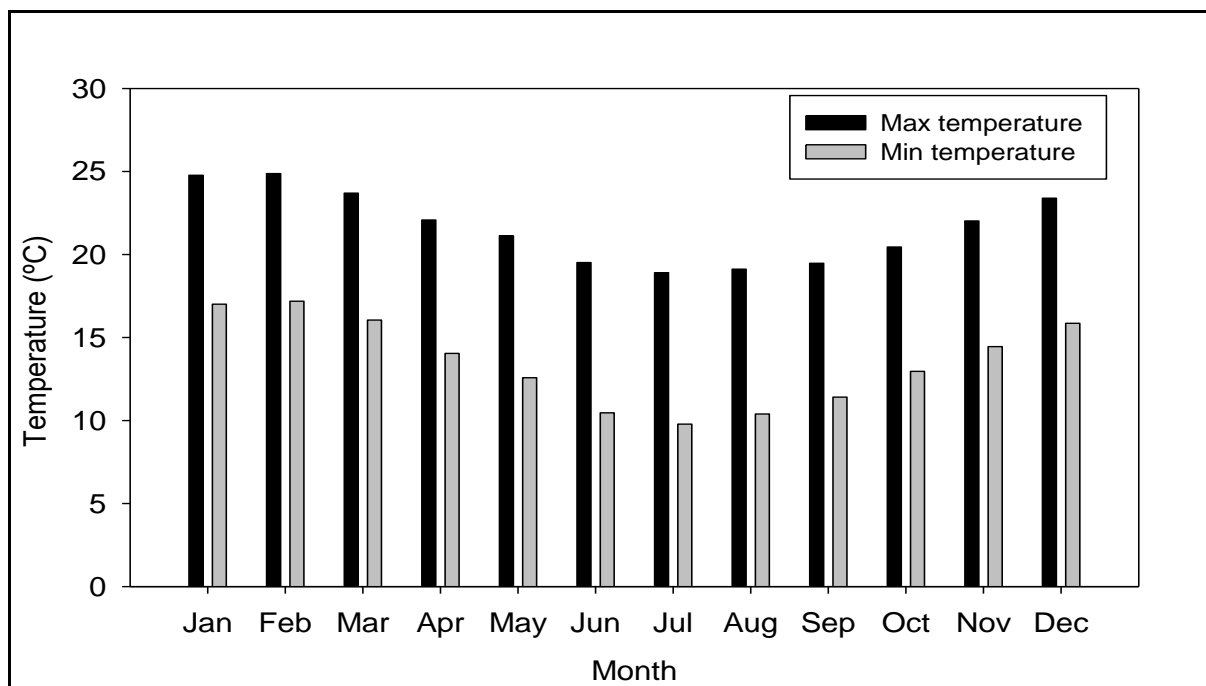


Figure 3.4: Average maximum and minimum monthly temperatures for the Tsitsikamma, Eastern Cape.

3.2 Experimental design

The project comprised several datasets from laboratory and field studies. The laboratory studies were done to quantify the availability of soil N and P in each field trial and comprehensive site characteristics. The N and P availability of each soil was then used to determine whether a correlation existed between the potential growth responses (induced by fertilisation), and the available N and P of the respective site by means of correlations and the soil nitrogen availability predictor (SNAP) model (Chapter 6).

The field study was based on a factorial design and included the interaction of six treatment combinations (in kg ha⁻¹) and the dominant soil groups from the region (Table 3.1). Fertiliser application rates consisted of a control treatment of 0 N and 0 P (T0), and then treatments of 0 N and 50 P (T1), 0 N and 100 P (T2), 100 N and 50 P (T3), 100 N combined with 100 P (T4), and a final treatment of 200 N and 100 P (T5). Each field trial consisted of six plots, representative of the fertiliser rates, replicated twice to give a total of 12 plots per trial. The experiment consisted of a total of 96 plots, distributed over the Tsitsikamma region.

3.3 Trial uniformity and layout

More than the minimum number of plots were initially laid out at the establishment of each field trial. Treatments were applied equally across all field trials and the plots were selected based on a comparatively uniform basal area and stem density per plot. An error margin of 10% was used for both parameters and, if either could not conform to the mean for the respective replication, the plot was discarded. A total of three of the 96 plots, from field trials A, B and F, did not adhere to the defined uniformity principle due to soil limitations and wind damage to compartments.

In addition to the basal area and stem count, plots were also demarcated per plot area. Plots were moved if the plot area, stem count and basal area did not conform to the mean for that replication. Each plot consisted of a boundary and inner plot, with dimensions of 12 x 12 and 8 x 8 rows respectively.

3.4 Trial establishment

Trials were established in intervals from April 2015 to August 2015. Each trial site, apart from site D, was initially planted at a spacing of 3.5 x 3.5 m and had a total inner plot area of approximately 0.970 ha. Site D was planted at a spacing of 2.7 x 2.7 m and had a total inner plot area of 0.510 ha; due to the limited number of compartments meeting the criteria, the field trial was included in the study. The basal area for each plot in site D was similar to the other trial sites, but stem numbers and plot area varied to some extent. Fertiliser treatments and plot sizes were adjusted accordingly to account for the different spacing. Trees were numbered and marked individually at 1.3 m (diameter at breast height) from the base at trial establishment.

3.4.1 Fertilisation

Fertiliser treatments were implemented across all 96 plots from 21 September to 28 September 2015. Limestone ammonium nitrate (LAN) and a phosphate blend, mixed by Nitrophoska Ltd, were used as N and P sources. The LAN fertiliser contained 28% N and 2% Ca. The phosphate blend contained 20% P, 15% Ca, 1.5% S and 0.5% Zn. Application rates were scaled down to application per strip (Table 3.4); strips were defined as the area between two rows of trees. Each plot contained 12 rows, thus 11 strips per plot.

Table 3.4: Individual application rates per strip and plot for both spacings.

Treatment	Symbol	3.5 x 3.5 m				2.5 x 2.5 m			
		kg strip ⁻¹		kg plot ⁻¹		kg strip ⁻¹		kg plot ⁻¹	
		N	P	N	P	N	P	N	P
N ₀ P ₀	T0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N ₀ P ₅₀	T1	0.0	4.0	0.0	43.5	0.0	2.0	0.0	22.2
N ₀ P ₁₀₀	T2	0.0	7.9	0.0	86.9	0.0	4.0	0.0	44.3
N ₁₀₀ P ₅₀	T3	5.7	4.0	63.0	43.5	2.9	2.0	32.1	22.2
N ₁₀₀ P ₁₀₀	T4	5.7	7.9	63.0	86.9	2.9	4.0	32.1	44.3
N ₂₀₀ P ₁₀₀	T5	11.5	7.9	126.0	86.9	5.8	4.0	64.2	44.3

3.5 Data collection

Data collection was done in quarterly, half yearly and annual intervals from 21 September 2015 to 5 October 2017. The time intervals depended on the nature of data to be collected.

3.5.1 Soil sampling

3.5.1.1 Chemical and physical properties

Samples were collected at trial establishment from 21 September to 4 October 2015 for site characterisation (soil nutrient concentrations and soil fractions). A Beater auger was used to collect soil samples; this auger is designed to take multiple, small cores in a given area, which are then bulked into a representative bulk sample of the area. Six cores were sampled per replication and bulked to produce a single sample.

3.5.1.2 N and P availability

A second and third sampling ran from 22 to 30 March 2016 and from 3 to 8 July 2016 for the aerobic and anaerobic N and P availability studies. Six cores were sampled (again using the Beater auger) for each replication and bulked to produce two soil samples per site.

3.5.1.3 Soil water-holding capacity

A third sampling was undertaken from 7 to 12 November 2016 to determine the soil water-holding capacity of each site. This was done for each replication per site and amounted to a total of 16 soil samples across all sites. Samples were collected from multiple depths in intervals of 20 cm, up to a maximum depth of 200 cm from the soil surface (dependent on soil

conditions). Soils were bagged per depth and textural classes. Soil depths (cm): 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140, 140-160, 160-180 and 180-200.

3.5.2 Foliage sampling

3.5.2.1 Chemical analyses

Needle samples were collected at three intervals throughout the experimental period. Sampling was limited to the inner plots of each field trial. Three trees were chosen randomly, and needle samples were removed with an extendable pruner. The first sampling was done at trial establishment, from 1 to 4 October 2015. Needles were collected from the upper 50% of the canopy in the canopy openings (sun-facing) and needles were approximately one year of age at the time of sampling. Juvenile needles were avoided, as the concentrations of most nutrients are usually higher in young needles due to the retranslocation of nutrients over time. Foliage samples were kept in plastic bags and stored in a cooling unit to prevent deterioration. A second and third foliage sampling was conducted from 4 to 9 September 2016 and again from 9 to 13 September 2017.

3.5.2.2 Specific leaf area

Needle samples were collected from 7 to 12 November 2016 to determine an average specific leaf area (SLA) and needle mass value per trial site. Tree selection was based on the three diameter classes for each site, viz. small, intermediate and large. Needle samples were collected at canopy openings in the upper 50% of the tree canopy, bulked, placed in plastic bags and stored in a cooling unit to prevent deterioration. Thirty-five grams of needles were collected and fed into a LI-COR Portable area meter (LI-3000) and a cumulative area (cm^2) was obtained. Needles were carefully placed on the apparatus to prevent overlapping. Samples were subsequently dried at 65°C (Pangle, Vose & Teskey, 2009) until constant weights were obtained to the nearest 0.1 gram. Specific leaf area was calculated and converted from $\text{cm}^2 \text{g}^{-1}$ to $\text{m}^2 \text{kg}^{-1}$ by dividing each value by 10.

3.5.2.3 LAI measurements

Leaf area index readings were taken in quarterly (three-month) intervals, using an AccuPAR LP-80 ceptometer. Quarterly intervals were selected to account for the probable effect of seasonality on the growth responses induced by fertilisation. Leaf area index ($\text{m}^2 \text{m}^{-2}$) measurements were limited to the inner plot, and a total of 50 ceptometer readings were taken

per plot. Readings started at the first tree of the inner plot, and a traverse between rows was maintained four times for each plot.

Several studies recommend the use of a correction factor for the underestimation of LAI with an AccuPAR ceptometer (Chen & Cihlar, 1995; Gower & Norman, 1991; Lopes, Walford, Viana & Sette, 2016). The underestimation is mainly due to foliar clumping and the non-random foliar spatial distribution of the canopy. The findings of the studies were based on using LAI estimates from allometric equations as a reference LAI for measurements made with a ceptometer. Gower and Norman (1991) and Lopes *et al.* (2016) proposed correction factors of 1.5 and 1.38 respectively for *P. pinaster*. Chen and Cihlar (1995) suggested a factor of 1.48 for *P. banksiana*. Leaf area indices were multiplied with a correction factor of 1.38 (after Lopes *et al.*, 2016).

3.5.3 Diameter measurements

Tree diameters at breast height (DBH) (1.3 m) were measured at six-month intervals following fertilisation on 21 September 2015 using a diameter tape. Diameter measurements were limited to the inner plots. Final data collection (24 months) was completed on from 9 to 13 September 2017.

3.5.4 Height measurements

Heights were measured throughout the experimental period using a Hagl f Vertex IV (L ngsele, Sweden). Heights were measured at six-month intervals. Three trees were selected per plot for every diameter class for the respective site, amounting to a total of 288 heights. Final data collection was done from 9 to 13 September 2017.

3.5.5 Volume estimations

Standing tree volumes were estimated using the Schumacher and Hall (1933) volume equation (Equation 1). Coefficients for *P. elliottii* were obtained from Bredenkamp (2012). No coefficients were available for *P. elliottii x caribaea* and, to account for this, the values for the coefficients of *P. elliottii* were substituted into the function. Coefficients for the respective species are shown in Table 3.5. The function was used to calculate the standing volume of individual trees, and volumes were upscaled to plot and trial level for data analyses and interpretation.

$$V = EXP[b_0 + b_1 \ln(dbh + f) + b_2 \ln H] \quad (1)$$

where:

V = stem volume (m³, under bark), usually to the 75 mm tip diameter

dbh = breast height diameter (cm, over bark)

H = tree height (m)

Table 3.5: Coefficients for volume determination, adapted from Bredenkamp (2012).

Species	Coefficients			
	b ₀	b ₁	f	b ₂
<i>P. elliptii</i>	-10.667	1.931	0	1.157

3.6 Laboratory procedures

The methodology and laboratory procedures for calculating the soil N and P availability of the field trial are outlined in the respective sections. Chemical analyses for estimating the ammonium, nitrate, phosphate, foliar and soil nutrient concentrations were outsourced to Bemlab Ltd. The laboratory procedures implemented by the company are outlined in the subsequent sections and sub-sections.

3.6.1 Soil analyses

3.6.1.1 Soil nutrient analyses

Soil samples were air dried and sieved (2-mm); this also allowed for the determination of the stone fraction of each sample. The pH of each sample was determined in 1 M KCl. Total C and N content was determined by means of high-temperature combustion using the Leco Truspec® C and N analyser. Phosphorous content was determined using the Bray II method, and extractable cations, K, Ca, Mg and Na, were extracted with 0.2 M ammonium acetate solution (pH 7). Extractable acidity was determined by titration with 0.05 M NaOH, after extraction with 1 M KCl. Extracted solutions were analysed for chemical composition and elemental concentrations by inductively coupled plasma optical emission spectroscopy (ICP-OES). Total P (Bray II) was extracted at 80°C for 30 minutes using a 1:1 mixture of 1 M nitric and hydrochloric acid. The phosphorous concentration was determined using Varian ICP-OES. Effective cation exchange capacity (ECEC) was calculated as the sum of the base cation charge plus the extractable acidity at ambient pH.

3.6.1.2 *Moisture content, undisturbed bulk density and water-holding capacity*

In-field soil moisture was determined on a mass/mass basis. Metal cylinders with a diameter of 7 cm were used to collect additional samples for soil bulk density determination. Undisturbed soil bulk density was determined by dividing the dry weight by the fixed volume of the sample and expressing it in g cm^{-3} . Dry weights were obtained by oven-drying at 105°C until a constant weight was obtained. Silt and clay contents were then determined by using the sedimentation rates at 20°C and an ASTM E100 (152H-TP) hydrometer. The soil water-holding capacity was then mathematically estimated using the soil texture model of Saxton, Rawls, Romberger and Papendick (1986) and Saxton and Rawls (2006). The model uses the average moisture content of different soil texture classes, together with the density and the conductivity, to calculate the soil water storage capacity of a given soil. The soil water storage capacity was then used to calculate a cumulative index of water availability (termed the water deficit), which is fully explained in Chapter 4.

3.6.2 *Foliar analysis*

Foliage samples were oven-dried, and the N content was determined by means of combustion in a Leco N analyser. Samples were washed with a low concentration of detergent solution (Teepol), rinsed with de-ionised water and oven dried at 70°C . The samples were then milled and ashed at 470°C . A 50:50 HCl (32%) solution was mixed into each ashed sample and extraction was done using filter paper. Macro- and micronutrients and cation concentrations of the extract were measured with Varian ICP-OES.

3.7 **Statistical analyses**

The effect of soil type and geographic distribution on the numeric variables used to describe the response of the *P. Elliottii* and *P. Elliottii x caribaea* trials to fertilisation were analysed in this study. The variables, height and diameter increment, N and P mineralisation rates, canopy development and stand nutrition were analysed using analysis of variance (ANOVA) statistics and Pearson correlation coefficients. A confidence level of 95% was used to determine whether an interaction was statistically significant, and interactions having $p < 0.05$ were reported as significant, unless stated otherwise. All data statistically analysed were tested for normality and homogeneity of variances prior to analysis. The Statistica 12 software package was used for all data analyses, and graphical illustrations were done with Statistica 12 and Sigmaplot 11 software.

CHAPTER 4

SOIL WATER DEFICIT AS AN ALTERNATIVE ESTIMATE OF WATER STRESS IN THE CAPE FOREST REGION, SOUTH AFRICA

4.1 Introduction

Forest productivity is significantly affected by the availability of resources needed for growth (light, nutrients and water) (Waring & Winner, 1995). The availability of resources for growth is governed and modified by evapotranspiration and rainfall (Albaugh *et al.* 2004; Álvarez, Allen, Albaugh, Stape, Bullock & Song, 2013; Gonçalves, Stape, Laclau, Bouillet & Ranger, 2008; Le Roux & Du Preez, 2006; Maggard, Will, Wilson & Meek, 2016a), soil properties (Gonçalves *et al.*, 2008; Le Roux & Du Preez, 2006; Ramírez *et al.*, 2016), topography and landscape (Le Roux & Du Preez, 2006) and the incidence of competing vegetation (Albaugh, Allen, Zutter & Quicke, 2003). Different management strategies can alter the chemical and physical properties of soil and subsequently affect forest productivity (Bodner, Scholl, Loiskandle & Kaul, 2013; Gonçalves & De Barros, 1999; Gonçalves *et al.*, 2008; Simpson, Xu, Smith, Keay, Osborne & Podberscek, 2000). The nutrient demand placed on the soil can aggravate soil nutrient problems; *Pinus elliottii* and *P. taeda* stands place a significant nutrient demand on the soil during initial canopy development (Jokela, 2004) and, if the soil cannot meet the nutritional demand of the trees, can reduce forest productivity.

In plantation forestry, silvicultural management can be viewed as consisting of a series of strategic decisions (e.g. which taxon to plant and which market to target) and management interventions (soil preparation, fertilisation, vegetation, pruning, thinning, etc.) (Du Toit & Norris, 2012). Over the last three decades, attempts have been made to ensure that silvicultural decision making becomes increasingly site specific in many plantation forest enterprises in Southern Africa. This is because researchers and managers have realised that forest productivity can be optimised (and risk profiles minimised) by site-specific management regimes (also referred to as precision forestry in some circles). However, attempts at site-specific silvicultural management in Southern Africa has been constrained by using fairly coarse input data and the fact that forestry is often an extensive form of land use in remote

locations, where edaphic data may be somewhat sparse. Examples are (a) the use of mean annual temperature (MAT), together with mean annual precipitation (MAP) (with limited soil data) to make decisions on site-species matching (Du Toit, 2012; Herbert, 2012) and (b) the use of very broad regions or soil groups to recommend fertiliser supplements (Kotze & Du Toit, 2012). One of the older site classification schemes used to inform tree planting in Southern Africa was that of Poynton (1979). This system used Thornthwaite's (1944) estimates of evaporation (albeit on a broad scale due to limited data availability). However, the most recent site and climatic classification system that has been widely adopted by the SA forest industry (Smith, Pallet, Kunz, Gardner & Du Plessis, 2005) has reverted to MAP as the main driver of water availability, with no consideration of rainfall seasonality and little consideration of evaporation and soil storage potential. The reason for using these low-precision inputs in the system was apparently driven by data constraints, as most of the forestry weather stations collected only rainfall data. This has subsequently changed with the expansion of the privately managed weather networks to supplement the national weather network. In the future, it will thus be possible to gauge the water availability of sites using more complex data. However, there are still many plantation forestry estates in Southern Africa where monthly mean rainfall and temperature data are the only reliable variables measured on site. We hypothesise that more accurate knowledge of soil water and nutrient availability may help target site-specific silvicultural management.

For the continued improvement of forest productivity on the sub-continent, and to enable good economic decisions in industrial forestry, we postulate that the interaction between water availability and silvicultural interventions needs to be better understood. Examples are responses to thinning or fertilisation over a water-availability gradient: e.g. stands seldom respond to improved nutrient status when experiencing water limitation (Du Toit, 2008). Simply put: at what level of water availability will there be an economic response to fertilisation or thinning? To characterise the potential response to fertiliser application in semi-mature stands as a function of water availability, we first set out to characterise stand water availability using simplified measures (cheap and easy but coarse) to more complex indicators (increasingly difficult to gauge but also potentially a more accurate reflection of stand stress).

The Southern coastal strip spanning the Western and Eastern Cape provinces in South Africa (hereafter referred to as the Cape Forest Region) constitutes an important forestry region in the country; it harbours more than 100 000 ha of indigenous high forest as well as more than 70 000 ha of exotic pine plantations. A clear understanding of how soil water availability is affected

by the individual physical properties of several soils in the Cape Forest Region, across a spatial and temporal gradient, would help identify sites that are more likely to respond positively to silvicultural interventions (e.g. soil preparation, fertilisation and thinning), given varying and sometimes unfavourable climatic conditions. Site-specific implementation of silvicultural operations would simultaneously reduce the overall cost and improve the productivity of responsive sites to what is achievable given the limitations and conditions of the growing environment. The identification of efficient techniques to measure soil water, and the difficulty of obtaining knowledge of soil hydraulic properties for modelling, remain challenging (Bittelli, 2011). The wide range of soil conditions and the significant effect of individual terrain and physical soil properties on soil water availability and nutrient retention accentuate the importance of comprehensive site characterisations for the planning and implementation of nutritional management strategies.

4.2 Measures of water availability

Estimates of plant-available water, arranged from single estimates with low data requirements to increasingly complex inputs that require more data inputs are tabulated in Table 4.6.

Table 4.6: Commonly used estimates of plant-available water in agriculture and forestry

Estimate	Data inputs	Comments
Mean annual precipitation (MAP) and effective precipitation class (MAP per mean annual temperature (MAT) bracket – see Smith <i>et al.</i> (2005).	Monthly rainfall: An annual sum is used; in practice, monthly data is commonly added up. The estimate is sometimes considered alongside an estimate of soil depth and texture (Herbert, 2012).	Very coarse approximation of water availability, as it does not integrate seasonality, distribution and storage of rainfall. This estimate also does not effectively account for the atmospheric demand for moisture, which has negative implications when extrapolating results to different regions.
Aridity index (AI) (Du Preez, Van Huyssteen & Mnkeni, 2011; Du Toit, Malherbe, Kunneke, Seifert & Wessels, 2017) and	AI: Annual rainfall and potential evapotranspiration (ETp) estimates.	Moderately crude index, but a substantial improvement on MAP estimates alone. It provides some balance between water supply as rainfall and atmospheric demand,

<p>moisture growing season (MGS) (Doorenbos & Kassam, 1979; Hendrickson & Durkin, 1984; Schulze, 1997).</p>	<p>MGS: Monthly rainfall and ETp estimates, as well as a predefined threshold value to define water stress (e.g. where $Precipitation < A * ETp$ (where A is the threshold value, substituted with values from 0.3 to 0.5).</p>	<p>but this is usually an annual time step and water storage is not factored in.</p> <p>MGS: Like the AI; however, slightly more sophisticated as a monthly time step is used.</p>
<p>Soil water deficit, initially by Thornthwaite (1948), as used by Poynton (1979). Additional application: Soil water-holding capacity, methodology described by Pereira, Angelocci & Sentelhas (2007) and used by Gonçalves, Alvares, Rocha, Brandani & Hakamada (2017) and Hakamada, Hubbard, Ferraz, Stape & Lemos (2017).</p>	<p>Monthly precipitation.</p> <p>Average monthly temperature (heat index and day length derived from temperature, time-of-year and location data).</p> <p>Soil water-holding capacity.</p>	<p>Moderately sophisticated index of plant water availability derived from basic monthly rainfall and temperature data. If used with soil water storage capacity, it provides a moderately accurate picture of water deficits over a time step that is meaningful to the growth of deep-rooted crops (e.g. trees and forests).</p>
<p>Actual evapotranspiration (Eta)/ETp, where Eta is based on the Penman Monteith equation. South African and international uses: Bie, Casper, Reiter & Vohland (2014), Champion, Dye & Scholes (2004), Fricke (2013) and Sumner and Jacobs (2005).</p>	<p>Air temperature, humidity, wind speed, atmospheric pressure and solar radiation for daily, weekly or monthly calculations.</p> <p>Soil water-holding capacity and several crop factors.</p>	<p>Highly sophisticated model, usually runs on a daily time step. High input requirements make it a useful research tool, but less often used in management applications due to the intensive input data requirements (that do not exist on a detailed enough spatial scale for many forest estates).</p>

The different techniques, listed with time steps and the inclusion of soil water storage, are commonly used in silvicultural decision making or in forestry research. For example, it is theoretically possible to use a monthly time step for the Eta/ET_p relationship; however, it is usually derived from daily data obtained from sophisticated weather stations, hence it makes sense to implement it as a daily time step. Estimates (such as the Eta/ET_p estimate) based on the Penman-Monteith equation are superior to the listed estimates; however, developing countries such as South Africa and isolated afforested regions often do not have the resources and historical datasets to meet the intensive data requirements of this method.

4.3 Research questions

- How did different edaphic properties affect the soil water availability and storage capacity of each site?
 - What edaphic properties were the main contributing factors to the observed variability, if any?
- Is water deficit an adequate and reliable estimate of plant-available water?
 - Is it an improvement on the MAP and the AI estimates?
- Can the observed responses be used to identify sites more likely to respond to fertilisation, given inconsistent climatic conditions?

4.4 Materials and methods

4.4.1 *Additional site descriptions*

Eight additional sites were carefully selected across the Cape Forest Region, South Africa to conduct this part of the study. These sites were geographically distributed in clusters from east (Knysna, Western Cape) to west (Jonkershoek, Western Cape) and ranged from 156 to 408 m above sea level (Table 4.7). The second cluster of sites was located in the Kruisfontein plantation near Knysna, Western Cape. This region has a mean annual temperature and rainfall of 13.3°C and 791 mm respectively. The third cluster of sites was in the Boland region, Western Cape. These sites were extensively distributed throughout the Grabouw, La Motte and Jonkershoek plantations where, mean annual temperatures and rainfall range from 9.1 to 11.9°C and 773 to 1188 mm respectively. The Knysna and Boland sites were afforested with *P. radiata*, and the other regions mentioned above are regarded as suitable sites for plantation forestry and are currently utilised for sawtimber production. The soils from the Tsitsikamma region are naturally waterlogged and were of the plinthic, cumulic, duplex and podzolic soil groups (Fey, 2010).

These soils are chemically and morphologically affected by the presence of water. Seasonal fluctuations and periods of saturation affect the oxidation rates of elements in hydromorphic soils (Van Breemen & Buurman, 1998). Similarly, the sites from the Knysna region were dominated by duplex, plinthic, cumulic and podzolic soils. Soils from the Boland region, i.e. Grabouw, La Motte and Jonkershoek, were located on plinthic, lithic and duplex soils (Fey, 2010). The soils from the Tsitsikamma had significantly larger porosities relative to those from the Knysna and Boland regions. The highest porosities were observed in the Lottering plantation at site G, and the smallest at A, with porosities of 63% and 46% respectively. The Knysna and Boland regions had similar porosities of 43% to 44%. The smaller porosities observed in these regions were largely due to the greater sand content of each site.

4.4.2 Site index

Site index refers to the dominant height at 20 years of age (Kotze, Kassier, Fletcher & Morley, 2011). In South Africa, dominant height refers to the regression height associated with the mean quadratic diameter at breast height (DBH) of the 20% thickest trees in a sample size of at least 30 DBH-height pairs (Bredenkamp, 1993). The dominant height of younger stands was projected to the selected age index of 20 years using the original Chapman Richards function and parameters of Pienaar and Turnbull (1973), parameterised (β_1 , t_0 and β_3) for *P. elliottii* in South Africa (Equation 2). This model is constrained to: If $\text{Age}_2 \leq (-\beta_2)$, then $\text{HD}_2 = 0$. Sites in the Knysna and Boland regions were afforested with *P. radiata* and those in the Stormsriver region with *P. elliottii*. The site index development of *P. elliottii* and *P. radiata* differs by a fair margin on similar site qualities. To account for these differences, the site indices for *P. radiata* were scaled down to those of *P. elliottii*, with a correction factor (ratio) derived from the site indices of both species at the age of 20 years, for the respective site quality in the regions of South Africa afforested with pine. Site indices for *P. radiata* were scaled down with a correction factor of 0.793.

$$HD_2 = HD_1 * \left[\frac{1 - \text{Exp}(\beta_1 * (\text{Age}_2 + t_0))}{1 - \text{Exp}(\beta_1 * (\text{Age}_1 + t_0))} \right]^{\beta_3} \quad (2)$$

where:

HD_2	= Projected height (m)
HD_1	= Current height (m)
Age_2	= Projected age (years)
Age_1	= Current age (years)

$$\beta_1 = -0.0423$$

$$t_0 = \beta_2 = -0.6$$

$$\beta_3 = 1.179$$

Table 4.7: Site locations and descriptions.

Site ID	Region	Plantation	Coordinates	Altitude (m)	MAT (°C)	MAP (mm)	Site index (age 20 years)	Soil group
A	Tsitsikamma	Witelsbos	34°01'32'' S 24°24'35'' E	261	17.5	1 094	24	Plinthic
B	Tsitsikamma	Witelsbos	34°02'48'' S 24°08'06'' E	162	17.5	1 094	24	Plinthic
C	Tsitsikamma	Lottering	33°58'48'' S 23°44'58'' E	233	17.5	1 025	29	Cumulic
D	Tsitsikamma	Lottering	34°00'30'' S 23°58'23'' E	231	17.5	1 025	31.4	Plinthic
E	Tsitsikamma	Lottering	34°00'01'' S 23°50'22'' E	219	17.5	1 025	28.3	Podzolic
F	Tsitsikamma	Lottering	34°00'23'' S 23°55'29'' E	213	17.5	1 025	27.7	Podzolic
G	Tsitsikamma	Lottering	33°59'16'' S 23°46'29'' E	227	17.5	1 025	26.7	Plinthic
H	Tsitsikamma	Lottering	33°59'39'' S 23°57'24'' E	218	17.5	1 025	29.4	Plinthic
I	Knysna	Kruisfontein	34°01'26'' S 23°06'40'' E	270	13.3	791	20.9	Podzolic
J	Knysna	Kruisfontein	34°02'02'' S 23°07'44'' E	247	13.3	791	19.2	Plinthic
K	Knysna	Kruisfontein	34°02'60'' S 23°06'32'' E	156	13.3	791	21.6	Cumulic
L	Boland	Grabouw	34°07'44'' S 19°00'54'' E	350	9.1	1 188	18.2	Lithic
M	Boland	Grabouw	34°04'26'' S 19°04'26'' E	394	11.9	954	19.8	Plinthic
N	Boland	Grabouw	34°10'51'' S 19°07'30'' E	368	11.3	773	18.2	Cumulic
O	Boland	Jonkershoek	33°58'16'' S 18°56'06'' E	246	10.4	1 073	19.8	Lithic
P	Boland	La motte	33°54'14'' S 19°05'13'' E	241	12.2	880	19.8	Cumulic

Sites from the Tsitsikamma are dominated by sandy loam texture classes (Table 4.8). The remaining sites had significantly greater sand and smaller clay and silt contents. These soils

were classified as having sandy textures. Soil depths ranged from a maximum sampling depth of 4 m in the Tsitsikamma, and the shallower depths, representative of the lithic soils in the region, ranged from 0.5 to 0.8 m in depth. A maximum soil depth of 4 m was observed at site A. Soil water storage capacity was determined by means of the Saxton model (refer to Section 3.6.1.2). The Saxton model relies on soil texture classes to calculate the soil water storage capacity. In addition, the soil water deficit model (Section 4.5) does not account for topographical differences between sites and uses the soil water storage capacity (calculated from the Saxton model), along with estimates of rainfall and evapotranspiration, to model the soil water availability for site-specific edaphic and climatic conditions. Site A is positioned on the footslope of a mountain, where the lateral movement of water from upslope positions could have affected the accuracy of the soil water deficit model. This was only the case in our experimental series where a trial site could substantially be enriched with lateral water movement. In all the remaining sites, water availability could realistically be estimated using the water deficit technique as described in Sections 4.5 and 4.6.

Table 4.8: Soil classification and physical properties of the 0-10 cm (Lottering and Witelsbos) and 0-20 cm (Kruisfontein, La Motte, Jonkershoek and Grabouw) topsoil layer for each site. Soil pH values were not available for the Jonkershoek, Kruisfontein and Grabouw sites.

Site	Plantation	pH	Clay	Silt	Sand	Fine sand	Medium sand	Coarse sand	Coarse fragments	Textural Classification	Soil depth (up to a max of 4 m)	Soil-profile water availability	Porosity
		(KCl)				(All textural data in %)					mm	%	
A	Witelsbos	4.0	14.0	21.0	65.0	36.0	23.9	5.3	0.0	SaLm	4.00	386.4	46
B	Witelsbos	3.9	12.0	13.0	75.0	50.3	24.8	0.2	0.0	SaLm	1.20	130.4	47
C	Lottering	3.8	20.0	39.0	41.0	36.0	2.9	2.4	0.0	SaLm	2.20	309.4	58
D	Lottering	3.8	18.0	39.0	43.0	35.2	4.7	3.3	0.0	SaLm	2.55	355.9	51
E	Lottering	3.7	18.0	35.0	47.0	40.0	3.6	3.7	0.0	SaLm	2.00	286.7	57
F	Lottering	3.4	18.0	40.0	42.0	36.9	4.0	1.3	0.0	SaLm	1.20	134.2	57
G	Lottering	3.4	16.0	44.0	40.0	34.2	2.5	3.5	0.0	SaLm	1.60	229.8	63
H	Lottering	3.3	19.0	40.0	41.0	35.8	3.3	2.0	0.0	SaLm	3.20	342.7	60
I	Kruisfontein	-	2.8	2.4	94.8	57.9	36.5	0.4	0.0	Sa	2.00	195.0	43
J	Kruisfontein	-	3.0	11.5	85.5	76.6	8.9	0.2	0.1	LmSa	1.80	313.0	43
K	Kruisfontein	-	6.0	11.5	82.5	68.2	11.2	6.2	0.0	LmSa	1.90	312.0	43
L	Grabouw	-	2.3	1.3	96.4	45.7	26.9	23.9	0.0	Sa	2.00	75.0	43
M	Grabouw	-	13.0	26.0	61.0	54.8	3.0	3.45	4.0	LmSa	0.50	115.0	44
N	Grabouw	-	8.4	14.8	76.8	67.7	2.8	6.4	62.2	SaLm	0.60	178.0	43
O	Jonkershoek	-	3.3	0.8	96.1	38.3	49.2	8.6	6.7	Sa	0.80	118.0	43
P	La Motte	-	2.8	2.0	95.2	65.2	24.7	5.3	0.0	Sa	2.00	177.0	43

4.4.3 Data collection and analyses

This chapter integrates additional soil and climatic data from Fischer (2011). Soil data, viz. textural data, maximum soil depth, soil water storage capacity and porosity, together with MAP, MAT and site index, was sourced from Fischer (2011). Soil sampling was done was at two intervals – the first in late September 2015 and the second in November 2016. Monthly precipitation and temperature data from 2000 to 2010 was acquired for each region, and the monthly soil water deficits for all sixteen sites were calculated using an adaptation of the original work by Thornthwaite (1944; 1948) and Thornthwaite and Mather (1955), outlined in Pereira *et al.* (2007). A detailed description of the methodology is outlined in Section 4.3. This 10-year period was chosen because comprehensive datasets were available on all sites and several weather stations were abandoned after 2010. Annual and monthly rainfall records for 1961 to 2017, from the Lottering and Witelsbos plantations in the Tsitsikamma region, fitted well within historical monthly rainfall records of the selected period. In addition, historical annual rainfall records from the towns of Knysna (Knysna region) and Grabouw (Boland region) fitted within the selected period. Refer to section 5.5.1 for a discussion of data collection for the subsequent periods (up to 2017).

4.4.4 Porosity

The soil porosity was determined by means of the undisturbed bulk density and incorporated particle density of each soil (Equation 3). Particle density varies according to the mineral content of the soil. Quartz is one of the dominant minerals and has a particle density of 2.65 g cm⁻³ (Blake, 2008; Brady & Weil, 1996). Particle density ranges from 2.4 to 2.9 g cm⁻³ within the group of mineral soils (Rühlmann, Körschens & Graefea, 2006). The soils from the Tsitsikamma region have sandy loam textures (Table 3.3) and the particle density was assumed to be 2.65 g cm⁻³ in this study.

$$Porosity = 1 - \left(\frac{Bulk\ density}{Particle\ density} \right) \quad (3)$$

where:

Porosity	= amount of pore space in the soil (%)
Bulk density	= g/cm ⁻³
Particle density	= 2.65 g cm ⁻³

4.4.5 Interpretation

There are several commonly used estimates of plant water availability in the South African commercial forestry industry; the aridity index, moisture growing season, mean annual precipitation and the soil water deficit of each field trial were correlated to the site index using a Pearson correlation. In addition, the effect of several edaphic properties on the water availability of the sixteen sites, distributed all over the Cape Forest Region, was evaluated. The capacity of each site to store water, and the availability of water in the soil, could potentially be used to identify pine-afforested sites that could respond more favourably to fertilisation in drought conditions. Graphical illustrations were created using Sigma Plot 11 statistical software.

4.5 Soil water deficit

4.5.1 Potential evapotranspiration

The heat index (I) was computed from a table compiled by Thornthwaite (1948); the table provides monthly heat-index values with corresponding mean monthly temperatures. The summation of the monthly values for one year provided the heat index required for Equation 4. The unadjusted monthly potential evapotranspiration (ET_p) values were calculated from the nomograph provided by Thornthwaite (1948). The final step required the conversion of unadjusted ET_p to adjusted ET_p values. The adjusted ET_p incorporates the number of hours of sunlight into units of 30 days of 12 hours each. The full methodology for WD calculation is described by Pereira *et al.* (2007).

$$ET_p = 16(10T_n/I)^a \quad (4)$$

where: ET_p = Potential evapotranspiration; millimetres (mean) for a 30-day month (mm month⁻¹)

T_n = Mean monthly air temperatures, units in degrees centigrade

I = Heat index

a = Cubic function of I

4.5.2 Heat index

The heat index was calculated using Equation 5 (Pereira *et al.*, 2007). The value depends on the historical mean temperature of each month and includes the monthly thermic effects for a year.

$$I = \sum_{n=1}^{12} (0.2 T_n)^{1.514} \quad (5)$$

where: I = Heat index

T_n = Mean monthly air temperatures (°C)

4.5.3 Cubic function of I (a)

A polynomial function was used to calculate exponent a (Equation 6).

$$a = 6.675 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.7912 \times 10^{-2} I + 0.49239 \quad (6)$$

where: a = Cubic function of a

I = Heat index

4.5.4 Solar azimuth and time of sunrise

The solar azimuth (δ) refers to the projected angle of the sun relative to its position in the plane of the local horizon. The Thornthwaite (1948) method requires the daily solar azimuth for each month of the year to determine the average monthly photoperiod. The first step requires calculating the daily solar azimuth angle for each site and requires the day number of the year as an input variable (Equation 7). The second step determines the angle at time of sunrise (h_n) (Equation 8). Equation 8 incorporates the solar azimuth value, determined in the preceding step, and the latitude of the selected region.

$$\delta = 23.45 * \sin \left[\text{RADIANS} \left(\frac{360(NDA-80)}{365} \right) \right] \quad (7)$$

where: δ = Solar azimuth (degrees)

NDA = Day number of the year

$$h_n = \arccos[-\tan \Phi * \tan \delta] \quad (8)$$

where: h_n = Angle at time of sunrise (degrees)

Φ = Latitude (degrees)

δ = Solar azimuth (degrees)

4.5.5 Average photoperiod

The photoperiod is defined as the time between sunrise and sunset on a given day or, more specifically, the duration of the day. To calculate the photoperiod, the angle at the time of sunrise is required (Equation 9).

$$N = 2h_n / 15^\circ \quad (9)$$

where: N = Photoperiod (hours)
 h_n = Angle at time of sunrise (degrees)

4.5.6 Corrected ETp

The ETp calculated in Equation 5 is for a one-month interval of 30 days and a photoperiod of 12 hours per day. To determine the ETp for the respective month, the ETp value needs to be corrected (Equation 10).

$$ETp = ETp * Cor$$

$$Cor = (ND/30)^{(N/12)} \quad (10)$$

where: Cor = Corrected ETp (mm month⁻¹)
 ND = Number of days for respective month (days)
 N = Average photoperiod for the respective month (hours)

4.6 Available soil water

4.6.1 Precipitation and ETp difference

The next step required calculating the difference between the actual monthly precipitation and the calculated potential evapotranspiration for each site (Equation 11).

$$Difference = P - ETp \quad (11)$$

where: P = Actual precipitation (mm month⁻¹)
 ETp = Potential evapotranspiration (mm month⁻¹)

4.6.2 Negative accumulation and soil water storage capacity

Negative soil water accumulation and available soil water were calculated concurrently. If the difference in precipitation and potential evapotranspiration for the succeeding month was

negative, the negative difference was cumulatively added to the difference of the preceding month. This was maintained for negative differences. A different approach was used for positive differences following a sequence of negative differences: The positive value was added to the available soil water of the preceding month, and this value should not have exceeded the soil water storage capacity of the soil. This available soil water value was then substituted into Equation 12, derived from Equation 13, to calculate the negative accumulation. Available soil water was calculated as a function of the preceding and present months' difference in precipitation and potential evapotranspiration. If the difference was negative, it was substituted in Equation 13 to determine the available soil water. If the differences were positive, the values were cumulatively added to the following month's difference.

$$NEG\ ACUM = CAD * Ln \left[\frac{ASW}{CAD} \right] \quad (12)$$

where: NEG ACUM = Negative accumulation (mm month⁻¹)

CAD = Soil water storage capacity (mm)

ASW = Available soil water (mm)

$$ASW = CAD e^{\left[\frac{NEG\ ACUM}{CAD} \right]} \quad (13)$$

where: ASW = Available soil water (mm)

CAD = Soil water storage capacity (mm)

NEG ACUM = Negative accumulation (mm month⁻¹)

4.6.3 Real evapotranspiration

The real evapotranspiration (ET_r) was calculated as a function of the positive or negative difference between the actual and potential evapotranspiration. A difference greater or equal to zero resulted in the potential evapotranspiration being recorded as the real evapotranspiration. If the difference was negative, the sum of the precipitation and change in available soil water for the current and preceding month were calculated as the ET_r (Equation 14).

$$ET_r = Prec + (ASW_{cur} - ASW_{prec}) \quad (14)$$

where: ET_r = Real evapotranspiration (mm month⁻¹)

Prec = Precipitation (mm month⁻¹)

ASW_{cur} = Available soil water of current month (mm)

ASW_{prec} = Available soil water of preceding month (mm)

4.6.4 *Water surplus and deficit*

If the available soil water was equal to the maximum soil water storage capacity for the site, the water surplus was calculated as the difference between the real and potential evapotranspiration and the change in available soil water (Equation 15). The water deficit was calculated as the difference in potential (ETp) and real evapotranspiration (ETr) (Equation 16).

$$Surplus = (Precipitation - ETp) - (ASW_{cur} - ASW_{prec}) \quad (15)$$

where: ETp = Potential evapotranspiration (mm month⁻¹)

ASW_{cur} = Available soil water of current month (mm)

ASW_{prec} = Available soil water of preceding month (mm)

$$Deficit = ETp - ETr \quad (16)$$

where: ETp = Potential evapotranspiration (mm month⁻¹)

ETr = Real evapotranspiration (mm month⁻¹)

4.7 Results

4.7.1 *Plant-available water*

The largest regional variability in plant-available water was observed in the Tsitsikamma, with ranges of 130 to 386 mm. Water availabilities in the Knysna and Boland regions ranged from 195 to 313 mm and 75 to 178 mm respectively. Water availability was largest for sites J, K and E, with values of 313, 312 and 287 mm respectively. The smallest water availabilities were observed in the Boland region, on sites L, M and O, with values of 75, 115 and 118 mm respectively (Table 4.9).

Table 4.9: Site-specific average and cumulative soil water deficits.

Site	Region	Soil water storage capacity (mm)	Soil water deficit 2000-2010 (mm)	
			Cumulative	Annual average
A	Tsitsikamma	386.4	190.3	19.0
B	Tsitsikamma	130.4	344.1	34.3
C	Tsitsikamma	309.4	140.5	14.1
D	Tsitsikamma	355.9	124.9	14.5
E	Tsitsikamma	286.7	149.8	15.0
F	Tsitsikamma	134.2	267.7	26.8
G	Tsitsikamma	229.8	179.2	17.9
H	Tsitsikamma	342.7	129.0	12.9
I	Knysna	195.0	1 510.0	151.0
J	Knysna	313.0	1 177.5	117.8
K	Knysna	312.0	1 179.3	117.9
L	Boland	75.0	2 521.2	252.1
M	Boland	115.0	2 187.7	218.8
N	Boland	178.0	1 800.1	180.0
O	Boland	118.0	2 282.9	228.3
P	Boland	177.0	3 438.4	343.8

4.1.1 Cumulative and average annual soil water deficits

The cumulative soil water deficits for the Tsitsikamma region were considerably smaller, and this reflected in the average annual deficits observed over the 10-year experimental period. Sites A to H had deficits in the range of 141 to 344 mm and 14 to 34 mm respectively. Site B had the greatest soil water deficit from 2000 to 2010, with a cumulative deficit of 344 mm. In addition, site D had the smallest water deficit, with a cumulative and mean water deficit of 125 mm and 15 mm respectively (Figure 4.5).

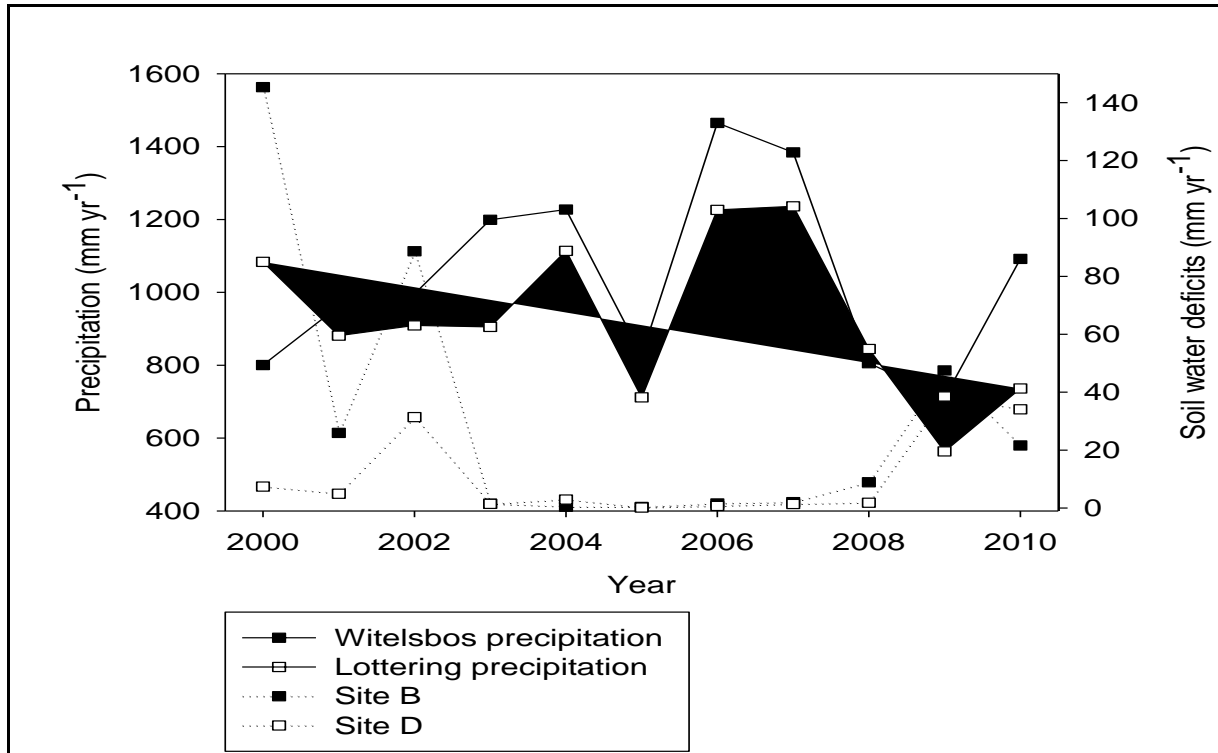


Figure 4.5: Annual soil water deficits and precipitation rates for the Witelsbos and Lottering plantations in the Tsitsikamma region.

Sites from the Kruisfontein plantation, Knysna region, had significantly greater water deficits relative to the Tsitsikamma region. Sites I to K had cumulative and annual average deficits in the range of 1 178 to 1510 mm and 118 to 151 mm respectively. The largest deficits were observed for site I, with a cumulative and annual average deficit of 1 510 mm and 151 mm. Sites J and K had similar water deficits, with the first having a slightly smaller water deficit, at 1 178 mm and 118 mm respectively (Figure 4.6).

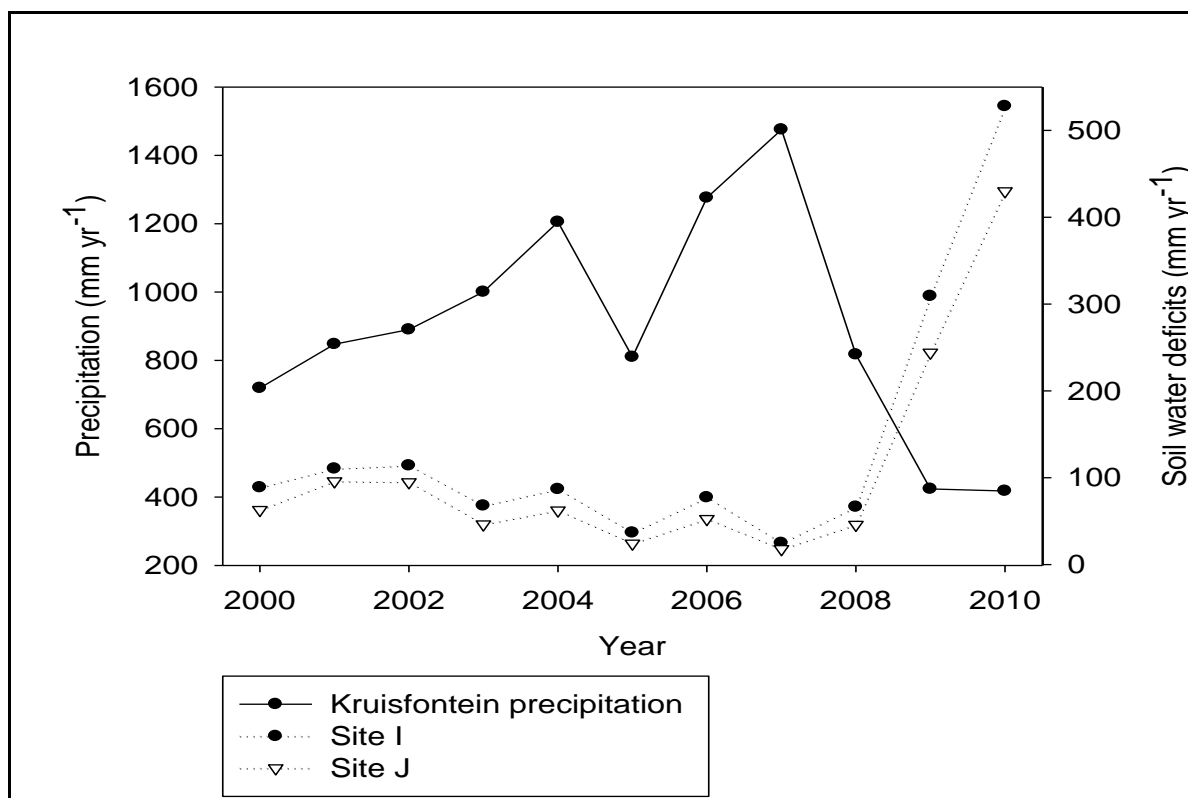


Figure 4.6: Annual soil water deficits and the regional precipitation rates for the sites in the Kruisfontein plantation, Knysna region.

Larger variations were observed in the Boland region. Sites L to P had cumulative and annual average soil water deficits of in the range of 1 800 to 3 438 mm and 164 to 313 mm respectively. The largest deficits were observed at site P, La Motte plantation, with values of 3 438 and 313 mm respectively (Figure 4.7). Site N had better water storage capabilities and had a cumulative and annual average deficit of 1 800 mm and 164 mm respectively (Figure 4.8). The large decrease in annual rainfall from 2008 to 2010, as illustrated in Figures 4.5 to 4.8, resulted in increased water deficits across most regions. This relationship accentuates the dependence of soil- and plant-water availability on precipitation.

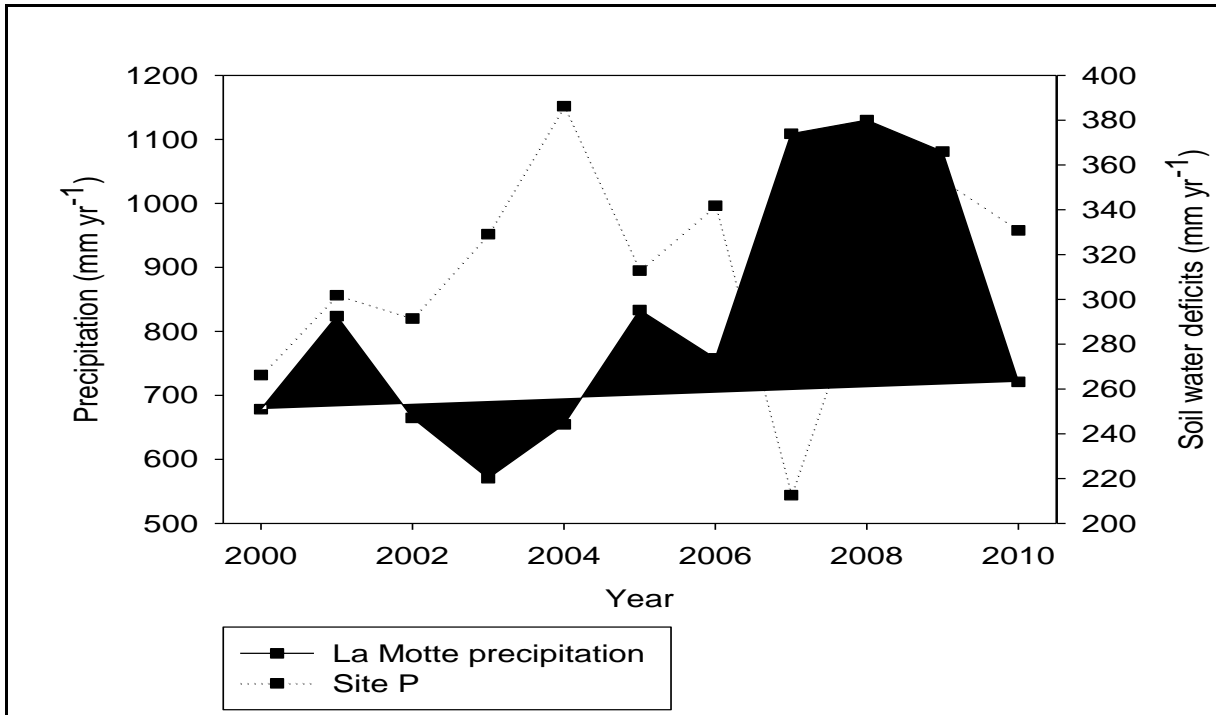


Figure 4.7: Annual soil water deficits and the regional precipitation rates for site P in the La Motte plantation, Boland region.

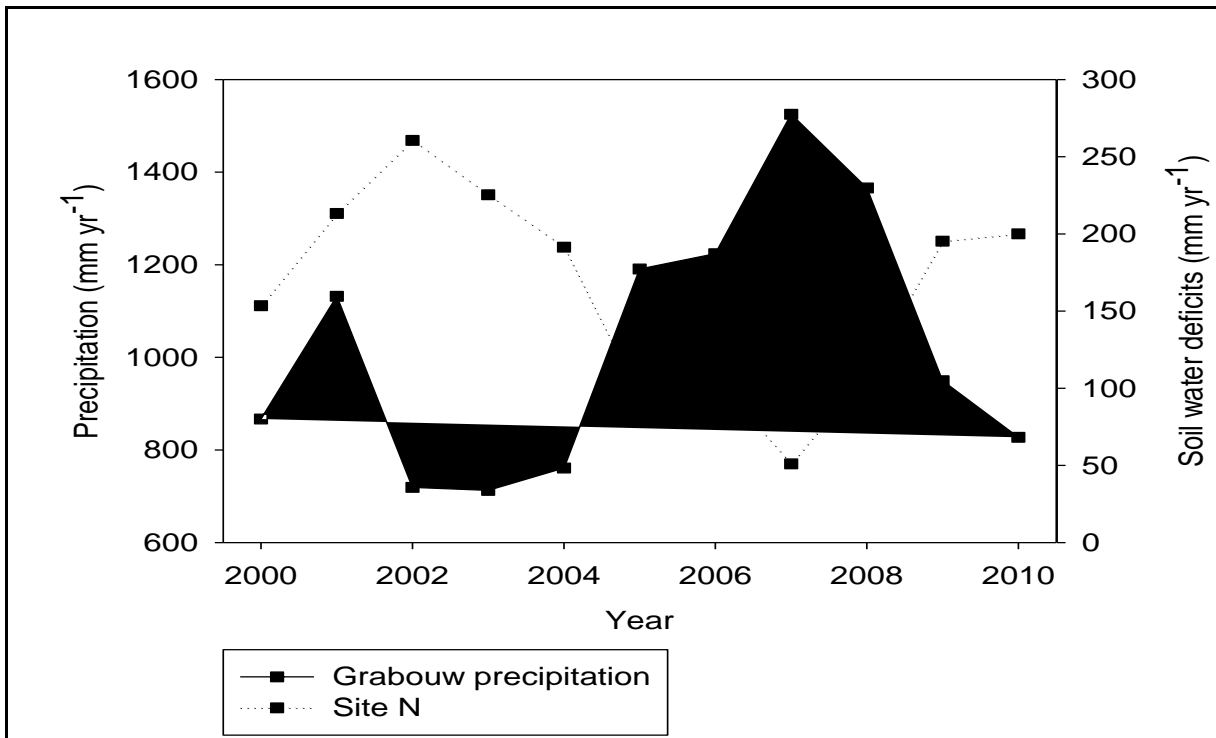


Figure 4.8: Annual soil water deficits and regional precipitation rates for site N in the Grabouw plantation, Boland region.

4.1.2 Correlations

The Pearson correlation, a measure of the linear correlation between two variables, revealed a significant correlation between the soil water deficit (WD) and the site index of each site ($r = -0.826$, $p < 0.001$) (Table 4.10). Like soil WD, a significant and strong positive correlation was observed between the moisture growing season (MGS) estimate and site index ($r = 0.775$, $p < 0.001$). Significant correlations were observed between the soil WD and both the MGS and aridity index (AI) estimates, with respective correlation coefficients and p -values of -0.957 ($p < 0.001$) and -0.535 ($p = 0.033$). The best-fitting models for the relationship between soil WD and MGS with site index showed minor variations, with R^2 values of 0.882 (Figure 4.9) and 0.612 (Figure 4.10) respectively.

Table 4.10: Pearson correlation coefficients and p -values; p -values less than 0.05 (*) denote a significant linear relationship between variables.

	Mean annual precipitation (mm)	Moisture growing season (no. of days per year)	Aridity index	Site index (dominant height in m at 20 years of age)
Soil WD (mm)	-0.223	-0.957	-0.538	-0.826
	0.394	< 0.001*	0.032*	< 0.001*
MAP (mm)		0.160	0.544	0.402
		0.554	0.029*	0.122
MGS (no. of days per year)			0.496	0.775
			0.051*	< 0.001*
AI				0.345
				0.191

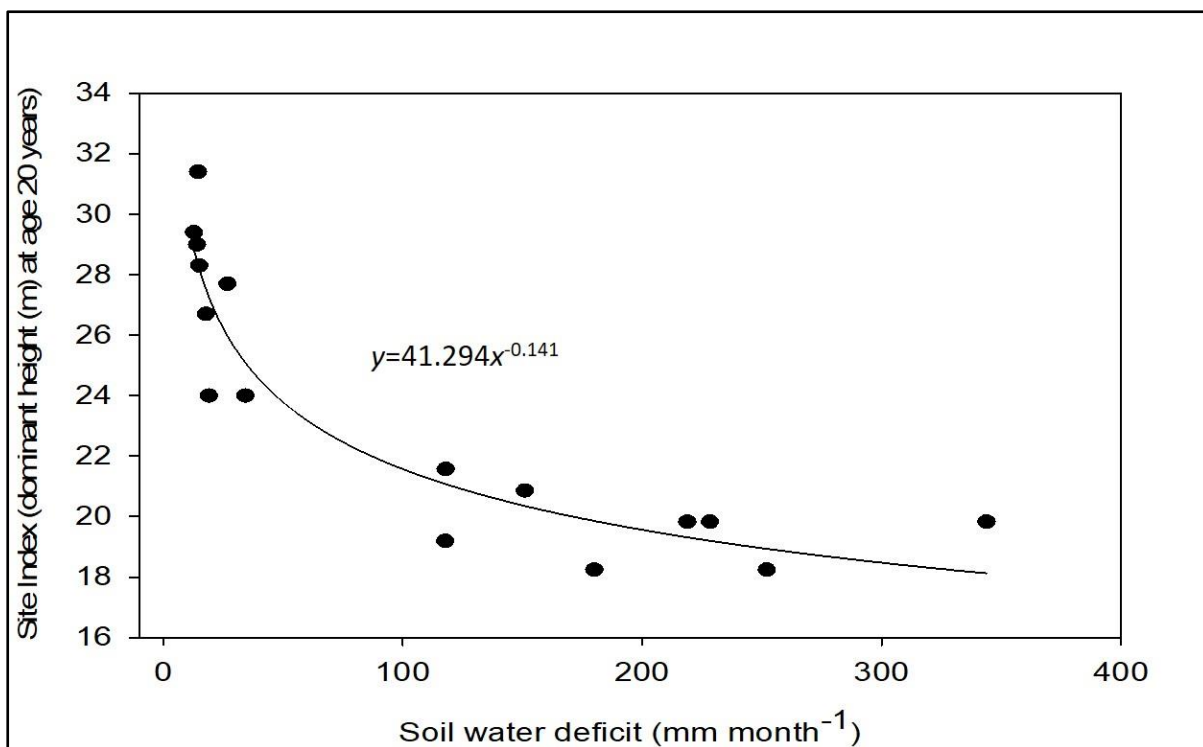


Figure 4.9: Significant relationship between the soil water deficits and site indices of each site.

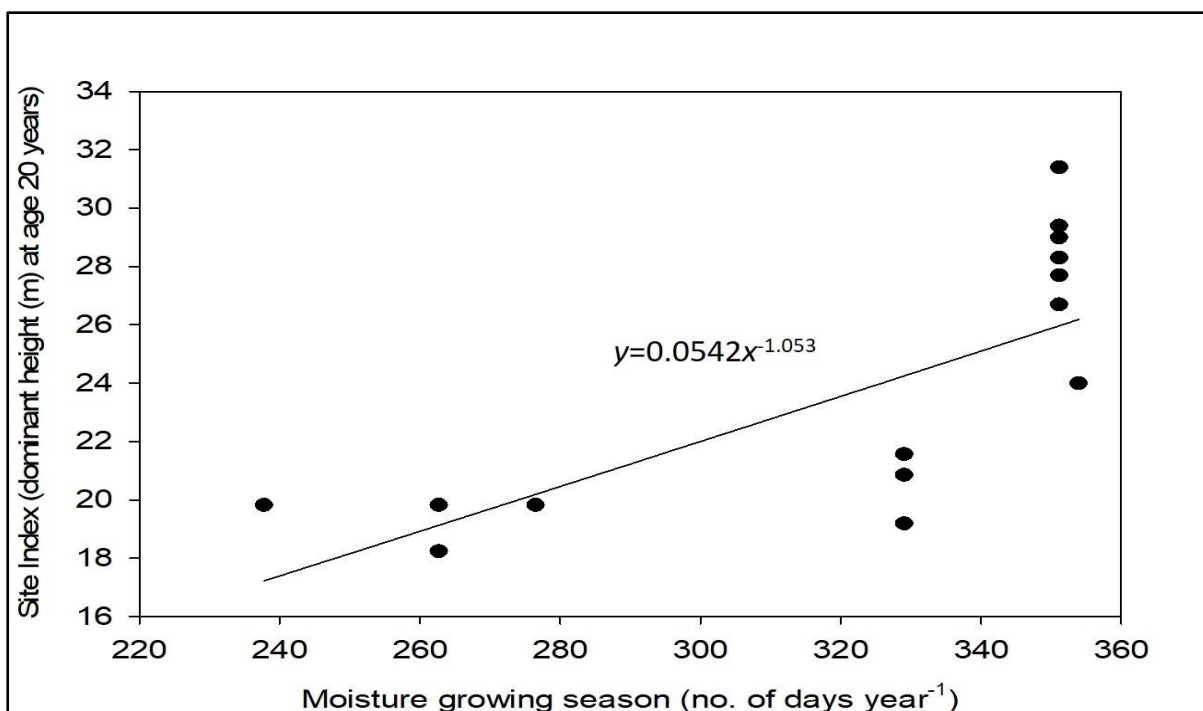


Figure 4.10: Significant relationship between the soil water deficits and moisture growing season of each site.

4.8 Discussion

4.8.1 Site and climatic effects

The rainfall in the Tsitsikamma region varies from approximately 1 000 to 1 100 mm per annum and is distributed evenly throughout the year, with slight increases from August to November. The rainfall in the Knysna region is approximately 700 mm per annum and relies increasingly on seasonality; monthly rainfall increases from November to March. The Boland receives approximately 1 000 mm per annum and, like the Knysna region, rainfall depends on seasonality and increases from May to August. The soils in the Tsitsikamma region had larger silt and clay contents, resulting in larger plant-available water storage potentials. This decreased the susceptibility of these soils to pass into a deficit from seasonally fluctuating or drought-induced (abnormally low) precipitation rates. Clayey and loamy soils have a higher porosity than sandy soils due to the size and distribution of particles (Lipsius, 2002). This was evident in the Tsitsikamma, as the monthly and cumulative deficits were significantly lower relative to the other regions. The larger soil WD and lower water-retention capacities observed in sites B and F in the Tsitsikamma region can be attributed to the physical soil properties. Both sites had shallower soils and belong to the plinthic and podzolic soil groups, with oxidic and duplex soil properties respectively. Periodic flooding, followed by drier conditions, can lead to advanced cementation and plinthite development (Le Roux & Du Preez, 2006; Soil Classification Working Group, 1991), and these soils characteristically have dense subsoils that inhibit the infiltration of water and root penetration (Fey, 2010). Hard plinthic B horizons appear more frequently in lower topographic positions, and horizon thickness increases with higher precipitation rates, together with the occurrence of hard plinthite (Verster, 1974). Podzolic soils have low water-holding capacities and often show water stress (Schwartz, 2006). These soils form under sandy parent materials in conditions that produce the translocation and accumulation of iron (Fe), aluminium (Al) and organic material in the subsoil. In podzols of which the clay content is less than 10%, soil texture ranges from sand to sandy loam and water-retention capacity can be as low as 50 mm (Schwartz, 2006). Abrupt changes in soil texture, and waterlogged or stagnant soil conditions are characteristic of duplex soils and can result in seasonal waterlogging (Hardie, Doyle, Cotching & Lisson, 2012; MacVicar *et al.*, 1977), due to permeable topsoils overlying less (more slowly) permeable diagnostic horizons that are not hardpans (MacVicar *et al.*, 1977). The low water-retention ability of site I was due to topographical and textural differences from the other sites, as this site contains a significantly higher medium-sand content. Soil texture significantly affects the water-retention ability of

soils, and sandy soils have a smaller water-retention ability relative to predominantly silt and clay soils (Fey, 2010; Geroy, Gribb, Marshall, Chandler, Benner & McNamara, 2011; Lipsius, 2002; Park, 2001). The remaining sites in the Knysna region, J and K, showed signs of waterlogged soil conditions, and K, a cumulic soil with duplex properties, was naturally positioned at the base of a slope or floodplain. Topography and landscape positioning are key indicators of a soil's water-retention ability (Le Roux & Du Preez, 2006). The poor water-retention capacities of sites L and P in the Boland region can be attributed to soil texture. Both sites had a sand content of more than 95%, and site L had a substantial coarse sand content. Sandy and shallow soils naturally have poor water-retention capabilities, and the cultivation of such soils requires frequent precipitation events (Chesworth, 2008). Lithic material underlying an E-horizon conforms to the properties of a lithocutanic soil, and cutanic characteristics may be weakly exhibited (MacVicar *et al.*, 1977). In addition, lithosols have naturally occurring rock fragments and saprolite within 250 mm of the soil surface (MacVicar *et al.*, 1977). The poor water-retention capabilities of both sites are due to the high sand contents and shallowness. The reasons for the observed water-storage capacity of site P was analogous to the observations made for duplex soil forms in the other regions.

4.8.2 Water dynamics

The degree of water loss from each site trailed the monthly precipitation significantly. Soil water losses, following a significant decrease in monthly precipitation, relied on the storage threshold of each site. Thresholds were larger in the Tsitsikamma, and it was only after a substantial or prolonged decrease in monthly or annual precipitation that the water availabilities changed from surplus to deficit values. Soil water availabilities were increasingly sensitive to the rainfall gradient (Famiglietti *et al.*, 1999) from the Knysna to Boland regions. Long-term water balance is determined by the interaction of precipitation and potential evapotranspiration and is regulated by soil water storage (Milly, 1994). The temporal variation between sites, and the change from surplus to deficit values, hinged substantially on seasonal fluctuations in regional precipitation, and more specifically in the rainfall frequency and intensity, but edaphic properties and topographic positioning did affect the degree of soil water loss observed at all sites. High precipitation in shallow soils may lead to excess water and losses may occur through runoff (Milly, 1994). Soil structural properties respond to the frequency and intensity of rainfall, together with seasonal cycles of wet and dry periods (Bodner *et al.*, 2013).

4.8.3 Relationship between site index and soil water availability estimates

The relationship between site index and either MAP and AI was insignificant and weak, indicating that both MAP and AI will be poor predictors of growth. The relationship between MGS and site index was much stronger, underscoring the importance of seasonal variation in evapotranspiration and seasonal distribution of rainfall. The MGS consists of the monthly rainfall, ET_p estimates as well as a predefined threshold value to define water stress. The estimate shows the changes in rainfall distribution and ET_p throughout the year, whereas the soil WD includes soil water availability. The WD estimate showed significant correlations with the MGS, AI and adjusted site index, and MGS was the only other estimate that correlated significantly with the adjusted SI values. The strongest (and highly significant) correlation was observed between the average annual soil WD and site index of each pine stand, and this was to some extent similar to the findings of Gonçalves *et al.* (2017). These authors reported a strong correlation ($r = 0.68$, $p < 0.001$) between the soil WD, in accordance with Thornthwaite and Mather (1955), and mean annual increments of several Eucalyptus-afforested regions in Brazil. The research presented in this chapter, supported by that of Gonçalves *et al.* (2017), advocates that soil WD could likely be used as a relatively simple, yet reliable, estimate of plant-available water for a given site, using datasets that are widely and readily available.

4.9 Conclusions

The findings of this study show that soil water storage is subject to the interaction of the supply (precipitation) and demand (evapotranspiration) of water in the ecosystem, and both are regulated by the ability of the soil to store water. In this experiment, soil WD was calculated annually on all sites (with varying intensities), regardless of optimal or suboptimal climatic conditions over the period of a decade. The climatic gradient produced variation between sites; however, the severity of the observed deficits was equally affected by the edaphic properties of each site. The large deficits observed in several sites with shallow, sandy and saprolitic soil conditions were quickly changed to surplus values following one month of high precipitation. The loamy soils showed moderate resilience to water loss, and surplus values were maintained for several months on most sites following smaller successive precipitation events. Only after a significant reduction in monthly or annual precipitation did large deficit values appear. Soil WD was shown to be an acceptable estimate of plant-available water, relative to the use of MAP, AI and MGS. The soil WD provides an excellent index of plant-available water and requires input data that is currently more readily available across South African forest site types. The key variable appears to be the inclusion of a site-based estimate of actual

evapotranspiration in the calculation. It therefore appears that gridded and satellite data, such as LocClim (FAO), MODIS and Landsat, could potentially also be used to estimate the ET_a and ET_p as an alternative to the methodology outlined by Pereira *et al.* (2007). In addition, this subcontinent has an abundance of historic and current monthly rainfall records, emphasising the practicality of using the WD estimate. The latter should be advocated as a preferred measure of soil water availability with the currently available datasets.

CHAPTER 5

PREDICTING SOIL NITROGEN AVAILABILITY IN SEMI-MATURE PINE STANDS IN THE TSITSIKAMMA USING THE SOIL NITROGEN AVAILABILITY PREDICTOR (SNAP) MODEL

5.1 Introduction

Soils are dynamic ecosystems, and understanding the cycling of nutrients is essential for future silvicultural advancements. The cycling of nitrogen (N) in forest systems is significantly affected by climate, aspect, soil surface roughness (Smethurst *et al.*, 2015), forest management practices, tree species, soil water availability (Arslan *et al.*, 2010; Knoepp & Swank, 1998; Lee & Jose, 2006) and other soil properties, such as soil texture, organic matter content, soil pH and the C:N ratio (Arslan *et al.*, 2010; Pulito *et al.*, 2015). Forest management practices, such as cultivation, forest floor removal, slash management practices, thinning and irrigation, significantly affect the net nitrogen mineralisation rates of a soil and subsequent N uptake by trees (Du Toit & Dovey, 2005; O'Connell *et al.*, 2004; Smethurst *et al.*, 2015). Nitrogen availability refers to the rate at which N is converted from unavailable to plant-available forms in the rooting zone (Binkley & Hart, 1989). The ability to quantify the cycling of N in the soil can contribute significantly to the improvement of accurate N fertiliser prescriptions in plantation forestry (Laclau *et al.*, 2010; Smethurst *et al.*, 2015), as well as to improve the empirical models for assessing the rates of nitrate leaching, decomposition, plant growth and the stand response to N fertilisation (Paul, Polglase, O'Connell, Carlyle, Smethurst & Khanna, 2003). The spatial variability observed in indices of nitrogen availability originates from the horizonation of soil, topographical and geomorphologic variation across terrain, and differences at the individual tree level (Binkley & Hart, 1989). The aforementioned factors, as well as climate, modify soil water availability and soil temperature (the fundamental drivers of nitrogen mineralisation) in spatial and temporal scales (Paul, Polglase, O'Connell, Carlyle, Smethurst & Khanna, 2002; Paul *et al.*, 2003). Soil water content, more specifically the in-field upper and lower limits, significantly affect the net mineralisation of a soil (Paul *et al.*, 2003; Smethurst *et al.*, 2015). Modelling the effect of soil water on the net mineralisation of a soil is challenging. The challenges are attributed to the various effects of soil water on the processes of gross mineralisation and immobilisation in different soils and under different growing

conditions (Paul *et al.*, 2003). The inconsistencies observed in laboratory and in-field studies regarding the effect of temperature and soil water on the net N mineralisation of a soil can be attributed to the range of different variables, diverse approaches in describing soil water and various incubation conditions (Paul *et al.*, 2003). The SNAP model was developed by Paul *et al.* (2002) to predict nitrogen mineralisation rates in soils. A sensitivity analysis by Smethurst *et al.* (2015) revealed the input values of the SNAP model to have varying degrees of importance. The SNAP model is particularly sensitive to the variables used to calculate the basal rate of N mineralisation, viz. soil water content, soil temperature and N mineralised at incubation (Paul *et al.*, 2002; Smethurst *et al.*, 2015). The model requires accurate quantification of data produced under optimal incubation conditions. Smethurst *et al.* (2015) evaluated the feasibility of using the SNAP model in tropical Eucalypt plantations in Brazil and found that the predicted net nitrogen mineralisation rates were highly correlated with the actual measured rates after 21 months. The authors recommend the model be applied to a wider range of tropical and temperate conditions.

The possibility of implementing the SNAP model in the softwood plantations of the Tsitsikamma has yet to be investigated, and the likelihood of correlating the mid-rotation fertiliser responses to the predicted mineralisation rates of the SNAP model supports the initiative to improve the softwood fertiliser regimes of the Eastern and Western Cape, South Africa. The following hypotheses were formulated for this study: no significant correlation exists between the predicted N mineralisation rate of each study site and (a) the observed short-term growth responses and (b) the site-specific edaphic properties.

5.2 Research questions

- Are there significant differences between the predicted net N mineralisation rates for the experimental sites studied in this project?
 - What are the potential reasons for the significant differences?
- Are there significant correlations between the documented fertiliser responses, predicted N mineralisation rates and soil water-holding capacities?
 - If such correlations exist, can they be used to formulate site-specific fertiliser recommendations?

5.3 Materials and methods

The soil nitrogen availability predictor empirical model, owned and developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), was used to calculate the net N mineralisation rates for each trial site.

The SNAP model requires the soil nitrogen availability in the field, based on the net mineralisation rate (k) (determined by aerobic incubation in the laboratory), which is subsequently modified by incorporating soil temperature (T_m) and soil water (W_m) (Paul *et al.*, 2002; Smethurst *et al.*, 2015). The soil classifications and characterisations provided most of the data entered in the SNAP model. One of the key components of the SNAP model, the basal net N mineralisation rate (k), was calculated according to the methodology outlined in Section 5.4. The additional required input variables, such as daily radiation, air temperatures, soil moisture content, bulk density, canopy LAI, fractional canopy cover, fractional litter cover, fractional weed cover, litter layer mass and litter layer height, were estimated separately. The abundance of understorey vegetation and large litter variations in several trials were included in the SNAP model (Table 5.13). A visual classification was used to determine the fractional litter and weed cover estimates per field trial. Leaf area indices, measured with an AccuPAR LP-80 ceptometer, were used to estimate the fractional canopy cover.

5.4 Aerobic N mineralisation

Nitrogen availability was determined per an adaptation of the methodology outlined by Vitousek, Gosz, Grier, Melillo and Reiners (1982). Freshly acquired soil samples were kept near field conditions prior to preparation and analysis. Samples were sieved (2 mm), wetted and allowed to drain for 48 hours. This was done to ensure that each soil was near field capacity before the incubation period and that moisture contents were kept near field capacity throughout the incubation period (Binkley & Vitousek, 1989; González-Prieto, Carballas & Villar, 1995; Rita, Gama-Rodrigues, Gama-Rodrigues, Zaia & Nunes, 2013; Roelcke, Han, Cai & Richther, 2002; Serna & Pomares, 1992). Two 25 g (fresh weight) samples of soil from each site were placed in wide-mouthed containers and weighed. At the same time, 10 g of each soil were extracted and analysed for NH_4^+ as a pre-incubation measurement. Several holes were drilled into each container to allow aeration during incubation. Samples were incubated for four weeks at 39°C. This elevated temperature was chosen because microbial activity is at an optimum at 30 to 35°C (Bremner, 1965; Cassman & Munns, 1980). Curtin and Campbell (2007), Mariano, Trivelin, Leite, Megda, Otto and Franco (2013) and Stanford and Smith

(1972) estimated the mineralisable N after aerobically incubating soil samples at 35°C, and aerobic incubation temperatures of 39 °C (Parfitt, Tate & McKercher, 1994; Searle, 1992) and 40 °C (Rita *et al.*, 2013) have been used to aerobically determine the P, sulphur and sulphate mineralisation rates of soils after incubation. Water loss was monitored daily (gravimetrically) in the morning and afternoon during incubation to ensure the soils remained at field capacity. After the incubation period, 100 ml of a 2 M KCl solution was used to extract each 10 g sample. Each solution was shaken for 60 min, and the supernatant was filtered through no. 42 Whatman filter paper and sent for NH_4^+ and NO_3^- analysis. Total N was calculated as the sum of NH_4^+ and NO_3^- after incubation. Bremner (1965) suggests subtracting the established quantities of N after and before incubation; however, the balance between mineralisation and immobilisation by microbial biomass in soils with poor nutrition may yield negative values and the process of restoring balance may not occur during short incubation periods. For this reason, two values were used in the SNAP model: the first involved the difference in N before and after incubation, and the second the total N pool after incubation (not subtracting the NH_4^+ before incubation). These incubation rates were used to calculate and predict the daily basal and annual N mineralisation rates that had been modified according to the soil water content and soil temperature of each site.

5.5 SNAP model inputs

5.5.1 Climatic data

The SNAP model required daily radiation, maximum and minimum air temperatures and precipitation data for a period of more than 12 months. This data was acquired from the Grasslands weather station (coordinates 34°00'12.8" S 23°56'35.4" E). The weather station is located at the centre of Storms River, Tsitsikamma. The weather station was selected as it recorded 14 years of nearly uninterrupted data. Field trials A and B were situated the furthest from the weather station, at 45 and 25 km respectively. The rainfall from field trial A was matched to climatic data from the Witelsbos plantation offices, which are 25 km away from the site.

5.5.2 Soil water content

Soil moisture content was gravimetrically calculated for every trial site. Twenty-five grams of topsoil (0 to 20 cm) was added to a porcelain bowl and oven-dried at 105°C until a constant weight was reached. The wet and dry weights, including the weights of the porcelain bowls, were substituted into Equation 18 to calculate the water content.

$$WC = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100\% \quad (18)$$

where: Wet weight = weight of soil sample and bowl (grams)
 Dry weight = weight of oven-dried soil sample and bowl (grams)
 WC = water content (%)

5.5.3 Interpolated canopy leaf area index

The SNAP model required daily leaf area index values for a minimum period of 12 months. The data was not immediately available, and a different approach was mandatory. Quarterly (three-month) leaf area measurements were made for one year at each trial site. The quarterly measurements were initially made to incorporate the effect of seasonality. To enable the estimation of N mineralisation rates over several years with varying climate using the SNAP model, the leaf area index values from October 2015 to October 2016 were repeated 14 times to match the climatic data record that was available. LAI values between discrete measurements were interpolated by calculating the mean values between intervals to account for where no data was available. An average value was used, as changes in LAI for the studied species were small between measurements, and this approach demonstrated the changes in LAI as the year progressed. Gonzalez-Benecke, Jokela and Martin (2014) found that pine needlefall production correlated linearly with the previous year's LAI ($p < 0.001$), and that the relationship was independent of resource availability ($p > 0.086$). However, this relationship was different between *P. taeda* and *P. elliotii* ($p < 0.001$). Furthermore, the authors showed that the projected and measured needlefall in *P. elliotii* remains nearly uniform at stand ages of approximately eight years and more, and that the projected LAI remains nearly uniform at a stand density index of 400 metric units and more in slash pine. Several studies recommend the use of a correction factor for the underestimation of LAI with an AccuPAR ceptometer. Chen and Cihlar (1995), Gower and Norman (1991) and Lopes *et al.* (2016) suggest the multiplication of the LAI with a correction factor. These authors based their findings on using LAI estimates from allometric equations as a reference LAI for measurements made with a ceptometer. Gower and Norman (1991) and Lopes *et al.* (2016) proposed correction factors of 1.5 and 1.38 respectively for *P. pinaster*. Chen and Cihlar (1995) suggested a factor of 1.48 for *P. banksiana*. Leaf area indices were multiplied with a correction factor of 1.38 (after Lopes *et al.*, 2016).

5.5.4 *STUF and SWUF*

The empirical sub-model of SNAP, soil temperature under forest (STUF), assumes annual soil temperatures as a symmetrical function. The model integrates several factors and their predictions that could produce daily deviations from the symmetrical function on which the model is based (Equation 19; Paul *et al.*, 2002). This function is normalised to a reference temperature of 40°C and calibrated to data on the decomposition of organic matter across a range of laboratory-incubated soils (Kirschbaum, 1995; 2000).

$$Tm = \exp^{[a.(T-b)/(T+c)]} \quad (19)$$

where: Tm = Soil temperature modifier (0-1)

T = soil temperature (°C)

a = 3.36

b = 40

c = 31.79

The soil water under forest (SWUF) sub-model is a water-balance model that accounts for the interception of rainfall by the canopy, understorey and litter. It is an extension of agricultural algorithms and calculates the surface runoff, drainage, evaporation, unsaturated flow and daily plant water uptake (Paul *et al.*, 2002). Paul *et al.* (2001) found that the effect of soil water on N mineralisation rates was universally best described with a sigmoidal function. The authors identified this function by calculating individual soil water modifier (Wm) values for numerous soils and soil layers from N mineralisation rates that were normalised to the basal rate, at optimal soil temperatures (Equation 20). The function incorporates the lower and upper limit of water content under field conditions and is labelled the relative field water content (RFWC) of the soil (Equation 21). The fractional canopy cover, litter cover and weed cover values range from 0 to 1. Fractional canopy covers were calculated using the average LAI per site, with the site with the highest LAI as a reference point relative to the remaining sites. Litter cover values were estimated from a combination of measurements taken for litter layer depths and a visual assessment. Lastly, weed cover was assessed according to a percentage value assigned for intensity and weed cover. A value of 1 meant a site was completely covered with woody vegetation and ferns.

$$Wm = \left[\frac{1}{(d.\exp(e.RFWC))} \right] \quad (20)$$

where: W_m = Soil water modifier (0-1)
 $RFWC$ = Relative field water content
 d = 6.63
 e = -5.69

$$RFWC = \frac{[W - W_{LL}]}{[W_{UL} - W_{LL}]} \quad (21)$$

Where: W = Soil water content (%)
 W_{LL} = In-field lower limit water content (%)
 W_{UL} = In-field upper limit water content (%)

Both STUF and SWUF rely on the litter height and litter mass of the forest to determine the soil temperature (T_m) and soil water modifiers (W_m) that are required to calculate the soil N mineralisation rates. The amount of N mineralised is normalised to that which occurs at a temperature of 40°C and relative water content of 1, using the T_m and W_m modifiers (Paul *et al.*, 2002).

5.5.5 Litter layer depth and mass

Litter layer depth was measured at 24 points in each field study and the average value was substituted into the SNAP model. A large metal ring (diameter 30 cm) was used to collect three litter samples from each field study, totalling 24 samples for the trial series. At the same time, four litter depths were measured in the ring at 0°, 90°, 180° and 270° with a metal pin and ruler. The litter was dried at 60°C until a constant weight was reached. The dry weight, per sample, expressed as a mass per unit area ($t\ ha^{-1}$), was then regressed on the average litter depth ($n = 4$) per sample. This regression was used to estimate a representative litter depth for the entire site, using the 24 depth measurements at each individual site as a primary input value.

5.6 Soil water availability

As in Chapter 4, the monthly soil water deficits for the most responsive field trials were determined per an adaptation of the work of Thornthwaite and Mather (1955), outlined in Pereira *et al.* (2007). A full methodological description is given in Chapter 4. The water deficits were calculated for the experimental period, from October 2015 to October 2017.

5.7 Interpretation

The effects of site properties, fertiliser application rate and soil N mineralisation rates on *P. elliotii* and *P. elliotii x caribaea* were analysed using analysis of variance (ANOVA) statistics. A confidence level of 95% was used to assess any significant interaction or treatment effects between variables. Variables, treatments and interactions with $p < 0.05$ were reported as having statistical significance. In addition, the Pearson correlation was used to show significant relationships between the predicted annual N mineralisation rates, edaphic soil properties and the volume response to fertilisation. Datasets were initially tested for normality using the Shapiro-Wilk test and normal probability plots. The test for normality was done using the Shapiro-Wilk test. Fischer's LSD test was used to compare specific treatment differences for data collected every six months in a 24-month period. Data analysis and graphical illustrations were completed using Statistica 12 and Sigma Plot 11 software. In all instances, we used the repeated structure of the treatments in the experiment to determine whether there were any significant interactions.

5.8 Results

5.8.1 Aerobically measured N mineralisation rates

The NH_4^+ concentrations, determined before incubation, ranged from 0.57 mg kg⁻¹ (at site F) to 0.96 mg kg⁻¹ (at site B). After four weeks of incubation, the concentrations ranged from 0.80 mg kg⁻¹ (at site F) to 1.69 mg kg⁻¹ (at site G). The same samples were analysed for NO_3^- concentrations, and all concentrations were less than 0.36 mg kg⁻¹. These values were possibly due to a detection limit in the analysis (Table 5.11); however, the values were substituted with 0.36 to calculate the net NH_4^+ mineralised per site (Table 5.12).

Table 5.11: Measured NH_4^+ concentrations before and after four weeks of incubation, along with NO_3^- .

Site	Replication	NH_4^+ (initial concentration)	NH_4^+ (final concentration) mg kg ⁻¹	NO_3^- (after incubation)
A	1	0.63	1.40	< 0.36
	2	0.67	1.35	< 0.36
B	1	0.96	1.25	< 0.36
	2	0.94	1.00	< 0.36
C	1	0.59	1.22	< 0.36
	2	0.65	1.32	< 0.36
D	1	0.77	1.14	< 0.36
	2	0.81	0.97	< 0.36
E	1	0.60	0.95	< 0.36
	2	0.58	1.00	< 0.36
F	1	0.61	0.80	< 0.36
	2	0.57	0.91	< 0.36
G	1	0.65	1.69	< 0.36
	2	0.61	1.50	< 0.36
H	1	0.60	0.87	< 0.36
	2	0.67	0.95	< 0.36

The net mineralised NH_4^+ concentration per site was calculated as the average between two replications in Table 5.11, and presented together with NO_3^- . Sites G and A had the highest net NH_4^+ concentrations after the initial concentration was subtracted from the final NH_4^+ concentration. Sites G and A also had the highest levels of N mineralisation if only the final values after incubation were used, yielding estimates of 1.33 mg kg⁻¹ and 1.96 mg kg⁻¹ respectively. The lowest NH_4^+ concentrations were observed in sites B and F, with values of 0.54 mg kg⁻¹ (subtraction of initial from final concentration) and 1.22 mg kg⁻¹ (final concentration) respectively.

Table 5.12: Estimates of mineralised NH_4^+ used by the SNAP model to predict the basal net mineralisation rate.

Site	Net NH_4^+ (subtraction of initial from final concentration)	NH_4^+ (final concentration)
	mg kg ⁻¹	
A	1.09	1.74
B	0.54	1.49
C	0.65	1.27
D	0.63	1.42
E	0.75	1.34
F	0.63	1.22
G	1.33	1.96
H	0.64	1.27

5.8.2 Predicted basal and annual N mineralisation rates

The daily and annual N mineralisation rates varied significantly between sites ($p < 0.001$). Site A had the highest daily and annual mineralisation rates, with values of 1.92 and 3.07 mg N ha⁻¹ day⁻¹ and 149 and 238 kg N ha⁻¹ yr⁻¹ respectively (using estimates where initial rate was subtracted from final or just final N mineralisation rate) (Table 5.13). Sites B and H had the smallest predicted daily N mineralisation basal rates, at 0.58 and 1.59 mg N ha⁻¹ day⁻¹ and 0.79 and 1.58 mg N ha⁻¹ day⁻¹ respectively. However, the lowest predicted annual rates of 29 and 57 kg N ha⁻¹ yr⁻¹ were observed in site H (Figure 5.11).

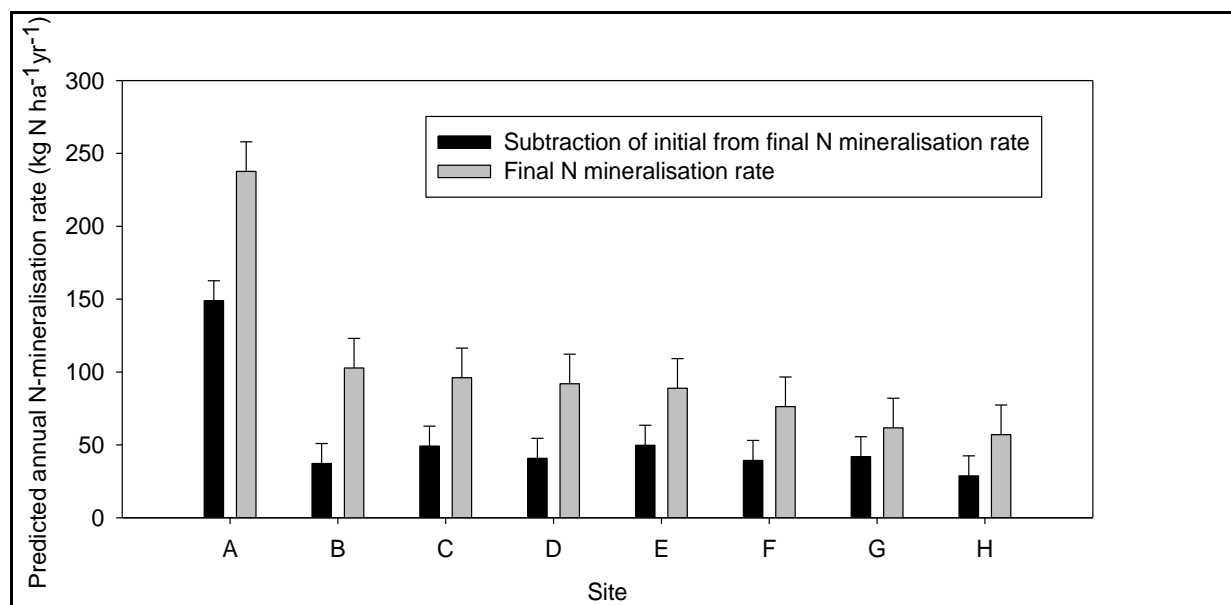


Figure 5.11: Predicted annual N mineralisation rates of each site

Table 5.13 Detailed data on the upper 10 cm layer of soil plus stand information required for the SNAP model per site.

Site	Undisturbed bulk density	Porosity	WC at incubation	WC as a percentage of FC	WC at permanent wilting point	Litter depth	Litter mass	Fractional litter cover	Fractional weed cover	Fractional canopy cover	Daily basal N mineralisation rate (subtraction of initial rate) *	Daily basal N mineralisation rate (final rate) *	Modelled annual N mineralisation rate (subtraction of initial rate)	Modelled annual N mineralisation rate (final rate)
	g cm ⁻³		%			cm	t ha ⁻¹		(0-1)		mg N ha ⁻¹ day ⁻¹		kg N ha ⁻¹ yr ⁻¹	
A	1.43	46	14.59	87.28	10.50	8.4	4.4	0.95	0.30	0.50	1.92	3.07	148.88	237.66
B	1.40	47	18.79	84.18	9.63	14.9	14.8	0.95	0.80	0.49	0.58	1.59	37.25	102.78
C	1.11	58	17.77	84.95	12.50	17.0	12.3	0.95	0.70	0.88	1.17	2.29	49.18	96.09
D	1.30	51	19.74	86.17	11.81	15.0	7.7	0.95	0.90	0.69	0.81	1.83	40.79	91.94
E	1.14	57	17.72	84.95	11.88	17.7	8.1	0.90	0.80	0.73	1.17	2.09	49.73	88.85
F	1.15	57	17.66	86.64	11.80	12.7	7.9	0.95	0.90	0.69	1.04	2.01	39.37	76.24
G	0.98	63	21.05	82.65	11.07	19.6	8.7	0.95	0.70	0.95	1.57	2.31	41.86	61.69
H	1.07	60	20.75	82.81	12.15	16.4	14.0	0.95	0.90	0.76	0.79	1.58	28.75	57.04

*N mineralisation rates under laboratory conditions with temperatures at 39°C and soil water at field capacity (FC) (moisture contents of 14 to 24%).

5.8.3 *Fertilisation responses*

The responses of the field trials to N fertiliser additions were investigated for this section. Treatments T2, T4 and T5 contained increasing quantities of N in the presence of P, in the following combinations (all in kg ha⁻¹): 0 N + 100 P, 100 N + 100 P and 200 N + 100 P respectively. These treatments were selected as they were representative of the effect of N fertilisation on stand growth. Furthermore, the response to N fertilisation could be indicative of inherently sub-optimal levels of N supply on specific sites, whereas non-responses on a given site would suggest that N dynamics supply sufficient N to cater for the needs of the stand at that stage of development.

The response of each field trial to treatments T4 and T5, minus the response to T2, was indicative of the effect of increasing N applications in the presence of P on growth. Field trials A, B and D exhibited inclinations of increased responsiveness to higher N application rates. Field trial B was the most responsive of the three sites, with volume increments of 9 ± 0.07 (T4) and 16 ± 2.08 (T5) m³ ha⁻¹ at 24 months after treatment (Figure 5.12). In addition, field trial C showed increased responsiveness to moderate applications of N (T4) and a negative response to the highest N application rate (T5), with volume increments of 4 ± 1.12 and 0 ± 0.15 m³ ha⁻¹ respectively. The opposite was observed in field trial G; this field trial was less responsive to moderate applications of N (T4) and more responsive to higher N application rates (T5), with increments of -2 ± 0.08 (T4) and -1 ± 0.04 (T5) m³ ha⁻¹. It is important to note that this field trial had a negative response to N application relative to field trials A, B and D. The responses of field trials A, B, C, D and G mean that each of these sites had different soil N demands, and each site responded according to that demand when increasing quantities of N were applied in the presence of P.

In contrast to the above-mentioned findings, field trial E responded negatively to increased N application rates, with volume increments of -1 ± 1.51 (T4) and -4 ± 2.81 (T5) m³ ha⁻¹. Field trials F and H responded positively to the N applications; however, the responses were similar to those of treatments T4 and T5, with values of 7 ± 0.52 and 3 ± 0.57 m³ ha⁻¹ respectively (Figure 5.12). The response of field trials E, F and H suggests that these sites likely had a larger P or different macro- or micronutrient requirement, and that supplementary N likely added to or intensified an existing nutrient imbalance in the soil. To conclude: field trials B and G were the most and least responsive to fertilisation respectively; field trial B had a high N requirement; and G required no supplementary N.

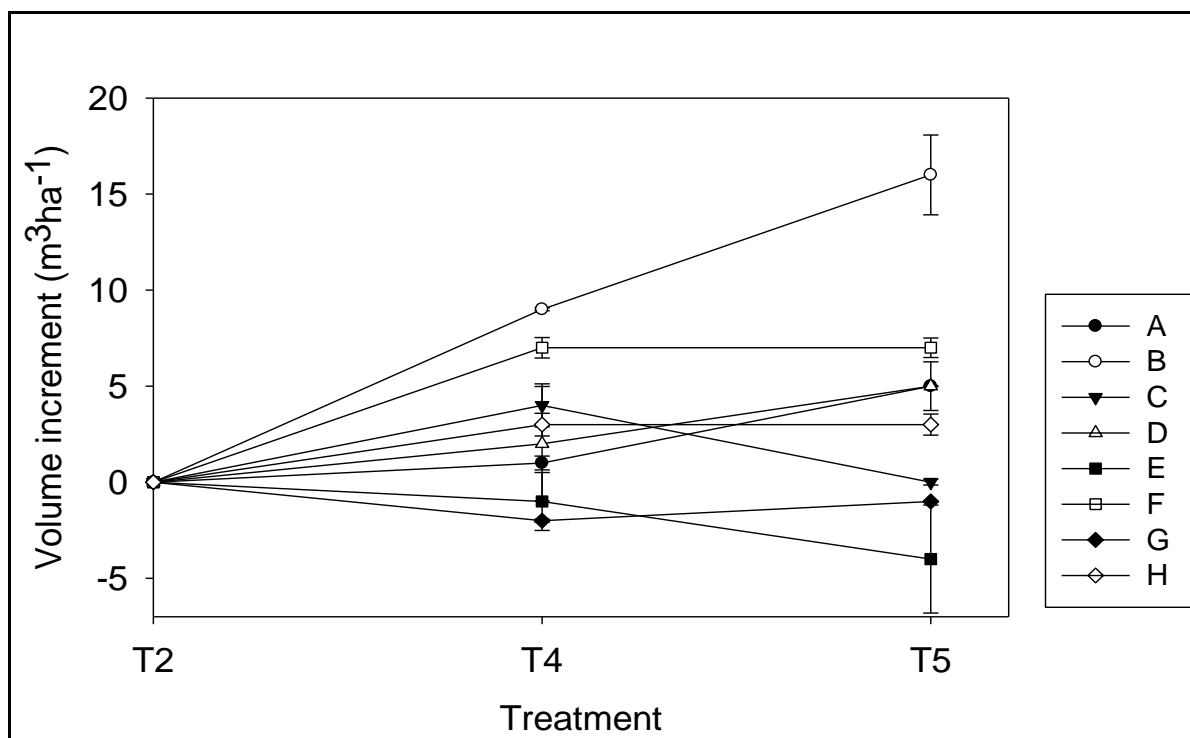


Figure 5.12: Growth response of treatments T4 and T5, after the subtraction of T2, for each field trial.

The interaction of trial site and fertiliser treatment was significant over the 24-month period ($p < 0.001$). The responses of each field trial to treatments T4 and T5, subtracting the response to T2, were standardised as a percentage of the response to the control treatment (Table 5.14).

Table 5.14: Volume increments, standardised responses and the maximum response per field trial at 24 months after treatment.

Field trial	T0	T1	T2	T3	T4	T5	Standardised T4	Standardised T5	Most responsive treatment	Maximum response
	$\text{m}^3 \text{ha}^{-1}$						%	%		%
A	26	27	24	26	25	29	4	18	T5	18
B	43	30	33	33	42	49	20	36	T5	36
C	36	38	37	36	41	37	11	-2	T4	11
D	53	52	59	55	61	64	4	11	T5	11
E	41	38	44	42	43	40	-2	-9	T4	-2
F	44	46	43	49	50	50	16	17	T5	17
G	42	48	46	48	44	45	-5	-3	T5	-3
H	34	36	34	37	37	37	9	8	T4	9

The largest response to N (in the presence of P) was observed in field trial B, treatment T5, with a response of 36%. In addition, field trials A, D and F were increasingly responsive to the highest N application rate (T5), with values of 18%, 11% and 17% respectively. Field trials C and H were increasingly responsive to lower N application rates (T4), with values of 11% and 9%. Trial site E was the least responsive to increased N application rates, with a response of -9% to treatment T5. As in the previous section, field trial G responded less to increased N application rates, with values of -5% and -3% to treatments T4 and T5 respectively. These normalised responses are graphically illustrated in Figure 5.13, using the mean volume increment ($\text{m}^3 \text{ha}^{-1}$) per treatment in each field trial.

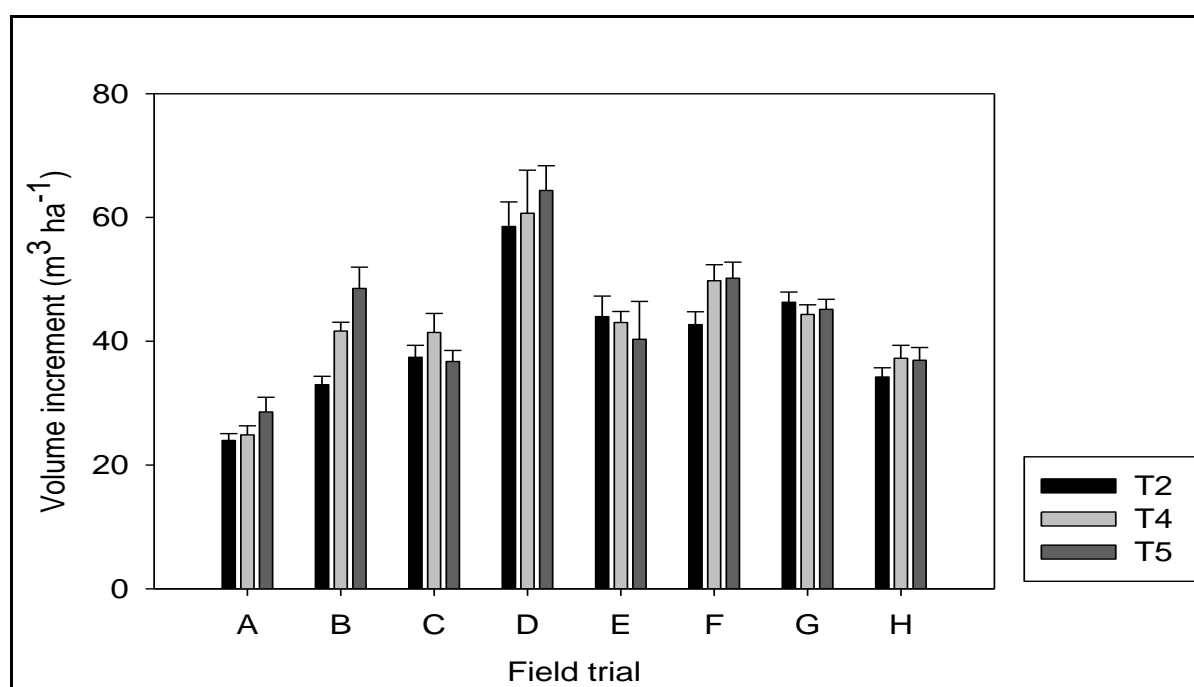


Figure 5.13: The interaction of trial site and the T2, T4 and T5 fertiliser treatments at 24 months after fertilisation (standardised growth responses).

The responses reported in this study are premature and, at 6, 12, 18 and 24 months after treatment, it was expected that the responses were still developing (Table 5.15). The most notable responses were: Field trial A was the least responsive to fertilisation (Figure 5.13), and the SNAP model predicted the highest annual N mineralisation rate for field trial A. Field trial B was located on a coastal hilltop with a large incidence of under-canopy vegetation throughout the experimental period, and the trial was most responsive to the highest applications of 200 kg N ha^{-1} and 100 kg P ha^{-1} (T5) at 24 months. The difference in volume increment between treatments T4 and T5 was small at six to 18 months after treatment, and this could perhaps be attributed to the under-canopy vegetation (likely taking up copious amounts of N) delaying the

response to fertilisation in this field trial. The poor response of field trial H to fertilisation could also be attributed to the significant wind damage at 20 months after treatment, and this field trial had the lowest soil pH values relative to the other trials (Table 3.2). Field trial D exhibited a notable volume response to 100/200 kg N ha⁻¹ and 100 kg P ha⁻¹ (T4 and T5) relative to the remaining treatments. Field trials C and H were more responsive to a balanced N and P fertiliser application of 100 kg N ha⁻¹ and 100 kg P ha⁻¹ (T4) at 24 months after treatment.

Table 5.15: Trial site and fertiliser treatment volume responses at 12 and 24 months after fertilisation. Volumes not standardised as a percentage over the control.

Field trial	6 months			12 months		
	T2	T4	T5	T2	T4	T5
A	11 ± 0.66	12 ± 0.97	10 ± 0.77	14 ± 0.72	15 ± 1.06	14 ± 0.89
B	12 ± 0.71	17 ± 0.81	20 ± 0.92	18 ± 0.91	25 ± 0.93	27 ± 1.05
C	17 ± 0.88	19 ± 1.02	19 ± 0.96	21 ± 1.12	23 ± 1.21	22 ± 1.18
D	29 ± 2.25	27 ± 2.18	30 ± 2.16	37 ± 2.56	35 ± 2.44	40 ± 2.59
E	18 ± 1.13	19 ± 1.15	19 ± 0.98	24 ± 1.20	23 ± 1.26	26 ± 1.29
F	17 ± 1.12	20 ± 1.13	17 ± 1.06	23 ± 1.41	27 ± 1.56	25 ± 1.30
G	24 ± 0.92	22 ± 0.98	23 ± 1.01	28 ± 1.13	27 ± 1.00	29 ± 1.14
H	12 ± 0.83	14 ± 1.11	13 ± 0.84	19 ± 1.06	20 ± 1.35	19 ± 1.29
	18 months			24 months		
A	19 ± 0.89	21 ± 1.41	22 ± 1.66	24 ± 1.11	25 ± 1.47	28 ± 1.61
B	26 ± 1.13	35 ± 1.24	36 ± 1.43	33 ± 1.35	42 ± 1.40	46 ± 2.00
C	31 ± 1.48	34 ± 1.79	32 ± 1.61	37 ± 1.74	40 ± 2.18	36 ± 1.68
D	49 ± 3.45	47 ± 3.28	56 ± 3.58	58 ± 3.94	56 ± 3.72	63 ± 3.64
E	36 ± 1.48	36 ± 1.74	40 ± 1.84	42 ± 1.78	43 ± 1.79	46 ± 2.01
F	36 ± 1.94	42 ± 2.34	41 ± 2.05	43 ± 2.00	49 ± 2.46	50 ± 2.38
G	41 ± 1.34	38 ± 1.35	41 ± 1.49	46 ± 1.63	44 ± 1.55	45 ± 1.59
H	28 ± 1.31	30 ± 1.80	29 ± 1.68	34 ± 1.50	37 ± 2.09	37 ± 2.05

5.8.4 Edaphic properties

No significant correlations were observed between the predicted N mineralisation rates and soil textural properties. Sites A and B had the lowest organic C contents, with values of 1.6 and 1.2% respectively, and the remaining sites ranged from 2.3 to 3.1%; however, no significant relationships were observed between the predicted mineralisation rates and the organic C contents. The annual predicted N mineralisation rates (final rate) increased at sites with higher bulk densities ($r = 0.848$; $p = 0.036$; $R^2 = 0.627$). In addition, a significant positive correlation

($r = 0.963$; $p < 0.001$; $R^2 = 0.570$) was observed between the soil pH and the annual N mineralisation rate (final rate) predicted by the SNAP model for each site. The highest and lowest soil pH values were observed for field trials A and B, with values of 4.0 and 3.3 respectively (Figure 5.14). The annual predicted N mineralisation rates were larger in less acidic soil conditions.

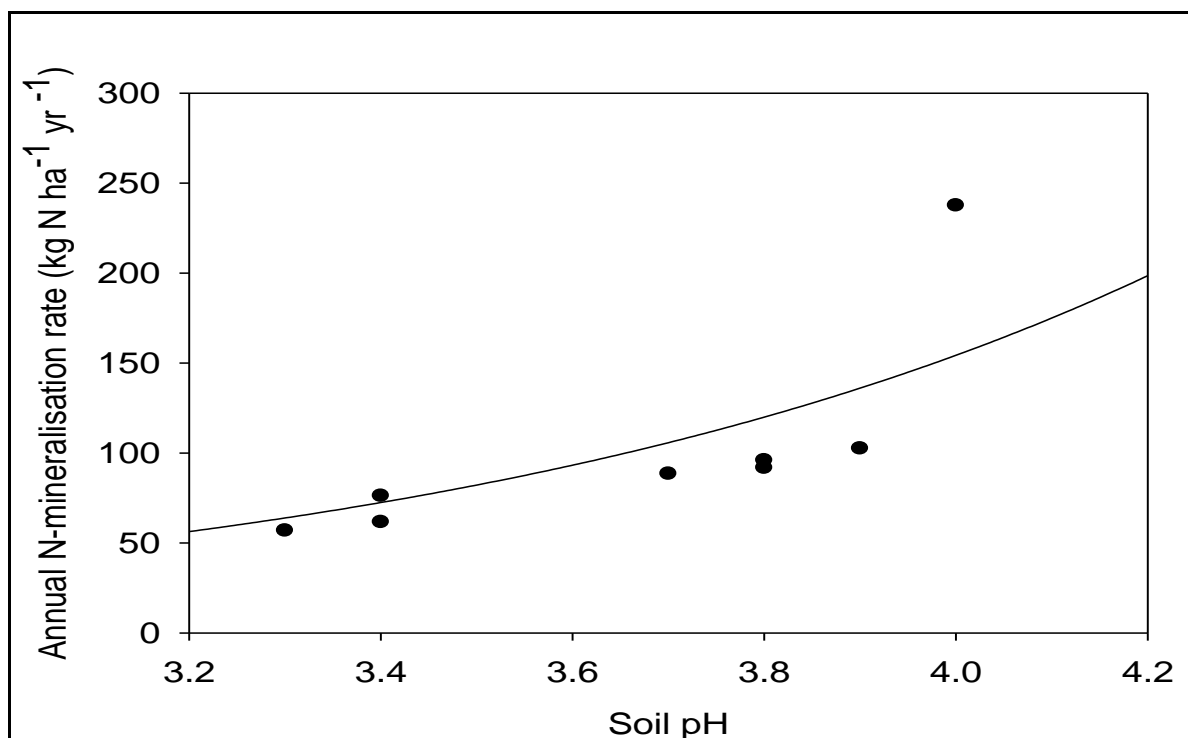


Figure 5.14: Correlation between soil pH and predicted annual N mineralisation rate (final rate).

5.8.5 Soil water availability and volume increment

Site F had the highest water deficit, which meant the site retained the least amount of water, with a cumulative deficit of 78 mm over 24 months. Sites D and G had smaller water deficits (better water-retention capabilities) over the experimental period and accumulated total deficits of 37 and 52 mm respectively. The largest monthly deficit of 17 mm was observed on site F, relative to the other sites. The deficits observed on sites D and G were similar to the cumulative deficits of the remaining sites, apart from sites A and B, which had significantly smaller total deficits. In ascending order, sites A, B, H, C and E had cumulative deficits of 10, 27, 38, 41 and 44 mm respectively. It was demonstrated earlier (Table 4.9) that the water deficit value for seasonally dry plantation forestry sites may exceed 300 mm in the Boland region (Mediterranean-type climate). Similar values have been presented by Gonçalves *et al.* (2017) for dry eucalypt forests in Brazil. We can therefore state that the cumulative soil water deficits

over the experimental period in the Tsitsikamma region showed that soil water availability is not a major constraint in plantation forestry.

A significant correlation ($r = 0.724$; $p = 0.042$) was observed between the volume increment for the most responsive treatment, T4 or T5 (minus T2), at 24 months after fertilisation and the average annual water deficit of each field trial over the experimental period (Figure 5.15). Field trials with lower water-retention capabilities were more responsive to N fertilisation in the presence of P.

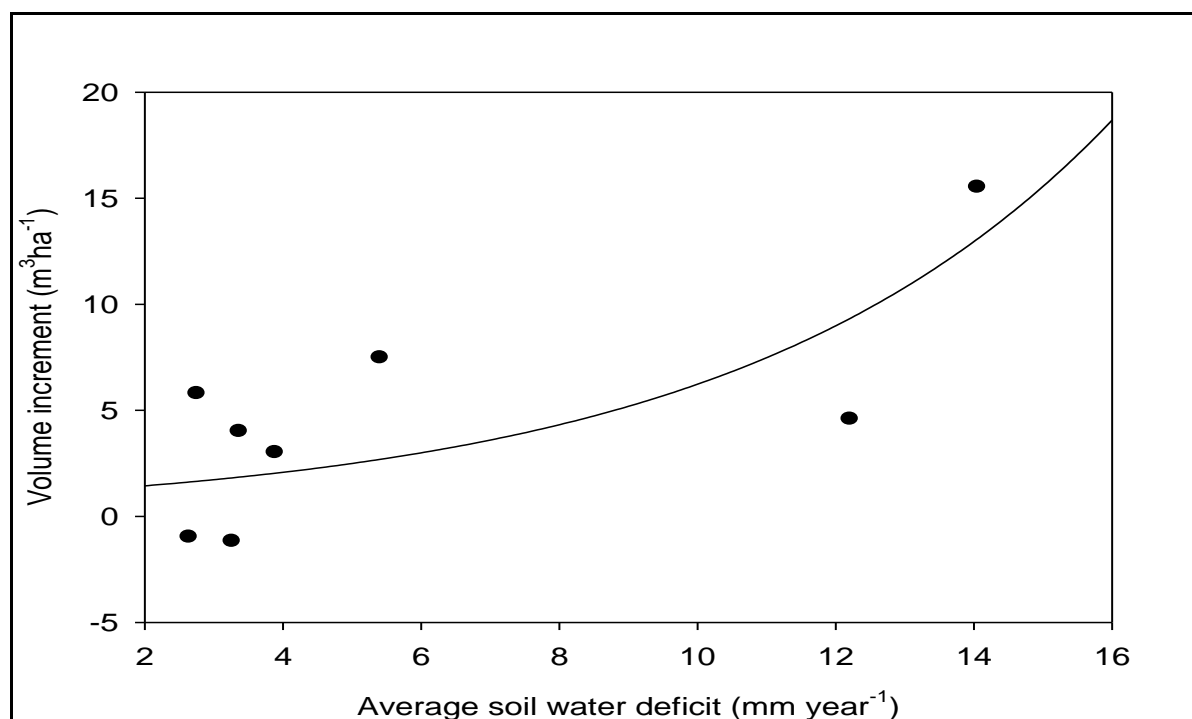


Figure 5.15: Soil water deficits for the most responsive trial sites and monthly precipitation of both plantations.

5.9 Discussion

The predicted annual soil N mineralisation rates reported in this study ranged from 28.75 to 49.73 and 57.04 to 102.78 among most sites, apart from trial site A, with predicted rates of 148.88 and 237.66 kg N ha⁻¹ year⁻¹. However, the rates were well in range of the values reported by similar studies, viz. 20 ± 1.00 kg ha⁻¹ year⁻¹ by Arslan et al. (2010), 23.6 kg ha⁻¹ year⁻¹ by Pajuste and Frey (2003) and 75 kg ha⁻¹ year⁻¹ by Lee and Jose (2006). The measured net mineralised NH_4^+ concentrations ranged from 0.63 to 1.33 and 1.22 to 1.96, and these values were well in the range of the values reported by Raath and Saayman (1995) for soils under different management practices in the Western Cape, South Africa. Trial site A had a larger

sand content and higher undisturbed bulk density. The higher sand content could likely have affected the annual N mineralisation rate observed in this field trial. Pulito *et al.* (2015) observed the highest N mineralisation rates during the early ages of Eucalyptus stand growth in sandy soils. These authors studied oxisols and quartzipsamments with organic matter and clay contents in the range of 18 to 55 g kg⁻¹ and 8 to 67% respectively. Site B had similar edaphic properties to site A, but both sites were located at very different landscape positionings, and the incidence of competing vegetation was apparent. It is well known that fertiliser can increase N mineralisation and availability in a soil for several years (Fox, Allen, Albaugh, Rubilar & Carlson, 2007; Ramírez Alzate *et al.*, 2016), but contrasting findings have also been reported in pine (Lee & Jose, 2006). Ramírez Alzate *et al.* (2016) observed increased N mineralisation rates up to six years after fertilisation in sandy soil and seven years in a granitic soil with a larger clay and silt content. However, the significantly larger mineralisation rates of site A were likely due to the lateral movement of water, due to the location of the site, and the edaphic site properties. Field trial A had the highest soil pH and this most likely contributed to the large annual N mineralisation rate in this field trial. A higher soil pH can increase the efficiency of N mineralisation and the accumulation of NH_4^+ (Anderson, Peterson & Curtin, 2017; Sapek, 1996; Zhang *et al.*, 2017), and microbial soil populations are more responsive at larger soil pH values (Bottomley, Taylor & Myrold, 2012; Date, Grundon, Rayment & Probert, 2012; Zwoliński, 2004). Le Roux and Du Preez (2006) showed that there is a strong association between topography, landscape positioning and the soil water-retention capability of a soil, and soil water content has a considerable influence on SNAP model predictions (Smethurst *et al.*, 2015). Microbial activity is higher under moist soil conditions, and this can increase N mineralisation rates and processes that might lead to N immobilisation (Paul *et al.*, 2003). Site B was positioned on a coastal cliff top on a shallow plinthic soil. Plinthite development in wet, periodically flooded soils can induce anoxic soil conditions that adversely affect root penetration (Fey, 2010), and higher denitrification rates are typical of waterlogged soil conditions (Hamonts *et al.*, 2013; Sirivedhin & Gray, 2006). Field trials E, F and G had larger silt and organic carbon contents; however, the soils were shallow and this contributed to the smaller soil water-retention capacities of these sites.

All field trials responded to fertilisation, with different degrees of responsiveness over each six-month interval. A study by Carlyle (1998) reported positive growth responses and significant treatment differences following the fertilisation of an 11-year old semi-mature *P. radiata* stand. The growth increments observed in the current study were at a time of severe

droughts in the region and this revealed the moderate resilience of *P. elliottii* and *P. elliottii x caribaea* to reduced water availability and stress. Ward *et al.* (2015) examined the effect of nutrient and water availability on stem volume and several canopy factors in semi-mature *P. taeda* stands. Fertilisation and a reduction in water throughfall of 30% increased the stem volume increment by 21% and the stand showed large increases in water-use efficiency of stem production, suggesting a minor resilience to short-term water stress; however, rainfall was unusually high for the study period. A similar study by Wightman, Martin, Gonzalez-Benecke, Jokela, Cropper and Ward (2016) found that fertilisation and reductions in water throughfall (30%) of a 10-year-old *P. taeda* stand did not affect stand productivity. They attributed the lack of response to an abundant rainfall and the ability of the trees to access shallow water tables. However, sustained droughts can decrease leaf biomass and stem volume growth (Maggard, Will, Wilson & Meek, 2016b). Pulito *et al.* (2015) observed poor growth responses to N fertilisation in sandy soils with high N mineralisation rates. The larger growth increments and increased responsiveness of sites A, B, D and F to the higher fertilisation rates after 24 months suggests that the afforested sites in this region could face a delayed response after fertilisation. Campoe *et al.* (2013) observed responses two years after a series of fertiliser and irrigation treatments in *P. taeda* stands, and Albaugh *et al.* (1998) reported meaningful results four years after in a similar study in an eight-year-old *P. taeda* stand. Chikumbu (2011) reported significant responses to P fertiliser applications two years after fertilisation in the Boland region, Western Cape. In addition, this project reports on the short-term response of semi-mature pine stands to fertilisation and the emergence of significant responses in these sites to the larger fertilisation rates at 24 months, suggest a time variable. The growth responses of all trial sites, apart from site A, were probably affected by the incidence of under-canopy vegetation. Most sites were covered by an abundance of ferns throughout the experimental period. Fern species are naturally endemic to the Tsitsikamma region and their occurrence is linked to seasonality and water availability. The ferns responded aggressively to the higher fertiliser application rates several months after fertilisation, and could likely have delayed growth responses. The larger response of site B to the highest application rate of 200 kg N ha⁻¹ and 100 kg P ha⁻¹ (T5) after 24 months was likely a product of N uptake and immobilisation by under-canopy weeds and woody vegetation several months after fertilisation. The occurrence of competing under-canopy vegetation can retard stand development in pines (Albaugh *et al.*, 2003; Fortson, Shiver & Shackelford, 1996; Oppenheimer, Shiver & Rheney, 1989), and soil N content is furthermore decreased by the uptake and immobilisation of soil N by the competing vegetation (Richter *et al.*, 2000).

5.10 Conclusions

Fertiliser applications were made to several sites with very different edaphic and growing conditions over a period of unusually low rainfall. The findings of this project re-emphasise the need for detailed site characterisation in forest nutrition-management strategies. Mid-rotation fertilisations in the Tsitsikamma have the potential to increase the volume increment, even when annual precipitation rates are lower than average. The pine plantations in the Tsitsikamma exhibit a degree of resilience to below-average rainfall and drought conditions. This resilience could also be a result of the strong water-retention capabilities of soils from this region; the annual rainfall decreased to less than 50% of normal at times during the experimental period, and the observed monthly soil water deficits were still far less deficient than the observations noted in Chapter 4 for the other main afforested regions in the Western Cape. A significant correlation was observed between the volume response to combined N and P fertiliser applications and the average annual water deficit across all field trials. Field trials with lower water-retention capabilities exhibited increased responsiveness to fertilisation, and this confirms that water is not a limitation to plantation forestry in the Tsitsikamma region. The SNAP model identified a single site that could potentially be less responsive to N fertilisation; however, no significant linear correlation was observed between the volume response to N fertiliser (T4 and T5, minus T2) and the predicted N availability. In addition, no significant correlations were observed between the N mineralisation rates predicted by the SNAP model and the edaphic properties, although soil pH appears to have a significant effect on the N mineralisation potential of sites in the Tsitsikamma region.

CHAPTER 6

ESTIMATES OF N AND P AVAILABILITY AS PREDICTORS OF GROWTH FOR FERTILISED SEMI-MATURE SLASH PINE STANDS IN THE TSITSIKAMMA, SOUTH AFRICA

6.1 Introduction

The biological process of N mineralisation is described as the conversion of organic N by micro-organisms to an organic mineral form that is more readily available to plants (Comerford, McLeod & Skinner, 2002; Stevenson, 1985). Some soils may contain substantial reserves of soil N, but at the same time its availability can be extremely low due to immobilisation by microbial activity or slow mineralisation rates (Mendham, Sankaran, O'Connell & Grove, 2002). The mineralisation rate of organic soil N is affected by the content of soil organic matter (Arslan *et al.*, 2010; Cartes, Jara, Demanet & Mora, 2009; Laclau, Deleporte, Ranger, Bouillet & Kazotti, 2003; Mendham *et al.*, 2002), soil moisture and temperature (Arslan *et al.*, 2010; Khanna & Raison, 2013), thinning and residue retention (Albaugh, Fox, Allen & Rubilar, 2015; Carlyle, 1998), and chemical and physical soil properties (Binkley & Hart, 1989; O'Connell & Rance, 1999; Scott & Bliss, 2012). Fertilisation can affect the cycling and bioavailability of N in a soil, but the magnitude and duration of the effects are not well understood and can vary significantly across different site conditions (Ramírez Alzate *et al.*, 2016). Increases in soil N mineralisation rates have been reported from the fertilisation of semi-mature pine forest (Carlyle, 1995; Raison *et al.*, 1992), and the increases can be attributed to the increased N pools in the soil and forest floor following fertiliser application (Gurlevik, Keltin & Allen, 2004).

The cycling of inorganic P is a combination of sorption and desorption processes in a soil and, together with mineralisation and immobilisation, these processes control the transfer of inorganic soil P between solid and solution phases (Barros, Comerford & Barros, 2005). As in the case of N, P fertiliser applications can increase the P availability in the mineral soil and the effects can last into the second rotation of a pine stand (Comerford *et al.*, 2002; Scott & Bliss, 2012). Parent materials with low mineral P give rise to soils with P deficiencies (Scott & Bliss, 2012), and the sorption and desorption reactions of the soil regulate the inorganic P

bioavailability (Barros *et al.*, 2005). Barros *et al.* (2005) found that the sorption and desorption of P was dependent on the clay content and amount of sorbed labile P in the soil ($r = 0.59$ to 0.99). Soil water availability affects the responsiveness of saw timber stands to fertiliser application (Fisher & Binkley, 2000; Jokela, Harding & Troth., 1988). The presence of sufficient plant-available water in the soil body post-fertilisation can significantly increase the aboveground biomass components in *P. elliotii* and *P. taeda* (Cobb, Will, Daniels & Jacobson, 2008).

Several indices of varying complexity are used to assess soil N availability. Simpler indices, such as total N, and aerobic and anaerobic incubations, are cost effective, less time consuming and have fewer data requirements. Aerobic incubations are considered the standard methodology to estimate the potentially mineralisable soil N (Stanford & Smith, 1972). Aerobic assays can provide the user with an estimate of nitrification in a soil; the methodology is relatively easy and it mimics field conditions. In addition, incubation periods of one month primarily assess the partial turnover of the soil microbial biomass and labile soil organic matter pools. The incubation period significantly affects the available N estimate, and soils with high nitrification capabilities may exhibit large accumulations of NO_3^- when the incubation period is extended. The use of field-moist samples may produce better estimates of mineralisation; however, the estimates may show larger variabilities (Binkley & Hart, 1989).

Anaerobic incubations address the shortcomings related to aerobic incubations, viz. maintaining a constant soil water content during incubation and the accumulation of NO_3^- . The existing NO_3^- is denitrified and no new NO_3^- is formed during incubation (Binkley & Hart, 1989). Several studies suggest that nitrification is indeed beneficial for tree nutrition, thus the use of anaerobic incubations may be limited if sites with high nitrification variabilities (where nitrification is of importance) are compared (Binkley & Hart, 1989). The formation of NH_4^+ during anaerobic incubations is driven by soil microbial biomass. The need for the inclusion of initial NH_4^+ in this method to estimate mineralisable N following anaerobic incubations remains uncertain. Yagi, Ferreira, Da Cruz & Barbosa (2009) found that the subtraction of the initial NH_4^+ did not improve the N mineralisation estimate and, in contrast to their findings, Mariano *et al.* (2013) observed improved reliability by including the initial NH_4^+ as an estimate of mineralisable N after anaerobic incubations.

The soil nitrogen availability predictor (SNAP) model (see Chapter 5) combines a basal N mineralisation rate with daily temperature and water content modifiers to estimate plant-available N (Paul *et al.*, 2002). It additionally requires several datasets and stand factors that

might not be easy to acquire. This model has proven to predict accurate annual and seasonal N mineralisation rates across different climatic and edaphic growing conditions (Paul *et al.*, 2002; Smethurst *et al.*, 2015). The growth responses following the fertilisation of semi-mature pine stands can be highly site specific (Albaugh *et al.* 2003; Champion & Du Toit, 2003; Carlson *et al.*, 2014; Donald, 1987; Fox *et al.*, 2007; Jokela *et al.*, 1988; Morris, 1995). This variability directly affects the costliness of fertilisation and the return of investment at harvesting age (Donald, 1987; Martin *et al.*, 1991). This chapter of the study investigates whether a relationship exists between the elicited growth responses following the fertilisation of several semi-mature slash pine stands and a number of different estimates of N and P availability in pine stands in the Tsitsikamma: The estimates range from simple edaphic properties, through incubation techniques as well as complex modelled predictors. The prospect of potentially significant correlations could significantly contribute to a better understanding and a possible refinement of the existing fertiliser regimes in the Cape Forest Region.

6.2 Research Questions

- Are there significant correlations between the documented fertiliser responses and the aerobically incubated (N and P mineralisation rates), anaerobically incubated N mineralisation rates and the daily predicted basal N mineralisation rate of the SNAP model, after being modified by the soil temperature and water modifiers?
 - Does the inclusion of the initial NH_4^+ measurement (anaerobic) affect the significance of the observed correlations, if any?
- Can estimates of N availability be used to identify sites that would be most responsive to fertilisation?
 - Which index of N availability is better suited to identify sites that could potentially be most responsive to fertilisation?

6.3 Materials and Methods

6.3.1 Incubation procedures

Aerobic incubation procedures are described in Section 5.4. Anaerobic N mineralisation rates were determined according to the methodology of Bloem, Hopkins and Benedetti (2006). The methodology was based on the amount of N mineralised in waterlogged soil conditions for seven days at 40°C, and the accumulated NH_4^+ was analysed as the available N. Incubations were done per replication for each field study, and an average value was used as the index for

available N. Forty millilitres of distilled water, together with 16 g of soil from each replication, was transferred into incubation tubes and replicated three more times. Soil samples were shaken until fully suspended and placed in the incubator. The initial NH_4^+ concentration was obtained by adding 40 ml KCl (4 M) to the 300 ml Erlenmeyer flask, shaking the solution for an hour, followed by filtration and analysis. The incubated samples were re-suspended daily throughout incubation and, after seven days, each solution was transferred from the incubation tube into a 300 ml Erlenmeyer flask. The tubes were washed with 10 ml 4 M KCl solution at transference, and this was repeated three more times to acquire 40 ml of the 4 M KCl solution and to ensure that no soil particles remained in the tubes. Each Erlenmeyer flask was mechanically shaken for an hour and filtered through no. 42 Whatman filter paper into a 100 ml plastic bottle. The filtrate was filtered until a clear solution was obtained, which was analysed for NH_4^+ . To verify whether anaerobic conditions occurred, the presence of nitrate and nitrite was assessed during the initial extraction, and only trace amounts of NO_3^- and NO_2^- were observed. Ammonium (NH_4^+) and NO_3^- concentrations were determined by means of an auto-analyser and the percentages of uncertainty were 1.33 and 0.89% respectively. Initial NH_4^+ was both included and excluded (subtracted and not subtracted) from the final value to estimate the total mineralisable N after the incubation period. A similar study was done by Yagi *et al.* (2009).

The P extraction procedures published by Olsen and Dean (1965) were used to determine the extractable soil phosphorous. The freshly collected samples were stored at field-moist conditions prior to analysis, then sieved (2 mm), wetted and allowed to drain for 48 hours prior to incubation to ensure field capacity. Twenty-five grams of soil for each replication per field study was placed in a wide-mouthed container, weighed and sealed with a lid. Several holes were drilled into each lid for aeration. Samples were incubated at 39°C for four weeks (Parfitt *et al.*, 1994) and water loss was gravimetrically monitored daily to ensure soils remained at field capacity during incubation. Distilled water was added if required. The initial and final extractions were done by adding 50 ml of distilled water to oven-dried sub-samples of 5 g. The samples were then mechanically shaken for five minutes at 60 rpm, followed by centrifuging at 26 000 g for 25 min. This was done to obtain a solution free of mineral particles. The extracts were furthermore filtered through no. 42 Whatman filter paper until clear solutions were obtained. The filtrate of each sample was then analysed for phosphorous using inductively coupled plasma-electron spectroscopy (ICP-ES).

6.3.2 Available soil water and SNAP model

Cumulative and monthly soil water deficits and the respective predicted N mineralisation rates were acquired from Chapter 5. The daily basal rates referred to in this chapter are the predicted N mineralisation rates of the SNAP model. The aerobic N mineralisation rate (obtained by means of the aerobic laboratory incubation) is modified by the SNAP model by incorporating the site-specific soil water content and soil temperatures.

6.3.3 Stand volume growth

Stand volume growth was determined according to the methodology outlined in Chapter 3, Section 3.5.5.

6.3.4 Interpretation

Soil nitrogen, carbon and textural properties were correlated with the aerobic (N and P) and anaerobic (N) assays, the predicted basal mineralisation rates of the SNAP model and, at the same time, the mineralisation rates were correlated with the growth rate per field trial. The Pearson correlation was used to test for significant relationships at a confidence level of 95%, unless stated differently. Stand volume increments were separated into six groups (Table 6.16) that are described here: 1) The response of T4, minus the response to treatment T2. 2) The response of T5, minus the response to treatment T2; the rationale for selecting volume response estimates 1 and 2 was to investigate whether the growth effect of increasing N applications in the presence of 100 kg P ha⁻¹ can be linked to different N and P mineralisation indices. 3) The response of T3, minus the response to treatment T1; this group was selected to investigate whether the growth effect of increasing N applications, in the presence of 50 kg P ha⁻¹, can be correlated with different indices of N and P. 4) The response of T1, minus the response to treatment T0. 5) The response of T2, minus the response to treatment T0; the rationale for selecting volume estimates 4 and 5 was to investigate whether the growth effect of increasing P applications, in the absence of N, can be linked to different indices of N and P. 6) The response of the control treatment from time of establishment, up to 24 months after treatment; the rationale for this value was to see if the inherent growth rate of a site (in the absence of fertilisation) is linked to N mineralisation indices. The volume responses of volume response estimates 1 to 5 were standardised as a percentage of the response to the control treatment and expressed as a percentage.

6.4 Results

6.4.1 Volume response estimates

The six groups into which the stand volume increments were separated are illustrated in the table below.

Table 6.16: Different volume response estimates correlated with the N and P mineralisation rates.

Site	Replication	Volume 1	Volume 2	Volume 3	Volume 4	Volume 5	Volume 6
				%			m ³ ha ⁻¹
A	1	2.88	3.52	7.22	-6.46	-3.10	19.79
	2	-20.78	15.26	11.09	17.02	15.76	19.71
B	1	36.64	51.87	-4.33	-38.97	-39.70	45.19
	2	18.30	33.87	22.73	-21.34	-20.88	34.94
C	1	-31.63	-3.24	-3.03	10.33	10.33	36.20
	2	3.06	-0.52	37.47	-43.12	-0.36	35.42
D	1	0.20	-10.88	-11.89	12.91	27.33	52.61
	2	7.45	-45.23	-73.01	-9.37	-3.67	52.99
E	1	17.51	-15.12	1.26	-28.84	-28.84	40.76
	2	-13.58	-6.83	10.75	-7.86	18.41	41.49
F	1	-16.30	6.35	16.14	-1.06	7.55	41.94
	2	25.43	26.69	-4.74	13.28	-11.53	45.53
G	1	-17.77	-89.98	-43.18	38.39	39.31	35.20
	2	25.05	-19.66	-29.55	9.23	-0.32	36.74
H	1	27.61	10.40	20.76	-10.52	-15.37	35.92
	2	9.07	16.36	9.16	1.66	-1.58	24.49

*Volume response estimate 1: The response of T4, minus the response to treatment T2.

*Volume response estimate 2: The response of T5, minus the response to treatment T2.

*Volume response estimate 3: The response of T3, minus the response to treatment T1.

*Volume response estimate 4: The response of T1, minus the response to treatment T0.

*Volume response estimate 5: The response of T2, minus the response to treatment T0.

*Volume response estimate 6: The response of the control treatment from time of establishment up to 24 months after treatment.

6.4.2 Correlation variables

The bulk densities of all field trials ranged from 0.95 to 1.50 g cm⁻³, and field trials A and B had the highest bulk densities, in the range of 1.32 to 1.50 g cm⁻³. In addition, both sites contained the smallest organic carbon contents of 0.89 to 1.66%. Field trials A and B contained slightly smaller silt and larger sand contents (Table 6.17), which explains the slightly higher bulk densities. The aerobically incubated N concentrations ranged from 1.16 to 2.05 mg N kg⁻¹ month⁻¹. In addition, extractable P concentrations ranged from 0.02 to 0.98 mg P kg⁻¹ month⁻¹, with the highest concentrations observed in field trial G (refer to Table 6.17). The anaerobically incubated N concentrations were significantly larger when the N pool before incubation was not subtracted from the final N pool. The NH_4^+ concentrations ranged from 2.76 ± 1.35 to 7.95 ± 0.43 mg N kg⁻¹ week⁻¹, with the highest concentration observed in field trial H. When the N pool before incubation was subtracted from the final pool, the N concentrations ranged from 1.19 ± 0.67 to 3.66 ± 0.08 mg N kg⁻¹ week⁻¹, with the highest value observed in field trial G. The daily basal N mineralisation rates calculated by the SNAP model ranged from 1.44 to 3.69 mg N kg⁻¹ day⁻¹. The model calculated the highest rate for field trial C (Table 6.17).

Table 6.17: Soil C, textural properties, N and P mineralisation rates for each replication (mean \pm standard deviation)

Site	Replication	Undisturbed bulk density	Soil (pH)	C	Clay	Silt	Sand	Total N	Aerobically mineralised P (P_{aer})	Aerobically mineralised N (N_{aer})	SNAP - Daily Basal N mineralisation rate	Anaerobically mineralised N (N_{an})	Anaerobically mineralised N: NH_4^+ before incubation subtracted from final NH_4^+ pool (N_{an})
		g cm ⁻³	%.....					mg P kg ⁻¹ month ⁻¹	mg N kg ⁻¹ month ⁻¹	mg N kg ⁻¹ day ⁻¹		mg N kg ⁻¹ week ⁻¹
A	1	1.36	4.0	1.46	14	22	64	0.03	0.08	1.76	3.10	4.49 \pm 1.90	2.85 \pm 1.90
	2	1.50	3.9	1.66	14	20	66	0.04	0.08	1.71	3.01	3.91 \pm 0.56	2.10 \pm 0.56
B	1	1.48	3.8	0.89	12	12	76	0.04	0.37	1.61	1.72	3.40 \pm 0.67	1.19 \pm 0.67
	2	1.32	3.9	1.40	12	14	74	0.03	0.34	1.36	1.45	2.76 \pm 1.35	1.38 \pm 1.35
C	1	1.13	3.7	2.46	18	38	44	0.07	0.03	2.05	3.69	4.24 \pm 0.28	2.57 \pm 0.28
	2	1.10	3.8	2.67	22	40	38	0.07	0.02	1.86	3.35	3.64 \pm 1.78	1.76 \pm 1.78
D	1	1.32	3.7	2.06	18	40	42	0.11	0.35	1.16	1.49	3.80 \pm 0.22	1.85 \pm 0.22
	2	1.28	3.8	2.50	18	38	44	0.05	0.35	1.27	1.64	4.57 \pm 0.22	2.04 \pm 0.22
E	1	1.18	3.5	2.33	16	42	42	0.05	0.24	1.31	2.04	4.05 \pm 0.57	2.56 \pm 0.57
	2	1.10	3.9	3.01	20	28	52	0.08	0.20	1.36	2.12	5.14 \pm 0.58	2.79 \pm 0.58
F	1	1.06	3.2	2.45	18	40	42	0.04	0.03	1.50	2.47	4.67 \pm 0.63	2.47 \pm 0.63
	2	1.23	3.5	2.77	18	40	42	0.04	0.04	1.33	2.19	3.65 \pm 0.63	1.83 \pm 0.63
G	1	0.96	2.9	3.36	16	46	38	0.13	0.98	1.22	1.44	5.37 \pm 0.08	3.66 \pm 0.08
	2	1.01	3.8	2.76	16	42	42	0.10	0.91	1.32	1.55	4.92 \pm 0.83	3.13 \pm 0.83
H	1	0.95	3.2	2.58	20	40	40	0.05	0.05	1.23	1.53	4.13 \pm 1.49	1.34 \pm 1.49
	2	1.18	3.3	2.53	18	40	42	0.09	0.05	1.31	1.63	7.95 \pm 0.43	3.00 \pm 0.43

6.4.3 Correlations

6.4.3.1 Edaphic properties and mineralisation rates

Significant correlations were observed between total N and the undisturbed bulk density ($r = -0.495$; $p = 0.051$), organic C ($r = 0.610$; $p = 0.012$), silt ($r = 0.579$; $p = 0.019$) and sand ($r = -0.556$; $p = 0.025$) contents. These correlations meant that total soil N contents were smaller at sites with higher undisturbed bulk densities and sand contents. Additionally, higher total N contents were observed at sites with increased organic C and silt contents. The undisturbed bulk density and N mineralised under anaerobic incubation conditions (after the subtraction of NH_4^+ before incubation from the final NH_4^+) correlated weakly and negatively ($r = -0.434$; $p = 0.093$) (Table 6.18). Nitrogen mineralisation rates were lower on sites with higher bulk densities. Soil carbon content correlated positively with both the anaerobic N rates when NH_4^+ before incubation was subtracted ($r = 0.552$; $p = 0.027$), but less clearly when it was not subtracted from the final NH_4^+ pool ($r = 0.459$; $p = 0.074$). The silt content of the soil correlated positively ($r = 0.447$; $p = 0.083$) with the N mineralised anaerobically (including the initial NH_4^+ concentration) at a slightly weak confidence level of 90%. Increasing amounts of N were mineralised at sites with larger silt contents.

Total soil N correlated ($r = 0.491$; $p = 0.054$) with the anaerobic N mineralisation rate (when the NH_4^+ after incubation was not subtracted from the final pool); however, stronger correlations were observed between the anaerobic N (including the initial NH_4^+ concentration) and aerobic P concentrations, with correlation coefficients and p -values of $r = 0.578$ and $p = 0.019$ and $r = 0.610$ and $p = 0.012$ respectively (Table 6.18). Higher total soil N contents were found at sites with higher anaerobic N and aerobic P mineralisation rates. Phosphorous availability was less in soils with higher aerobic N mineralisation rates ($r = -0.445$), although at a slightly weaker confidence level of 90% ($p = 0.084$). The aerobically mineralised N correlated strongly with the basal rate predicted by the SNAP model ($r = 0.915$; $p < 0.001$), which meant the N mineralisation rate predicted by the SNAP model (refer to Section 6.1.2 for a definition of the basal rate) increased linearly with the N mineralised under aerobic incubation conditions (which was to be expected). The N mineralised under anaerobic incubation conditions, after subtracting the NH_4^+ before incubation, correlated positively with N concentrations when the NH_4^+ before incubation was not subtracted ($r = 0.692$; $p = 0.003$). The daily N mineralisation rates predicted by the SNAP model decreased with increasing P availability under aerobic incubation conditions ($r = -0.568$; $p = 0.022$).

Table 6.18: Pearson correlation coefficients and p -values between the soil properties and indices of N and P mineralised under aerobic incubations, anaerobic incubations (N) and the predicted SNAP model rates.

	Total N (%)	N _{aer} (mg N kg ⁻¹ month ⁻¹)	N _{an} (mg N kg ⁻¹ week ⁻¹)	N _{an} : subtraction of NH ₄ ⁺ before incubation from final NH ₄ ⁺ pool after incubation (mg N kg ⁻¹ week ⁻¹)	P _{aer} (mg P kg ⁻¹ month ⁻¹)	SNAP basal rate (mg N ha ⁻¹ day ⁻¹)
BD (g cm ⁻³)	-0.495 0.051+	0.254 0.343	-0.354 0.179	-0.434 0.093+	-0.252 0.346	0.141 0.603
Soil pH	-0.378 0.149	0.420 0.105	-0.417 0.108	-0.301 0.257	-0.176 0.514	0.339 0.199
C (%)	0.610 0.012*	-0.315 0.235	0.459 0.074+	0.552 0.027*	0.234 0.384	-0.0877 0.747
Clay (%)	0.330 0.211	-0.0452 0.868	0.273 0.307	0.0819 0.763	-0.311 0.241	0.185 0.492
Silt (%)	0.579 0.019*	-0.319 0.228	0.411 0.113	0.447 0.083+	0.164 0.544	-0.092 0.734
Sand (%)	-0.556 0.025*	0.277 0.299	-0.403 0.121	-0.392 0.134	-0.070 0.734	0.040 0.892

+ denotes $p \leq 0.100$; * denotes $p \leq 0.05$

6.4.3.2 Relationship between stand volume increments and mineralisation rates

A strong linear correlation was observed between total soil N and volume response estimates 2 ($r = -0.656$; $p = 0.004$), 4 ($r = 0.508$; $p = 0.045$) and 5 ($r = 0.673$; $p = 0.004$). The significant negative correlation with volume estimate 2 showed that the volume responses to higher N application rates, in the presence of P, were smaller at sites with higher total N contents. In addition, the positive correlation of volume estimates 4 and 5 showed that the responsiveness of sites treated purely with P increased at sites with higher total N contents. The anaerobic N estimate (after subtracting the NH₄⁺ before incubation from final NH₄⁺ pool after incubation) correlated negatively with volume response estimates 1 ($r = -0.482$; $p = 0.059$) and 2 ($r = -0.660$; $p = 0.005$). The significantly stronger negative correlation with volume estimate 2 showed that sites with higher anaerobic N values were less responsive to higher N application rates in the presence of P. The opposite was observed for volume estimates 4 ($r = 0.569$; $p = 0.022$) and 5 ($r = 0.574$; $p = 0.020$); the responses to P applications were larger at sites with

higher anaerobic N values. The aerobic P estimate correlated negatively with volume response estimates 2 ($r = -0.605$; $p = 0.013$) and 3 ($r = -0.635$; $p = 0.008$). The negative correlation with volume response estimate 2 showed that sites were less responsive to the highest N applications, in the presence of P, at sites with high aerobic P estimates. Similarly, the response to 100 kg N ha^{-1} , in the presence of 50 kg P ha^{-1} , decreased at sites with higher aerobic P estimates. The correlations observed between the total soil N, anaerobic N estimate and the responses of volume estimates 2 and 5 are graphically illustrated in Figures 6.16 ($R^2 = 0.4301$), 6.17 ($R^2 = 0.4817$), 6.18 ($R^2 = 0.2853$) and 6.19 ($R^2 = 0.4356$). The Pearson correlation showed a significant linear relationship between the aerobic P estimates and volume estimates 2 and 3, although the data showed a large degree of variation with poor best-fitting lines.

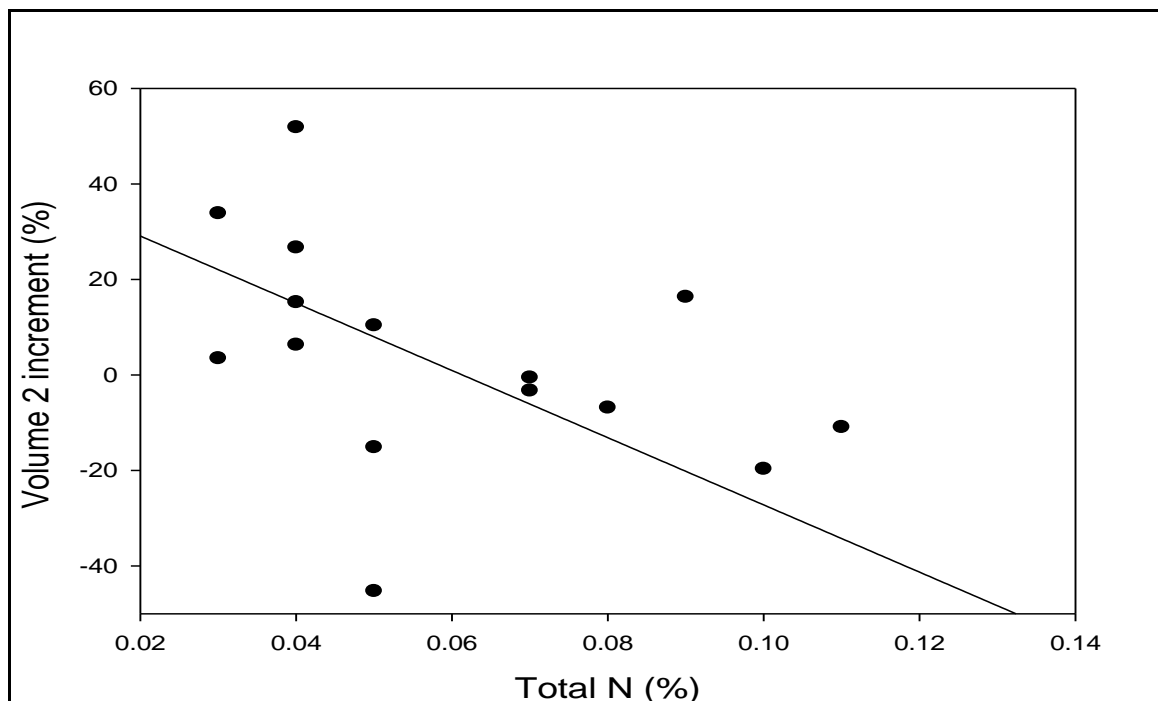


Figure 6.16: Relationship between total N and the response to treatment T5 minus T2 (volume estimate 2) at 24 months after treatment.

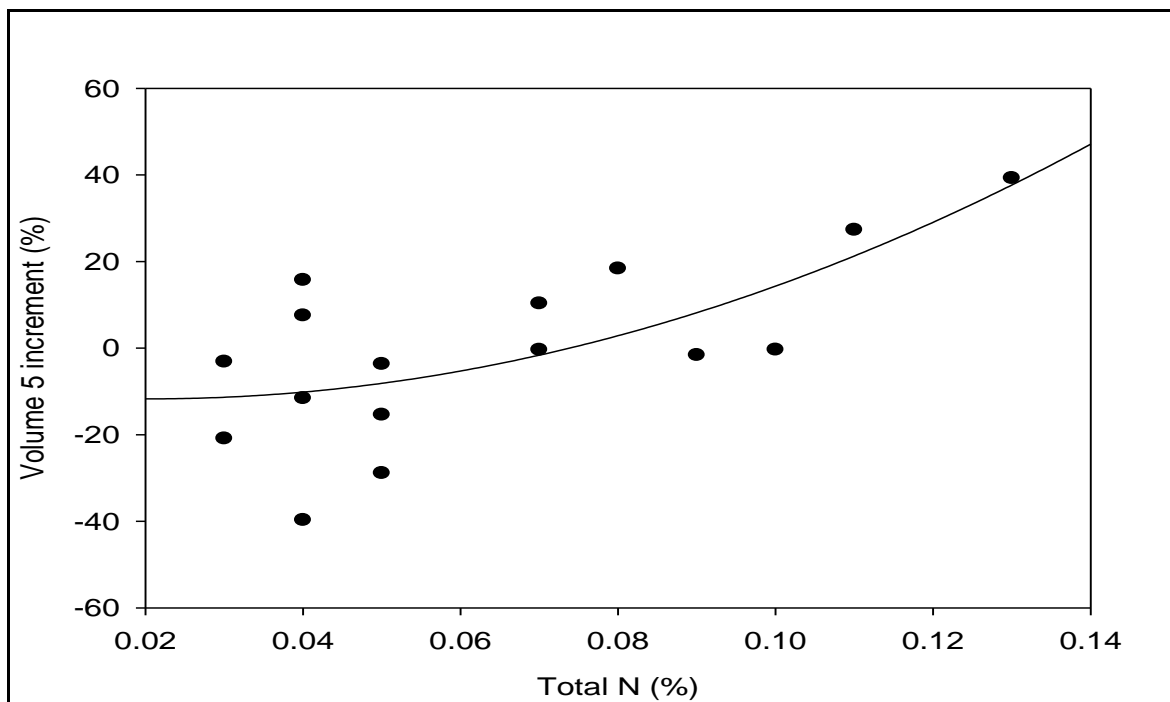


Figure 6.17: Relationship between total N and the response to treatment T2 minus T0 (volume estimate 5) at 24 months after treatment.

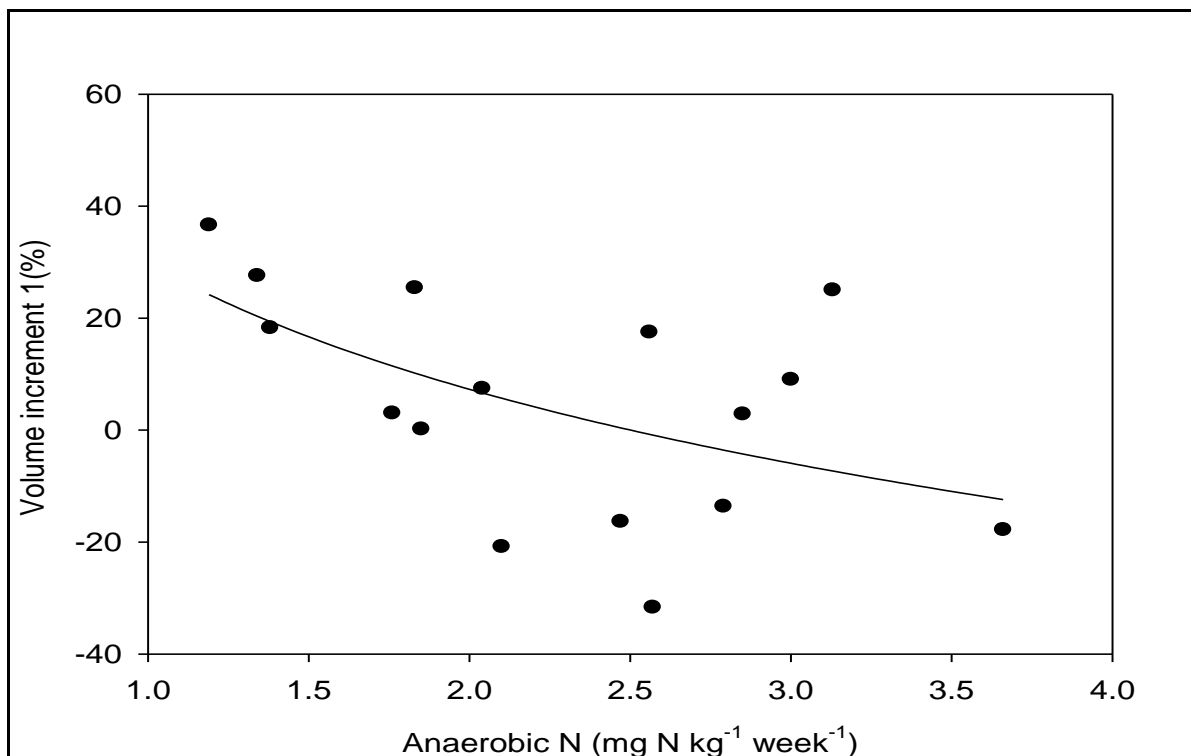


Figure 6.18: Relationship between anaerobic N and the response of treatment T4 minus T2 (volume response estimate 2) at 24 months after treatment.

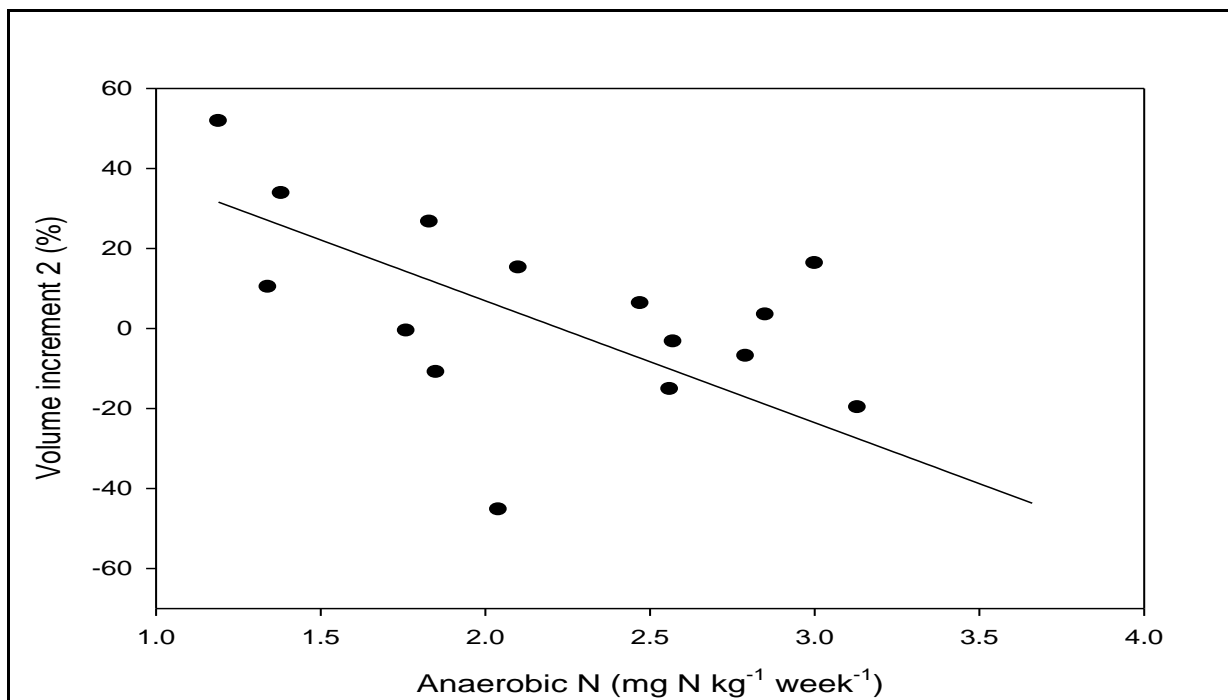


Figure 6.19: Relationship between anaerobic N and the response of treatment T5 minus T2 (volume response estimate 2) at 24 months after treatment.

Table 6.19: Pearson correlation coefficients (top entries in each row) and p -values (bottom entries in each row) between the volume increments and indices of N and P mineralised under aerobic incubations, anaerobic incubations (N) and the predicted SNAP model rates.

	N_{aer}	N_{an}	N_{an} : including initial NH_4^+	P_{aer}	SNAP basal rate	Volume 1 (%)	Volume 2 (%)	Volume 3 (%)	Volume 4 (%)	Volume 5 (%)	Volume 6 ($\text{m}^3 \text{ha}^{-1}$)
Total N (%)	-0.339	0.491	0.578	0.610	-0.310	-0.267	-0.656	-0.367	0.508	0.673	0.136
	0.199	0.054+	0.019*	0.012*	0.243	0.318	0.006*	0.162	0.045*	0.004*	0.616
N_{aer} ($\text{mg N kg}^{-1} \text{month}^{-1}$)		-0.225	-0.064	-0.445	0.915	-0.404	0.298	0.383	-0.232	-0.047	-0.420
		0.402	0.813	0.084+	<0.001*	0.121	0.262	0.143	0.387	0.864	0.106
N_{an} ($\text{mg N kg}^{-1} \text{week}^{-1}$)			0.692	0.082	-0.170	-0.209	-0.307	-0.180	0.354	0.334	-0.306
			0.003*	0.763	0.530	0.438	0.248	0.505	0.179	0.207	0.249
N_{an} : including initial NH_4^+ ($\text{mg N kg}^{-1} \text{week}^{-1}$)				0.423	0.054	-0.482	-0.660	-0.337	0.569	0.574	-0.306
				1.103	0.843	0.059+	0.005*	0.202	0.022*	0.020*	0.249
P_{aer} ($\text{mg P kg}^{-1} \text{month}^{-1}$)					-0.568	0.117	-0.605	-0.635	0.351	0.255	0.190
					0.022*	0.666	0.013*	0.008*	0.182	0.340	0.481
SNAP basal rate ($\text{mg N ha}^{-1} \text{day}^{-1}$)						-0.543	0.165	0.400	-0.094	0.125	-0.404
						0.030*	0.542	0.125	0.730	0.644	0.120

+ denotes $p \leq 0.100$; * denotes $p \leq 0.05$

6.5 Discussion

6.5.1 Growth responses

The measured (N and P) and annual predicted mineralisation rates of the SNAP model were well in range of the findings of Harrison and Maynard (2014) and Lee and Jose (2006). Harrison and Maynard (2014) reported similar N mineralisation rates, of 1.6 and 1.7 mg kg⁻¹, after pine forest soils were incubated for 12 weeks. The pine forest soils were loamy texture and classified as orthic humo-ferric podzols. Lee and Jose (2006) reported annual N mineralisation rates of 75 kg N ha⁻¹ year⁻¹ for a seven-year-old *P. taeda* stand grown on a sandy loam soil in the 0 to 10 cm soil layer (Chapter 5). Pulito *et al.* (2015) reported annual N mineralisation rates of 100 to 200 kg ha⁻¹ year⁻¹ for oxisols and quartzipsamments in *Eucalyptus* stands with different clay and organic matter contents in the 0 to 20 cm layer.

It is important to note that N additions to softwood plantations in the Cape forest regions generally do not respond to fertilisation alone; they require supplementary P to illicit a response (Chikumbu, 2011; Donald, 1987; Payn *et al.*, 1988). The increments of volume estimates 1 and 2 at 24 months after fertilisation were significantly affected by the anaerobically mineralisable N. Sites with larger inherent N mineralisation rates responded less to N fertilisation in the presence of P (Figures 6.18 and 6.19). Pulito *et al.* (2015) similarly attributed the slow initial responses of two *Eucalyptus* species to the inherently high mineralisation rate of the sandy soils investigated in their study. The daily basal N rate of the SNAP model correlated negatively and weakly with volume response estimate 1 at 24 months after fertilisation. The strong negative correlation of the aerobic P estimate with volume response estimates 2 and 3, together with the aforementioned findings, is indicative that an accompanying and optimally balanced P source is essential on some sites for the fertilisation of pine stands in the Cape forest region. With regard to treatments T2, T4 and T5, the highest responses were observed for treatments T4 and T5 across most field trials (Table 5.14), apart from field trials E and G. The highest responses were observed for treatment T2 at both these sites. In addition, the annual mineralisable N predicted by the SNAP model in Chapter 5 identified a single site with a higher N mineralisation rate, and this site was least responsive to fertilisation with N (Figure 5.13). This finding, together with the significant relationship of the anaerobic estimate of N with the response of volume estimates 1 and 2, suggests that the addition of larger quantities of P (together with a N source) is essential for positive growth responses in the pine-afforested regions of the Cape forest region.

The strong negative correlation observed between the total N estimate and volume response estimate 2 showed that sites with higher total N contents were less responsive to higher fertilisation rates (Figure 6.16). Total N perhaps provides an indication of the accumulation and resultant mineralisation of N in the soil, thus sites with higher total N contents have a sufficient amount of N and the negative response could likely result from an imbalance arising from additional N applications, i.e. treatments T3, T4 and T5. This could possibly also explain the strong positive correlations observed between the total soil N and both anaerobic N mineralisation rates (Table 6.19). These three variables describe the pool of N in the soil, thus soils with a high flux (cycling of N) could have larger N pools. Hart, Binkley and Campbell (1986) reported a significant positive correlation ($r = 0.73$) between the NH_4^+ concentrations and growth responses following the application of N and P fertiliser to five- to 11-year-old *P. taeda* stands. Like those of Hart *et al.* (1986), the findings of Maimone, Morris and Fox (1991) contrast with findings of this study. These authors observed significant positive correlations ($r = 0.81$; $P > 0.0002$) between the available N, determined by means of 30-day aerobic incubations, and the growth responses of a 14-year old *P. taeda* plantation at two years after fertiliser application. The strong negative correlation observed between the aerobically incubated P and the response of volume estimates 2 and 3 shows that increased N applications, in the presence of 50 or 100 kg P ha⁻¹, did not increase the responsiveness to fertilisation. This means that the aerobically incubated P estimate could provide an indication of the flux (cycling) of soil P, and the decreased responsiveness to N fertilisation was likely due to the larger P requirements. The decreased volume responses at sites with larger P mineralisation rates suggest that the natural mineralisation of soil P, plus the addition of a supplementary P source, did satisfy the nutritional demand imposed by the semi-mature trees.

6.5.2 Edaphic properties and N estimates

The N mineralisation rates observed under anaerobic incubation conditions, after the subtraction of the initial NH_4^+ concentrations before incubation, best correlated with several edaphic properties, viz. soil bulk density (undisturbed) and silt content. Smaller N concentrations were observed at sites with higher bulk densities. Field trials A and B had higher bulk densities, and N extractions at both sites were in the higher and lower ranges relative to the remaining sites. However, in this study it was unlikely that soil texture had a significant effect on the N concentrations. Field trials D, G and H had larger organic carbon contents and exhibited lower predicted N mineralisation rates. This contrasts with the findings of Mariano *et al.* (2013), who attributed higher N mineralisation rates to high C:N ratios and lower soil pH

values. Although not tested in this study, it is important to note that the microbial biomass pool (Booth, Stark & Rastetter, 2005) and the C mineralisation rate (Parfitt and Salt, 2001) of a soil can significantly affect the net N mineralisation rate. Both field trials A and B had comparatively small soil water storage capabilities, high sand fractions and small organic C contents. The SNAP model predicted the highest annual N mineralisation rate, of 238 kg N ha⁻¹ yr⁻¹, for field trial A, and this, together with a higher than average soil pH, probably contributed to the low response to added N fertilisation observed in Chapter 5. These findings suggest that N mineralisation rates from different sites are highly soil-specific. Field trial B had similar edaphic properties to trial A. However, it was positioned on a flat coastal cliff top on a shallow soil with a thick and substantial carpet of natural under-canopy vegetation. Both field trials A and B were planted in plinthic soil conditions and had higher sand contents (Table 3.1 and Table 3.3). The soil pH, textural properties, sloped growing conditions (field trial A) and resource competitiveness of the understorey vegetation probably accounted for the stunted growth (Albaugh *et al.*, 2003; Fortson *et al.*, 1996; Schabenberger & Zedaker, 1999) and poor response to fertilisation, described in Chapter 5, at 24 months after fertilisation. Field trial A was partially sloped and located at the base of a mountain, which would suggest significantly increased lateral movement of soil and surface water through the plantation, followed by moisture loss after precipitation events. Take note that the lateral movement of water is not accounted for in the Saxton model, which is used in this study to determine the soil water storage capacity of each site; however, the soil was sampled to a maximum depth of 4 m. In addition, field trial A was established on a plinthic soil and had a moderate organic carbon content of 1.5% (Table 3.2) (Fey, 2010). Nitrogen mineralisation rates can fluctuate due to different environmental factors, such as temperature, initial moisture, soil pH (Pajuste & Frey, 2003), elevation gradients, vegetation types and seasonal changes (Knoepp & Swank., 1998). The remaining sites were naturally waterlogged for several months or more per year. The SNAP model does not incorporate soil carbon content; however, it does include stand inputs such as litter mass, litter depth and the fraction of the soil surface covered by the canopy, weeds, understorey vegetation and litter (Smethurst *et al.*, 2015). Higher quantities of N are mineralised under anaerobic incubations (Keeney, 1982), and no significant correlations were observed between the anaerobic mineralisation rates and the N mineralisation rates predicted by the SNAP model (Table 6.19). The anaerobic N mineralisation rates reported in this study were indicative of the effect of different soil properties on the N mineralisation rates of the studied sites, as these rates correlated significantly with the undisturbed soil bulk density, organic carbon and silt content. No other mineralisation rates correlated with any other soil

properties. Additionally, the anaerobic N estimates were a suitable substitute for the aerobic N estimate required by the SNAP model. The findings of this study agree with the findings of Mariano *et al.* (2013), who found that anaerobic incubations could provide reliable estimates of N mineralisation.

Aerobic estimates of N correlated positively with the predicted mineralisation rates of the SNAP model, and the aerobically incubated N mineralisation rates were used as input in the SNAP model. The aerobic estimates of mineralisable N were significantly smaller relative to the anaerobic estimates; this was probably due to aerobic incubations assessing only the partial turnover of microbial biomass and the labile organic matter pools (Binkley & Hart, 1989). Smaller NH_4^+ concentrations could perhaps be attributed to the immobilisation by microbial biomass (Azam, Malik & Hussain, 1986; Binkley & Hart, 1989; Mariano *et al.*, 2013).

6.6 Conclusion

The total N estimate correlated with both anaerobic N estimates and exhibited the strongest correlation with the volume responses from increased N application rates, in the presence of P, and applications of P, in the absence of N, at 24 months after fertilisation. The negative correlation observed between the total N estimate and the volume response to higher N applications agreed with the findings of the current literature. The total N estimate does have potential for further study. The subtraction of the NH_4^+ concentration after incubation may still well be an improvement if mineralisable N estimates are determined by means of anaerobic incubations. The anaerobically incubated N mineralisation rates exhibited strong correlations with several soil properties; this was likely due to the strong occurrence of anaerobic soil processes in poorly drained soils or soils subjected to seasonal waterlogging. In addition, the anaerobic N estimate describes the N pool in a soil. The findings of this study demonstrate that the mineralisation of N in a soil is site specific. The Pearson correlation coefficient did reveal significant linear correlations between the anaerobically incubated N mineralisation rates and the volume increments of different treatment combinations at 24 months after fertilisation. Aerobically incubated N and P estimates correlated positively and negatively, respectively, with the basal N mineralisation rate of the SNAP model. In this study, the total N estimate, the simplest of the estimates, and the anaerobic estimates of N, were superior to those of aerobic incubations and support the feasibility of using these estimates in N and P mineralisation studies.

CHAPTER 7

CANOPY NUTRIENT CONTENT AS GROWTH PREDICTOR OF FERTILISED, SEMI-MATURE SLASH PINE STANDS IN THE TSITSIKAMMA, SOUTH AFRICA

7.1 Introduction

Several processes and management practices may affect forest nutrition during the life cycle of plantation forests. Short rotations, often incorporating intensive harvesting, and site management practices can lead to the exhaustion of ecosystem nutrient resources over successive rotations (Du Toit & Scholes, 2002; Du Toit, Gush, Pryke, Samways & Dovey, 2014; Gonçalves *et al.*, 2008; Laclau *et al.*, 2003; Shoulders & Tiarks, 1984). The limited resource availability and intra-specific competition for resources are two factors that significantly affect stand productivity and growth (Barron-Gafford *et al.*, 2003). Forest managers can manipulate water and nutrient availability to alleviate the effect of these resource restrictions on site productivity; this is achieved by implementing residue management, fertiliser and fire regimes (Albaugh *et al.*, 1998; Gonçalves *et al.*, 2008), as well as vegetation management such as pruning, thinning and weeding (Albaugh *et al.*, 2003; Carlyle, 1998). Higher planting densities can lead to an increased N demand in certain pine species (Allen, Dougherty & Campbell, 1990), and the N demand is at its peak during canopy development around the time of canopy closure (Turner & Lambert, 1986). *Pinus elliottii* and *P. taeda* stands place a significant nutrient demand on the soil during initial canopy development (Jokela, 2004).

Fertilisation or other operations that enhance stand nutrient availability may result in changes to foliar nutrient concentrations, changes in leaf area and mass, and lastly also changes to canopy nutrient content (Blinn & Buckner, 1989; Weetman, 1989; Weetman & Wells, 1990). The foliage mass after the fertilisation of *P. elliottii* and *P. taeda* stands can provide an adequate estimator of growth (Barron-Gafford *et al.*, 2003), and Barron-Gafford *et al.* (2003) observed strong correlations ($r = 0.76$) between the biomass of one-year-old foliage and total stem biomass growth. Fertilisation can increase foliar development, leaf area and light-use efficiency significantly (Albaugh *et al.*, 1998; Carlyle, 1998; Chikumbu, 2011; Rubilar, Albaugh, Allen, Alvarez, Fox & Stape, 2013), although the response of foliar nutrient concentrations to

fertilisation can vary; increases in foliar P and K (Moilanen, Hytönen, Hökkä & Ahtikoski, 2015) and decreases in foliar N and P (Barron-Gafford *et al.*, 2003) have been reported following applications of N, P and K. These variations are likely a consequence of genotypic, edaphic (site) and climatic differences across sites and, more notably, of whether the growing conditions (or resource availabilities) are growth limiting. Stem wood production in trees depends on the absorption of light (PAR) and the efficiency of converting the light into stem wood (Binkley, Campoe, Gspaltl & Forrester, 2011; Campoe *et al.*, 2013; Landsberg & Waring, 1997; Linder, 1985). Quantifying LAI can be challenging due to large spatial and temporal variability (Bréda, 2003). Indirect assessments (from below the canopy) of LAI with equipment that relies on ambient light (passive sensors), such as ceptometers or canopy analysers, can lead to underestimations of LAI due to foliage clumping (Gower, Kucharik & Norman, 1999), light distortion and the interception of radiation by stem wood and branches (Bréda, 2003; Chianucci and Cutini, 2012; Dovey & Du Toit, 2006). These estimates can range from slight overpredictions in young eucalypt stands (Dovey & Du Toit, 2006; Lopes *et al.*, 2016) to underestimations of up to 40% (Gower & Norman, 1991) in conifer species (Cutini, Matteucci & Mugnozza, 1998; Gower *et al.*, 1999; Lopes *et al.*, 2016). Lopes *et al.* (2016) demonstrated that species-specific calibrations are required in pine stands, and age-specific calibrations are required in in pre-canopy closure eucalypt stands (Dovey & Du Toit, 2006). Lopes *et al.* (2016) propose that a correction factor be incorporated for the indirect estimations of LAI for pine species. The foliar clumping, or non-random distribution of foliage (Chen, Black & Adams, 1991; Fournier, Rich & Landry, 1997; Ryu, Nilson, Kobayashi, Sonnetag, Law & Baldocchi, 2010), and underestimation of LAI (Gower & Norman, 1991; Lopes *et al.*, 2016) using both the AccuPAR LP-80 and Li-Cor LAI-2000 devices have been addressed in several studies (Dovey & Du Toit, 2006; Lopes *et al.*, 2016). Lopes *et al.* (2016) showed that LAI observations with a ceptometer require a correction factor and suggested the multiplication of the LAI with an appropriate correction factor.

There have been several studies on the fertilisation of pine plantations in Southern Africa, but relatively few studies have linked the response in fertiliser trials to variables that can be used for extrapolation to commercial plantations, i.e. as decision support systems (Du Toit, 2006; Payn *et al.*, 1989). While several studies have used soil, foliar nutrient concentrations and soil C content in decision support systems, few studies have explored the possibility of using canopy nutrient content as predictor of response to fertilisation (Haase & Rose, 1995; Hans & Du Toit, submitted). Canopy nutrient content should be of interest to the researcher, as it

integrates nutrient concentrations and leaf mass, thus being fundamental to two key physiological processes driving growth, viz. light interception and light-use efficiency (Landsberg & Waring, 1997). This study explores how different N and P fertiliser combinations affect the canopy nutrient contents of eight *P. elliottii* and *P. elliottii x caribaea* field trials in the Tsitsikamma. Firstly, field trials were assessed to identify potential nutrient deficiencies and whether the application of increasing quantities of N and P fertiliser can address the observed deficiencies. Secondly, it investigated whether the changes in stand nutrition and development could be used as a decision support tool to understand the mechanisms of the observed responses, using information from this and previous chapters. Incorporating these growth predictors in the decision support system for pine fertilisation in the Cape forest region could identify (and then disqualify) stands that would not yield a reasonable return on investment after fertilisation. A complete and accurate integration of several edaphic, geographic and stand properties could significantly improve the response of pine plantations to fertilisation and, at the same time, raise the economic feasibility of fertilisation in semi-mature softwood plantations.

7.2 Primary research questions

- Were any of the field trials nutrient deficient and, if so, did fertilisation address the potential deficiencies?
 - Which treatment combination was the most effective to alleviate these deficiencies?
 - Were any of the responses site specific?
 - Did any treatments induce or overcome nutrient imbalances?
- Did fertilisation significantly affect canopy N and P content?
- Can foliar N and P be used to identify sites likely to respond to fertiliser?

7.3 Materials and Methods

7.1.1 Canopy nutrient content

Leaf mass was calculated from LAI and scaled up to an area basis (Equation 23). The nutrient content was determined by multiplying the leaf mass with the foliar nutrient concentration of

the respective macronutrient (Equation 24). Specific leaf area and foliar nutrient analyses were done according to the procedures outlined in Chapter 3 (Section 3.5.2).

$$\text{Leaf mass} = \frac{\text{LAI}}{\text{SLA}} * 10\ 000 \quad (23)$$

where: Leaf mass = Canopy leaf mass (kg ha⁻¹)

LAI = Leaf area index (m² m⁻²)

SLA = Specific leaf area (m² kg⁻¹)

*The conversion factor of 10 000 is used to scale up from kg m⁻² to kg ha⁻¹

$$\text{Canopy nutrient content} = \text{Canopy leaf mass} \times \text{nutrient concentration} / 1000 \quad (24)$$

where: Nutrient content = kg ha⁻¹

Needle mass = kg ha⁻¹

Nutrient concentration = g kg⁻¹

7.1.2 Leaf area index (LAI)

The suggested correction factor (used to correct for the underestimation of LAI with an AccuPAR ceptometer) of Chen and Cihlar (1995), Gower and Norman (1991) and Lopes *et al.* (2016) is based on using LAI estimates from allometric equations as a reference LAI for measurements made with a ceptometer. Gower and Norman (1991) and Lopes *et al.* (2016) proposed correction factors of 1.5 and 1.38 respectively for *P. pinaster*. Chen and Cihlar (1995) suggested a factor of 1.48 for *P. banksiana*. The leaf area indices measured in this chapter were multiplied with a correction factor of 1.38 (after Lopes *et al.*, 2016); this factor was selected as *P. banksiana* is relatively unknown in South African plantation forestry and the more recent estimate by Lopes *et al.* (2016) is an additional refinement of the work by Chen and Cihlar (1995). Leaf area indices were recorded quarterly for a period of 24 months. This afforded us the opportunity to average the values resulting from predominantly summer growth (January and April, i.e. three to six and 15 to 18 months after treatment), as well as winter growth (July and Oct, i.e. nine to 12 and 21 to 24 months after treatment). The averaging was done to improve the reliability of the optical measurements (which are known to be rather variable). Averaging was done given the relatively slow canopy development of softwood species. Refer to Appendix 1, Section 7.7.1 for the full dataset.

7.1.3 Critical levels and nutrient ratio

Foliar nutrient concentrations were assessed according to critical nutrient values for slash pine (*P. elliotii*) at maturity (Table 7.20). Refer to Chapter 3.5.2.1 for a description of the foliage sampling methodology. Blinn and Buckner (1989) and Boardman, Cromer, Lambert and Webb (1997) have defined foliage concentrations as being deficient, marginal, adequate or toxic. These authors based the concentrations on sampling of the youngest mature foliage in mature slash pine trees. The critical value of Mg suggested by Blinn and Buckner (1989) was used, instead of that of Boardman *et al.* (1997). The value suggested by Boardman *et al.* (1997) was apparently a typographical error, as it differs with an order of magnitude from other sources. Foliar nutrient concentrations were furthermore assessed according to the nutrient ratio assessment method. Nutrients were expressed as a ratio relative to N, and the ratio was assessed according to the optimal values suggested by Linder (1995). Optimal ratios used were: P:N (10), K:N (35), Ca:N (2.5), Mg:N (4), Mn:N (0.05), Fe:N (0.2), Cu:N (0.03), Zn:N (0.05) and B:N (0.05). These ratios are tabulated in Appendix 6, Section 7.7.4, together with the ratios of each nutrient.

Table 7.20: Critical values used for foliar nutrient assessments, adapted from Blinn and Buckner (1989), Boardman *et al.* (1997), Jokela (2004) and Mead (1978).

Nutrient	Concentration range					Citation
	Deficient	Marginal	Adequate	High	Toxic	
N (%)	≤ 1	1.0	1.2*	-	-	Boardman <i>et al.</i> (1997); Jokela (2004)
P (%)	< 0.08	0.08	0.13	-	-	Mead (1978)
K (%)	< 0.30	0.30	0.35 - 0.40	-	-	Boardman <i>et al.</i> (1997)
Ca (%)	< 0.10	0.10	0.10 - 0.45*	-	-	Blinn and Buckner (1989)
Mg (%)	< 0.06	0.06	0.10 - 0.40*	-	-	Blinn and Buckner (1989)
Cu (mg kg ⁻¹)	< 2		2 - 18	-	-	
Zn (mg kg ⁻¹)	6 - 10		10 - 68	-	-	
Mn (mg kg ⁻¹)		21	284	-	-	Boardman <i>et al.</i> (1997)
Fe (mg kg ⁻¹)			65 - 404	-	-	
B (mg kg ⁻¹)	< 8 - 10		16 - 70*	-	-	

* Italicised values are for *P. radiata* and are included merely as a guideline, since no “adequate” range is published for these elements in mature *P. elliottii*.

7.1.4 Vector analysis

A vector analysis was performed of the stand nutrition at 12 and 24 months after treatment. The vector analysis is a diagnostic technique that compares the plant growth, foliar nutrient concentrations and foliar nutrient content of individual trees with each other (Haase & Rose, 1995; Weetman, 1989). The information and data gathered with this technique is then graphically expressed as a vector nomogram. The dry weight, nutrient contents and concentrations were normalised around the control treatment to a value of 100:100, and the control treatment was then used as the reference point to simplify the interpretation of the shift. Equations (25) and (26) were used to normalise the nutrient contents and concentrations, and this allowed for comparisons between individual treatments and nutrients. The nutrient content of each treatment was furthermore calculated using Equation 27. All equations were adapted from Haase and Rose (1995).

$$(x - axis) = \frac{\text{nutrient content of treatment}}{\text{nutrient content of control}} \times 100 \quad (25)$$

$$(y - axis) = \frac{\text{nutrient concentration of treatment}}{\text{nutrient concentration of control}} \times 100 \quad (26)$$

$$\text{Nutrient content} = \text{foliar nutrient concentration} \times \text{unit dry weight} \quad (27)$$

where:

Nutrient content = % * g

Nutrient concentration = %

Dry weight = g

Vectors diagrams were interpreted by assessing the magnitude and direction of each vector using the guidelines in Table 7.21. Diagonal shifts on the nomogram indicated no change in dry weight, and horizontal shifts by a diagonal indicated a change in unit weight. In the same way, horizontal shifts meant there was no change in nutrient concentration, and vertical shifts that there were no changes in nutrient content. A horizontal shift was indicative of a change in nutrient content, and vertical shifts of a change in concentration.

Table 7.21: Interpretation and diagnosis of directional shifts in dry weight, nutrient concentration and nutrient content. Adapted from Haase and Rose (1995) and Salifu and Timmer (2001).

Direction of shiftResponse in.....			Interpretation	Possible diagnosis
	Dry weight	Nutrient concentration	Nutrient content		
I	+	-	+	Dilution	Growth dilution
II	+	0	+	Sufficiency	Steady state
III	+	+	+	Deficiency	Limiting
IV	0	+	+	Luxury consumption	Accumulation
V	-	++	±	Excess	Toxic accumulation
VI	-	-	-	Excess	Antagonistic
VII	0, +	-	-	Depletion	Retranslocation

* The symbols +, - and 0 represent an increase, decrease and no change in dry weight, nutrient concentration or nutrient content.

7.1.1 Volume response to fertilisation

The volume of the treatment (T3, T4 or T5) with the highest response, minus the response to treatment T0, was used to determine the site responsiveness to the best combination of N and P. Volumes were determined according to the methodology outlined in Section 3.5.5 in Chapter 3. In each case, the response of the best treatment combination was standardised as a percentage of the response to the control treatment.

7.1.2 Statistical analyses and interpretation

Firstly, stand nutrition was assessed according to the critical nutrient and nutrient ratio assessment methods at 0, 12 and 24 months after fertilisation. Secondly, the leaf area indices for the control and most responsive treatments were visually interpreted to establish whether and how LAI changed over time. Thirdly, the canopy N and P contents (which incorporate LAI) were calculated for all eight sites at 0, 12 and 24 months after fertilisation. An analysis of variance (ANOVA) was used to determine whether any significant effects were observed between the canopy N and P contents and the treatment combinations in each field study at 0, 12 and 24 months after fertilisation. A confidence level of 95% was used, and $p < 0.05$ showed a significant interaction between the variables. In most instances, the mean \pm standard error is

reported, unless stated differently. As a final assessment, a vector analysis was done to establish whether the fertiliser treatments used in this study were able to address the nutrient imbalances/deficiencies in the field trials. In each case, the control treatment was used as the reference point to illustrate the nutrient response to fertilisation on the vector nomograms.

7.4 Results

7.4.1 Critical foliar nutrient levels

Section 7.7.1 provides the tabulated foliar nutrient concentrations and critical levels of each field study at 0, 12 and 24 months after treatment. Several treatments from field trials B, C, D and E were N deficient at the time of trial establishment; N concentrations were less than the suggested minimum value of 1% for slash pine (Jokela, 2004). At time of trial establishment, most field trials had deficient P nutrient concentrations. The average P concentration across all sites was 0.06%, and sites were classified as deficient once the P concentration was less than 0.08%. Several treatments from field trials A, B and D had deficient K concentrations, with a mean concentration of 0.26%, just short of the 0.3% that classifies a tree as K deficient. None of the field trials were Mg deficient at the time of trial establishment; the field trials had a mean Mg concentration of 0.21% and trees are classified as deficient once the concentration is less than 0.06%. Most of the treatments in field trials C, E, F and G had significantly lower Fe concentrations, with an average concentration of 49 mg kg⁻¹. Trees are classified deficient once Fe concentrations are less than 65 mg kg⁻¹, and sufficient at concentrations of 65 to 404 mg kg⁻¹. Several treatments in most of the field trials had deficient Zn concentrations, apart from trial F, which was completely deficient. Field trial F had a mean Zn concentration of 7.3 mg kg⁻¹; sites are classified as deficient once values are less than 10 mg kg⁻¹. All field trials were close to Zn-deficient concentrations, as the average Zn concentrations across all field trials was 9.5 mg kg⁻¹. Table 7.22 provides a summary of the mean concentrations of each nutrient per site and treatment.

Table 7.22: Foliar nutrient concentrations (mean \pm standard error) at time of trial establishment

Site	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
	%			mg kg ⁻¹						
A	1.11 \pm 0.02	0.07 \pm 0.00	0.28 \pm 0.01	0.75 \pm 0.17	0.31 \pm 0.03	177 \pm 30	82 \pm 8	3 \pm 0.27	10 \pm 1.31	27 \pm 2.22
B	0.92 \pm 0.05	0.05 \pm 0.00	0.32 \pm 0.03	0.55 \pm 0.06	0.18 \pm 0.01	173 \pm 46	77 \pm 9	2 \pm 0.20	9 \pm 0.95	13 \pm 0.84
C	0.95 \pm 0.02	0.07 \pm 0.00	0.37 \pm 0.01	0.69 \pm 0.11	0.22 \pm 0.01	166 \pm 29	55 \pm 4	2 \pm 0.08	12 \pm 1.07	22 \pm 1.95
D	0.90 \pm 0.03	0.06 \pm 0.00	0.24 \pm 0.01	0.81 \pm 0.09	0.26 \pm 0.04	170 \pm 32	105 \pm 10	2 \pm 0.26	8 \pm 1.06	22 \pm 2.81
E	0.96 \pm 0.07	0.07 \pm 0.00	0.41 \pm 0.04	0.61 \pm 0.14	0.18 \pm 0.03	108 \pm 20	49 \pm 4	2 \pm 0.21	10 \pm 1.23	18 \pm 1.41
F	1.01 \pm 0.04	0.07 \pm 0.00	0.50 \pm 0.04	0.54 \pm 0.08	0.16 \pm 0.02	118 \pm 13	48 \pm 3	2 \pm 0.00	7 \pm 0.48	18 \pm 1.27
G	1.12 \pm 0.07	0.07 \pm 0.00	0.40 \pm 0.03	0.73 \pm 0.05	0.20 \pm 0.01	183 \pm 17	44 \pm 1	2 \pm 0.21	9 \pm 1.01	21 \pm 1.73
H	1.21 \pm 0.07	0.05 \pm 0.00	0.42 \pm 0.03	0.58 \pm 0.06	0.16 \pm 0.02	318 \pm 76	74 \pm 14	3 \pm 0.22	12 \pm 1.12	21 \pm 2.58
Treatment	%			mg kg ⁻¹						
T0	1.02 \pm 0.04	0.05 \pm 0.00	0.35 \pm 0.05	0.34 \pm 0.05	0.14 \pm 0.01	110 \pm 14	47 \pm 4	2 \pm 0.13	7 \pm 0.81	16 \pm 0.82
T1	0.98 \pm 0.04	0.07 \pm 0.00	0.39 \pm 0.05	0.74 \pm 0.07	0.21 \pm 0.02	176 \pm 30	71 \pm 8	2 \pm 0.13	10 \pm 0.80	22 \pm 2.17
T2	0.99 \pm 0.05	0.07 \pm 0.01	0.41 \pm 0.04	0.79 \pm 0.11	0.21 \pm 0.03	185 \pm 27	72 \pm 11	3 \pm 0.19	11 \pm 0.76	20 \pm 2.29
T3	1.04 \pm 0.06	0.06 \pm 0.00	0.37 \pm 0.02	0.64 \pm 0.04	0.23 \pm 0.02	201 \pm 69	69 \pm 11	2 \pm 0.16	10 \pm 0.90	22 \pm 1.72
T4	1.05 \pm 0.08	0.06 \pm 0.00	0.32 \pm 0.02	0.73 \pm 0.09	0.23 \pm 0.02	219 \pm 17	65 \pm 8	3 \pm 0.19	10 \pm 1.16	21 \pm 2.13
T5	1.06 \pm 0.07	0.06 \pm 0.00	0.37 \pm 0.03	0.69 \pm 0.07	0.24 \pm 0.03	169 \pm 18	76 \pm 12	2 \pm 0.16	10 \pm 0.93	21 \pm 2.58

At 12 months after fertilisation, nearly all the treatments in field trials B and C remained N deficient, despite the N application in some treatments; in addition, field trial F developed deficient N concentrations in all treatments at 12 months. Treatments T0, T1 and T2 showed deficient N concentrations in field trials A, D, G and H. A total of three control treatments from sites B, F and H had deficient P concentrations. This was expected, as these plots were unfertilised (treatment T0), thus no supplementary N and P nutrients were introduced to the stands, and this suggests that fertilisation alleviated the P deficiencies sufficiently. Treatments T2 and T4 from field trial D were K deficient at 12 months after fertilisation; however, field trial F exhibited a complete deficiency of K for all treatments. This was not expected, as this field trial had sufficient K concentrations at the time of trial establishment. Once again, none of the field trials exhibited Ca or Mg deficiencies at 12 months after fertilisation. In addition, a significantly larger number of treatments from all field trials had deficient Fe and Zn concentrations at 12 months after fertilisation. Zinc concentrations remained largely unaffected. Lastly, all the trials exhibited a Cu deficiency at 12 months after treatment. Table 7.23 provides a summary of the mean concentrations of each nutrient per site and treatment at 12 months after fertilisation.

Table 7.23: Foliar nutrient concentrations (mean \pm standard error) at 12 months after fertilisation.

Site	N	P	K %	Ca	Mg	Mn	Fe	Cu mg kg ⁻¹	Zn	B
A	1.09 \pm 0.03	0.13 \pm 0.02	0.44 \pm 0.02	0.64 \pm 0.04	0.18 \pm 0.01	150 \pm 9	29 \pm 2	1 \pm 0.00	10 \pm 0.22	22 \pm 1.12
B	0.971 \pm 0.04	0.11 \pm 0.02	0.38 \pm 0.02	0.68 \pm 0.04	0.17 \pm 0.01	173 \pm 31	44 \pm 3	1 \pm 0.00	11 \pm 0.84	13 \pm 0.33
C	1.00 \pm 0.03	0.13 \pm 0.01	0.40 \pm 0.01	0.68 \pm 0.04	0.18 \pm 0.01	140 \pm 19	43 \pm 8	1 \pm 0.00	13 \pm 1.91	22 \pm 2.25
D	1.15 \pm 0.08	0.11 \pm 0.01	0.31 \pm 0.01	0.55 \pm 0.04	0.22 \pm 0.01	110 \pm 10	64 \pm 5	1 \pm 0.00	11 \pm 0.45	20 \pm 1.24
E	1.04 \pm 0.03	0.12 \pm 0.01	0.46 \pm 0.02	0.63 \pm 0.06	0.16 \pm 0.01	119 \pm 10	30 \pm 2	1 \pm 0.00	10 \pm 0.58	20 \pm 0.71
F	0.96 \pm 0.03	0.09 \pm 0.01	0.31 \pm 0.02	0.79 \pm 0.06	0.22 \pm 0.01	122 \pm 14	61 \pm 5	1 \pm 0.00	8 \pm 0.67	17 \pm 0.80
G	1.06 \pm 0.05	0.14 \pm 0.01	0.45 \pm 0.01	0.82 \pm 0.06	0.18 \pm 0.01	172 \pm 31	29 \pm 1	1 \pm 0.00	9 \pm 0.52	22 \pm 2.12
H	1.17 \pm 0.08	0.12 \pm 0.02	0.55 \pm 0.04	0.56 \pm 0.05	0.14 \pm 0.02	254 \pm 23	47 \pm 8	2 \pm 0.22	15 \pm 0.58	24 \pm 2.28
Treatment	%			mg kg ⁻¹						
T0	1.01 \pm 0.04	0.08 \pm 0.01	0.42 \pm 0.03	0.61 \pm 0.04	0.18 \pm 0.01	149 \pm 26.26	46 \pm 8	1 \pm 0.13	11 \pm 1.03	19 \pm 2.02
T1	0.98 \pm 0.04	0.11 \pm 0.01	0.40 \pm 0.03	0.69 \pm 0.04	0.19 \pm 0.01	141 \pm 19.73	46 \pm 6	1 \pm 0.00	10 \pm 0.77	19 \pm 1.13
T2	1.02 \pm 0.04	0.15 \pm 0.01	0.40 \pm 0.04	0.67 \pm 0.04	0.19 \pm 0.01	165 \pm 16.69	42 \pm 4	1 \pm 0.13	11 \pm 1.00	20 \pm 1.78
T3	1.03 \pm 0.03	0.10 \pm 0.01	0.39 \pm 0.02	0.72 \pm 0.07	0.18 \pm 0.02	157 \pm 25.90	45 \pm 7	1 \pm 0.00	10 \pm 0.98	21 \pm 1.90
T4	1.07 \pm 0.05	0.14 \pm 0.01	0.42 \pm 0.04	0.69 \pm 0.04	0.18 \pm 0.01	173 \pm 27.29	41 \pm 6	1 \pm 0.00	11 \pm 1.31	20 \pm 1.24
T5	1.23 \pm 0.06	0.13 \pm 0.01	0.45 \pm 0.04	0.65 \pm 0.06	0.17 \pm 0.01	144 \pm 22.55	41 \pm 7	1 \pm 0.13	12 \pm 1.28	21 \pm 2.15

All field trials, apart from A, contained some treatments with N deficiencies at 24 months after fertilisation. These deficiencies were not treatment specific, as they were observed in a variety of different treatments. A larger number of the T0 (control) treatments had deficient P concentrations at 24 months after trial initiation. Several treatments from field trials A and D had deficient K concentrations, but field trial F showed no signs of the K deficiencies that were initially observed at 12 months after fertilisation. Similar to the situation at 0 and 12 months, all field trials showed no signs of Mg deficiencies at 24 months after treatment. A smaller number of treatments had deficient Fe concentrations, but field trials C, E, F, G and H remained deficient. The widespread Cu deficiencies observed at 12 months after fertilisation diminished by 24 months, with only four treatments being deficient. As in the case with Cu, a smaller number of treatments exhibited deficient Zn concentrations at 24 months after treatment. Table 7.24 provides a summary of the mean concentrations of each nutrient per site and treatment at 24 months after fertilisation.

Table 7.24: Foliar nutrient concentrations (mean \pm standard error) at 24 months after fertilisation.

Site	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
			%					mg kg ⁻¹		
A	1.15 \pm 0.04	0.09 \pm 0.01	0.28 \pm 0.02	0.42 \pm 0.03	0.21 \pm 0.01	128 \pm 13	76 \pm 4	2 \pm 0.00	12 \pm 1.17	17 \pm 1.05
B	0.95 \pm 0.03	0.10 \pm 0.01	0.38 \pm 0.02	0.45 \pm 0.02	0.17 \pm 0.01	161 \pm 18	63 \pm 4	2 \pm 0.00	14 \pm 1.61	15 \pm 0.80
C	0.96 \pm 0.02	0.10 \pm 0.01	0.35 \pm 0.02	0.60 \pm 0.05	0.19 \pm 0.01	152 \pm 16	45 \pm 2	2 \pm 0.17	12 \pm 1.94	19 \pm 1.50
D	0.94 \pm 0.04	0.08 \pm 0.01	0.29 \pm 0.03	0.62 \pm 0.04	0.22 \pm 0.02	167 \pm 14	82 \pm 3	2 \pm 0.17	10 \pm 0.87	19 \pm 2.35
E	0.96 \pm 0.04	0.09 \pm 0.01	0.39 \pm 0.02	0.45 \pm 0.05	0.17 \pm 0.01	148 \pm 16	43 \pm 2	2 \pm 0.17	12 \pm 1.09	17 \pm 1.34
F	0.99 \pm 0.02	0.10 \pm 0.00	0.42 \pm 0.02	0.44 \pm 0.02	0.17 \pm 0.01	136 \pm 8	46 \pm 1	2 \pm 0.17	11 \pm 0.31	15 \pm 0.70
G	1.00 \pm 0.03	0.13 \pm 0.01	0.40 \pm 0.02	0.76 \pm 0.06	0.21 \pm 0.01	204 \pm 20	48 \pm 3	2 \pm 0.00	9 \pm 0.49	25 \pm 2.83
H	1.07 \pm 0.04	0.10 \pm 0.01	0.40 \pm 0.02	0.46 \pm 0.03	0.16 \pm 0.01	330 \pm 22	54 \pm 2	2 \pm 0.17	19 \pm 1.77	18 \pm 1.54
Treatment			%					mg kg ⁻¹		
T0	0.93 \pm 0.03	0.07 \pm 0.00	0.34 \pm 0.03	0.52 \pm 0.06	0.18 \pm 0.01	188 \pm 22	62 \pm 7	2 \pm 0.00	11 \pm 0.48	18 \pm 2.12
T1	0.97 \pm 0.03	0.10 \pm 0.01	0.39 \pm 0.02	0.44 \pm 0.04	0.17 \pm 0.01	153 \pm 20	56 \pm 6	2 \pm 0.00	11 \pm 0.84	16 \pm 0.84
T2	0.98 \pm 0.03	0.11 \pm 0.01	0.34 \pm 0.02	0.54 \pm 0.04	0.20 \pm 0.01	171 \pm 34	59 \pm 7	2 \pm 0.00	12 \pm 1.97	18 \pm 1.46
T3	1.06 \pm 0.03	0.10 \pm 0.01	0.37 \pm 0.03	0.58 \pm 0.08	0.19 \pm 0.02	176 \pm 24	54 \pm 4	2 \pm 0.19	12 \pm 1.40	18 \pm 1.29
T4	1.00 \pm 0.04	0.10 \pm 0.01	0.38 \pm 0.02	0.51 \pm 0.05	0.18 \pm 0.01	184 \pm 36	56 \pm 5	2 \pm 0.18	13 \pm 1.64	18 \pm 2.52
T5	1.08 \pm 0.04	0.11 \pm 0.01	0.36 \pm 0.02	0.55 \pm 0.05	0.19 \pm 0.01	198 \pm 18	55 \pm 5	2 \pm 0.00	15 \pm 1.63	21 \pm 1.66

7.4.2 Foliar nutrient ratios

At the time of establishment, P:N ratios were suboptimal in all field trials, apart from a single site in field trial H, which had a much lower ratio. The term “suboptimal” was used, as nutrient ratios were lower than what is defined as sufficient, but not near complete deficiency. (Refer to Section 7.1.3 for a description of the optimal ratios for each nutrient.) Treatments T0, T1 and T2 are hereafter referred to as the lower fertiliser treatments, and T3, T4 and T5 as the higher fertiliser treatments. The whole of field trials A and D had suboptimal K:N ratios at the time of establishment. In addition, several plots in field trials B, C, G and H similarly had suboptimal nutrient ratios. Nearly all field trials had suboptimal Cu:N ratios, apart from two sites in field trials D and E. Two sites from field trials A and D had suboptimal Zn:N ratios.

Fertilisation increased the P:N ratios of nearly all field trials after 12 months, but field trials D and F continued to have suboptimal P:N ratios. The control treatments in field trials A, B, E and H showed suboptimal P:N ratios, although higher fertiliser treatments in field trials B, E and H also exhibited deficient P:N ratios at 12 months after fertilisation. The whole of field trials D and F had suboptimal K:N ratios. Fertilisation seemed to have alleviated the nutritional shortcomings in field trial A, as only a single treatment (T1) had a suboptimal K:N ratio after

12 months. The lower treatments (T0, T1 and T2) in field trials A, B and C had suboptimal K:N ratios. All field trials shifted from suboptimal to poor Cu:N ratios after 12 months.

Field trials A, D, E and F had suboptimal P:N ratios at 24 months after fertilisation. In addition, a larger number of field trials had suboptimal P:N ratios, and field trial A shifted back from having sufficient ratios at 12 months after treatment to suboptimal ratios. Fertilisation seemed to temporarily address the nutritional shortcomings in field trials A and E. The whole of field trial A shifted back to suboptimal K:N ratios after 12 months, and field trial D continued to have suboptimal K:N ratios. Field trials C and H had suboptimal K:N ratios for treatments T0, T2, T3 and T5, and suboptimal nutrient ratios were observed in field trials B, E and F for the lower treatments – T2 and T0.

7.4.3 Leaf area index

7.4.3.1 Visual analysis of T0

The LAI of the unfertilised treatments in each field trial was plotted as a function of time after treatment (Figure 7.19). The control treatments were selected to establish a baseline response of the LAI across all field trials for the experimental period. The leaf area index is a modest approximation of canopy development over time, and the data is subjected to small variations, due to the equipment used for data capturing and variable in-field conditions. The leaf area indices of field trials A, B, D, E, F and H remained similar throughout the experimental period; these field trials exhibited small leaf area index variations from time of trial establishment up to 24 months after treatment, although field trial B showed a notable decrease, from 4.44 ± 0.56 to 3.33 ± 0.56 at 0 and 12 months after fertilisation. Field trial C exhibited an increase from 4.69 ± 0.55 to 6.45 ± 0.55 at 12 and 24 months after fertilisation. In addition, field trial G showed an initial decrease from 6.22 ± 0.57 to 5.47 ± 0.57 from 0 to 12 months after fertilisation. Throughout the experimental period, in 2016 and 2017, the rainfall in the Cape forest region was at a historic low. The unusual drought conditions could have affected the leaf area indices observed in this study, although increases were observed in most field trials. In addition, field trial E suffered from baboon damage at 20 months after treatment, and field trials F and H experienced significant wind damage in the same period. The damage inflicted in these field trials probably contributed to some of the variation observed in this study. The findings could also be partially attributed to the effect of seasonality. Temperatures were significantly lower at six and 18 months after treatment, with mean monthly temperatures of 16.9 and 16.8°C respectively. Both these measurement periods were at the onset of winter, and the lowest mean monthly winter temperatures recorded at both time intervals were 10.7 (2016)

and 11.5°C (2017). The monthly temperatures and rainfall increased gradually after both these periods, signalling the start of the growing season.

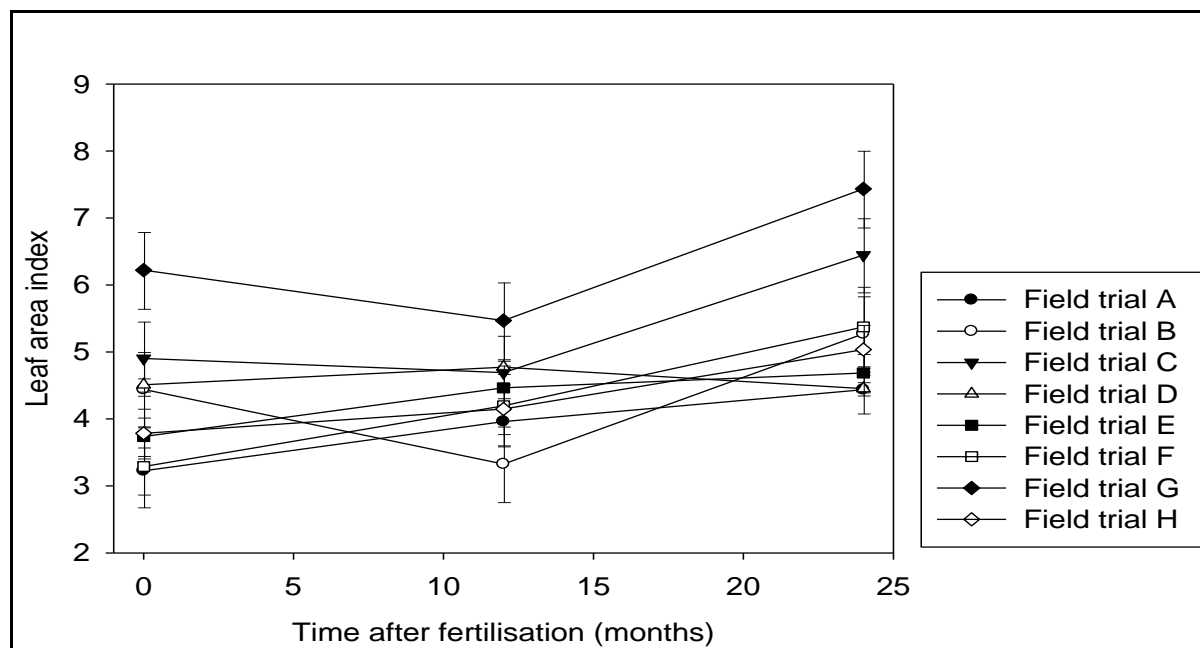


Figure 7.20: Leaf area index of the control treatments (T0) for each field trial as a function of time after fertilisation (mean and standard error of each field trial illustrated).

7.4.3.2 Relationship of LAI and fertilisation

The reader is referred to Appendix 2 for the tabulated responses to fertilisation for each field trial at 0, 6, 12 and 24 months after fertilisation. Fertilisation did not have a significant effect on the LAI across all field trials (Figure 7.20), although there was a significant interaction between site and time after fertilisation ($p < 0.001$). The difference in LAI between the control and the most responsive fertiliser treatment of each field trial could not be plotted as a function of time after fertilisation, due to several trials exhibiting negative differences. This could also be attributed to the equipment used for data capturing and variable in-field conditions. Chikumbu (2011) noted that stands with small initial LAI values in the Boland region (Western Cape) were more responsive to fertilisation. All the study sites in the Tsitsikamma had initial LAI values of higher than 3. The leaf area indices exhibited a general increase across all field trials at 0 to 24 months after fertilisation, and little variation was observed throughout the experimental period relative to the control treatments (Figure 7.19). Fertilisation did not seem to influence the canopy development across all field trials, factoring in the probable effect of seasonality and the drought conditions experienced throughout the experimental period. As in the aforementioned section, field trial E suffered from baboon damage at 20 months after treatment, and field trials F and H experienced significant wind damage in the same period.

The findings of this section support the notion of further investigating the effect of fertilisation on the canopy nutrient contents of each field trial.

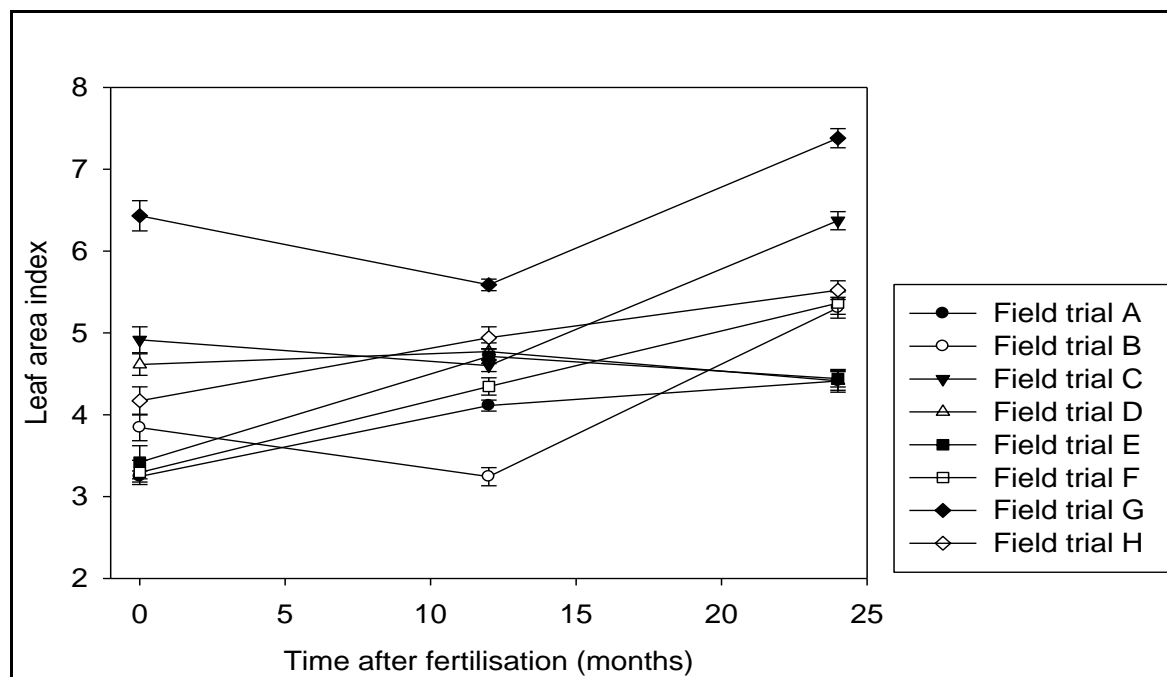


Figure 7.21: Relationship between the leaf area index and site at 0, 12 and 24 months after fertilisation (mean and standard error values are illustrated).

7.4.4 Canopy N and P contents

7.4.4.1 Effect of trial site and fertiliser treatments

Canopy N and P contents differed significantly between sites ($p < 0.001$). The highest N content was observed in field trial G, with a value of $184 \pm 7.63 \text{ kg ha}^{-1}$. The smallest N content was observed in field trial D, with a value of $101 \pm 4.99 \text{ kg ha}^{-1}$ (Figure 7.21). The highest P content was observed in site G, with $19 \pm 1.58 \text{ kg ha}^{-1}$ (Figure 7.22). Lastly, the smallest P content was observed in field trial D, with a low content of $8 \pm 0.74 \text{ kg ha}^{-1}$.

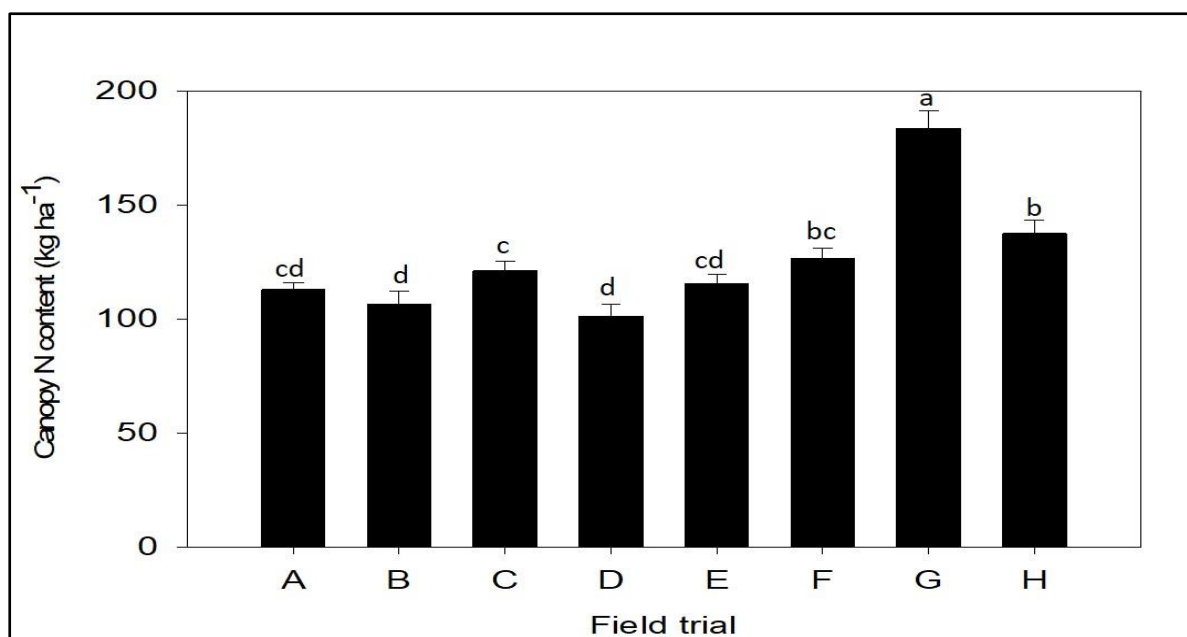


Figure 7.22: Mean canopy N content for each field trial at 24 months after treatment.

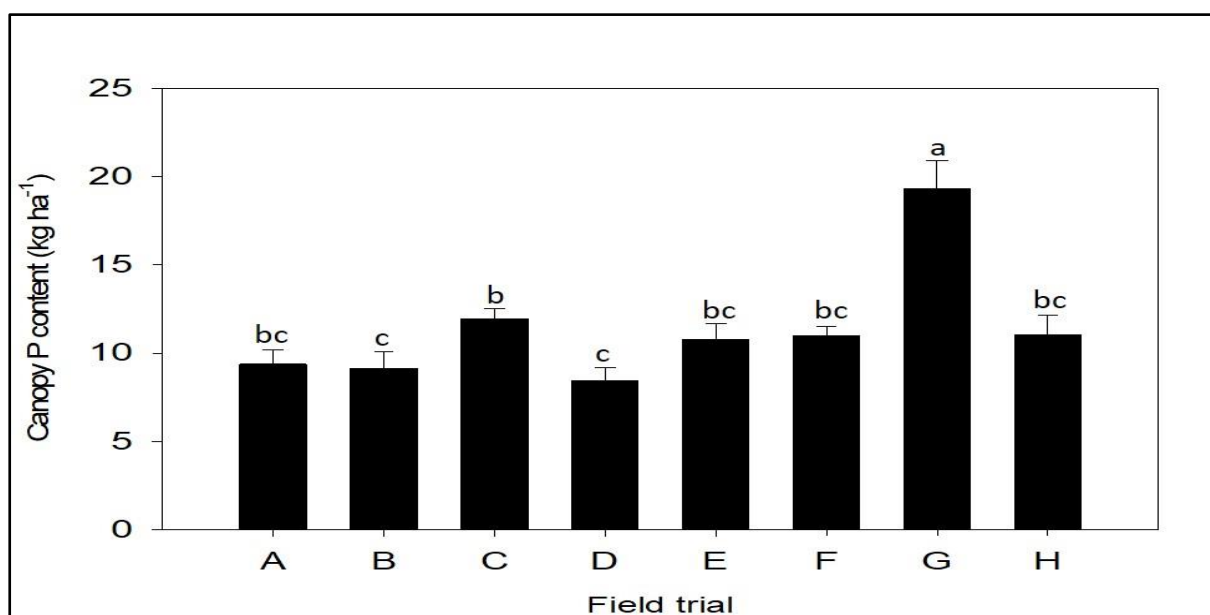


Figure 7.23: Mean canopy P content for each field trial at 24 months after treatment.

The effect of fertilisation on the canopy N contents was significant ($p = 0.007$), and significant treatment differences were observed for the P content ($p = 0.014$). No significant interactions between site and fertiliser treatment on canopy N and P contents were observed at 24 months after treatment. In ascending order, mean N contents of all field trials and their respective treatments at 24 months after fertilisation were: 118 ± 4.85 (T0), 119 ± 5.78 (T1), 123 ± 7.29 (T2), 127 ± 7.96 (T3), 127 ± 7.45 (T4) and 140 ± 5.81 (T5) kg ha⁻¹ (Figure 7.23).

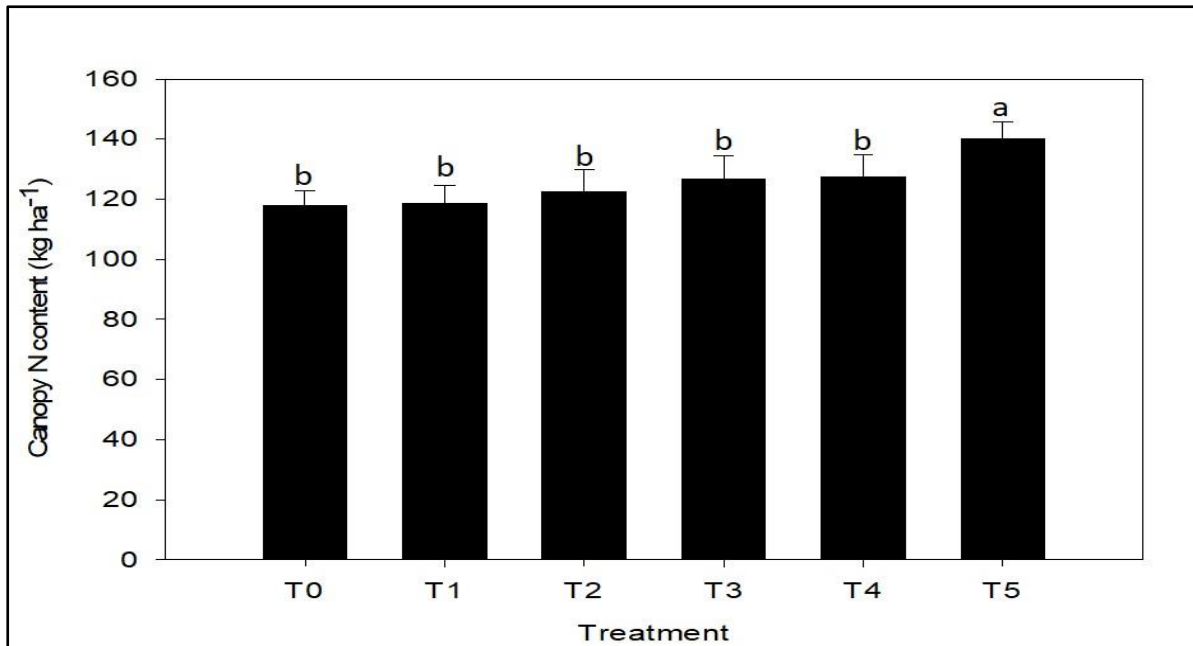


Figure 7.24: Mean canopy N content for the single effect of fertiliser treatment at 24 months after fertilisation.

The highest mean canopy P content was observed for treatment T2, with a value of 13 ± 1.07 kg ha⁻¹. As expected, the lowest P content was observed for the T0 (control) treatment, with a value of 8 ± 0.58 kg ha⁻¹ (Figure 7.24). The remaining treatments had respective values (in ascending order) of: 11 ± 1.02 (T3), 11 ± 1.02 (T1); 12 ± 1.19 (T4) and 12 ± 1.07 (T5) kg ha⁻¹.

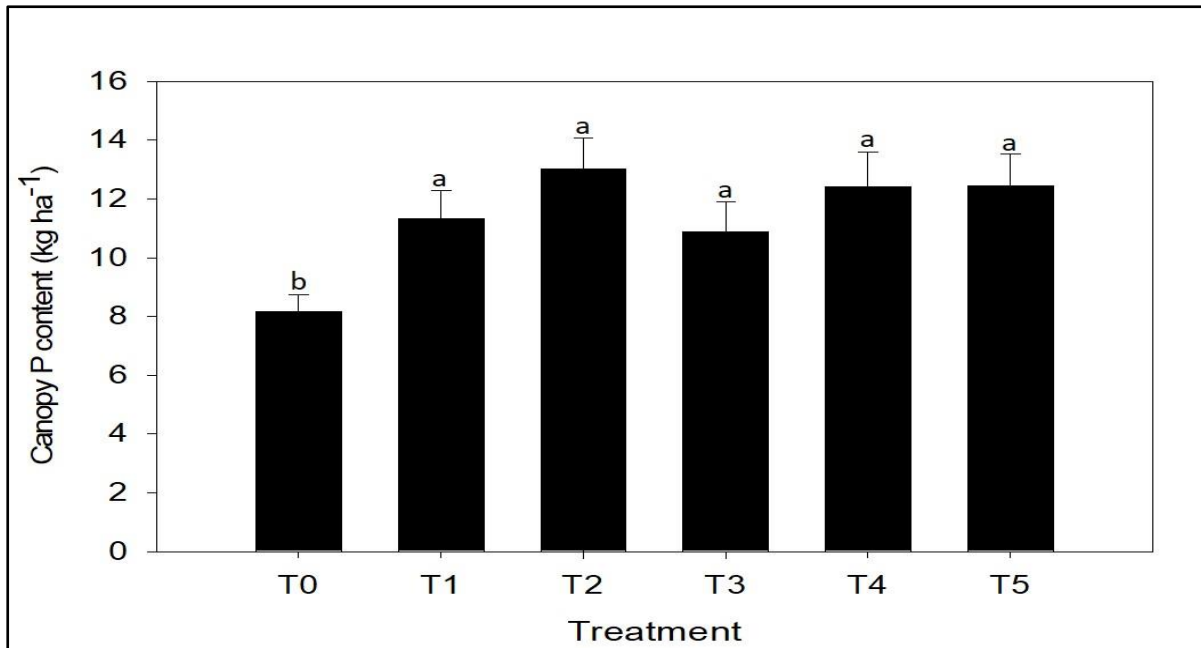


Figure 7.25: Mean canopy P content for the single effect of fertiliser treatment at 24 months after fertilisation.

7.4.4.2 Effect of site and time after fertilisation

Only the N-containing treatments were analysed for the interaction of time and fertiliser treatment on the canopy N content (T3, T4 and T5). All the treatments contained P, thus T1 to T5 were analysed for canopy P content. Canopy N and P contents differed significantly for the single effect of time after fertilisation, with similar p -values of $p < 0.001$. Mean canopy N contents decreased from 137 ± 9.15 to 122 ± 5.76 kg ha⁻¹ from time of trial establishment up to 12 months after fertilisation across all field trials (Figure 7.25). Furthermore, the mean N content increased to 135 ± 5.88 kg ha⁻¹ from 12 to 24 months after fertilisation. Canopy P content increased from 8 ± 0.53 to 14 ± 1.02 kg ha⁻¹ from time of trial establishment to 12 months after fertilisation respectively. At 24 months after fertilisation, the canopy P content remained nearly unchanged at 14 ± 1.20 kg ha⁻¹ (Figure 7.26).

More importantly, significant treatment differences were observed for the combined effect of time after fertilisation and field trial on the canopy N ($p < 0.001$) and P content ($p < 0.001$). Take note that the values at 0 months (at time of trial establishment) in Figures 7.25 and 7.26 represent canopy N and P contents of trials that were not treated with any fertiliser. Both time intervals were included to illustrate the increased or decreased N and P contents from time of establishment up to 12 months after treatment. The highest canopy N contents were observed for field trial G at 0, 12 and 24 months after fertilisation, with values of 223 ± 16.42 , 163 ± 4.84 and 191 ± 5.14 kg ha⁻¹ respectively. The canopy N contents of field trials A, B, C, F, G and H

decreased in the first 12 months, but increased slightly from 12 to 24 months. In contrast to the abovementioned sites, field trials D and E showed increased canopy N contents in the first 12 months after fertilisation, followed by slight decreases in the second year. The highest canopy P contents were observed in field trial G, with contents of 13 ± 1.09 , 22 ± 3.48 and 27 ± 2.59 kg ha^{-1} at 0, 12 and 24 months after fertilisation respectively. Field trials B, F and G showed increased contents from 0 to 24 months after treatments; however, the remaining field trials showed decreased contents from 12 to 24 months after treatment. It is important to note that the slight increases and decreases described in this section could be attributed to the LAI variations described in the previous section. The methodology used to calculate the canopy nutrient contents in this study required the LAI and nutrient concentration of the respective nutrients as input variables. A slight increase or decrease in canopy N and P contents could mean that there was little or no change in the contents due to the variation reported in the LAI values across all field trials.

To investigate whether fertilisation addressed the site-specific nutrient imbalances identified using the critical value and nutrient ratio assessment methods, a vector analysis was performed on the macro- and micronutrients of field trials that exhibited significant differences and contrasting results.

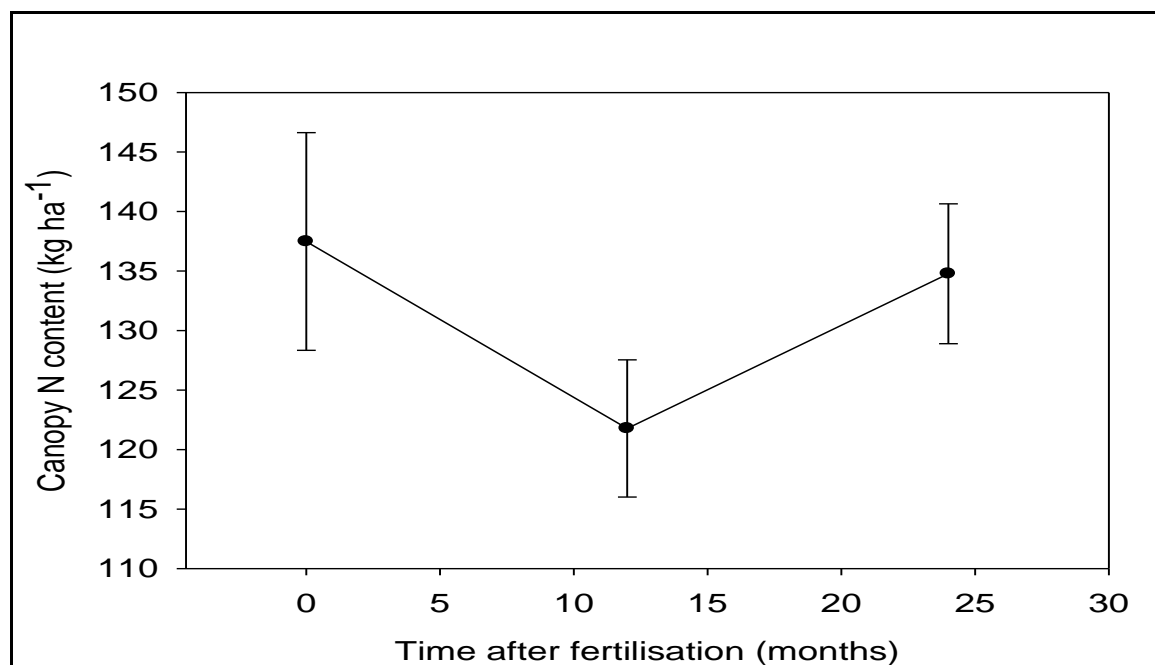


Figure 7.26: Mean canopy N content at 0, 12 and 24 months after fertilisation for the N-containing treatments.

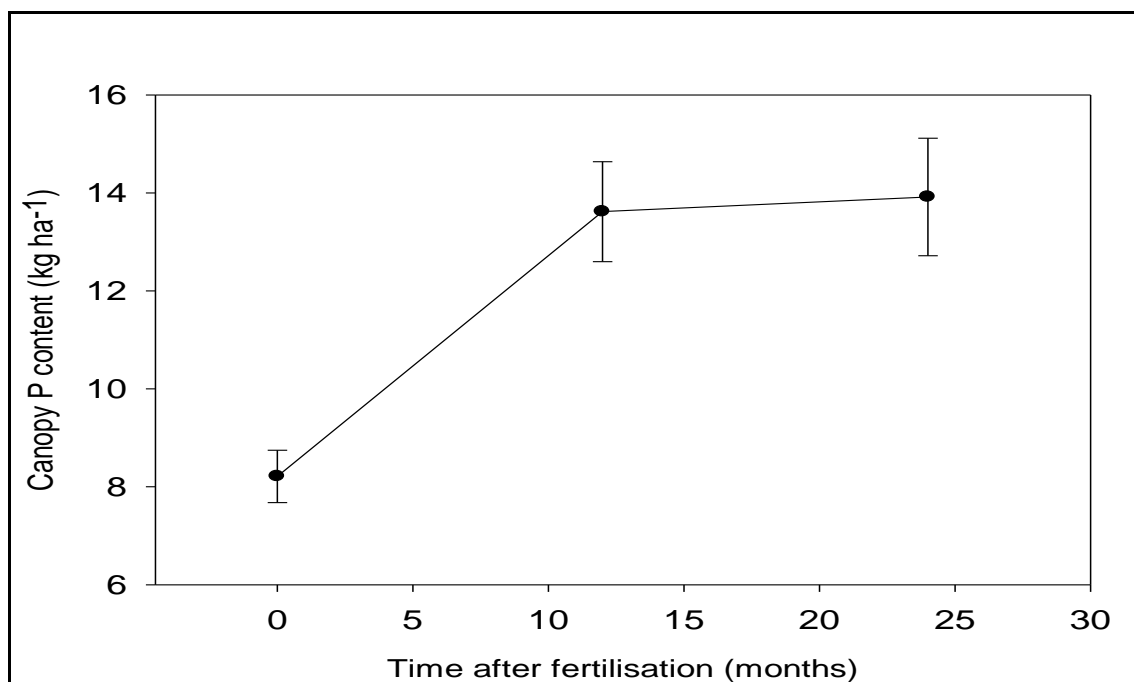


Figure 7.27: Mean canopy P content at 0, 12 and 24 months after fertilisation for the P-containing treatments.

7.4.5 Vector analyses

Vector analyses were performed on each field trial, and notable and similar responses between field trials are described below.

7.4.5.1 N

Field trials B, C, D, G and H exhibited deficient foliar N concentrations for the lower fertiliser rates at 12 months after treatment and, at 24 months, most of the field trials, apart from A, exhibited deficient concentrations for all fertiliser treatments (Table 7.25). Field trials A, B, G and H showed deficiencies for the lower fertiliser rates, which meant the higher fertiliser rates alleviated the N deficiencies in these sites. Field trials C, D, E and F had deficient N concentrations across all treatments at 24 months after fertilisation. Field trial F also exhibited deficient N concentrations for treatments T0, T1 and T4 at 24 months. The foliar N concentrations in field trial A were most responsive to the higher fertiliser treatments throughout the experimental period. The vector nomogram for field trial A showed a deficiency of N at 12 months for the lower treatments, and a dilution and luxury consumption for the higher treatments, at 24 months after fertilisation. Field trial F exhibited small signs of N deficiencies at the time of trial establishment. After 12 months, the nomogram showed an excess of N for treatments T1, T3 and T4, but treatments T2 and T5 exhibited a dilution and deficiency of N. Nitrogen remained deficient across all treatments at 24 months.

Table 7.25: Tsitsikamma nomograms of N for all field trials at 12 and 24 months after fertilisation. Cells demarcated as X represent a response in unit dry weight, nutrient concentration and nutrient content that did not match any of the interpretations defined by Haase and Rose (1995). For representative purposes, graphic illustrations of the highlighted cells are illustrated in Figures 7.27 to 7.30 in Section 7.7.6.

Field trial	Treatment	N (12 months)		N (24 months)	
		Interpretation	Diagnosis	Interpretation	Diagnosis
A	T0	Control	Control	Control	Control
A	T1	Deficiency	Limiting	X	X
A	T2	Deficiency	Limiting	Deficiency	Limiting
A	T3	Deficiency	Limiting	Deficiency	Limiting
A	T4	Dilution	Growth dilution	Dilution	Growth dilution
A	T5	Luxury consumption	Accumulation	Deficiency	Limiting
B	T0	Control	Control	Control	Control
B	T1	Depletion	Retranslocation	Deficiency	Limiting
B	T2	Deficiency	Limiting	Deficiency	Limiting
B	T3	Depletion	Retranslocation	Deficiency	Limiting
B	T4	Deficiency	Limiting	Sufficiency	Steady state
B	T5	Deficiency	Limiting	Deficiency	Limiting
C	T0	Control	Control	Control	Control
C	T1	Excess	Antagonistic	Luxury consumption	Accumulation
C	T2	Excess	Antagonistic	Excess	Antagonistic
C	T3	Excess	Antagonistic	Excess	Antagonistic
C	T4	Luxury consumption	Accumulation	X	X
C	T5	Luxury consumption	Accumulation	Luxury consumption	Accumulation
D	T0	Control	Control	Control	Control
D	T1	Deficiency	Limiting	Deficiency	Limiting
D	T2	Depletion	Retranslocation	Deficiency	Limiting
D	T3	Dilution	Growth dilution	Deficiency	Limiting
D	T4	Deficiency	Limiting	Dilution	Growth dilution
D	T5	Deficiency	Limiting	Deficiency	Limiting
E	T0	Control	Control	Control	Control
E	T1	Dilution	Growth dilution	Depletion	Retranslocation
E	T2	Dilution	Growth dilution	Sufficiency	Steady state
E	T3	Deficiency	Limiting	Deficiency	Limiting
E	T4	Dilution	Growth dilution	Dilution	Growth dilution
E	T5	Deficiency	Limiting	Deficiency	Limiting
F	T0	Control	Control	Control	Control
F	T1	Excess	Antagonistic	Deficiency	Limiting
F	T2	Depletion	Retranslocation	Deficiency	Limiting
F	T3	Excess	Antagonistic	X	X
F	T4	Excess	Antagonistic	X	X
F	T5	Deficiency	Limiting	Deficiency	Limiting
G	T0	Control	Control	Control	Control
G	T1	Deficiency	Limiting	Deficiency	Limiting
G	T2	Deficiency	Limiting	Deficiency	Limiting
G	T3	Deficiency	Limiting	Deficiency	Limiting
G	T4	Deficiency	Limiting	Dilution	Growth dilution
G	T5	Deficiency	Limiting	X	X
H	T0	Control	Control	Control	Control
H	T1	Depletion	Retranslocation	Depletion	Retranslocation
H	T2	Deficiency	Limiting	Depletion	Retranslocation

H	T3	Depletion	Retranslocation	Deficiency	Limiting
H	T4	X	X	X	X
H	T5	Depletion	Retranslocation	Deficiency	Limiting

7.4.5.2 P

Fertiliser application induced a significant increase in foliar P in field trials A, D, E, F and H after 12 months, although the nutrient ratio assessment showed the effect to be temporary (Table 7.26). The P:N ratios decreased to suboptimal quantities after 12 months. The nomograms for field trial A showed a shift in foliar P to deficiencies (limiting) for all treatments, apart from treatment T4, which exhibited a dilution, at 12 months after fertilisation. Furthermore, the deficiencies were maintained up to 24 months in this field trial. Field trials B and C showed no discernible responses to either the lower or higher treatments. Field trial B exhibited suboptimal nutrient ratios throughout the experimental period for both the lower and higher fertiliser treatments. The vector nomograms revealed deficiencies (limiting) of P in all treatments.

Table 7.26: Tsitsikamma nomograms of P for all field trials at 12 and 24 months after fertilisation. Cells demarcated as X represent a response in unit dry weight, nutrient concentration and nutrient content that did not match any of the interpretations defined by Haase and Rose (1995). For representative purposes, graphic illustrations of the highlighted cells are illustrated in Figures 7.31 to 7.34 in Section 7.7.6.

Field trial	Treatment	P (12 months)		P (24 months)	
		Interpretation	Diagnosis	Interpretation	Diagnosis
A	T0	Control	Control	Control	Control
A	T1	Deficiency	Limiting	X	X
A	T2	Deficiency	Limiting	Deficiency	Limiting
A	T3	Deficiency	Limiting	Deficiency	Limiting
A	T4	Dilution	Growth dilution	X	X
A	T5	Deficiency	Limiting	Deficiency	Limiting
B	T0	Control	Control	Control	Control
B	T1	Deficiency	Limiting	Deficiency	Limiting
B	T2	Deficiency	Limiting	Deficiency	Limiting
B	T3	Deficiency	Limiting	Deficiency	Limiting
B	T4	Deficiency	Limiting	Deficiency	Limiting
B	T5	Deficiency	Limiting	Deficiency	Limiting
C	T0	Control	Control	Control	Control
C	T1	X	X	X	X
C	T2	X	X	X	X
C	T3	Luxury consumption	Accumulation	X	X
C	T4	Deficiency	Limiting	X	X
C	T5	Luxury consumption	Accumulation	Luxury consumption	Accumulation
D	T0	Control	Control	Control	Control

Field trial	Treatment	P (12 months)		P (24 months)	
		Interpretation	Diagnosis	Interpretation	Diagnosis
D	T1	Depletion	Retranslocation	Deficiency	Limiting
D	T2	Deficiency	Limiting	Deficiency	Limiting
D	T3	Depletion	Retranslocation	Deficiency	Limiting
D	T4	Luxury consumption	Accumulation	Sufficiency	Steady state
D	T5	Sufficiency	Steady state	Deficiency	Limiting
E	T0	Control	Control	Control	Control
E	T1	Deficiency	Limiting	Deficiency	Limiting
E	T2	Deficiency	Limiting	Deficiency	Limiting
E	T3	Deficiency	Limiting	Deficiency	Limiting
E	T4	Deficiency	Limiting	Deficiency	Limiting
E	T5	Deficiency	Limiting	Deficiency	Limiting
F	T0	Control	Control	Control	Control
F	T1	X	X	Deficiency	Limiting
F	T2	Deficiency	Limiting	Deficiency	Limiting
F	T3	X	X	X	X
F	T4	Sufficiency	Steady state	Sufficiency	Steady state
F	T5	Deficiency	Limiting	Deficiency	Limiting
G	T0	Control	Control	Control	Control
G	T1	X	X	X	X
G	T2	Luxury consumption	Accumulation	Luxury consumption	Accumulation
G	T3	Deficiency	Limiting	Deficiency	Limiting
G	T4	Deficiency	Limiting	Dilution	Growth dilution
G	T5	Luxury consumption	Accumulation	Luxury consumption	Accumulation
H	T0	Control	Control	Control	Control
H	T1	Deficiency	Limiting	Deficiency	Limiting
H	T2	Deficiency	Limiting	Deficiency	Limiting
H	T3	Deficiency	Limiting	Deficiency	Limiting
H	T4	Deficiency	Limiting	Dilution	Growth dilution
H	T5	Deficiency	Limiting	Deficiency	Limiting

7.4.5.3 K

Field trials A and C had a suboptimal K:N ratio at the time of trial establishment, and fertiliser application seemed to correct the deficiency after 12 months, apart from treatment T1, which remained at a suboptimal ratio (Table 7.27). However, field trial A returned to suboptimal K:N ratios 24 months after treatment. The vector nomogram for field trial A showed an antagonistic effect of all treatments on canopy K content at 12 months after fertilisation, which coincided with the nutrient ratio assessment. At 24 months, the nomograms continued to illustrate antagonistic and K deficiencies across all treatments, with no discernible differences between the lower and higher fertiliser treatments. Field trials B and E exhibited suboptimal K:N ratios for the lower fertiliser treatments throughout the experimental period. The nomograms for field trial B showed a depletion (retranslocation) across all treatments at 12 months, and deficiencies

(limiting) at 24 months after fertilisation in all treatments, apart from treatment T2, which had a sufficiency of K at 24 months. Field trial F exhibited optimal K:N ratios at the time of establishment, and suboptimal ratios at 12 months. At 24 months, the lower fertiliser treatments exhibited suboptimal K:N ratios. The nomograms for this field trial showed antagonistic and deficiency effects for all treatments at 12 months, apart from treatment T2, which again had a sufficiency of K.

Table 7.27: Tsitsikamma nomograms of K for all field trials at 12 and 24 months after fertilisation. Cells demarcated as X represent a response in unit dry weight, nutrient concentration and nutrient content that did not match any of the interpretations defined by Haase and Rose (1995). For representative purposes, graphic illustrations of the highlighted cells are illustrated in Section 7.7.6, Figures 7.34 - 7.40.

Field trial	Treatment	K (12 months)		K (24 months)	
		Interpretation	Diagnosis	Interpretation	Diagnosis
A	T0	Control	Control	Control	Control
A	T1	Excess	Antagonistic	Excess	Antagonistic
A	T2	Excess	Antagonistic	Luxury consumption	Accumulation
A	T3	Depletion	Retranslocation	Deficiency	Limiting
A	T4	Excess	Antagonistic	Excess	Antagonistic
A	T5	Excess	Antagonistic	Excess	Antagonistic
B	T0	Control	Control	Control	Control
B	T1	Depletion	Retranslocation	Deficiency	Limiting
B	T2	Depletion	Retranslocation	Sufficiency	Steady state
B	T3	Depletion	Retranslocation	Deficiency	Limiting
B	T4	Depletion	Retranslocation	Deficiency	Limiting
B	T5	Dilution	Growth dilution	Deficiency	Limiting
C	T0	Control	Control	Control	Control
C	T1	X	X	X	X
C	T2	X	X	Excess	Antagonistic
C	T3	X	X	Excess	Antagonistic
C	T4	X	X	Excess	Antagonistic
C	T5	Luxury consumption	Accumulation	Depletion	Retranslocation
D	T0	Control	Control	Control	Control
D	T1	Depletion	Retranslocation	Deficiency	Limiting
D	T2	Depletion	Retranslocation	Depletion	Retranslocation
D	T3	Dilution	Growth dilution	Depletion	Retranslocation
D	T4	Depletion	Retranslocation	Deficiency	Limiting
D	T5	Dilution	Growth dilution	Deficiency	Limiting
E	T0	Control	Control	Control	Control
E	T1	Deficiency	Limiting	Deficiency	Limiting
E	T2	Depletion	Retranslocation	Deficiency	Limiting
E	T3	Deficiency	Limiting	Deficiency	Limiting
E	T4	Dilution	Growth dilution	Dilution	Growth dilution
E	T5	Deficiency	Limiting	Deficiency	Limiting
F	T0	Control	Control	Control	Control

Field trial	Treatment	K (12 months)		K (24 months)	
		Interpretation	Diagnosis	Interpretation	Diagnosis
F	T1	Excess	Antagonistic	Excess	Antagonistic
F	T2	Sufficiency	Steady state	Depletion	Retranslocation
F	T3	Excess	Antagonistic	Excess	Antagonistic
F	T4	X	X	Excess	Antagonistic
F	T5	Deficiency	Limiting	Depletion	Retranslocation
G	T0	Control	Control	Control	Control
G	T1	X	X	X	X
G	T2	Luxury consumption	Accumulation	Luxury consumption	Accumulation
G	T3	Dilution	Growth dilution	Deficiency	Limiting
G	T4	Deficiency	Limiting	Deficiency	Limiting
G	T5	Excess	Antagonistic	X	X
H	T0	Control	Control	Control	Control
H	T1	Depletion	Retranslocation	Deficiency	Limiting
H	T2	Deficiency	Limiting	Deficiency	Limiting
H	T3	Depletion	Retranslocation	Deficiency	Limiting
H	T4	Deficiency	Limiting	Dilution	Growth dilution
H	T5	Deficiency	Limiting	Deficiency	Limiting

7.4.5.4 *Cu*

All field trials exhibited suboptimal Cu:N ratios throughout the experimental period (represented by field trial B). The nomograms illustrate a slight shift towards sufficient (non-limiting) Cu quantities across all treatments at 12 and 24 months after fertilisation (Table 7.28). Responses were similar across treatments, apart from treatments T1, T3 and T4 in some instances. The control treatment is omitted in each case. This small shift was likely to offset the suboptimal/deficient Cu concentrations observed in all field trials.

Table 7.28: Tsitsikamma nomograms of Cu for all field trials at 12 and 24 months after fertilisation. Cells demarcated as X represent a response in unit dry weight, nutrient concentration and nutrient content that did not match any of the interpretations defined by Haase and Rose (1995). For representative purposes, graphic illustrations of the highlighted cells are illustrated in Figures 7.41 to 7.42 in Section 7.7.6.

Field trial	Treatment (12 months) T1, T2, T3, T4 & T5	Treatment (24 months) T1, T2, T3, T4 & T5
A	X	X
B	Sufficiency (steady state)	Sufficiency (steady state)
C	X	X
D	Sufficiency (steady state)	Sufficiency (steady state)
E	Sufficiency (steady state)	Sufficiency (steady state)
F	X	Sufficiency (steady state) T4-Excess (antagonistic)
G	X T3 & T4 – Dilution (growth dilution)	X T3 & T4 – Sufficiency (steady state)
H	X T1 & T3 – Dilution (growth dilution)	Sufficiency (steady state) T4 – Dilution (growth dilution) T3 – Deficiency (limiting)

7.4.6 Volume response to fertilisation

Field trials A, B, D and F were most responsive to the highest treatment combination of 200 kg N ha⁻¹ and 100 kg P ha⁻¹ (T5), with responses of 12, 13, 22 and 15% respectively. In addition, there was little difference between the treatments in field trial H, with a response of 8% for all N and P combinations. Field trials C and E were most responsive to a balanced application rate of 100 kg N ha⁻¹ and 100 kg P ha⁻¹ (T4), with responses of 15 and 5% respectively. Field trial G was most responsive to a higher N application rate of 100 kg N ha⁻¹, together with a reduced rate of 50 kg P ha⁻¹ (T3) (Table 7.29). In most instances, field trials were most responsive to the highest N-P fertiliser combination.

Table 7.29: Most responsive N and P treatment combination for each field trial. Responses standardised as percentage of the control treatment.

Site	Most responsive treatment	Volume response (%)
A	T5	12
B	T5	13
C	T4	15
D	T5	22
E	T4	5
F	T5	15
G	T3	13
H	T3, T4 & T5	8

7.5 Discussion

The leaf area indices showed a slight increase in most sites over the experimental period (Figures 7.21), apart from field trials A and D. In addition, the significant effect of the fertiliser treatments on the N and P contents, together with the alleviation of critical-level deficiencies observed in several of the field studies (Section 7.7.3), showed that fertilisation had an effect on the uptake of N and P. As in this study, Zhang and Allen (1996) and Choonsig *et al.* (2013) observed larger N concentrations in the foliage of fertilised trees. Applications of N can increase foliar N concentrations by 30% in *P. taeda* trees (Murthy, Dougherty & Allen, 1996). A review by Yuan and Chen (2015) reported N and P increases of 27% and 73% in the green plant foliage of boreal, temperate, sub-tropical and tropical forest types following combined applications of N and P in several forest and ecosystem types. The critical nutrient analysis revealed P to be most limiting for nearly all the tested fertilisation rates. However, the vector analyses illustrated that fertilisation induced a temporary shift in foliar N. This was apparent in field trials C and F; these field trials exhibited a temporary increase in N up to 12 months after treatment, and exhibited deficiencies for the lower treatments. However, at 24 months, foliar N shifted to deficiencies in field trial F relative to the control for all treatments. Field trials D, E and F were established on waterlogged plinthic and podzolic soils (Table 3.1). In addition, field trials A, B, D, G and H exhibited a shift type that showed that fertilisation did not address the deficiency after 24 months. All these field trials were established on plinthic soils with higher water-retention capabilities. The SNAP model predicted the highest annual N mineralisation rate for field trial A, followed by B, with mineralisation rates of 238 and 103 kg

$\text{N ha}^{-1} \text{ year}^{-1}$ respectively (Figure 5.11). The nutrient ratio assessment showed suboptimal P:N ratios across all field trials at the time of establishment. Most field trials responded with increased P:N ratios at 12 months for the higher fertilisation rates, except for field trials D, E and F, which exhibited suboptimal ratios in response to larger fertilisation rates. Jokela (2004) attribute the decreases in foliar P and Mg to the dilution effect of the growth responses induced by N fertilisation. Field trial A exhibited optimum P:N ratios at 12 months after fertilisation across all treatments (apart from the control), although the effect was temporary and P:N ratios reverted back to suboptimal ratios at 24 months. Foliar P:N ratios remained suboptimal in field trial D throughout the experimental period. Field trial D was established on a plinthic soil and had a high incidence of under-canopy ferns throughout the experimental period. As in the case of N, the vector analyses illustrated the temporary and variable effect of fertilisation on foliar P quantities. Zhang and Allen (1996) observed decreased foliar P concentrations following N fertilisations in an 11-year-old *P. radiata* stand. Increased applications of N can decrease the P:N, K:N and Mg:N ratios in *Picea abies* (Linder, 1995) and the ratio of P:N in semi-mature *P. taeda* (Adams and Allen, 1985). In addition, Zhang and Allen (1996) found that N fertilisations increased foliar Ca, decreased Mg and had no effect on foliar K concentrations. The vector analyses illustrated an antagonistic effect of foliar K at 12 months across most field trials; as in the case of P, these increases were temporary, and there were few observable differences between treatments. Combined applications of N and P can have negative effects on the resorption efficiencies of plants (Yuan & Chen, 2015), and increases in foliar Ca concentrations can also be attributed to the immobility of the nutrient; Ca tends to accumulate in older needles and Mg decreases (Aronsson & Elowson, 1980; Helmisaari, 1990).

The canopy N contents differed significantly between field studies and increased with larger fertilisation rates; the increases were also a product of time after fertilisation. The mean N content exhibited a slight decrease into the second year after fertilisation, although the variability observed for the leaf area indices suggests that the N contents were likely maintained into the second year. The canopy P contents were higher for treatment T2, and this treatment contained no supplementary N. The remaining treatments, excluding the control, had similar P contents after 24 months. As in the case of N, the increased P contents were a product of time and exhibited a slight decrease into the second year after fertilisation. This small decrease also suggests that the canopy P content was maintained into the second year after fertilisation. Aronsson and Elowson (1980) observed increased foliar N contents after the fertilisation of a young Scots pine stand. Zhang and Allen (1996) reported decreased foliar P concentrations

following the fertilisation of an 11-year-old *P. radiata* stand, although fertilisation increased the P content. The findings of this study suggest that the response of foliar N, P and K to fertilisation is more likely a function of site-specific edaphic and topographical differences, rather than fertilisation rates. In addition, the N:P ratio might affect the availabilities of foliar P and K, and a balanced ratio is suggested. Different soil and climatic conditions significantly affect fertilisation practices across regions (Birk, 1995). The fertilisation of conifer stands can significantly increase growth (Albaugh *et al.*, 1998; Carlyle, 1998; Jokela & Martin, 2000; Pinno, Lieffers & Landhäusser., 2012), although the responses are highly variable (Pinno *et al.*, 2012). The large variation observed by Pinno *et al.* (2012) was attributed to a lack of nutrient uptake after fertilisation. In addition, Carlyle (1998) attributed the observed growth responses to the increased uptake of N that was facilitated by the increased leaf area index to fertilisation. Ramírez Alzate *et al.* (2016) observed site-specific responses of semi-mature *P. radiata* to fertilisation. Three sites with different parent materials, water and nutrient availabilities were subjected to fertiliser applications and the largest growth responses were observed in granitic and sandy soils at eight years after fertilisation. The authors attributed the growth variations to soil textural differences and the different nutrient availabilities of each soil type; the studied red-clay soils with higher nutrient availabilities were less responsive to fertilisation. Albaugh *et al.* (1998) hypothesised that the growth responses to fertilisation and irrigation can be attributed to increased biomass partitioning in foliage and less to fine root development. Sikström, Nohrstedt, Pettersson and Jacobson (1998) observed growth responses of 11 to 104% for *P. sylvestris* stands five years after fertilisation. Stands were spread out across 28 sites and no relationships were observed between the growth responses and site characteristics.

Foliage was sampled at a mid-crown position due to accessibility and height restrictions. Crown positioning significantly affects nutrient concentrations (Madgwick & Mead, 1990) and nutrients have different mobilities (Zhang & Allen, 1996). Foliar N, P and K tends to accumulate in the apical region of a tree (Madgwick, 1964). Zhang and Allen (1996) suggested foliar samples be collected from one-year-old foliage at mid-crown position due to potential overestimations at a higher crown positions. The latter authors observed larger nutrient contents in new foliage, and the contents increased with needle elongation over time. The authors studied the effect of N fertilisations on the nutrient dynamics of an 11-year-old *P. taeda* stand at different foliage ages and crown locations.

Nutrient availability appeared to be the greatest growth-limiting variable in the slash pine stands of the Tsitsikamma region, rather than water availability (Chapter 4). Furthermore, in this study, nutrient availability seemed to depend on the site-specific edaphic properties of each field trial. The field trials were categorised, in descending order, according to the annual N mineralisation rate predicted by the SNAP model (Chapter 5). Field trial A had the highest annual N mineralisation rate, followed by the remaining field trials (Figure 5.11). In addition, significant correlations were observed between the predicted annual N mineralisation rate and soil acidity (Figure 5.12). Field trial A had the highest soil pH, with a value of 4, but was still considered highly acidic. As in this study, Jokela *et al.* (2004) found that nutrient availability has a greater effect on *P. taeda* yield than water availability. At the time of trial establishment, field trials A, C, E and G had smaller soil P concentrations, and the critical ratio assessment showed suboptimal and variable P:N ratios for all treatments across all field trials after 24 months, except for trials B and G. In addition, the soils in this study had low K concentrations (Table 3.2), and this was reflected in the K:N ratios at the time of trial establishment. Field trials B, E, F and G exhibited optimal K:N ratios at 24 months for the higher fertiliser treatments. Plant-available Zn is higher in moderately acidic soils (Moraghan & Mascagni, 1991), and one of the largest Zn limitations in soils is due to the similar ionic radii shared by Zn^{2+} , Fe^{2+} and Mg^{2+} , which compete for plant uptake and the replacement on the mineral surface (Mengel & Kirby, 2001). The critical-level assessment showed that foliar Fe concentrations were deficient for most treatments throughout the experimental period. Acidic soil conditions favour Fe solubility, although it is plausible that the Fe concentrations in the soils were low and that the acidic soil conditions, which favour solubility, could not sufficiently supply Fe. In addition, the waterlogged soil conditions likely increased the loss of Fe in the soil by means of reduction. Nearly all treatments exhibited deficient foliar Cu concentrations at 12 months after fertilisation, although most of the treatments across all field trials were approximately 1 mg kg^{-1} short of adequate levels. The vector analyses illustrated sufficient quantities of foliar Cu relative to the control treatments at both time intervals. Foliar Cu concentrations are directly related to soil pH and decrease significantly at lower soil pH values (North Carolina State University Forest Nutrition Cooperative [NCSUFNC], 1991). A probable explanation for the Cu deficiencies in this study is that the acidic soil conditions increased the solubility of Cu and, over time, the Cu leached from the soils. The soils in this study are sandy loams, and Cu deficiencies are more likely to occur in sands developed from sandy and/or sandstone parent materials (Moraghan & Mascagni, 1991). The application of N fertiliser could have stimulated soil microbial activity and, as a result, increased the availability of Cu from

the increased activity in the soil organic fraction. Lastly, the low Cu values reported in this study could also be attributed to the accuracy of the analytical methodology used in the study, as a small degree of irregularities can be expected when small concentrations are measured. Site variations largely attributed to the findings of this study and Pinno *et al.* (2012) found that site factors and pre-treated foliar estimates, such as of nutrient concentrations, ratios and thresholds, are unreliable predictors due to the variable growth responses often observed in conifer species.

7.6 Conclusion

The fertilisation of semi-mature pine stands has the potential to increase forest/plantation yields, but the responses are variable and not easily projected. Several factors, such as the edaphic properties, genotype, pest and disease incidence, and the incidence of under-canopy vegetation of a site, may significantly affect the growth response to fertilisation. This sub-study showed that supplementary N and P fertilisations are significantly affected by edaphic and topographical site differences. Nitrogen and P fertilisations have the potential to alleviate foliar deficiencies in the Tsitsikamma, although nutrient imbalances are probable from higher application rates, and the large edaphic variations between sites can significantly affect the feasibility of mid-rotation fertilisation. Macronutrient availabilities seemed to increase temporarily and reverted to suboptimal levels within approximately two years. This effect could be attributed to the seasonality (time of sampling and growing season), the drought experienced throughout the experimental period, or site-specific edaphic properties such as N mineralisation rates. Water availability does not seem to be a limiting factor in the Tsitsikamma, although the strongly acidic soil conditions could be attributing to the poor plant availabilities of several nutrients observed in this study. The findings of this sub-study, together with the findings of Chapter 5 regarding the effect of soil pH on the N mineralisation potential of the soil, support the conclusion that lime application should be investigated in this region to understand its effect on the stimulation of nutrient mineralisation rates. Lime applications should perhaps be investigated in combination with N, P and trace element fertiliser treatments. The low foliar levels of Fe, Cu and Zn further indicate that cationic micronutrient nutrition should be one of the focus areas of future nutritional studies in the region.

Even though the growth responses between the control, relative to the two highest fertiliser treatments (T4 and T5), were significantly different at 24 months after fertilisation, the difference in volume increases was not as high as initially expected between treatments. This suggests that similar or improved growth responses are achievable with smaller amounts of

fertiliser. More specifically, application rates like that of treatment T5 (200 kg N ha⁻¹ and 100 kg P ha⁻¹) can be reduced to that of T4 (100 kg N ha⁻¹ & 100 kg P ha⁻¹) on most sites. Simple site-specific edaphic properties such as soil pH, total N, sand and silt content (soil water retention – soil WD) should be incorporated into the decision-making process. The effect of increasingly complex variables, such as modelled N mineralisation (SNAP model) and aerobic and anaerobic N and P mineralisation rates, on the volume increment of sites in the Cape Forest Region after fertilisation should be incorporated, although further investigation is recommended due to the site-specific results observed in this study.

7.7 Appendices

7.7.1 Leaf area index

Appendix 1: Full dataset for leaf area index across all sites.

Site	Plot	Time after fertilisation (months)								
		0	3	6	9	12	15	18	21	24
A	1	2.96	3.63	3.63	3.93	3.35	2.77	3.45	3.60	3.69
A	2	3.10	3.48	4.31	4.24	3.80	3.37	3.86	4.09	4.26
A	3	2.89	2.90	4.14	4.28	3.78	3.28	3.93	4.17	4.35
A	4	3.32	3.11	4.00	4.26	3.90	3.53	3.78	3.99	4.14
A	5	2.97	3.61	4.46	4.47	4.01	3.55	4.10	4.37	4.57
A	6	3.12	2.88	4.13	4.03	3.80	3.56	3.96	4.21	4.39
A	7	3.52	3.28	4.22	4.17	3.89	3.62	4.08	4.35	4.56
A	8	3.36	2.58	4.07	4.32	4.20	4.07	4.39	4.71	4.97
A	9	3.55	3.47	4.89	4.68	4.45	4.22	4.58	4.94	5.23
A	10	3.33	3.14	4.39	4.16	3.86	3.56	4.18	4.47	4.69
A	11	3.52	2.70	4.69	4.54	4.13	3.71	4.39	4.71	4.97
A	12	3.32	3.00	4.04	4.39	4.06	3.74	3.91	4.14	4.31
B	1	4.43	3.17	4.14	3.04	3.27	3.51	4.13	5.28	6.35
B	2	4.30	2.30	3.39	2.87	2.95	3.04	3.49	4.53	5.48
B	3	3.15	3.27	3.23	3.05	3.29	3.53	3.49	4.53	5.48
B	4	3.72	3.10	3.99	3.04	3.16	3.28	3.75	4.84	5.84
B	5	3.11	2.98	3.38	2.75	3.03	3.31	3.09	4.05	4.94
B	6	4.30	3.67	3.45	3.19	3.38	3.57	3.44	4.46	5.41
B	7	3.10	2.68	3.20	2.72	2.77	2.82	3.35	4.36	5.30
B	8	3.25	2.68	3.16	2.87	2.85	2.83	3.92	5.04	6.07
B	9	4.09	3.25	3.97	3.39	3.53	3.67	3.93	5.05	6.08
B	10	4.59	3.54	3.57	3.68	3.80	3.91	3.91	5.02	6.05
B	11	3.92	2.93	4.14	3.85	4.06	4.26	4.22	5.40	6.48
B	12	4.19	3.29	3.77	3.51	3.80	4.10	4.00	5.14	6.18
C	1	4.72	3.98	4.25	3.84	5.11	6.39	4.61	5.61	6.52
C	2	5.26	3.21	4.03	3.96	5.27	6.58	4.55	5.55	6.45
C	3	4.36	2.72	4.11	3.86	5.14	6.42	5.00	6.07	7.05
C	4	5.03	3.25	4.21	3.51	4.72	5.93	4.32	5.27	6.13
C	5	3.55	3.72	4.57	3.96	4.99	6.02	4.87	5.93	6.88
C	6	4.67	3.91	4.76	4.17	5.13	6.09	4.65	5.66	6.58
C	7	5.21	4.20	4.69	4.26	4.74	5.22	4.93	5.99	6.95
C	8	5.62	4.11	4.75	4.29	5.40	6.50	5.33	6.47	7.50
C	9	5.04	4.18	4.47	3.91	5.26	6.62	4.61	5.61	6.52
C	10	5.08	3.62	5.01	4.51	5.31	6.10	5.20	6.32	7.33
C	11	5.03	4.28	4.76	3.77	5.12	6.47	4.98	6.06	7.03
C	12	5.41	3.90	5.00	4.55	5.65	6.75	5.12	6.22	7.22
D	1	5.14	4.71	4.58	4.25	4.13	4.00	3.04	3.39	3.70

D	2	4.89	4.24	5.60	4.36	4.72	5.08	3.57	4.03	4.43
D	3	4.64	3.97	4.98	5.09	4.45	3.81	3.93	4.46	4.92
D	4	5.65	4.38	5.33	4.71	4.58	4.46	3.97	4.51	4.97
D	5	4.88	3.96	5.01	4.75	4.51	4.28	3.23	3.62	3.96
D	6	4.42	3.35	4.94	4.20	4.61	5.02	3.62	4.08	4.49
D	7	4.10	3.41	4.89	4.21	4.95	5.70	3.66	4.13	4.54
D	8	4.43	4.08	5.58	5.01	5.38	5.75	3.42	3.85	4.22
D	9	4.25	4.12	5.59	5.02	4.60	4.17	4.20	4.77	5.27
D	10	4.53	5.25	4.94	5.44	5.68	5.92	4.03	4.58	5.05
D	11	4.28	4.30	4.84	4.87	5.17	5.46	3.67	4.15	4.56
D	12	4.14	4.14	5.04	4.64	5.20	5.75	4.26	4.86	5.37
E	1	3.36	5.35	4.84	3.92	5.37	6.82	5.05	5.03	4.93
E	2	3.18	4.17	4.25	3.88	4.24	4.61	4.24	4.06	3.82
E	3	3.74	4.37	4.58	4.73	4.93	5.13	4.47	4.34	4.14
E	4	5.11	4.14	4.93	4.26	4.40	4.53	5.00	4.96	4.85
E	5	3.32	3.26	4.77	4.66	4.65	4.64	4.61	4.50	4.33
E	6	3.65	4.34	4.76	4.98	5.26	5.55	4.15	3.96	3.71
E	7	2.82	4.56	5.29	4.50	4.96	5.42	4.72	4.63	4.48
E	8	4.14	4.61	5.56	4.93	5.39	5.85	4.72	4.63	4.48
E	9	3.03	3.52	5.31	4.93	4.39	3.85	4.65	4.55	4.38
E	10	3.01	4.94	4.80	4.60	5.31	6.02	4.43	4.29	4.08
E	11	3.32	4.27	5.05	4.42	5.22	6.03	4.89	4.83	4.70
E	12	2.36	3.27	4.68	4.58	4.62	4.65	4.65	4.55	4.38
F	1	3.37	1.68	4.98	4.60	5.38	6.17	5.26	5.82	6.28
F	2	2.85	3.52	4.65	3.78	4.53	5.27	4.72	5.18	5.55
F	3	3.08	3.40	4.14	3.96	4.77	5.58	4.54	4.96	5.31
F	4	2.56	3.69	4.53	4.37	4.84	5.31	4.35	4.73	5.05
F	5	3.33	4.77	4.51	4.35	4.84	5.33	4.61	5.05	5.40
F	6	4.03	4.89	4.83	4.15	5.04	5.93	5.02	5.54	5.97
F	7	3.30	2.99	3.81	3.56	4.55	5.55	4.15	4.50	4.78
F	8	3.74	4.04	4.76	3.92	4.82	5.71	4.95	5.46	5.87
F	9	3.50	4.01	4.39	3.92	4.14	4.36	4.91	5.41	5.81
F	10	2.72	3.30	4.10	3.88	3.60	3.33	4.40	4.80	5.12
F	11	4.19	4.41	4.66	4.47	4.91	5.35	5.31	5.88	6.36
F	12	2.87	3.29	3.93	3.77	4.12	4.47	4.40	4.80	5.12
G	1	6.31	5.46	6.06	5.18	6.11	7.04	5.88	7.13	8.25
G	2	7.77	5.92	5.31	5.29	5.75	6.22	5.74	6.96	8.06
G	3	7.10	5.35	5.53	4.58	6.20	7.81	5.19	6.31	7.31
G	4	6.79	5.86	5.84	5.27	6.13	7.00	6.04	7.32	8.48
G	5	6.16	4.95	5.16	5.02	5.59	6.15	5.67	6.88	7.97
G	6	7.03	5.51	5.78	5.13	5.48	5.82	6.10	7.39	8.55
G	7	6.13	5.47	6.20	5.27	5.32	5.37	5.48	6.65	7.71
G	8	6.45	5.70	5.75	5.31	6.27	7.23	5.46	6.63	7.69
G	9	6.17	5.58	5.64	5.16	5.80	6.44	5.04	6.12	7.11
G	10	5.94	5.91	5.41	5.40	6.49	7.59	5.56	6.75	7.82

G	11	5.44	5.88	6.18	5.30	6.05	6.80	5.84	7.08	8.20
G	12	5.88	6.00	5.88	5.15	6.84	8.53	5.63	6.83	7.91
H	1	3.91	4.50	5.49	4.80	5.40	5.99	4.91	5.31	5.62
H	2	5.04	6.02	5.56	5.48	5.72	5.96	5.27	5.74	6.11
H	3	4.99	5.18	4.87	4.61	5.26	5.91	5.27	5.74	6.11
H	4	4.02	4.05	4.36	4.44	4.20	3.96	4.50	4.82	5.06
H	5	4.19	5.90	5.42	5.13	5.55	5.96	5.24	5.70	6.07
H	6	4.82	5.17	5.12	5.11	5.39	5.67	5.12	5.56	5.90
H	7	3.62	4.66	5.40	5.05	4.79	4.53	4.58	4.92	5.17
H	8	4.28	5.75	5.42	4.89	5.60	6.31	4.73	5.10	5.38
H	9	4.59	5.92	5.71	4.97	5.59	6.21	5.09	5.52	5.87
H	10	3.55	2.89	4.08	3.91	4.04	4.18	4.65	5.00	5.27
H	11	3.19	4.71	4.21	4.55	4.69	4.82	4.72	5.08	5.36
H	12	3.84	4.97	4.51	4.39	5.04	5.69	5.38	5.87	6.26

7.7.2 Volume responses

Appendix 2: Fertiliser responses of treatments at each time interval.

Field trial	T0	T1	T2	T3	T4	T5
6 months						
A	13 ± 0.63	11 ± 0.67	11 ± 0.66	13 ± 0.66	12 ± 0.97	10 ± 0.77
B	21 ± 1.04	13 ± 0.74	12 ± 0.71	12 ± 0.76	17 ± 0.81	20 ± 0.92
C	18 ± 1.18	20 ± 1.14	17 ± 0.88	18 ± 0.96	19 ± 1.02	19 ± 0.96
D	26 ± 1.46	25 ± 1.64	29 ± 2.25	26 ± 2.05	27 ± 2.18	30 ± 2.16
E	19 ± 0.99	17 ± 0.86	18 ± 1.13	19 ± 1.31	19 ± 1.15	19 ± 0.98
F	17 ± 1.11	16 ± 1.08	17 ± 1.12	19 ± 1.63	20 ± 1.13	17 ± 1.06
G	21 ± 0.98	23 ± 0.84	24 ± 0.92	24 ± 1.24	22 ± 0.98	23 ± 1.01
H	15 ± 1.03	14 ± 0.77	12 ± 0.83	13 ± 0.85	14 ± 1.11	13 ± 0.84
12 months						
A	15 ± 0.69	15 ± 0.71	14 ± 0.72	16 ± 0.71	15 ± 1.06	14 ± 0.89
B	26 ± 1.06	19 ± 0.88	18 ± 0.91	19 ± 0.85	25 ± 0.93	27 ± 1.05
C	21 ± 1.45	23 ± 1.27	21 ± 1.12	21 ± 1.13	23 ± 1.21	22 ± 1.18
D	35 ± 1.49	35 ± 2.15	37 ± 2.56	36 ± 2.42	35 ± 2.44	40 ± 2.59
E	24 ± 1.04	21 ± 0.99	24 ± 1.20	25 ± 1.46	23 ± 1.26	26 ± 1.29
F	23 ± 1.34	23 ± 1.38	23 ± 1.41	27 ± 1.98	27 ± 1.56	25 ± 1.30
G	26 ± 1.14	27 ± 0.90	28 ± 1.13	30 ± 1.48	27 ± 1.00	29 ± 1.14
H	20 ± 1.35	20 ± 1.20	19 ± 1.06	20 ± 1.11	20 ± 1.35	19 ± 1.29
18 months						
A	21 ± 0.84	19 ± 0.85	19 ± 0.89	21 ± 1.00	21 ± 1.41	22 ± 1.66
B	34 ± 1.27	25 ± 1.09	26 ± 1.13	26 ± 1.18	35 ± 1.24	36 ± 1.43

C	31 ± 1.88	33 ± 1.68	31 ± 1.48	32 ± 2.58	34 ± 1.79	32 ± 1.61
D	42 ± 1.91	44 ± 2.83	49 ± 3.45	48 ± 3.39	47 ± 3.28	56 ± 3.58
E	36 ± 1.51	34 ± 1.40	36 ± 1.48	37 ± 1.83	36 ± 1.74	40 ± 1.84
F	37 ± 2.10	37 ± 1.95	36 ± 1.94	41 ± 2.65	42 ± 2.34	41 ± 2.05
G	38 ± 1.39	42 ± 1.38	41 ± 1.34	44 ± 1.87	38 ± 1.35	41 ± 1.49
H	28 ± 1.63	29 ± 1.42	28 ± 1.31	29 ± 1.45	30 ± 1.80	29 ± 1.68
24 months						
A	26 ± 1.64	27 ± 2.47	24 ± 1.11	26 ± 1.17	25 ± 1.47	28 ± 1.61
B	43 ± 2.55	30 ± 1.17	33 ± 1.35	33 ± 1.48	42 ± 1.40	46 ± 2.00
C	36 ± 2.24	38 ± 1.94	37 ± 1.74	36 ± 2.62	40 ± 2.18	36 ± 1.68
D	53 ± 2.52	52 ± 3.09	58 ± 3.94	55 ± 3.66	56 ± 3.72	63 ± 3.64
E	41 ± 1.63	38 ± 1.54	42 ± 1.78	42 ± 1.96	43 ± 1.79	46 ± 2.01
F	44 ± 2.16	46 ± 2.86	43 ± 2.00	49 ± 2.96	49 ± 2.46	50 ± 2.38
G	42 ± 1.47	48 ± 1.38	46 ± 1.63	48 ± 1.96	44 ± 1.55	45 ± 1.59
H	34 ± 1.87	36 ± 1.78	34 ± 1.50	37 ± 1.82	37 ± 2.09	37 ± 2.05

7.7.3 Foliar nutrient concentrations

Appendix 3: Foliage nutrient concentrations for each site at the time of trial establishment (2015). Sub-optimal concentrations are shown in red.

Site	Treatment	N	P	K	Ca	Mg	mg kg ⁻¹					
							Na	Mn	Fe	Cu	Zn	B
A	T0	1.08	0.05	0.24	0.28	0.17	378	69.5	57	1.5	5	18.5
A	T1	1.11	0.07	0.28	0.93	0.33	235	220	75	3	9	25
A	T2	1.01	0.06	0.26	1.49	0.43	268	241	113	3	14	25
A	T3	1.10	0.06	0.26	0.59	0.31	516	101	73	2	7	30
A	T4	1.14	0.07	0.30	0.60	0.33	630	240	86	3	11	30
A	T5	1.19	0.08	0.32	0.59	0.29	442	190	90	3	11	34
B	T0	1.00	0.04	0.25	0.35	0.14	824	129	48	1.5	5	12.5
B	T1	0.84	0.05	0.27	0.62	0.18	1763	129	80	2	10	16
B	T2	0.81	0.04	0.33	0.66	0.16	1907	173	100	2	9	11
B	T3	0.87	0.04	0.34	0.47	0.15	1981	112	95	2	10	13
B	T4	1.11	0.05	0.25	0.50	0.23	1590	398	84	3	12	15
B	T5	0.91	0.06	0.47	0.71	0.21	890	94	53	2	9	11
C	T0	1.01	0.06	0.36	0.30	0.18	212.5	124	60.5	1.5	8.5	18.5
C	T1	0.95	0.08	0.41	0.74	0.25	390	118	65	2	11	15
C	T2	0.90	0.08	0.39	1.01	0.22	524	309	58	2	14	24
C	T3	0.93	0.08	0.37	0.64	0.22	383	145	47	2	12	20
C	T4	0.99	0.07	0.32	0.49	0.19	249	145	41	2	11	25
C	T5	0.94	0.07	0.37	0.94	0.26	475	156	57	2	16	28
D	T0	0.85	0.05	0.22	0.44	0.19	941	116	61.5	1	4	14

D	T1	1.04	0.06	0.22	1.05	0.19	1328	292	104	2	11	32
D	T2	0.92	0.06	0.25	0.69	0.24	1655	146	109	2	10	29
D	T3	0.90	0.06	0.30	0.88	0.28	1271	134	132	3	8	19
D	T4	0.87	0.05	0.23	0.79	0.24	1228	90	97	2	6	18
D	T5	0.81	0.05	0.24	0.98	0.44	767	243	125	2	9	22
E	T0	1.07	0.06	0.34	0.25	0.12	270.5	84.5	37	2	10	18
E	T1	0.99	0.07	0.52	0.43	0.18	341	74	43	2	14	18
E	T2	0.93	0.07	0.55	0.52	0.11	239	55	41	3	11	13
E	T3	0.94	0.06	0.38	0.65	0.30	400	129	57	2	8	23
E	T4	0.67	0.06	0.28	1.26	0.23	942	191	55	2	5	17
E	T5	1.16	0.07	0.40	0.52	0.16	245	117	59	3	10	21
F	T0	1.08	0.06	0.60	0.20	0.09	258.5	56.5	34.5	2	5.5	15
F	T1	0.82	0.07	0.56	0.73	0.14	818	123	60	2	6	19
F	T2	1.07	0.09	0.57	0.62	0.18	378	136	52	2	8	17
F	T3	1.10	0.06	0.39	0.61	0.18	446	114	45	2	8	23
F	T4	0.97	0.07	0.40	0.64	0.21	314	134	48	2	8	17
F	T5	1.00	0.08	0.50	0.43	0.16	218	147	46	2	8	15
G	T0	0.89	0.05	0.31	0.61	0.16	255	118	43	2	5	15
G	T1	1.00	0.07	0.51	0.66	0.19	407	152	41	2	8	25
G	T2	1.23	0.07	0.41	0.77	0.19	257	233	47	3	11	24
G	T3	1.37	0.08	0.46	0.63	0.19	227	198	42	2	12	24
G	T4	1.14	0.07	0.41	0.96	0.25	275	211	45	3	10	17
G	T5	1.08	0.06	0.29	0.74	0.22	292	183	46	2	9	23
H	T0	1.15	0.05	0.48	0.30	0.09	143	184	37	2	9	15
H	T1	1.08	0.06	0.38	0.72	0.20	815	299	96	2	12	28
H	T2	1.06	0.05	0.52	0.54	0.18	353	184	59	3	11	16
H	T3	1.12	0.06	0.42	0.66	0.19	264	676	58	3	14	23
H	T4	1.47	0.06	0.39	0.61	0.14	467	342	65	3	15	29
H	T5	1.39	0.04	0.35	0.62	0.16	462	224	130	2	8	17

Appendix 4: Foliage nutrient concentrations for each N and P combination at one year after treatment implementation (2016). Sub-optimal concentrations are shown in red.

Site	Treatment	N	P	%			mg kg ⁻¹					
				K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
A	T0	0.98	0.08	0.49	0.55	0.17	315	152	29	1	10	20
A	T1	1.14	0.12	0.35	0.61	0.18	300	172	26	1	9	23
A	T2	1.02	0.20	0.47	0.79	0.21	432	170	36	1	9	26
A	T3	1.12	0.13	0.43	0.76	0.17	419	155	31	1	9	21
A	T4	1.09	0.11	0.42	0.62	0.16	406	136	27	1	10	18
A	T5	1.21	0.13	0.48	0.53	0.17	288	113	27	1	10	22
B	T0	0.95	0.07	0.44	0.61	0.20	1096	286	38	1	12	14
B	T1	0.86	0.09	0.32	0.67	0.18	1049	118	43	1	9	14
B	T2	1.01	0.21	0.31	0.7	0.16	1286	240	57	1	9	13

B	T3	0.89	0.09	0.40	0.55	0.13	1276	102	43	1	14	12
B	T4	0.96	0.11	0.37	0.72	0.16	1009	177	45	1	11	14
B	T5	1.14	0.11	0.42	0.81	0.18	933	113	36	1	9	13
C	T0	0.98	0.09	0.34	0.75	0.19	419	212	80	1	15	30
C	T1	0.92	0.13	0.43	0.73	0.22	555	108	49	1	11	20
C	T2	0.97	0.14	0.40	0.65	0.21	490	175	32	1	9	27
C	T3	0.96	0.11	0.40	0.61	0.15	356	83	30	1	8	15
C	T4	1.06	0.14	0.44	0.54	0.15	273	145	29	1	18	21
C	T5	1.08	0.15	0.39	0.78	0.18	455	118	36	1	19	19
D	T0	1.05	0.11	0.35	0.66	0.24	583	81	80	1	9	21
D	T1	1.07	0.1	0.31	0.60	0.22	490	155	55	1	11	18
D	T2	0.95	0.12	0.26	0.57	0.24	528	96	57	1	11	16
D	T3	1.04	0.09	0.34	0.45	0.20	580	116	51	1	12	20
D	T4	1.3	0.13	0.28	0.63	0.23	489	103	63	1	11	20
D	T5	1.48	0.11	0.31	0.41	0.18	606	106	78	1	12	25
E	T0	1.06	0.08	0.43	0.51	0.15	282	124	28	1	12	23
E	T1	0.99	0.12	0.50	0.63	0.17	442	92	36	1	8	18
E	T2	1.00	0.13	0.37	0.77	0.18	411	126	30	1	10	20
E	T3	1.12	0.11	0.48	0.62	0.14	429	115	27	1	10	21
E	T4	0.96	0.16	0.45	0.81	0.17	553	158	34	1	9	21
E	T5	1.12	0.11	0.53	0.44	0.14	404	97	26	1	11	19
F	T0	0.98	0.07	0.29	0.74	0.21	984	106	45	1	9	14
F	T1	0.91	0.09	0.27	0.98	0.21	1333	92	78	1	7	17
F	T2	0.92	0.11	0.29	0.71	0.22	900	123	53	1	8	16
F	T3	0.95	0.08	0.28	0.96	0.26	1341	149	59	1	6	20
F	T4	0.89	0.08	0.30	0.67	0.18	1714	88	68	1	6	17
F	T5	1.09	0.11	0.40	0.70	0.23	989	174	62	1	10	16
G	T0	0.83	0.10	0.43	0.68	0.17	398	59	31	1	8	13
G	T1	1.07	0.15	0.46	0.66	0.18	258	133	28	1	9	23
G	T2	1.03	0.15	0.49	0.73	0.17	271	194	27	1	11	22
G	T3	1.08	0.13	0.42	1.06	0.15	425	236	34	1	8	28
G	T4	1.13	0.2	0.48	0.91	0.24	258	269	25	1	10	26
G	T5	1.21	0.13	0.40	0.90	0.16	351	140	27	1	8	21
H	T0	1.21	0.07	0.56	0.41	0.11	343	175	34	2	16	18
H	T1	0.90	0.10	0.52	0.60	0.17	420	260	49	1	14	22
H	T2	1.26	0.16	0.57	0.46	0.11	419	196	42	2	17	23
H	T3	1.05	0.09	0.37	0.73	0.22	759	296	87	1	13	27
H	T4	1.14	0.16	0.59	0.58	0.13	389	307	34	1	15	19
H	T5	1.48	0.16	0.67	0.60	0.12	318	290	38	2	15	33

Appendix 5: Foliage nutrient concentrations for each N and P combination at two years after treatment implementation (2017). Sub-optimal concentrations are shown in red.

Site	Treatment	N	P	K	Ca	Mg	mg kg ⁻¹					
							Na	Mn	Fe	Cu	Zn	B
A	T0	1.04	0.06	0.29	0.46	0.18	679	137	89	2	10	20
A	T1	1.05	0.08	0.25	0.45	0.22	440	133	76	2	10	17
A	T2	1.10	0.09	0.36	0.50	0.23	369	151	83	2	9	17
A	T3	1.19	0.10	0.30	0.44	0.22	248	148	73	2	12	19
A	T4	1.16	0.09	0.23	0.36	0.18	420	63	66	2	12	13
A	T5	1.33	0.10	0.23	0.29	0.20	536	134	66	2	17	15
B	T0	0.86	0.05	0.33	0.46	0.17	1107	210	74	2	10	13
B	T1	0.89	0.08	0.43	0.37	0.14	646	102	55	2	10	13
B	T2	0.98	0.13	0.33	0.49	0.18	589	188	63	2	19	14
B	T3	1.01	0.11	0.41	0.39	0.18	390	111	54	2	18	16
B	T4	1.01	0.12	0.43	0.45	0.15	862	167	73	2	13	14
B	T5	0.97	0.10	0.35	0.51	0.20	567	188	56	2	12	18
C	T0	0.96	0.08	0.35	0.49	0.17	292	127	50	2	12	17
C	T1	1.03	0.12	0.44	0.53	0.17	340	164	44	2	11	16
C	T2	0.89	0.09	0.30	0.78	0.23	698	119	48	2	7	20
C	T3	0.93	0.08	0.31	0.72	0.19	350	202	46	1	8	24
C	T4	0.94	0.11	0.38	0.49	0.16	396	110	41	2	18	14
C	T5	1.02	0.09	0.34	0.59	0.21	327	188	41	2	18	21
D	T0	0.82	0.06	0.26	0.63	0.21	1384	179	89	2	9	13
D	T1	1.04	0.10	0.35	0.55	0.20	831	174	84	2	10	17
D	T2	0.87	0.10	0.23	0.58	0.24	1175	119	90	2	9	18
D	T3	1.06	0.07	0.20	0.78	0.30	941	170	69	2	8	22
D	T4	0.83	0.07	0.37	0.48	0.17	1676	140	79	1	9	15
D	T5	1.00	0.09	0.32	0.69	0.21	1126	222	78	2	14	29
E	T0	0.93	0.07	0.32	0.46	0.18	250	148	52	2	12	17
E	T1	0.81	0.08	0.40	0.28	0.14	222	106	44	2	11	15
E	T2	0.93	0.09	0.33	0.37	0.15	253	113	36	2	11	14
E	T3	1.04	0.09	0.42	0.46	0.16	279	138	37	2	15	15
E	T4	0.93	0.13	0.39	0.60	0.21	185	206	45	1	9	23
E	T5	1.12	0.10	0.45	0.52	0.18	271	178	42	2	16	18
F	T0	0.92	0.08	0.50	0.41	0.16	290	145	49	2	10	18
F	T1	0.99	0.11	0.41	0.35	0.16	231	108	43	2	12	13
F	T2	1.02	0.10	0.35	0.45	0.19	205	130	46	2	11	15
F	T3	1.01	0.09	0.46	0.52	0.12	214	124	47	2	11	14
F	T4	0.96	0.09	0.39	0.46	0.19	445	141	48	1	11	15
F	T5	1.05	0.11	0.40	0.45	0.18	289	166	45	2	12	16
G	T0	0.89	0.08	0.34	0.86	0.23	308	265	42	2	11	32
G	T1	0.96	0.13	0.44	0.54	0.18	278	161	38	2	10	20

G	T2	1.05	0.14	0.37	0.65	0.23	321	143	54	2	10	26
G	T3	1.08	0.15	0.39	0.98	0.19	448	190	57	2	8	16
G	T4	1.01	0.12	0.45	0.79	0.21	383	256	45	2	8	34
G	T5	0.99	0.17	0.40	0.74	0.21	243	208	51	2	9	23
H	T0	1.03	0.07	0.34	0.36	0.16	167	291	51	2	13	17
H	T1	0.98	0.09	0.36	0.47	0.18	250	273	60	2	17	14
H	T2	0.98	0.13	0.46	0.51	0.16	178	404	48	2	23	21
H	T3	1.14	0.12	0.49	0.37	0.14	154	323	48	3	16	15
H	T4	1.12	0.10	0.36	0.47	0.18	232	388	54	2	21	18
H	T5	1.19	0.11	0.41	0.57	0.16	233	302	60	2	24	24

7.7.4 Foliar nutrient ratios

Appendix 6: Foliage nutrient concentrations for each site at the time of trial establishment (2015).

Site	Treatment	N	P:N	K:N	Ca:N	Mg:N	Mn:N	Fe:N	Cu:N	Zn:N	B:N
%											
Optimal ratios			10	35	2.5	4	0.05	0.2	0.03	0.05	0.05
A	T0	1.08	4.63	22.22	25.93	15.74	0.64	0.53	0.01	0.05	0.17
A	T1	1.11	6.31	25.23	83.78	29.73	1.98	0.68	0.03	0.08	0.23
A	T2	1.01	5.94	25.74	147.52	42.57	2.39	1.12	0.03	0.14	0.25
A	T3	1.10	5.45	23.64	53.64	28.18	0.92	0.66	0.02	0.06	0.27
A	T4	1.14	6.14	26.32	52.63	28.95	2.11	0.75	0.03	0.10	0.26
A	T5	1.19	6.72	26.89	49.58	24.37	1.60	0.76	0.03	0.09	0.29
B	T0	1.00	4.00	25.00	35.00	14.00	1.29	0.48	0.02	0.05	0.13
B	T1	0.84	5.95	32.14	73.81	21.43	1.54	0.95	0.02	0.12	0.19
B	T2	0.81	4.94	40.74	81.48	19.75	2.14	1.23	0.02	0.11	0.14
B	T3	0.87	4.60	39.08	54.02	17.24	1.29	1.09	0.02	0.11	0.15
B	T4	1.11	4.50	22.52	45.05	20.72	3.59	0.76	0.03	0.11	0.14
B	T5	0.91	6.59	51.65	78.02	23.08	1.03	0.58	0.02	0.10	0.12
C	T0	1.01	5.94	35.64	29.70	17.82	1.23	0.60	0.01	0.08	0.18
C	T1	0.95	8.42	43.16	77.89	26.32	1.24	0.68	0.02	0.12	0.16
C	T2	0.90	8.89	43.33	112.22	24.44	3.43	0.64	0.02	0.16	0.27
C	T3	0.93	8.60	39.78	68.82	23.66	1.56	0.51	0.02	0.13	0.22
C	T4	0.99	7.07	32.32	49.49	19.19	1.46	0.41	0.02	0.11	0.25
C	T5	0.94	7.45	39.36	100.00	27.66	1.66	0.61	0.02	0.17	0.30
D	T0	0.85	5.88	25.88	51.76	22.35	1.36	0.72	0.01	0.05	0.16
D	T1	1.04	5.77	21.15	100.96	18.27	2.81	1.00	0.02	0.11	0.31
D	T2	0.92	6.52	27.17	75.00	26.09	1.59	1.18	0.02	0.11	0.32
D	T3	0.90	6.67	33.33	97.78	31.11	1.49	1.47	0.03	0.09	0.21
D	T4	0.87	5.75	26.44	90.80	27.59	1.03	1.11	0.02	0.07	0.21
D	T5	0.81	6.17	29.63	120.99	54.32	3.00	1.54	0.02	0.11	0.27
E	T0	1.07	5.61	31.78	23.36	11.21	0.79	0.35	0.02	0.09	0.17

E	T1	0.99	7.07	52.53	43.43	18.18	0.75	0.43	0.02	0.14	0.18
E	T2	0.93	7.53	59.14	55.91	11.83	0.59	0.44	0.03	0.12	0.14
E	T3	0.94	6.38	40.43	69.15	31.91	1.37	0.61	0.02	0.09	0.24
E	T4	0.67	8.96	41.79	188.06	34.33	2.85	0.82	0.03	0.07	0.25
E	T5	1.16	6.03	34.48	44.83	13.79	1.01	0.51	0.03	0.09	0.18
F	T0	1.08	5.56	55.56	18.52	8.33	0.52	0.32	0.02	0.05	0.13
F	T1	0.82	8.54	68.29	89.02	17.07	1.50	0.73	0.02	0.07	0.23
F	T2	1.07	8.41	53.27	57.94	16.82	1.27	0.49	0.02	0.07	0.16
F	T3	1.10	5.45	35.45	55.45	16.36	1.04	0.41	0.02	0.07	0.21
F	T4	0.97	7.22	41.24	65.98	21.65	1.38	0.49	0.02	0.08	0.18
F	T5	1.00	8.00	50.00	43.00	16.00	1.47	0.46	0.02	0.08	0.15
G	T0	0.89	5.62	34.83	68.54	17.98	1.33	0.48	0.02	0.06	0.17
G	T1	1.00	7.00	51.00	66.00	19.00	1.52	0.41	0.02	0.08	0.25
G	T2	1.23	5.69	33.33	62.60	15.45	1.89	0.38	0.02	0.09	0.20
G	T3	1.37	5.84	33.58	45.99	13.87	1.45	0.31	0.01	0.09	0.18
G	T4	1.14	6.14	35.96	84.21	21.93	1.85	0.39	0.03	0.09	0.15
G	T5	1.08	5.56	26.85	68.52	20.37	1.69	0.43	0.02	0.08	0.21
H	T0	1.15	4.35	41.74	26.09	7.83	1.60	0.32	0.02	0.08	0.13
H	T1	1.08	5.56	35.19	66.67	18.52	2.77	0.89	0.02	0.11	0.26
H	T2	1.06	4.72	49.06	50.94	16.98	1.74	0.56	0.03	0.10	0.15
H	T3	1.12	5.36	37.50	58.93	16.96	6.04	0.52	0.03	0.13	0.21
H	T4	1.47	4.08	26.53	41.50	9.52	2.33	0.44	0.02	0.10	0.20
H	T5	1.39	2.88	25.18	44.60	11.51	1.61	0.94	0.01	0.06	0.12

Appendix 7: Foliage nutrient concentrations for each N and P combination at one year after treatment implementation (2016).

Site	Treatment	N	P:N	K:N	Ca:N	Mg:N	Mn:N	Fe:N	Cu:N	Zn:N	B:N
		%									
Optimal ratios			10	35	2.5	4	0.05	0.2	0.03	0.05	0.05
A	T0	0.98	8.16	50.00	56.12	17.35	1.55	0.30	0.01	0.10	0.20
A	T1	1.14	10.53	30.70	53.51	15.79	1.51	0.23	0.01	0.08	0.20
A	T2	1.02	19.61	46.08	77.45	20.59	1.67	0.35	0.01	0.09	0.25
A	T3	1.12	11.61	38.39	67.86	15.18	1.38	0.28	0.01	0.08	0.19
A	T4	1.09	10.09	38.53	56.88	14.68	1.25	0.25	0.01	0.09	0.17
A	T5	1.21	10.74	39.67	43.80	14.05	0.93	0.22	0.01	0.08	0.18
B	T0	0.95	7.37	46.32	64.21	21.05	3.01	0.40	0.01	0.13	0.15
B	T1	0.86	10.47	37.21	77.91	20.93	1.37	0.50	0.01	0.10	0.16
B	T2	1.01	20.79	30.69	69.31	15.84	2.38	0.56	0.01	0.09	0.13
B	T3	0.89	10.11	44.94	61.80	14.61	1.15	0.48	0.01	0.16	0.13
B	T4	0.96	11.46	38.54	75.00	16.67	1.84	0.47	0.01	0.11	0.15
B	T5	1.14	9.65	36.84	71.05	15.79	0.99	0.32	0.01	0.08	0.11
C	T0	0.98	9.18	34.69	76.53	19.39	2.16	0.82	0.01	0.15	0.31
C	T1	0.92	14.13	46.74	79.35	23.91	1.17	0.53	0.01	0.12	0.22

C	T2	0.97	14.43	41.24	67.01	21.65	1.80	0.33	0.01	0.09	0.28
C	T3	0.96	11.46	41.67	63.54	15.63	0.86	0.31	0.01	0.08	0.16
C	T4	1.06	13.21	41.51	50.94	14.15	1.37	0.27	0.01	0.17	0.20
C	T5	1.08	13.89	36.11	72.22	16.67	1.09	0.33	0.01	0.18	0.18
D	T0	1.05	10.48	33.33	62.86	22.86	0.77	0.76	0.01	0.09	0.20
D	T1	1.07	9.35	28.97	56.07	20.56	1.45	0.51	0.01	0.10	0.17
D	T2	0.95	12.63	27.37	60.00	25.26	1.01	0.60	0.01	0.12	0.17
D	T3	1.04	8.65	32.69	43.27	19.23	1.12	0.49	0.01	0.12	0.19
D	T4	1.30	10.00	21.54	48.46	17.69	0.79	0.48	0.01	0.08	0.15
D	T5	1.48	7.43	20.95	27.70	12.16	0.72	0.53	0.01	0.08	0.17
E	T0	1.06	7.55	40.57	48.11	14.15	1.17	0.26	0.01	0.11	0.22
E	T1	0.99	12.12	50.51	63.64	17.17	0.93	0.36	0.01	0.08	0.18
E	T2	1.00	13.00	37.00	77.00	18.00	1.26	0.30	0.01	0.10	0.20
E	T3	1.12	9.82	42.86	55.36	12.50	1.03	0.24	0.01	0.09	0.19
E	T4	0.96	16.67	46.88	84.38	17.71	1.65	0.35	0.01	0.09	0.22
E	T5	1.12	9.82	47.32	39.29	12.50	0.87	0.23	0.01	0.10	0.17
F	T0	0.98	7.14	29.59	75.51	21.43	1.08	0.46	0.01	0.09	0.14
F	T1	0.91	9.89	29.67	107.69	23.08	1.01	0.86	0.01	0.08	0.19
F	T2	0.92	11.96	31.52	77.17	23.91	1.34	0.58	0.01	0.09	0.17
F	T3	0.95	8.42	29.47	101.05	27.37	1.57	0.62	0.01	0.06	0.21
F	T4	0.89	8.99	33.71	75.28	20.22	0.99	0.76	0.01	0.07	0.19
F	T5	1.09	10.09	36.70	64.22	21.10	1.60	0.57	0.01	0.09	0.15
G	T0	0.83	12.05	51.81	81.93	20.48	0.71	0.37	0.01	0.10	0.16
G	T1	1.07	14.02	42.99	61.68	16.82	1.24	0.26	0.01	0.08	0.21
G	T2	1.03	14.56	47.57	70.87	16.50	1.88	0.26	0.01	0.11	0.21
G	T3	1.08	12.04	38.89	98.15	13.89	2.19	0.31	0.01	0.07	0.26
G	T4	1.13	17.70	42.48	80.53	21.24	2.38	0.22	0.01	0.09	0.23
G	T5	1.21	10.74	33.06	74.38	13.22	1.16	0.22	0.01	0.07	0.17
H	T0	1.21	5.79	46.28	33.88	9.09	1.45	0.28	0.02	0.13	0.15
H	T1	0.90	11.11	57.78	66.67	18.89	2.89	0.54	0.01	0.16	0.24
H	T2	1.26	12.70	45.24	36.51	8.73	1.56	0.33	0.02	0.13	0.18
H	T3	1.05	8.57	35.24	69.52	20.95	2.82	0.83	0.01	0.12	0.26
H	T4	1.14	14.04	51.75	50.88	11.40	2.69	0.30	0.01	0.13	0.17
H	T5	1.48	10.81	45.27	40.54	8.11	1.96	0.26	0.01	0.10	0.22

Appendix 8: Foliage nutrient concentrations for each N and P combination at two years after treatment implementation (2017).

Site	Treatment	N	P:N	K:N	Ca:N	Mg:N	Mn:N	Fe:N	Cu:N	Zn:N	B:N
%											
Optimal ratios			10	35	2.5	4	0.05	0.2	0.03	0.05	0.05
A	T0	1.04	5.77	27.88	44.23	17.31	1.32	0.86	0.02	0.10	0.19
A	T1	1.05	7.62	23.81	42.86	20.95	1.27	0.72	0.02	0.10	0.16
A	T2	1.10	8.18	32.73	45.45	20.91	1.37	0.75	0.02	0.08	0.15

A	T3	1.19	8.40	25.21	36.97	18.49	1.24	0.61	0.02	0.10	0.16
A	T4	1.16	7.76	19.83	31.03	15.52	0.54	0.57	0.02	0.10	0.11
A	T5	1.33	7.52	17.29	21.80	15.04	1.01	0.50	0.02	0.13	0.11
B	T0	0.86	5.81	38.37	53.49	19.77	2.44	0.86	0.02	0.12	0.15
B	T1	0.89	8.99	48.31	41.57	15.73	1.15	0.62	0.02	0.11	0.15
B	T2	0.98	13.27	33.67	50.00	18.37	1.92	0.64	0.02	0.19	0.14
B	T3	1.01	10.89	40.59	38.61	17.82	1.10	0.53	0.02	0.18	0.16
B	T4	1.01	11.88	42.57	44.55	14.85	1.65	0.72	0.02	0.13	0.14
B	T5	0.97	10.31	36.08	52.58	20.62	1.94	0.58	0.02	0.12	0.19
C	T0	0.96	8.33	36.46	51.04	17.71	1.32	0.52	0.02	0.13	0.18
C	T1	1.03	11.65	42.72	51.46	16.50	1.59	0.43	0.02	0.11	0.16
C	T2	0.89	10.11	33.71	87.64	25.84	1.34	0.54	0.02	0.08	0.22
C	T3	0.93	8.60	33.33	77.42	20.43	2.17	0.49	0.01	0.09	0.26
C	T4	0.94	11.70	40.43	52.13	17.02	1.17	0.44	0.02	0.19	0.15
C	T5	1.02	8.82	33.33	57.84	20.59	1.84	0.40	0.02	0.18	0.21
D	T0	0.82	7.32	31.71	76.83	25.61	2.18	1.09	0.02	0.11	0.16
D	T1	1.04	9.62	33.65	52.88	19.23	1.67	0.81	0.02	0.10	0.16
D	T2	0.87	11.49	26.44	66.67	27.59	1.37	1.03	0.02	0.10	0.21
D	T3	1.06	6.60	18.87	73.58	28.30	1.60	0.65	0.02	0.08	0.21
D	T4	0.83	8.43	44.58	57.83	20.48	1.69	0.95	0.01	0.11	0.18
D	T5	1.00	9.00	32.00	69.00	21.00	2.22	0.78	0.02	0.14	0.29
E	T0	0.93	7.53	34.41	49.46	19.35	1.59	0.56	0.02	0.13	0.18
E	T1	0.81	9.88	49.38	34.57	17.28	1.31	0.54	0.02	0.14	0.19
E	T2	0.93	9.68	35.48	39.78	16.13	1.22	0.39	0.02	0.12	0.15
E	T3	1.04	8.65	40.38	44.23	15.38	1.33	0.36	0.02	0.14	0.14
E	T4	0.93	13.98	41.94	64.52	22.58	2.22	0.48	0.01	0.10	0.25
E	T5	1.12	8.93	40.18	46.43	16.07	1.59	0.38	0.02	0.14	0.16
F	T0	0.92	8.70	54.35	44.57	17.39	1.58	0.53	0.02	0.11	0.20
F	T1	0.99	11.11	41.41	35.35	16.16	1.09	0.43	0.02	0.12	0.13
F	T2	1.02	9.80	34.31	44.12	18.63	1.27	0.45	0.02	0.11	0.15
F	T3	1.01	8.91	45.54	51.49	11.88	1.23	0.47	0.02	0.11	0.14
F	T4	0.96	9.38	40.63	47.92	19.79	1.47	0.50	0.01	0.11	0.16
F	T5	1.05	10.48	38.10	42.86	17.14	1.58	0.43	0.02	0.11	0.15
G	T0	0.89	8.99	38.20	96.63	25.84	2.98	0.47	0.02	0.12	0.36
G	T1	0.96	13.54	45.83	56.25	18.75	1.68	0.40	0.02	0.10	0.21
G	T2	1.05	13.33	35.24	61.90	21.90	1.36	0.51	0.02	0.10	0.25
G	T3	1.08	13.89	36.11	90.74	17.59	1.76	0.53	0.02	0.07	0.15
G	T4	1.01	11.88	44.55	78.22	20.79	2.53	0.45	0.02	0.08	0.34
G	T5	0.99	17.17	40.40	74.75	21.21	2.10	0.52	0.02	0.09	0.23
H	T0	1.03	6.80	33.01	34.95	15.53	2.83	0.50	0.02	0.13	0.17
H	T1	0.98	9.18	36.73	47.96	18.37	2.79	0.61	0.02	0.17	0.14
H	T2	0.98	13.27	46.94	52.04	16.33	4.12	0.49	0.02	0.23	0.21
H	T3	1.14	10.53	42.98	32.46	12.28	2.83	0.42	0.03	0.14	0.13
H	T4	1.12	8.93	32.14	41.96	16.07	3.46	0.48	0.02	0.19	0.16
H	T5	1.19	9.24	34.45	47.90	13.45	2.54	0.50	0.02	0.20	0.20

7.7.5 Canopy nutrient contents

Appendix 9: Canopy nutrient contents at time of trial establishment.

Site	Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
kg ha ⁻¹												
A	T0	76.55	3.54	16.66	19.49	12.05	2.68	0.49	0.40	0.01	0.04	0.13
A	T1	80.65	5.09	20.34	67.57	23.98	1.71	1.60	0.54	0.02	0.07	0.18
A	T2	72.07	4.28	18.55	106.33	30.69	1.91	1.72	0.81	0.02	0.10	0.18
A	T3	88.63	4.83	20.95	47.54	24.98	4.16	0.81	0.59	0.02	0.06	0.24
A	T4	91.85	5.64	24.17	48.34	26.59	5.08	1.93	0.69	0.02	0.09	0.24
A	T5	95.30	6.41	25.63	47.25	23.23	3.54	1.52	0.72	0.02	0.09	0.27
B	T0	105.81	3.72	26.59	37.22	14.36	8.76	1.37	0.51	0.02	0.05	0.13
B	T1	70.26	4.18	22.58	51.86	15.06	14.75	1.08	0.67	0.02	0.08	0.13
B	T2	73.06	3.61	29.77	59.53	14.43	17.20	1.56	0.90	0.02	0.08	0.10
B	T3	67.22	3.09	26.27	36.31	11.59	15.30	0.87	0.73	0.02	0.08	0.10
B	T4	117.29	5.28	26.42	52.83	24.30	16.80	4.21	0.89	0.03	0.13	0.16
B	T5	89.89	5.93	46.42	70.13	20.74	8.79	0.93	0.52	0.02	0.09	0.11
C	T0	109.00	6.48	38.85	31.84	19.43	2.29	1.33	0.65	0.02	0.09	0.20
C	T1	96.43	8.12	41.62	75.12	25.38	3.96	1.20	0.66	0.02	0.11	0.15
C	T2	79.95	7.11	34.64	89.72	19.54	4.65	2.74	0.52	0.02	0.12	0.21
C	T3	108.86	9.36	43.31	74.91	25.75	4.48	1.70	0.55	0.02	0.14	0.23
C	T4	108.32	7.66	35.01	53.61	20.79	2.72	1.59	0.45	0.02	0.12	0.27
C	T5	106.07	7.90	41.75	106.07	29.34	5.36	1.76	0.64	0.02	0.18	0.32
D	T0	94.93	5.06	24.72	48.87	21.35	10.57	1.30	0.69	0.01	0.04	0.16
D	T1	119.90	6.92	25.36	121.05	21.90	15.31	3.37	1.20	0.02	0.13	0.37
D	T2	95.82	6.25	26.04	71.87	25.00	17.24	1.52	1.14	0.02	0.10	0.30
D	T3	86.08	5.74	28.69	84.17	26.78	12.16	1.28	1.26	0.03	0.08	0.18
D	T4	85.64	4.92	22.64	77.76	23.62	12.09	0.89	0.95	0.02	0.06	0.18
D	T5	76.47	4.72	22.66	92.52	41.54	7.24	2.29	1.18	0.02	0.08	0.21
E	T0	89.82	4.62	28.54	20.98	10.07	2.27	0.71	0.31	0.02	0.08	0.15
E	T1	112.58	7.96	59.13	48.90	20.47	3.88	0.84	0.49	0.02	0.16	0.20
E	T2	83.17	6.26	49.19	46.51	9.84	2.14	0.49	0.37	0.03	0.10	0.12
E	T3	84.07	5.37	33.98	58.13	26.83	3.58	1.15	0.51	0.02	0.07	0.21
E	T4	51.96	4.65	21.72	97.72	17.84	7.31	1.48	0.43	0.02	0.04	0.13
E	T5	84.62	5.11	29.18	37.93	11.67	1.79	0.85	0.43	0.02	0.07	0.15
F	T0	85.49	4.75	47.49	15.83	6.73	2.05	0.45	0.27	0.02	0.04	0.11
F	T1	58.86	5.02	40.19	52.40	10.05	5.87	0.88	0.43	0.01	0.04	0.14
F	T2	100.29	8.44	53.43	58.11	16.87	3.54	1.27	0.49	0.02	0.07	0.16
F	T3	98.66	5.38	34.98	54.71	16.14	4.00	1.02	0.40	0.02	0.07	0.21
F	T4	76.78	5.54	31.66	50.66	16.62	2.49	1.06	0.38	0.02	0.06	0.13
F	T5	89.87	7.19	44.93	38.64	14.38	1.96	1.32	0.41	0.02	0.07	0.13
G	T0	160.51	9.02	55.91	110.01	27.95	4.60	2.13	0.78	0.04	0.09	0.27
G	T1	177.87	12.45	90.71	117.40	33.80	7.24	2.70	0.73	0.04	0.14	0.44
G	T2	207.70	11.82	69.23	130.02	32.08	4.34	3.93	0.79	0.05	0.19	0.41
G	T3	220.69	12.89	74.10	101.48	30.61	3.66	3.19	0.68	0.03	0.19	0.39

G	T4	176.79	10.86	63.58	148.87	38.77	4.26	3.27	0.70	0.05	0.16	0.26
G	T5	156.60	8.70	42.05	107.30	31.90	4.23	2.65	0.67	0.03	0.13	0.33
H	T0	114.52	5.00	47.51	30.01	8.50	1.44	1.84	0.37	0.02	0.09	0.15
H	T1	108.69	6.04	38.24	72.46	20.13	8.20	3.01	0.97	0.02	0.12	0.28
H	T2	106.67	5.03	52.33	54.34	18.11	3.55	1.85	0.59	0.03	0.11	0.16
H	T3	98.89	5.30	37.09	58.28	16.78	2.33	5.97	0.51	0.03	0.12	0.20
H	T4	133.65	5.46	35.46	55.46	12.73	4.25	3.11	0.59	0.03	0.14	0.26
H	T5	109.23	3.14	27.50	48.72	12.57	3.63	1.76	1.02	0.02	0.06	0.13

Appendix 10: Canopy nutrient contents 12 months after fertilisation.

Site	Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
kg ha ⁻¹												
A	T0	90.91	7.42	45.45	51.02	15.77	2.92	1.41	0.27	0.01	0.09	0.19
A	T1	105.47	11.10	32.38	56.43	16.65	2.78	1.59	0.24	0.01	0.08	0.21
A	T2	99.23	19.46	45.72	76.85	20.43	4.20	1.65	0.35	0.01	0.09	0.25
A	T3	112.44	13.05	43.17	76.30	17.07	4.21	1.56	0.31	0.01	0.09	0.21
A	T4	102.73	10.37	39.59	58.44	15.08	3.83	1.28	0.25	0.01	0.09	0.17
A	T5	121.77	13.08	48.30	53.34	17.11	2.90	1.14	0.27	0.01	0.10	0.22
B	T0	76.97	5.67	35.65	49.42	16.20	8.88	2.32	0.31	0.01	0.10	0.11
B	T1	73.87	7.73	27.49	57.55	15.46	9.01	1.01	0.37	0.01	0.08	0.12
B	T2	70.71	14.70	21.70	49.01	11.20	9.00	1.68	0.40	0.01	0.06	0.09
B	T3	65.34	6.61	29.37	40.38	9.54	9.37	0.75	0.32	0.01	0.10	0.09
B	T4	79.80	9.14	30.76	59.85	13.30	8.39	1.47	0.37	0.01	0.09	0.12
B	T5	91.89	8.87	33.85	65.29	14.51	7.52	0.91	0.29	0.01	0.07	0.10
C	T0	99.39	9.13	34.48	76.06	19.27	4.25	2.15	0.81	0.01	0.15	0.30
C	T1	88.95	12.57	41.57	70.58	21.27	5.37	1.04	0.47	0.01	0.11	0.19
C	T2	95.92	13.84	39.55	64.27	20.77	4.85	1.73	0.32	0.01	0.09	0.27
C	T3	90.24	10.34	37.60	57.34	14.10	3.35	0.78	0.28	0.01	0.08	0.14
C	T4	111.34	14.70	46.22	56.72	15.76	2.87	1.52	0.30	0.01	0.19	0.22
C	T5	108.77	15.11	39.28	78.55	18.13	4.58	1.19	0.36	0.01	0.19	0.19
D	T0	112.31	11.77	37.44	70.59	25.67	6.24	0.87	0.86	0.01	0.10	0.22
D	T1	115.85	10.83	33.56	64.96	23.82	5.31	1.68	0.60	0.01	0.12	0.19
D	T2	106.02	13.39	29.02	63.61	26.78	5.89	1.07	0.64	0.01	0.12	0.18
D	T3	102.19	8.84	33.41	44.22	19.65	5.70	1.14	0.50	0.01	0.12	0.20
D	T4	145.18	14.52	31.27	70.36	25.69	5.46	1.15	0.70	0.01	0.12	0.22
D	T5	155.04	11.52	32.47	42.95	18.86	6.35	1.11	0.82	0.01	0.13	0.26
E	T0	121.55	9.17	49.31	58.48	17.20	3.23	1.42	0.32	0.01	0.14	0.26
E	T1	112.91	13.69	57.03	71.85	19.39	5.04	1.05	0.41	0.01	0.09	0.21
E	T2	126.06	16.39	46.64	97.07	22.69	5.18	1.59	0.38	0.01	0.13	0.25
E	T3	137.56	13.51	58.96	76.15	17.20	5.27	1.41	0.33	0.01	0.12	0.26
E	T4	124.21	20.70	58.22	104.80	22.00	7.15	2.04	0.44	0.01	0.12	0.27
E	T5	133.79	13.14	63.31	52.56	16.72	4.83	1.16	0.31	0.01	0.13	0.23
F	T0	104.71	7.48	30.99	79.07	22.44	10.51	1.13	0.48	0.01	0.10	0.15
F	T1	100.19	9.91	29.73	107.89	23.12	14.68	1.01	0.86	0.01	0.08	0.19

F	T2	103.59	12.39	32.65	79.95	24.77	10.13	1.38	0.60	0.01	0.09	0.18
F	T3	108.01	9.10	31.84	109.15	29.56	15.25	1.69	0.67	0.01	0.07	0.23
F	T4	94.47	8.49	31.84	71.12	19.11	18.19	0.93	0.72	0.01	0.06	0.18
F	T5	124.55	12.57	45.71	79.99	26.28	11.30	1.99	0.71	0.01	0.11	0.18
G	T0	116.23	14.00	60.22	95.23	23.81	5.57	0.83	0.43	0.01	0.11	0.18
G	T1	154.14	21.61	66.27	95.08	25.93	3.72	1.92	0.40	0.01	0.13	0.33
G	T2	149.02	21.70	70.89	105.61	24.60	3.92	2.81	0.39	0.01	0.16	0.32
G	T3	154.68	18.62	60.15	151.81	21.48	6.09	3.38	0.49	0.01	0.11	0.40
G	T4	163.69	28.97	69.53	131.82	34.77	3.74	3.90	0.36	0.01	0.14	0.38
G	T5	171.43	18.42	56.67	127.51	22.67	4.97	1.98	0.38	0.01	0.11	0.30
H	T0	112.19	6.49	51.92	38.01	10.20	3.18	1.62	0.32	0.02	0.15	0.17
H	T1	100.76	11.20	58.22	67.17	19.03	4.70	2.91	0.55	0.01	0.16	0.25
H	T2	138.93	17.64	62.85	50.72	12.13	4.62	2.16	0.46	0.02	0.19	0.25
H	T3	127.19	10.90	44.82	88.42	26.65	9.19	3.59	1.05	0.01	0.16	0.33
H	T4	130.09	18.26	67.33	66.19	14.83	4.44	3.50	0.39	0.01	0.17	0.22
H	T5	166.26	17.97	75.27	67.40	13.48	3.57	3.26	0.43	0.02	0.17	0.37

Appendix 11: Canopy nutrient contents 24 months after fertilisation.

Site	Treatment	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
kg ha ⁻¹												
A	T0	108.07	6.23	30.13	47.80	18.70	7.06	1.42	0.92	0.02	0.10	0.21
A	T1	104.35	7.95	24.84	44.72	21.86	4.37	1.32	0.76	0.02	0.10	0.17
A	T2	106.82	8.74	34.96	48.56	22.34	3.58	1.47	0.81	0.02	0.09	0.17
A	T3	129.78	10.91	32.72	47.99	23.99	2.70	1.61	0.80	0.02	0.13	0.21
A	T4	117.19	9.09	23.24	36.37	18.18	4.24	0.64	0.67	0.02	0.12	0.13
A	T5	145.60	10.95	25.18	31.75	21.89	5.87	1.47	0.72	0.02	0.19	0.16
B	T0	110.42	6.42	42.37	59.06	21.83	14.21	2.70	0.95	0.03	0.13	0.17
B	T1	122.28	10.99	59.08	50.84	19.24	8.88	1.40	0.76	0.03	0.14	0.18
B	T2	119.95	15.91	40.39	59.97	22.03	7.21	2.30	0.77	0.02	0.23	0.17
B	T3	120.15	13.09	48.78	46.40	21.41	4.64	1.32	0.64	0.02	0.21	0.19
B	T4	131.19	15.59	55.86	58.45	19.48	11.20	2.17	0.95	0.03	0.17	0.18
B	T5	134.52	13.87	48.54	70.73	27.74	7.86	2.61	0.78	0.03	0.17	0.25
C	T0	133.75	11.15	48.76	68.27	23.69	4.07	1.77	0.70	0.03	0.17	0.24
C	T1	145.86	16.99	62.31	75.05	24.07	4.81	2.32	0.62	0.03	0.16	0.23
C	T2	121.12	12.25	40.83	106.15	31.30	9.50	1.62	0.65	0.03	0.10	0.27
C	T3	118.26	10.17	39.42	91.55	24.16	4.45	2.57	0.58	0.01	0.10	0.31
C	T4	129.18	15.12	52.22	67.34	21.99	5.44	1.51	0.56	0.03	0.25	0.19
C	T5	147.54	13.02	49.18	85.34	30.38	4.73	2.72	0.59	0.03	0.26	0.30
D	T0	81.81	5.99	25.94	62.86	20.95	13.81	1.79	0.89	0.02	0.09	0.13
D	T1	106.02	10.19	35.68	56.07	20.39	8.47	1.77	0.86	0.02	0.10	0.17
D	T2	88.69	10.19	23.45	59.13	24.47	11.98	1.21	0.92	0.02	0.09	0.18
D	T3	93.64	6.18	17.67	68.90	26.50	8.31	1.50	0.61	0.02	0.07	0.19
D	T4	81.17	6.85	36.19	46.94	16.63	16.39	1.37	0.77	0.01	0.09	0.15
D	T5	103.71	9.33	33.19	71.56	21.78	11.68	2.30	0.81	0.02	0.15	0.30

E	T0	111.93	8.42	38.51	55.36	21.66	3.01	1.78	0.63	0.02	0.14	0.20
E	T1	90.53	8.94	44.71	31.30	15.65	2.48	1.18	0.49	0.02	0.12	0.17
E	T2	107.10	10.36	38.00	42.61	17.27	2.91	1.30	0.41	0.02	0.13	0.16
E	T3	117.42	10.16	47.42	51.93	18.06	3.15	1.56	0.42	0.02	0.17	0.17
E	T4	95.75	13.38	40.15	61.77	21.62	1.90	2.12	0.46	0.01	0.09	0.24
E	T5	135.81	12.13	54.57	63.06	21.83	3.29	2.16	0.51	0.02	0.19	0.22
F	T0	125.85	10.94	68.40	56.09	21.89	3.97	1.98	0.67	0.03	0.14	0.25
F	T1	124.34	13.82	51.49	43.96	20.10	2.90	1.36	0.54	0.03	0.15	0.16
F	T2	149.12	14.62	51.17	65.79	27.78	3.00	1.90	0.67	0.03	0.16	0.22
F	T3	141.55	12.61	64.47	72.88	16.82	3.00	1.74	0.66	0.03	0.15	0.20
F	T4	130.89	12.27	53.17	62.72	25.91	6.07	1.92	0.65	0.01	0.15	0.20
F	T5	141.05	14.78	53.73	60.45	24.18	3.88	2.23	0.60	0.03	0.16	0.21
G	T0	169.44	15.23	64.73	163.73	43.79	5.86	5.05	0.80	0.04	0.21	0.61
G	T1	187.52	25.39	85.95	105.48	35.16	5.43	3.14	0.74	0.04	0.20	0.39
G	T2	198.95	26.53	70.11	123.16	43.58	6.08	2.71	1.02	0.04	0.19	0.49
G	T3	200.75	27.88	72.49	182.16	35.32	8.33	3.53	1.06	0.04	0.15	0.30
G	T4	189.78	22.55	84.56	148.44	39.46	7.20	4.81	0.85	0.04	0.15	0.64
G	T5	183.12	31.45	73.99	136.88	38.84	4.49	3.85	0.94	0.04	0.17	0.43
H	T0	115.91	7.88	38.26	40.51	18.01	1.88	3.27	0.57	0.02	0.15	0.19
H	T1	115.10	10.57	42.28	55.20	21.14	2.94	3.21	0.70	0.02	0.20	0.16
H	T2	119.92	15.91	56.29	62.41	19.58	2.18	4.94	0.59	0.02	0.28	0.26
H	T3	142.18	14.97	61.11	46.15	17.46	1.92	4.03	0.60	0.04	0.20	0.19
H	T4	145.42	12.98	46.74	61.02	23.37	3.01	5.04	0.70	0.03	0.27	0.23
H	T5	158.95	14.69	54.76	76.14	21.37	3.11	4.03	0.80	0.03	0.32	0.32

7.7.6 Vector nomograms

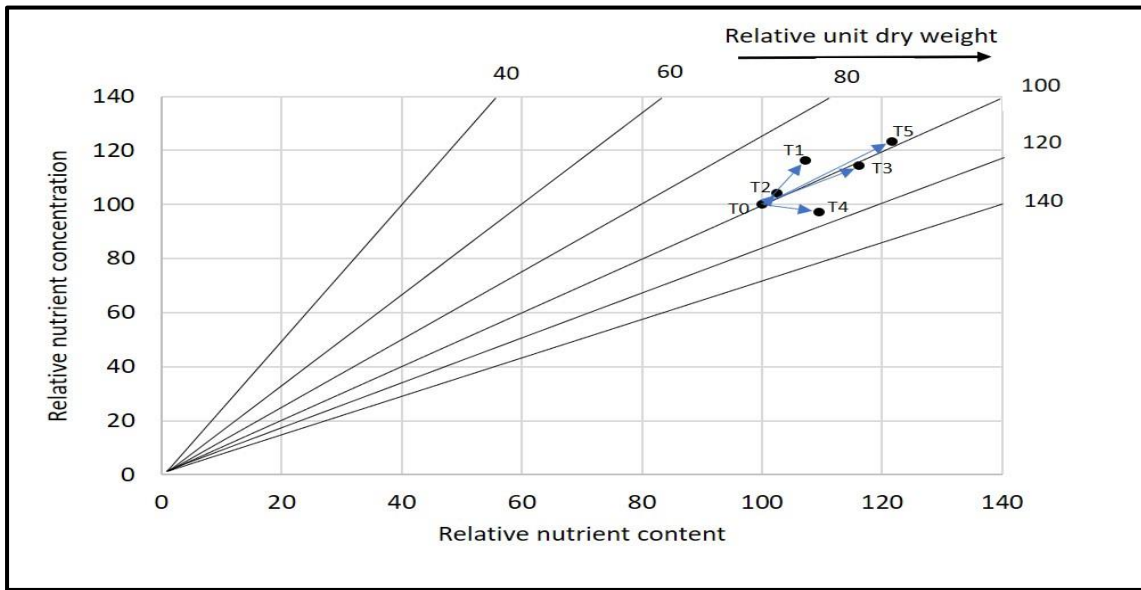


Figure 7.28: Vector nomogram for the response of N to fertilisation in field trial A at 12 months after fertilisation.

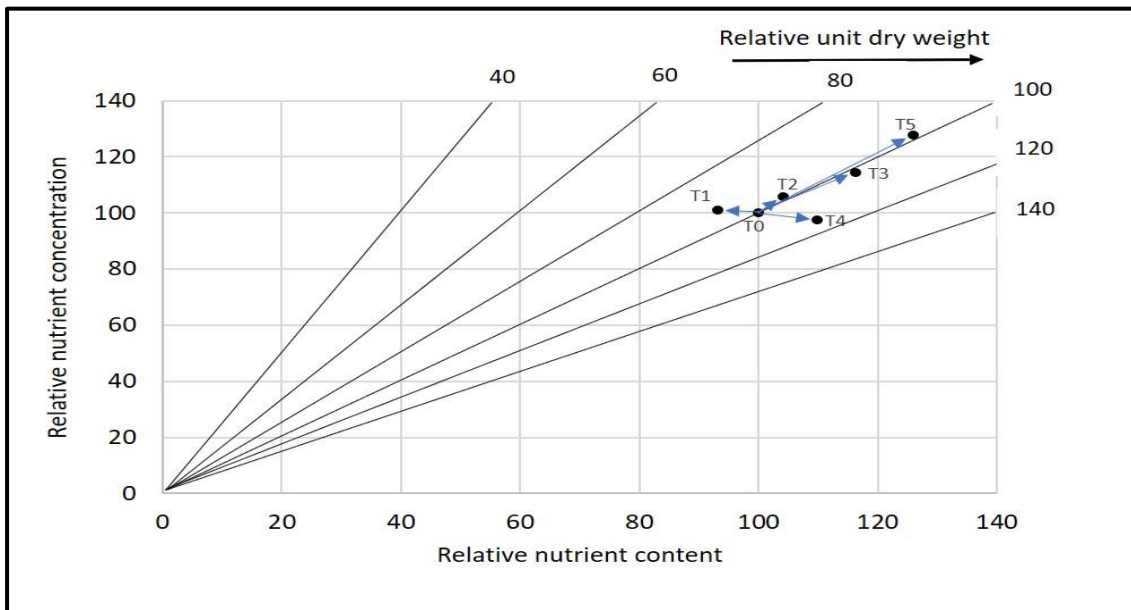


Figure 7.29: Vector nomogram for the response of N to fertilisation in field trial A, at 24 months after fertilisation.

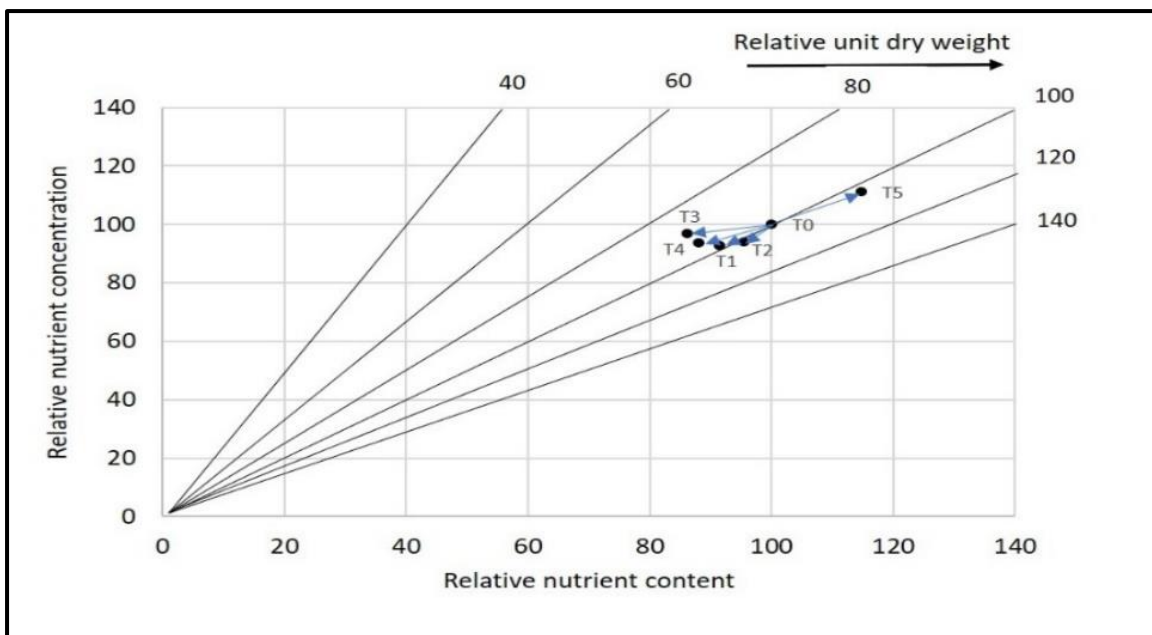


Figure 7.30: Vector nomogram for the response of N to fertilisation in field trial F, at 12 months after fertilisation.

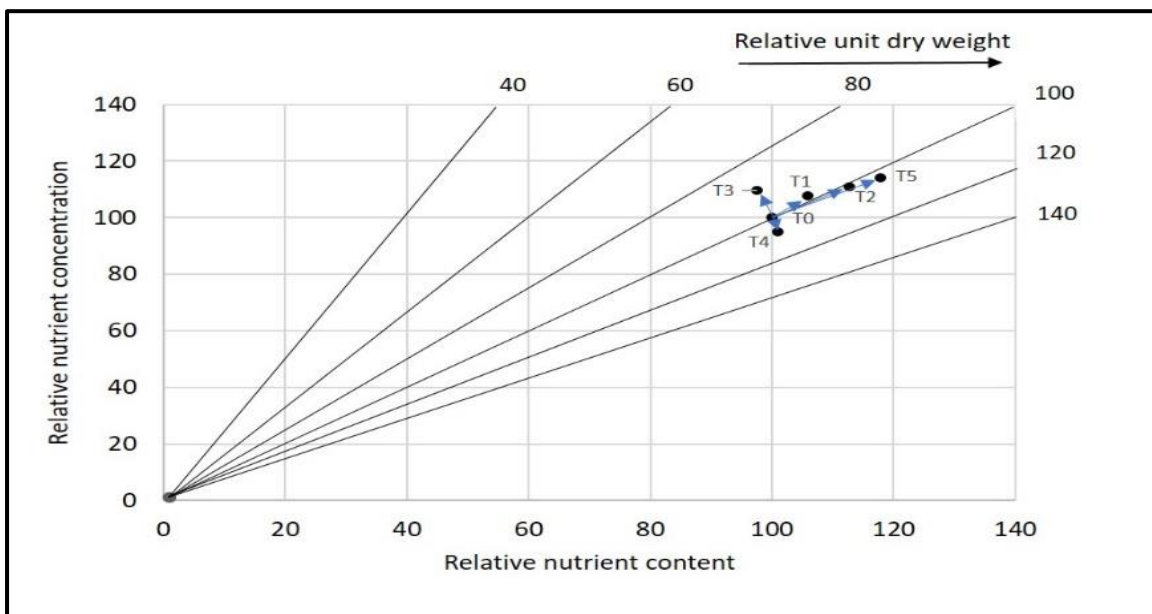


Figure 7.31: Vector nomogram for the response of N to fertilisation in field trial F, at 24 months after fertilisation.

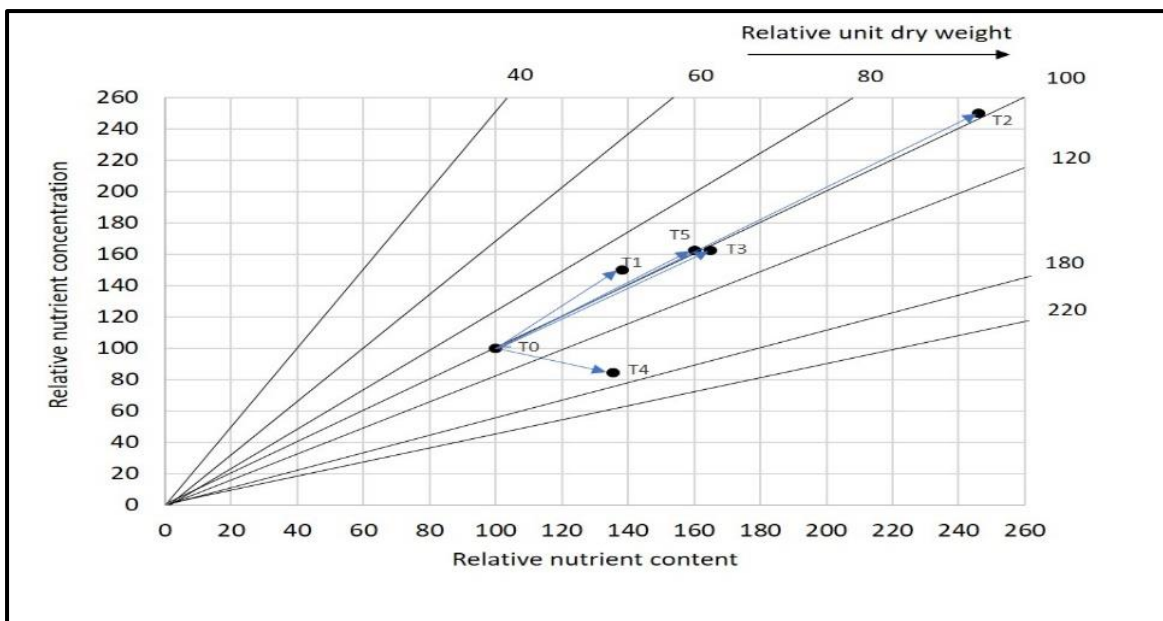


Figure 7.32: Vector nomogram for the response of P to fertilisation in field trial A, at 12 months after fertilisation.

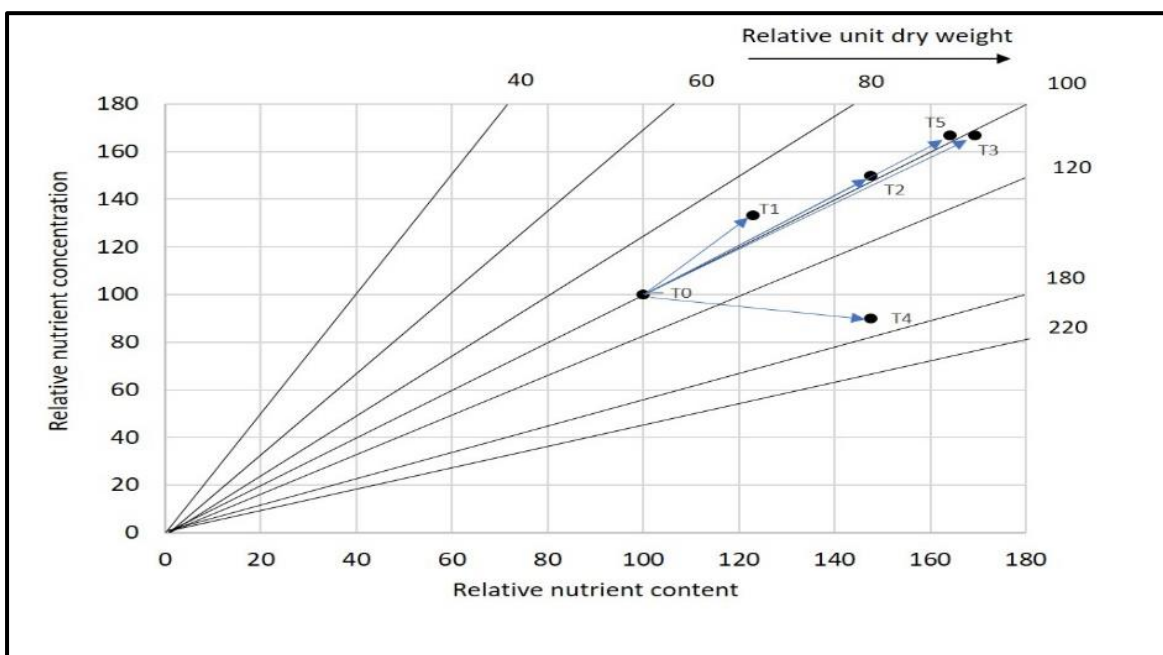


Figure 7.33: Vector nomogram for the response of P to fertilisation in field trial A, at 24 months after fertilisation.

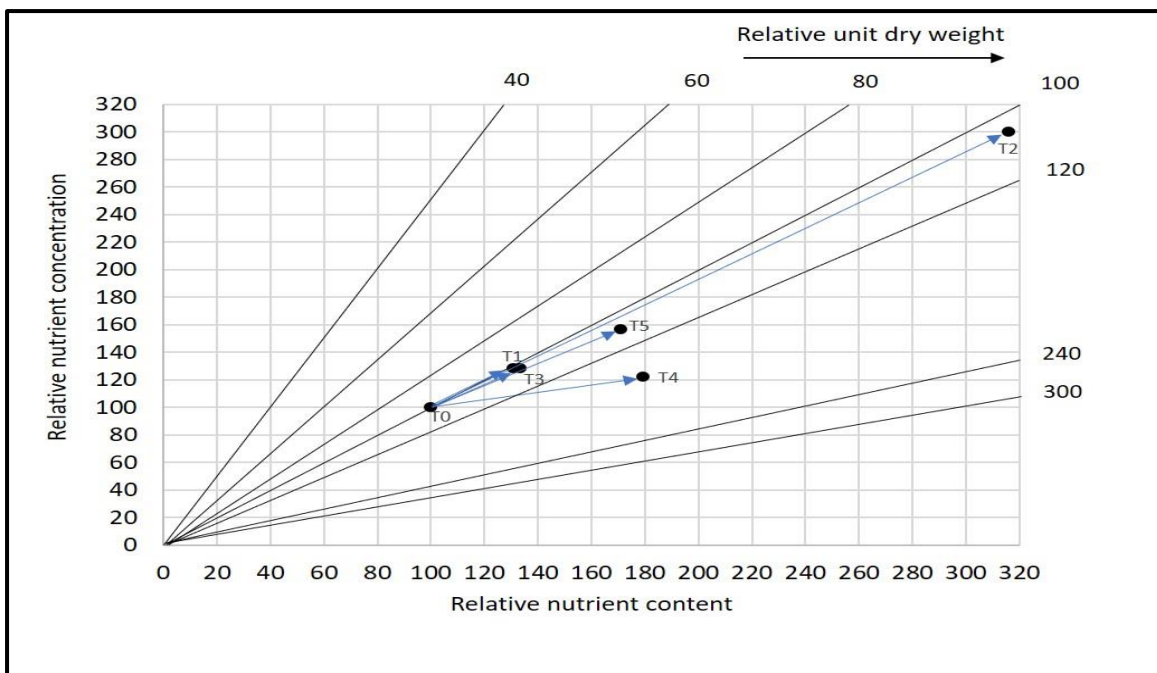


Figure 7.34: Vector nomogram for the response of P to fertilisation in field trial B, at 12 months after fertilisation.

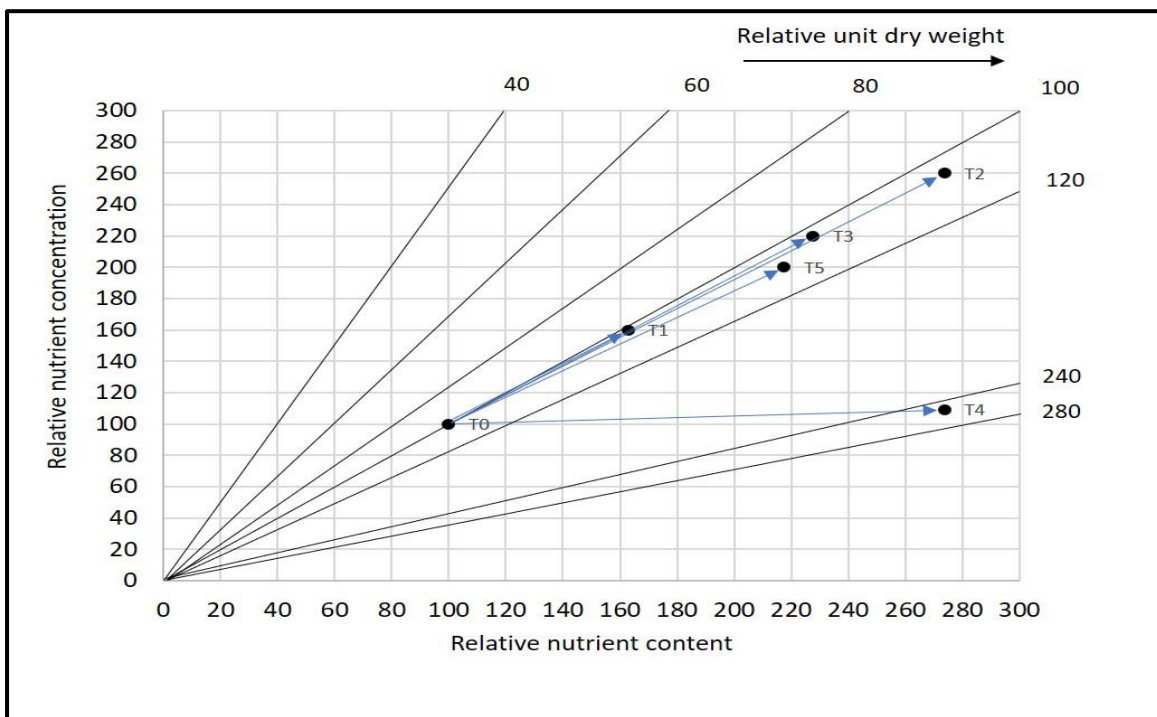


Figure 7.35: Vector nomogram for the response of P to fertilisation in field trial B, at 24 months after fertilisation.

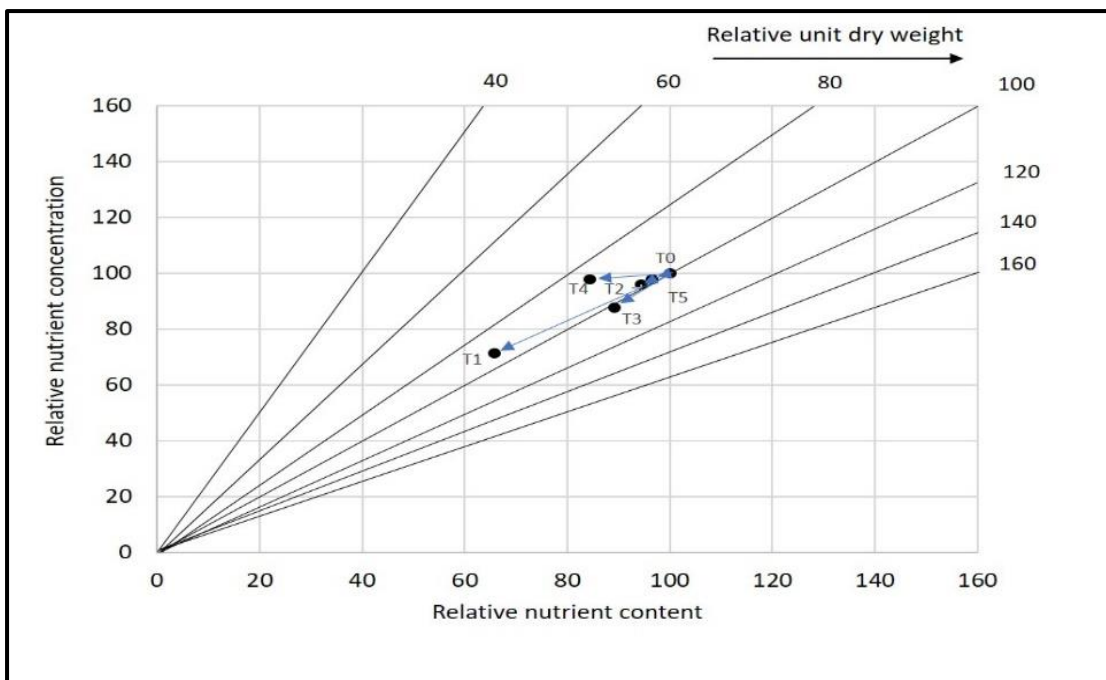


Figure 7.36: Vector nomogram for the response of K to fertilisation in field trial A, at 12 months after fertilisation.

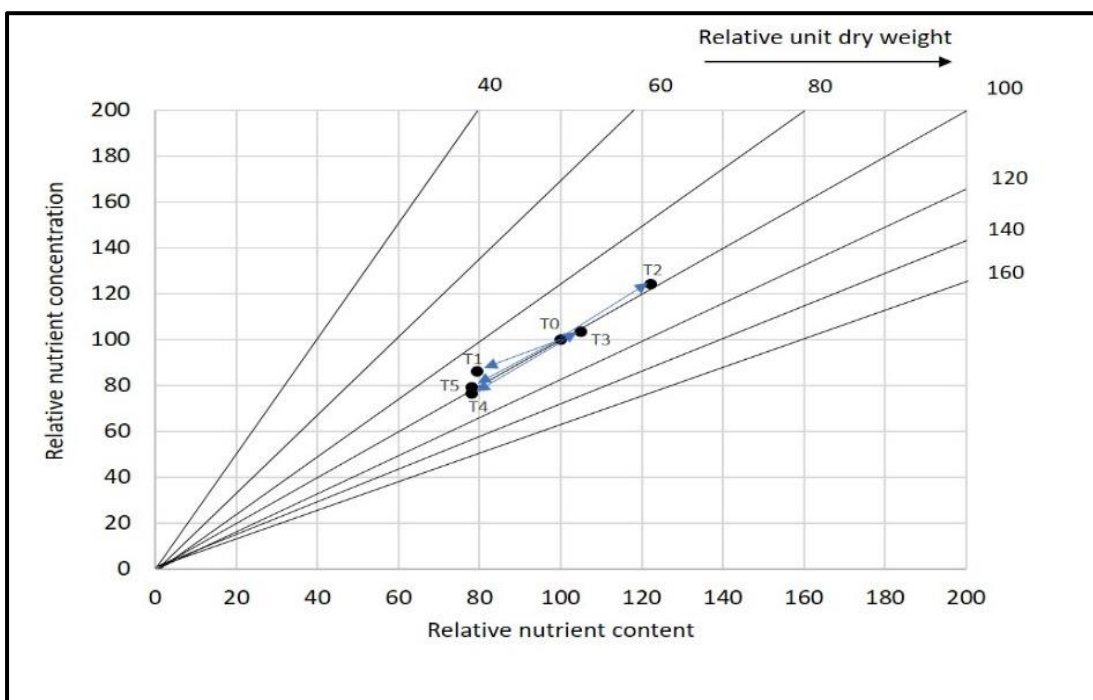


Figure 7.37: Vector nomogram for the response of K to fertilisation in field trial A, at 24 months after fertilisation.

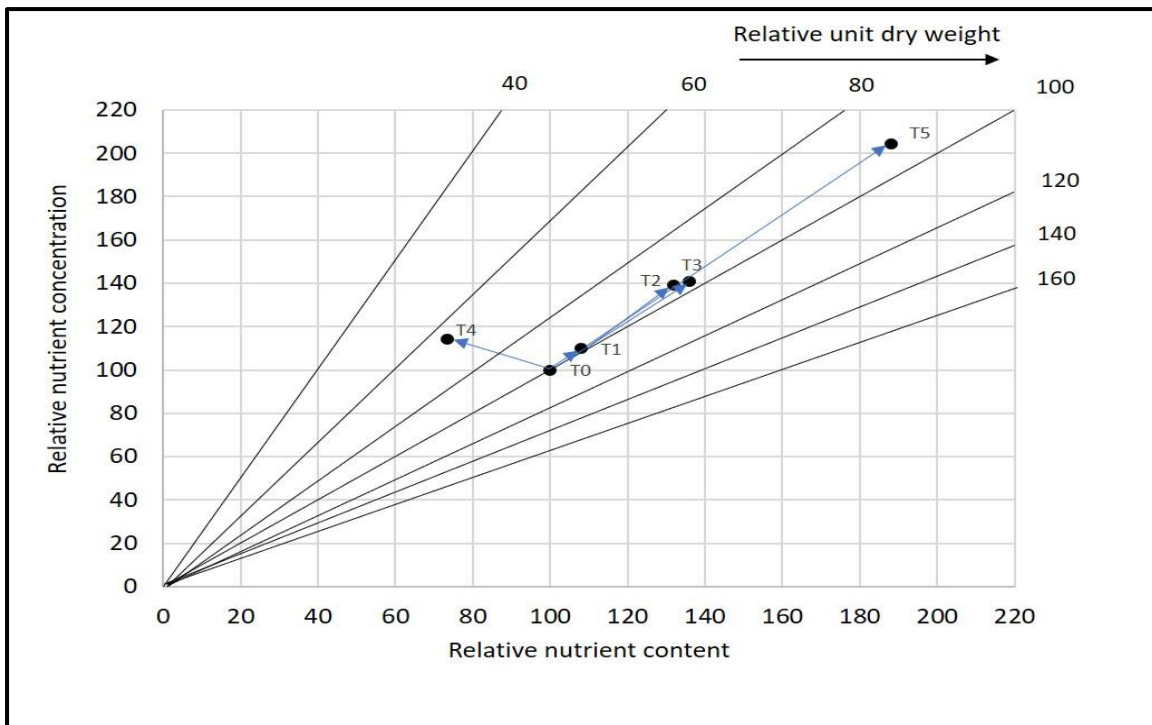


Figure 7.38: Vector nomogram for the response of K to fertilisation in field trial B, at 12 months after fertilisation.

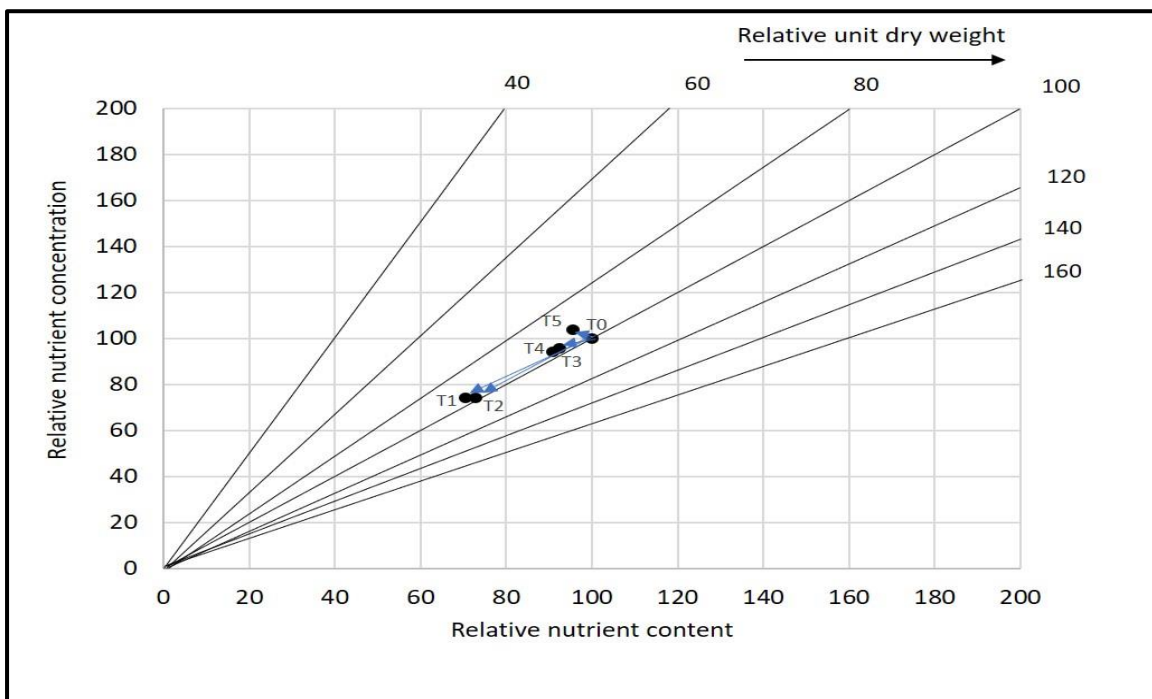


Figure 7.39: Vector nomogram for the response of K to fertilisation in field trial B, at 24 months after fertilisation.

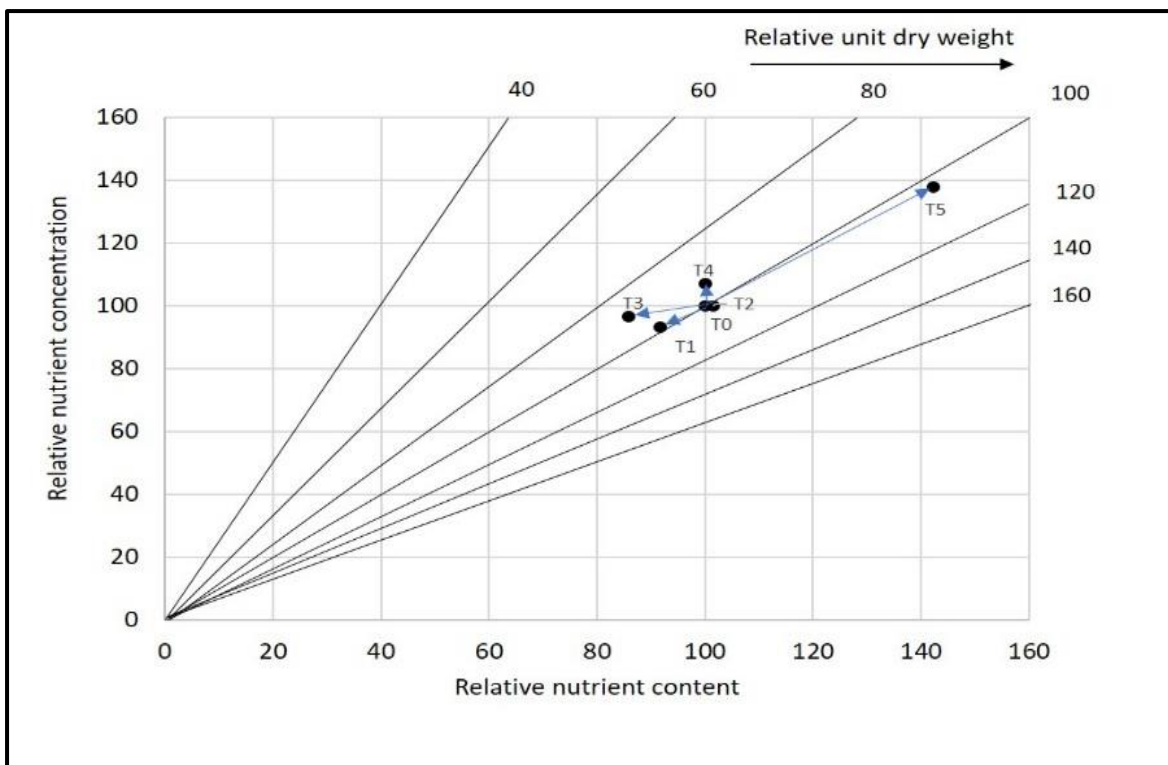


Figure 7.40: Vector nomogram for the response of K to fertilisation in field trial F, at 12 months after fertilisation.

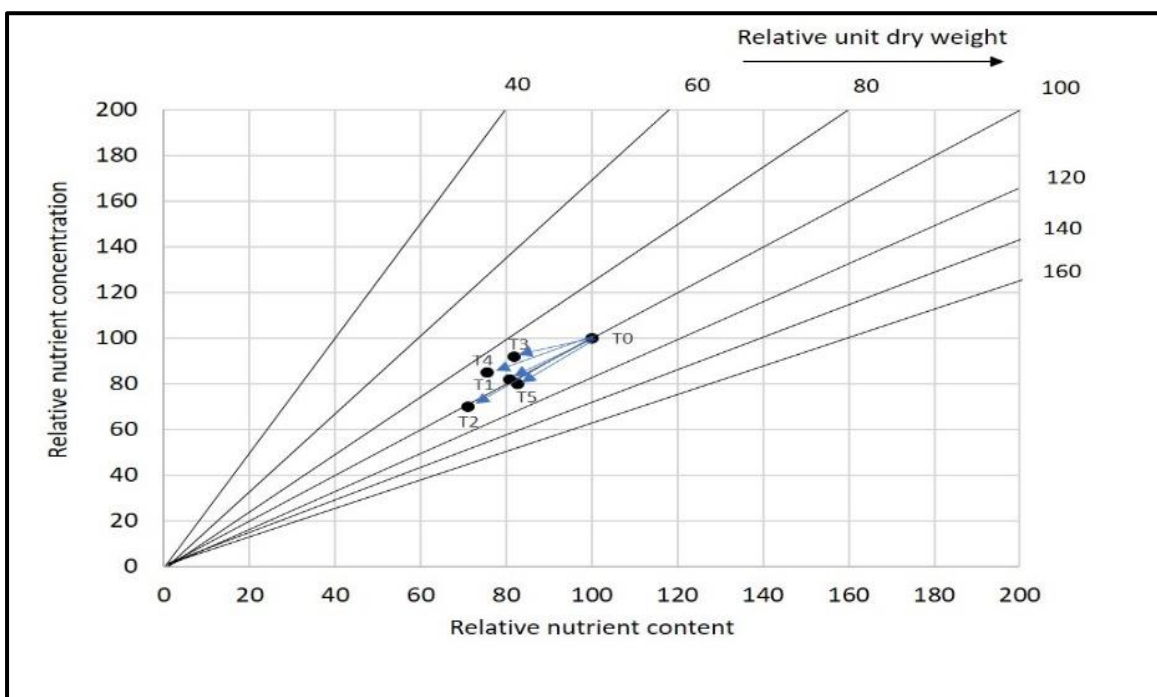


Figure 7.41: Vector nomogram for the response of K to fertilisation in field trial F, at 24 months after fertilisation.

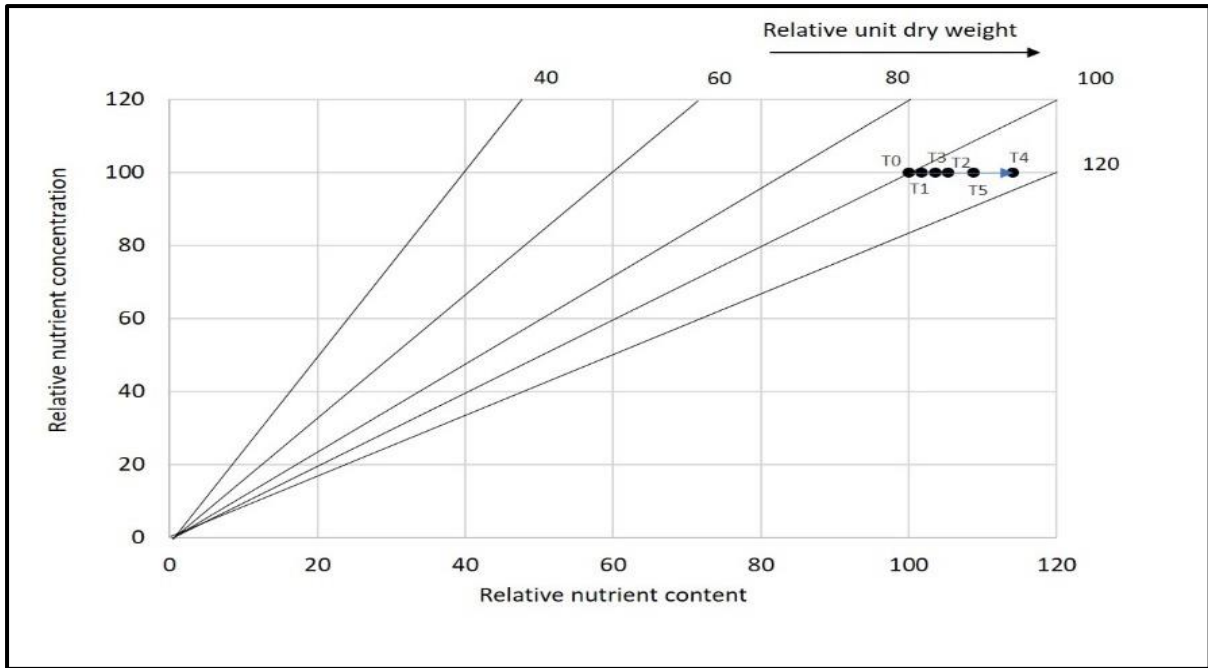


Figure 7.42: Vector nomogram for the response of Cu to fertilisation in field trial B, at 12 months after fertilisation.

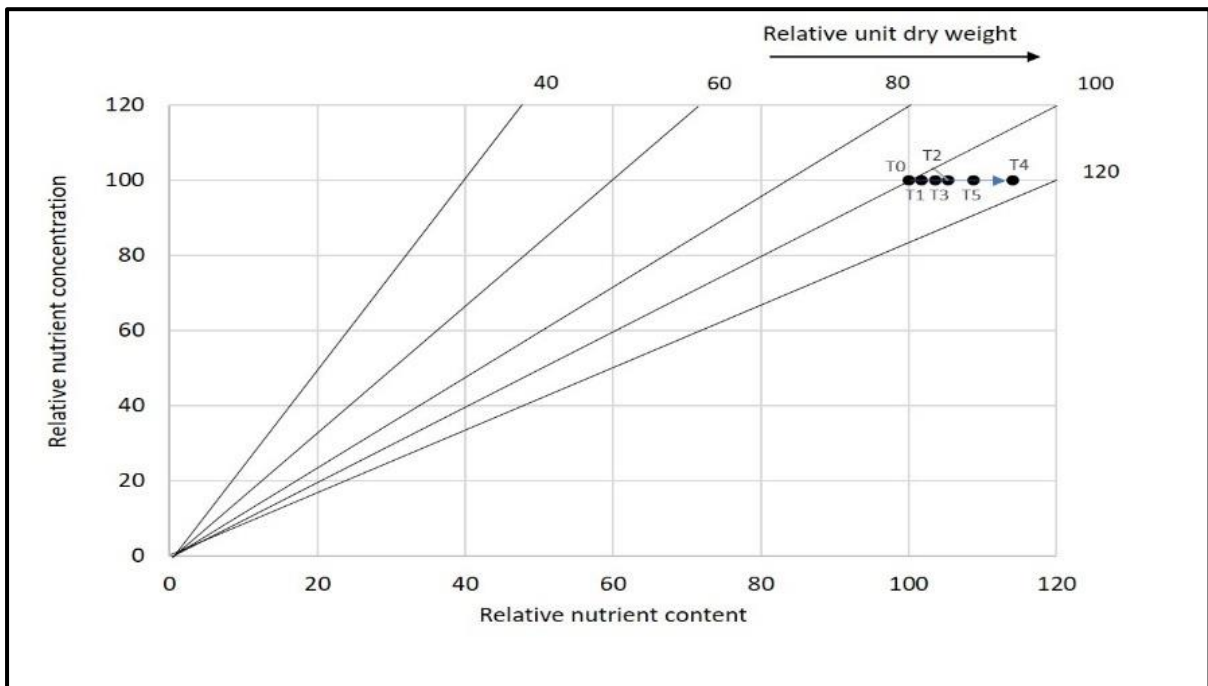


Figure 7.43: Vector nomogram for the response of Cu to fertilisation in field trial B, at 24 months after fertilisation.

CHAPTER 8

CONCLUSIONS

A review of the available literature identified several very distinctive key aspects regarding the fertilisation of semi-mature pine stands: 1) Fertilisation can induce growth responses, although the degree and duration of the responses are highly variable. 2) Responses are governed by several edaphic, geographic and climatic conditions. 3) Responses can be species and site specific. 4) There is room for refinement of the current fertilisation strategies in plantation forestry.

The findings of this study managed to address the research questions formulated for each of the main chapters. The WD estimate proved to be a reliable estimate of soil water stress in several afforested regions in the Cape Forest Region relative to the more commonly used measures of water availability, such as MAP, AI and MGS. The estimate was significantly affected by edaphic and climatic site conditions, and it managed to provide an excellent index of plant-available water over a time step with fewer data requirements. The WD estimate revealed that soil water availability is not a growth-limiting factor for the afforested areas in the Tsitsikamma region due to the superior water-retention capabilities of soils from this region. This finding demonstrates that the fertilisation of commercial and privately afforested sites in this region is potentially viable, even at times of inconsistent climatic conditions and lengthy dry periods. Positive growth responses were maintained throughout the experimental period, even though the region was severely affected by droughts at the time. No significant relationship was observed between the annual soil N mineralisation rates predicted by the SNAP model and the growth response to fertilisation at 24 months in this study. A novel finding for this region was the significant relationship observed between the predicted annual N mineralisation rates and the highly acidic soil conditions of each field trial. This was the first direct evidence that soil pH might be a growth-limiting factor in the Tsitsikamma, and that it might indirectly affect optimum (and site-specific) fertilisation rates. The SNAP model has moderately high data requirements, thus the next logical step was to investigate whether simplified estimates of mineralisable N and P, by means of aerobic and anaerobic incubations, have the potential to be accurate predictors of growth. Studies by Mariano *et al.* (2013) and Pullito *et al.* (2015) suggest that anaerobic estimates of mineralisable N might be quicker, more

cost-effective and potentially superior to aerobic incubations, and the findings of this study are parallel to their findings. The anaerobically mineralised N estimates were better correlated with the growth responses at 24 months. The findings of this study show that mineralisable N from anaerobic incubations has the potential to identify sites that are more likely to respond to fertilisation, thus putting commercial companies and private growers in the position to apply smaller quantities of fertiliser and still achieve large growth responses on sites with naturally higher or lower soil N mineralisation rates. The critical value and nutrient ratio assessment methods identified several macro- and micronutrient deficiencies over the 24 months. The vector nomograms illustrate a temporary shift in N and P stand nutrition, alongside increases in K in some field trials at 12 and 24 months after fertilisation. This finding, together with the critical level and nutrient ratio assessments, highlights the temporary effect of N and P fertilisation on stand nutrition over a short experimental period. The above-mentioned findings, together with: 1) the ability of the soil WD estimate to paint a moderately accurate picture of soil water availability, 2) the significant effect of soil pH on the predicted annual N mineralisation rates of the SNAP model, and 3) the significant relationship between the mineralisable N from anaerobic incubations and the fertiliser growth responses in this study, can provide the user with a set of tools to refine the fertiliser regimes of the Cape Forest Region. The growth response to treatments T2, T4 and T5 (a 100 kg N ha⁻¹ and 50/100 kg P ha⁻¹ difference) were similar from an economic perspective (Section 5.8.3, Figure 5.13) for most field trials, apart from field trials A, B and D, in which larger responses to treatment T5 were more apparent. This observation, together with the findings of this study, provides evidence that the formulation of site-specific application rates can improve the economic feasibility of mid-rotation fertilisation.

Plots were standardised at trial establishment to reduce the likelihood of large growth variabilities overshadowing the effect of fertilisation. Nonetheless, growth variability remained one of the main challenges of this experiment. Due to time constraints, the growth responses were monitored for a period of 24 months after fertilisation, and this observation period is very short to capture the fertilisation response of semi-mature pines. Carlson *et al.* (2014) and Jokela and Stearns-Smith (1993) reported significant responses at four years after fertilisation, while Albaugh *et al.* (1998) and Ramírez Alzate *et al.* (2016) reported significant responses eight and six years after fertilisation respectively. The abovementioned studies reported significant findings after a period of four and more years after fertilisation, thus suggesting that continuous monitoring is crucial. The use of a ceptometer to monitor short-term canopy development in

softwood plantations was not very accurate and repeatable; the estimate requires a correction factor due to foliage clumping, and stand variability affects the reliability of the equipment. Precautionary steps were taken to reduce variation in this study, although this aspect remained a challenge. The position under canopy was kept as uniform as possible, and an attempt was made to maintain a constant traverse through the plots of each field trial. Measurements were taken in clear-sky conditions and, if possible, at a similar time of day for each field trial throughout the period of the experiment. Lastly, wind damage altered canopy structure throughout the experimental period, and this led to increased variation in canopy size, canopy nutrient content and, lastly, stand growth rate.

FUTURE WORK AND RECOMMENDATIONS

Future work that might contribute significantly to this project's goals is the continuous monitoring of field trials to establish the degree and duration of the response of slash pine to fertilisation in the Tsitsikamma, and to correlate these findings with the N mineralisation rates reported in this study. The prospect would be to further refine this study and identify, class and fertilise potential sites according to soil N mineralisation rates, water availability, degree of under-canopy vegetation and foliar nutrient concentrations. This would potentially allow the researcher to formulate progressively more accurate site-specific fertiliser applications rates for the Tsitsikamma or other regions. The addition of the micronutrients Zn, Fe and Cu should be investigated, as the levels of these elements were marginal to sub-optimal in many plots. Lastly, the effect of acidity (and lime applications) on the soil N mineralisation rates, plant nutrient availability and the growth responses of young and semi-mature pine stands to fertilisation in the Tsitsikamma needs to be investigated.

The site-specific edaphic properties seem to be a significant driving force as far as the growth responses of stands to fertilisation are concerned. Recommendations arising from this study would include:

1. Detailed plant water availability estimations that are similar to or improved versions of methods like the WD estimate are required to better understand how climatic variations affect the soil water availability and the feasibility of fertilising pine sites.
2. Comprehensive soil characterisation of productive and less productive sites. Soil N mineralisation rates of dominant soil types should be determined by means of anaerobic incubation studies and be modelled accurately.

3. Slash pine sites in the Tsitsikamma can be treated with moderate fertilisation rates (especially on less acidic soils), as N mineralisation rates and the nutrient availability of several nutrients seem to be limited by the highly acidic soil conditions.
4. For the fertilisation of semi-mature slash pine in the Tsitsikamma, under-canopy vegetation management is essential, as large occurrences of vegetation compete for resources and apparently delay growth responses.

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