RESEARCH PROJECT

Investigating the use of soil and foliar analyses as indicators of productivity in short rotation plantations in South Africa.

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A project report submitted in partial fulfillment of the requirements for the Masters Degree by coursework and research project in Resource Conservation Biology.

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Abstract

The global increased demand for forest products has led to an increase in the area of exotic fast-growing forest plantations. An understanding of nutrient cycling in plantations is essential to enhance their productivity. Sustainable forest productivity involves the managing of nutrients and genetic factors to maximize yields such that they are increasing or non-declining through the maintenance of soil quality and selection of superior tree species and breeds. Komatiland Forests Limited (KFL), a South African forestry company, initiated a permanent sampling plot (PSP) programme in 1998, where it monitors over 30 foliar and soil parameters, as well as tree growth parameters. This study utilized a subset of the permanent sample plots (PSPs) database to compile a suite of foliar and soil parameters that can be used to better interpret stand productivity in pine plantations. Data from PSPs of pine species *Pinus patula, Pinus elliottii* and the hybrid *Pinus elliottii x caribaea* planted on dolomite, granite and shale were used in the statistical analyses as they were well represented in the dataset. The geological analysis revealed that parent material significantly affects soil organic carbon content; soil exchangeable K, soil Fe, soil Mn and foliar Mn concentrations. Exchangeable K was found to be low across the geologies ranging on average from 0.08 – 0.11cmol/kg. An accumulative effect was found in foliar concentration of Mn across the geologies and species, with average foliar Mn concentrations being as high as 1086ppm. No statistically significant differences were found at the geological level in soil N, P, exchangeable Ca, Mg & Na, Al, pH or soil texture. Neither were there any significant differences in foliar concentration of N, P, Ca, Mg, Na, Cu, Fe, Zn, B and S at the geological level of analysis. However significant correlations were found between soil cation exchange capacity, soil pH and foliar concentration of Zn, Mn, Mg and Ca. *Pinus patula* had significantly higher foliar concentrations of N ($p<0.001$), P ($p<0.001$). Mg ($p=0.001$), B ($p=0.001$) and S ($p<0.001$) than the other pine variants under analysis. However when species x geology interaction analysis was used *P. patula* only had significantly higher foliar concentrations with regard to N ($p<0.001$) and P ($p<0.001$), and lower foliar concentrations of Zn ($p<0.001$) and Na ($p=0.041$) than the other pine variants under analysis. Across the species and geologies, soil acidification resulted in low Ca (0.15-1.6 cmol/kg) and Mg (0.1-0.7cmol/kg) availability. Positive and significant correlations were found between foliar and soil concentrations of N ($p=0.022$), P ($p=0.030$), Mg ($p<0.001$) and Ca ($p<0.001$). Productivity of the hybrid was significantly higher than the other two species ($p<0.001$), while *P. elliottii* had significantly lower productivity than *P. patula* ($p=0.001$). Regression models and a principal component analyses revealed that from the dataset of soil and foliar chemical and physical parameters Mg Soil, CEC, N soil, N foliar, P foliar, K foliar, Cu foliar, B foliar, S foliar, C:N soil, Ca:Al soil, N:Ca foliar, N:K foliar, clay and silt are best correlated with stand productivity.

Declaration

I declare that this research project is the result of my own investigations, unless acknowledged to the contrary in the text. It is being submitted in partial fulfillment of the requirements for a Masters degree by coursework in Resource Conservation Biology for the University of Witwatersrand, Johannesburg.

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Nokukhanya Maplanka

Dedication

To Mom, for her endless support, love and prayers

Richard for the financial help and love

Brendon and Musa for always believing

The boys, you are my inspiration

Siphiwe and Buna for listening and encouraging me on

"Success is neither magical nor mysterious.
Success is the natural consequence of consistently applying basic fundamentals"

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1. Introduction

1.1 General Introduction

The demand for plantation goods and services has been related to the size of the world's population which is estimated to increase by 900 million per decade for the next 50 years (Fox 2000). While the demand for plantation products is increasing, the area of plantations in the world is decreasing (FAO 1997). Increasingly the world will have to rely on intensively managed short-rotation forest plantations to supply societal needs (Evans 1976 & 1992, Nambiar 1999, Fox 2000).

A commonly expressed opinion, although not based on any reliable evidence, is that sustained productivity of intensively managed plantations of monocultures is at greater risk than low-input, multi species forests. Long-term research and its systematic application have produced economically viable silvicultural options which not only maintain yield but also enhance it over extensive areas. With scientifically-based management, ongoing overall improvement in wood yield from plantations is being achieved across a range of soil and environmental conditions in pine plantations throughout the world (Nambiar 1999).

Plantation productivity has been identified in many policies and standards as a criterion of sustainability (Richardson et al. 1999, Schutz 1982). Plantation management tries to ensure that productivity is non-declining or positive over successive rotations and harvests while maintaining and enhancing the quality of the soil resource base in perpetuity (Nambiar 1996). This is because productive plantations are supported by ecosystems with the following characteristics (Richardson et al. 1999):

- Good water holding capacity;
- Adequate fertility, organic matter and soil organisms for decomposition;
- Good aeration and drainage to permit root growth and consequently plant uptake of water and nutrients and
- Maintenance of soil structure and symbioses.

Any site has an inherent capacity to support plantation growth that is set by abiotic factors such as soil fertility and climate. The realized plantation productivity from a site is also affected by other factors (e.g. disease and wildfire) and especially by management practices (Figure 1.1) such as stand density, fertilization, competition control, genetics and soil quality (Fox 2000). The core business of forest plantations is to ensure long-term productivity. Sustainable productivity depends on the total amount of each nutrient in the ecosystem as well as the availability of the nutrients (Federer et al. 1989). High production rates can be sustained through advanced, full cycle nutrient management techniques (Allen 2001). This is because productivity depends on the rate of photosynthesis which requires the stoichiometric availability of nutrients. Soil is the primary source of most mineral nutrients. Foresters have always relied on their knowledge of chemical and physical properties (i.e. soil quality) to assess the capacity of sites to support productivity.

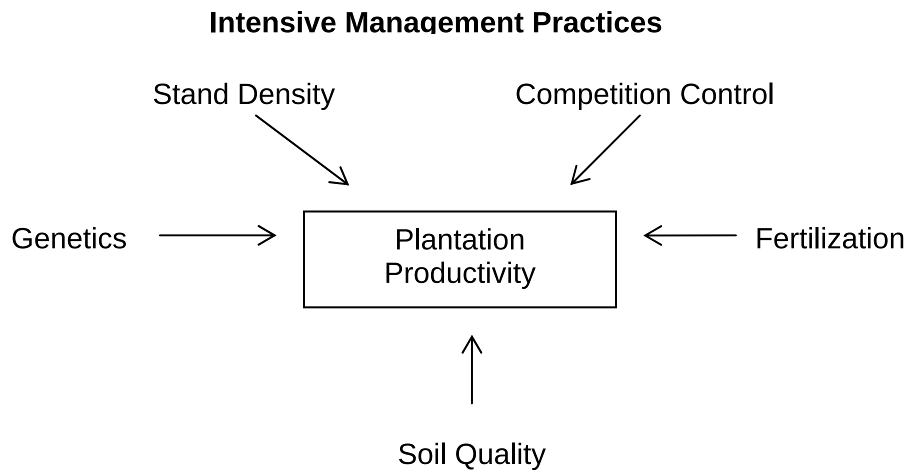

Figure 1.1 Plantation management practices affecting productivity of forests (Fox 2000).

The total elemental composition of a soil may reflect the minerals present but it does not indicate the amounts of nutrients that may become available for plant uptake (Barber 1995). No absolute conversion of total elemental content to plant-available content can be made because the mineral forms differ among soils as well as the demand for nutrients among the species (Boul 1995). Foliar nutrients give an indication of the amount of nutrients that can be extracted from the soil and which minerals are unavailable for uptake.

Currently timber yields in South African plantations compare favourably internationally (Evans 1999). This has been achieved by using genetically excellent (superior) trees and matching them to environments where they can attain satisfactory productivity. In South Africa, plantation nutrient management is becoming increasingly relevant to assure the long term sustainability of plantations as the region is characterised by soils of variable underlying geology which translates into variable nutrient content. Most plantation organisations have realised the importance of monitoring soil and foliar properties and have embarked on research projects that involve nutrient management and sustainable productivity

Komatiland Forests Limited (KFL) is one of South Africa's important timber producing companies, with at least twenty plantation estates distributed among the Limpopo, Mpumalanga, Eastern Cape and Western Cape provinces (Figure 1.2). In 1998 KFL initiated a project on monitoring plantation productivity through the establishment of permanent sampling plots (PSPs). A PSP is a 40 x 40m plot that is located within an existing compartment of trees, receiving the standard silvilcultural and management treatments. The plots are permanently marked for re-sampling. Foliar, soil and growth parameters are measured in these plots to give an indication of the tree performance and any necessary management interventions that may be required to maintain productivity. One of the primary objectives of the program was to establish a range of baseline values for the various soil and foliar chemical parameters for productive plantations (Mudimeli 2003, Kotze & Strydom 2003).

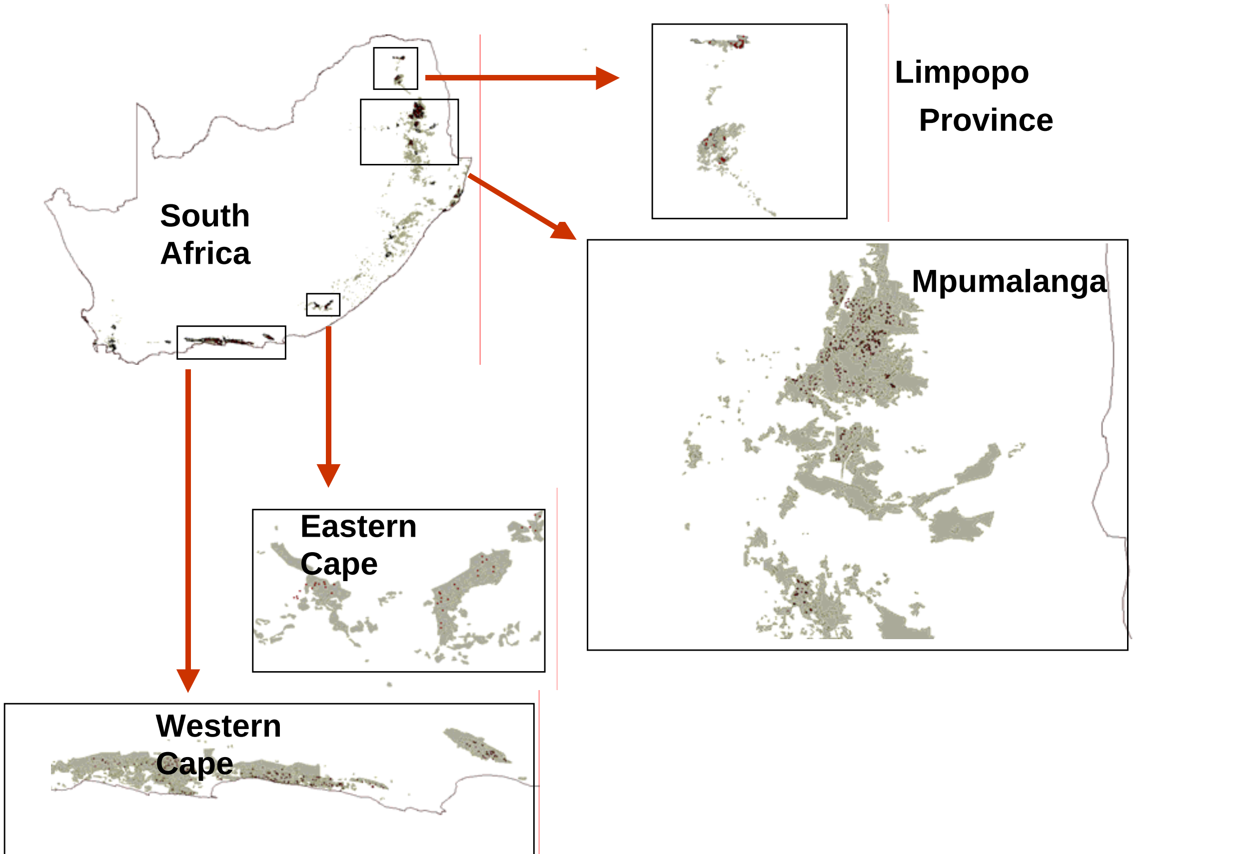

Figure 1.2 Location of Komatiland Forests Limited. PSPs are indicated by the small black dots in their plantations indicated by the grey colour (Adapted from Kotze & Strydom 2003).

1.2 Objective of the study

Komatiland Forests Ltd collects and stores compartment level soil, foliar and growth data in a PSP database. The PSPs are selected using GIS technology to represent the widest possible range in values of site variables including mean annual rainfall and temperature, geology, species and age-class. Currently KFL is monitoring more than 30 soil and foliar parameters in each of the PSPs. Soil and foliar analyses are expensive and laborious. Monitoring all 30+ parameters may not be necessary. This research project will use part of the PSP database to understand some of the underlying mechanisms involved in nutrient cycling and productivity of pine plantations using statistical tools.

1.2.1 Aim

To examine the relationship between foliar nutrient concentrations of short-rotation plantation species and soil chemical and physical characteristics, in order to identify a suite of key foliar and soil indicators for monitoring sustainable productivity.

1.2.2 Key questions

1. How are foliar nutrient concentrations influenced by geology (parent material) and tree species?
2. What is the relationship between the foliar and the corresponding soil analyses in pine plantations?
3. Which combination of foliar elemental concentrations and soil chemical and physical characteristics can be used to help interpret the productivity of pine plantations?

1.2.3 Approach to the study

The Komatiland Forests database contains more than 30 soil and foliar analyses results sampled in 1999 and again in 2001. New plots were also sampled in 2001 as some plots initially sampled in 1999 were lost to pest, fire or disease. Three tree species *Pinus patula, Pinus elliottii* and the hybrid *Pinus elliottii x caribaea* will be used as these were the most extensively sampled by Komatiland Forests. Most of the plantations are found on dolomite, granite and shale and these are the geologies that will be used to assess the influence of parent material. Principle component analyses, ANOVA tests and correlations analyses will be carried out to investigate the relationships between tree productivity, tree species and geology. The results from the statistical analyses will be compared to what is already known in literature from previous work done in this field. This report has been written for submission and examination to comply with Faculty regulations. The report contains an introduction, a lengthy literature review and a generic section on materials and methods. The results of the study are reported in the form of a manuscript prepared for journal publication.

2. Literature Review

2.1 Plantation forestry and productivity

Throughout the world, intensive management of plantations is becoming the norm as foresters have become more aware of the opportunities to improve production through the manipulation of resources. Productivity is dependent on resource availability, especially nutrients and water, and on the understanding of how nutrient and water availability interact with climatic conditions to determine production potential (Jokela & Martin 2000, Albaugh et al. 2004). The productivity of forest plantations is usually viewed from the perspective of stemwood accumulation. The net increment in stem growth is often expressed as the mean annual increment (MAI).

Productivity of stemwood is, in addition to other stress, affected by water and nutrient stress. This is because plants under stress produce less leaf area and therefore intercept less radiation resulting in less photosynthesis and ultimately stemwood production (Nambiar & Sands 1993). In order to maintain or improve productivity, the soil-plant relationship must be better understood, as soil is the primary source of nutrients needed for photosynthesis. Soil structure in forest plantations, as in other systems, is the result of pedogenic processes as well as anthropogenic activities. The complex series of nutrient additions (e.g. fertilization and decomposition) and losses (e.g. harvesting and leaching) from the soil, as well as climatic effects and microbial activity determine soil structure (Lal 1991). These processes may converge to play a significant part in nutrient availability. Favourable soil structure may be adversely affected by the use of heavy mechanical equipment on certain soil types and under certain moisture conditions. The increasing demands on plantation sites by intensive management coupled with potentially harmful processes operating in pine plantation ecosystems could prove critical in maintaining productivity in the long-term. Practices that alter site quality can have lasting effects on soil properties such as phosphorus application, soil compaction and drainage (Schutz 1982). Management practices that produce a deterioration in the physical, chemical and biological properties will reduce soil sustainability and hence productivity (Richardson et al. 1999). Studies have shown that increasing nutrient limitations in older stands accounts for a considerable part of the decline in stand growth. Gonclaves et al. (1997) identify four common constraints to productivity encountered in plantation forests:

i. Soil compaction that occurs during plantation operations, especially harvesting. Compaction restricts plant growth by reducing nutrient uptake and access to water;
ii. Nutrient depletion via harvesting. Although nutrients can be lost via other means, nutrient loss from stem harvesting can be high, particularly with short-rotation plantations;
iii. Nutrient losses via leaching and soil erosion and
iv. Competition for water and nutrients. This mainly relates to understorey competition and crop density.

All the constraints identified by Goncalves et al. (1997) involve the availability of nutrients. However, there are other factors that affect productivity. Temperature, hail, rainfall and strong winds are some of the conditions that can have positive or adverse effects on plantation productivity (Grey & Taylor 1983). However, management cannot affect the prevailing climatic conditions but can significantly alter the microclimate around individual trees via altering nutrient content of soils and drainage.

Productivity does not only depend on the environment i.e. nutrient and water supply, but species is also important. In plantation forestry, tree species are chosen primarily for their capacity to achieve high growth rates over a wide range of sites and for the quality and value of their wood. Ecological adaptations or tolerances are improved by genetic selection and breeding. The concept of combining plantation management i.e. site preparation or fertilization with controlled parentage to improve the overall yields and quality of plantation products is called tree improvement. Tree breeding allows for the creation of something entirely different by recombining the variability produced in nature into a new "package", the hybrid tree. Breeding makes it possible to create a plant with characteristics for difficult environments (e.g. drought-prone areas), pest resistance or specially desired products. Productivity is determined both by genetic makeup of the tree and by its interaction with the environment in which it grows. The objective of intensive plantation management can be simply stated as the production of desired-quality timber in maximum amounts in the shortest period of time (rotations) at a reasonable cost (Zobel & Talbert 1984).

Foresters have developed models that help them predict the yields of plantations at or near the time of harvesting. Yield forecasts have been developed at a regional level for plantations based on the assumption of a constant mean annual increment (MAI) (Chikumbo et al. 1998). Foresters use MAI to describe the wood growing capacity of a site and can be expressed as cubic meters of wood per hectare per year (m^3ha^{-1}. yr^{-1}.). MAI equations are also called yield equations and are derived from yield data found in published yield tables. The yield studies are done for a particular species by taking tree measurements (diameter, height and age to determine the individual tree volume) from many representative sample areas, and then computing basal area per unit area (Hanson et al. 2002). ForstatMAI20 is one such derived model base on site index. Site index is a measure of the plantation's potential productivity. It is usually defined as the height of the dominant or codominant trees at a specific age in a stand of trees. It is calculated in an equation that uses tree height and age. Site index equations differ by tree species and region because species differ in biomass allocation and nutrient demands (Hanson et al. 2002, Jokela & Martin 2000). Plantation productivity is reliant on appropriate soil management and monitoring.

2.2 Nutrient cycling in forest plantations

2.2.1 Macro- and micronutrients

Mineral nutrients essential for plant growth can be divided into macro- and micronutrients based on the amounts that are required by plants (Salisbury & Ross 1992, Marschner 1986). In general lack of one or more nutrients limits plant development and growth (Ingestad 1991). Macronutrients are elements required in relatively large quantities such as nitrogen, phosphorus and magnesium. On the other hand, micronutrients such as boron, chlorine and iron are nutrients required in small amounts.

Macronutrients are generally directly involved in most biological and physiological processes such as protein synthesis and osmoregulation (Marshner 1986). The function of micronutrients within plantation trees have been extrapolated from other plant species as little is known about them in plantations (Will 1985). In general cobalt, copper, iron, manganese and zinc activate enzyme systems through chelation of enzyme and substrate and/or through a valency shift of the micronutrient cation. Most micronutrients are constituents of several different enzymes. Other mineral elements can also be classified as beneficial nutrients. Beneficial elements are not essential for plant growth but can stimulate growth or become essential only under specific conditions (Marshner 1986, Barber 1995). For photosynthesis and other physiological processes that result in healthy plant growth to take place, these nutrients must be present in plant leaves in the right proportions. The productivity of vegetation relies on both plant physiological processes and soil nutrient dynamics.

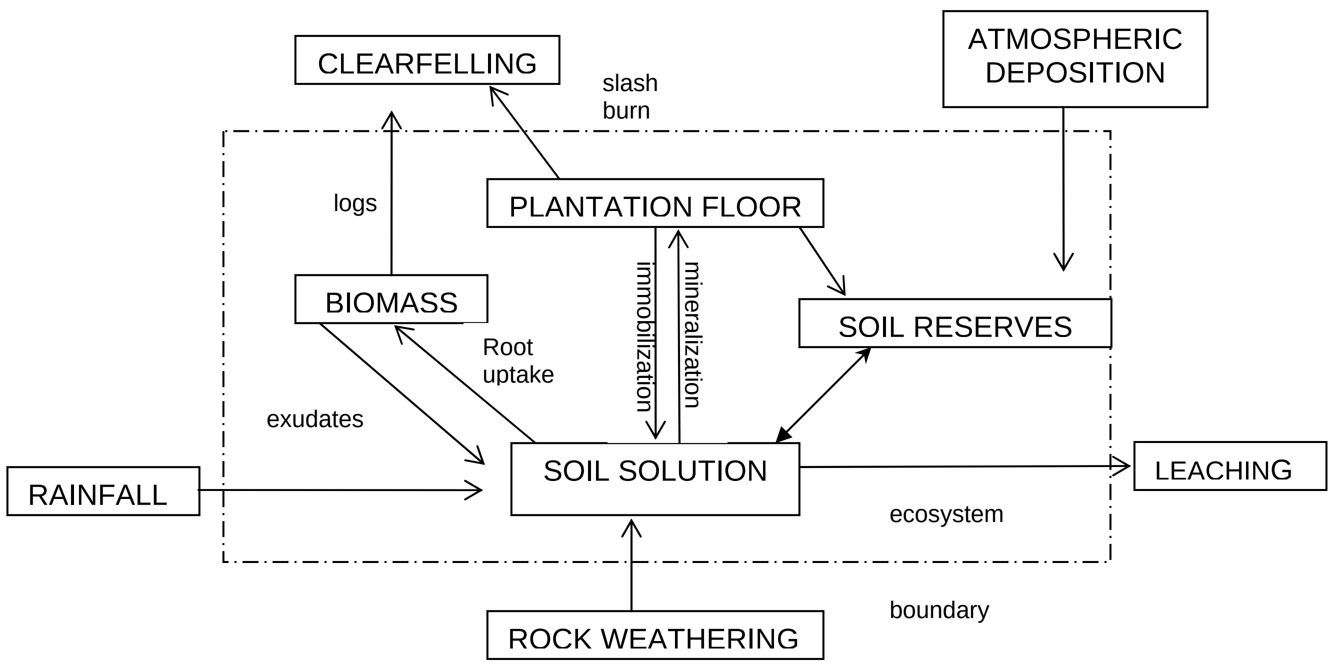

Figure 2.1 Nutrient cycling in forest plantations (adapted from Morris 1986).

In plantation ecosystems the forest floor (Figure 2.1) is the major source of nutrients. Nutrients are found in soil and on the floor in the form of soil organic matter or organic carbon. In plantation ecosystems, organic carbon is the result of decomposed litterfall. Organic carbon is of paramount importance in the maintenance of soil fertility and structure. It can be conceptualized as a series of pools whose turnover times differ because of differences in the complexity of the material and its association with soil particles (Parton et al. 1987). These include an active pool, which plays a major part in determining nutrient availability and corresponds to microbial biomass and plant metabolic material; a slow pool which corresponds to inter-micro aggregate material and is a major source of nutrients following soil disturbance; and a passive pool consisting of humified intra-micro aggregate material which is largely inert as a nutrient source (Szott et al. 1991, Parton et al. 1987). Organic content of soils is dependent on microbial activity. Microbial communities are affected by soil moisture, pH and temperature. Soils with higher clay content favour the formation of aggregates in which organic carbon may be protected from microbial degradation; they are also cooler than sandier soil because they hold more water and consequently have higher organic matter contents (Motavalli et al. 1995, Szott et al. 1991, Parton et al. 1987).

Apart from affecting nutrient availability, organic inputs can affect other parameters of soil fertility. Some organic residues temporarily reduce aluminium toxicity, presumably by complexation of aluminium in soil solution by organic acids, polysaccharides and other initial decomposition products, and may temporarily increase plant productivity. The effect may be temporary since aluminium may be released later upon further decomposition (Szott et al. 1991).

The breakdown of organic forms by micro organisms into inorganic products makes nutrients available for plant uptake. Once taken up by plants, the inorganic form is often converted back into its organic state. This process forms part of a complex cycle of various sources or pools that are interconnected called the nutrient cycle.

2.2.2 The forest nutrient cycle

The forest nutrient cycle consists of a series of interdependent processes, generally referred to as nutrient pools connected by transfer paths. The rate of nutrient transfer from one pool to another varies among plant species, soils and ecosystems (Jorgensen et al. 1975). It has been established that each nutrient usually has mobile (or potentially mobile) and non-mobile (structurally bound) forms within the ecosystem (Marschner 1986). Plantation communities differ in their nutrient regime and turnover rates in response to nutrient availability, stand age and several other environmental factors. The nutrient capital of plantation ecosystems is almost entirely confined to three pools, in decreasing order: the soil, trees and plantation floor (Singh 1982).

Most studies on plantation nutrient cycling have been conducted in natural plantations (Morris 1986, Sighn 1982, Jordan 1982). However, the basic principles and concepts apply to short-rotation plantations. This has been demonstrated in the *Pinus patula* plantations of Usutu Plantations, in Swaziland. There are three components of the nutrient cycle that have been recognized (Jordan 1982):

a. The geochemical cycle: involves inputs of nutrients from atmospheric deposition, weathering and the outputs of nutrients through leaching.
b. The biological cycle involving the movement of mineral nutrients from the soil to the plants, including the movement of nutrients from the plantation floor back to the soil.
c. The physiological cycle involving the storage and retranslocation of nutrients within the tree.

Morris (1986) proposed the simplified nutrient cycling diagram above (Figure 2.1) to represent the major cycles in plantation nutrient transfer. This diagrammatic representation is but a tip of the complexity of the transfer processes that exist between each nutrient pool. The processes involved can be characterised into nutrient gain or loss processes. Balanced cycles provide protection to the ecosystem from degradation and allow for optimal yields with sustained use of mineral resources at any particular site (Singh 1982).

2.2.3 Nutrient gains

The accumulation of nutrients in the biomass is important to both the geochemical and biological cycles in the forest plantation ecosystem. Nutrients become available to plants by (Szott et al. 1991):

i. Weathering. Weathering from primary and secondary soil minerals or changes from non- or slowly available to readily available forms. Weathering is the conversion of minerals from stable forms, i.e. rock or soil minerals, into forms that can participate in a variety of reactions involving exchange, leaching and biological uptake (Federer 1989). Nutrient weathering from primary and secondary minerals is controlled by soil type, inorganic chemical processes, temperature and rainfall (Szott et al. 1991).
ii. Atmospheric inputs (rain and aerosols). Atmospheric deposition of nutrients is usually small in magnitude. However, Thomas & Miller (1992) confirmed through experiments that high levels of nitrogen deposition could cause limited growth if the status of other nutrients is not proportionally increased. An increase in growth will place additional demands on the soil for other nutrients unless internal reserves are mobilized. Nutrient additions can vary between each rainfall event, seasons and years (Kellman et al. 1982, Probert 1978, Jordan 1982).
iii. Fixation of nitrogen from the air. Soil acidity and associated factors such as aluminium and manganese toxicity, along with phosphorus, calcium and molybdenum deficiencies can constrain symbiotic associations that result in N fixation. Mycorrhizal associations are important for optimal N fixation and productivity, since increased phosphorus uptake by host plants via mycorrhizae has been shown to be associated with improved growth and nitrogen fixation in tree species. However, this does not apply to this report and the species used in this study as they do not have N-fixing associations.
iv. Decomposition and mineralization of nutrients from organic forms. The productive capacity of a healthy ecosystem is maintained through the activities of soil organisms that contribute to the development of soil structure, decomposition of organic matter and nutrient mineralization and transformation (Richardson et al. 1999). The soil receives nutrients in thoroughfall, litterfall and through root death (Miller et al. 1979), which are converted to available nutrients by organisms. The material for decomposition develops in the plant prior to litterfall. Litter production is a major process by which carbon and nutrients are transferred from vegetation to soil. Litter production and the return of nitrogen, phosphorus, calcium and magnesium in litter are greater on more fertile soils. The availability of both carbon and nitrogen to the plants results in the formation of either high- or low- quality litter material. Litter quality is controlled by the plant species and the growing conditions that the plant experiences. Litter quality determines rates of decomposition and release of nutrients from organic residues. By manipulation of species it may be possible to affect the short- and long-term storage and mineralization of carbon and nutrients. Generally, leaf litter quality is higher and rates of decomposition more rapid on more fertile soils. Rates of decomposition are a function of the soil biota, substrate quality, microclimate and ecosystem condition (Szott et al. 1991, Yarie et al. 1994, Coleman et al. 2004). The litter layer in plantation forestry is important particularly in coarse-textured soils, not only as a nutrient reservoir, but also for moisture retention.

v. Addition from sources external to the system. Short rotation plantations have high demands on soil mineral content and nutrient supply and limitations can be addressed with suitable dressings of fertilizer to compensate for nutrient losses (Boardman 1978). Growing demand for plantation products is leading to increased intensification of plantation management practices, particularly with regard to increased use of fertilizers. In South Africa the use of fertilizers is one of the most effective and economical management practice that has increased productivity of commercial tree plantations. The earliest fertilizer experiments with pine in South Africa were initiated in 1935. Not all experiments have had high success in increasing productivity (Schutz & de Villiers 1988). Incorrect placements of fertilizers and the timing thereof are some of the reasons for the low success rate (Fox 2000). There are two approaches to fertility management of short rotation plantation plantations (Heilman & Norby 1998):

   a. The conservative approach which involves the use of fertilizer only when the diminished supply of mineral begins to impact growth. This approach minimizes fertilizer use, maximises nutrient use efficiency by the crop and the economic return, but does not assure maximum yield and therefore has potentially lower profits and low quality crops; and
   b. The ‘steady state” approach involves maintaining fertility at a high steady state in order to assure the optimal nutritional status of the crop. High rates of fertilizer input are required to supply nutrients for plant growth and also to steadily increase soil fertility.

Fertility management should fall somewhere between these two approaches. Maintaining high nitrogen levels is costly and is associated with increased potential for leaching and denitrification. On the other hand, the conservative approach has the risk of reduced yields since fertilizers are only applied under nutrient stress conditions which can be difficult to determine. Carey et al. (1982) concur that fertilization can be used effectively to enhance productivity. However, fertilization should be used with an understanding of nutrient dynamics along with the quantification of the underlying processes under different resource availability regimes (Albaugh et al. 2004).

2.2.4 Nutrient Loss

Nutrient losses are characteristic of any ecosystem. Mineral stress is the primary constraint to plant growth. Mineral stress can be defined as the sub-optimal availability of essential nutrients or toxicity of nutrients or non-nutrient minerals (especially aluminium, sodium, chloride, manganese and other heavy metals). Managed forests are largely characterized by multiple mineral stresses (Lynch 2004). Factors that influence rates of gain also affect the rates of loss. Nutrients can be lost when the ecosystem becomes saturated by the nutrient resulting in the plants being unable to take up the nutrients at the rate that they are made available. Nutrients are also lost from natural ecosystems by leaching, erosion, runoff or gaseous exchange. The factors determining leaching, sediment erosion, and runoff losses are complex and methodological difficulties in quantifying such fluxes, especially for leaching, result in scarcity of reliable data. Leaching losses of potassium, calcium and magnesium are generally larger on more fertile than infertile soils, but losses of nitrogen and phosphorus appear to be small regardless of soil type (Szott et al. 1991). Erosion losses after logging steep slopes may be extreme. The choice of cropping practice and site preparation can produce an increase in soil loss as high as 250-fold (Federer et al. 1989). Fire, through subsequent erosion, can also cause extreme soil loss and adversely affect many other soil properties. In managed agricultural systems, nutrients are principally removed as harvested products. Plantation harvesting removes nutrients from the system in large quantities but at infrequent intervals compared to leaching (Federer et al. 1989). Monitoring nutrient availability and uptake has been part of agriculture for decades. This is achieved via chemical analysis of soil and crop plant material. Chemical analysis has been used to detect deficiencies and toxicities in plants, allowing for the appropriate intervention by management in order to achieve maximum potential productivity. Soil and plant chemical analysis each have advantages and disadvantages and will each be discussed in the following sections.

2.2.5 Soil mineral content analyses

Soil quality can be broadly defined as a soil's capacity to function effectively as a component of a healthy ecosystem. It is a combination of physical, chemical and biological properties that contribute to soil function (Knoepp et al. 2000). Any given soil function is supported by a number of soil attributes, while any property may be relevant to several soil attributes and/or functions simultaneously. Many soil chemical properties (e.g. pH) directly influence microbial processes and these processes together with physico-chemical processes determine the capacity of soils to hold, supply and cycle plant nutrients (Schoenholtz et al. 2000).

Soil material results from hundreds to thousands of years of physical, chemical and biological weathering of the earth's crust. The chemical composition of soil is largely the result of the underlying geology. Geology can be divided into three categories defined by their formation: igneous, metamorphic and sedimentary rocks. The different types of rocks have an influence on the elemental composition and physical characteristics of the soil (Black 1957). Although soil inherently contains the same elements as the underlying geology, the proportions may differ greatly. Elements such as calcium, magnesium, potassium and sodium may be lost as soluble cations during weathering depending on climatic conditions. On the other hand, some other elements such as iron or aluminium are resistant to leaching losses and their proportions may increase compared to the underlying rocks (Coleman et al. 2004).

The total elemental composition of a soil may reflect the minerals present; however, it does not indicate the amounts of nutrients that may become available for plant uptake. Plant nutrient uptake does not only depend on the amount of the element present, but also on the nature of the mineral elements in the soil water and their association with nutrients adsorbed by or contained within the soil material (Barber 1995).

Chemical properties can also significantly influence the availability of soil nutrients particularly soil pH and cation exchange capacity (CEC). Soil pH can affect nutrient availability by its effect on beneficial microorganisms which are often pH-sensitive. Acidic soils (pH 4-5) usually have high and toxic concentrations of soluble aluminium and manganese. On the other hand, basic soils (pH>9) reduce the solubility of all micronutrients, especially iron, zinc, copper and manganese (Miller & Donahue 1990, Marschner 1986). Cation exchange capacity is an important determinant of nutrient availability as it maintains soil acidity and base status. Clay particles have a net negative charge which attracts mobile cations. However, cations can be displaced (exchanged) by other cations in solution via mass action (i.e. higher concentrations of the displacing cation). This exchange of one cation by another is called cation exchange. The most numerous cations on exchange sites in soils are calcium, magnesium, hydrogen, sodium and potassium. Cation exchange capacity is measured in centimoles of cations per kilogram of soil. The term centimole is used to indicate the positive charge which is constant because the number of negatively charged sites of a given soil is constant. However, the mass of the cations that may be adsorbed at one time can be different (Miller & Donahue 1990).

The advantages of soil analysis include ease of sampling and comparatively minor seasonal effects. The main disadvantage is that soil analysis is an abstraction of actual nutrient availability (Powers 1984). Soil tests for micronutrients have often proved to be unreliable over a wide range of areas because of insufficient knowledge about their soil chemistry and interactions with plant absorption (Hill & Lambert 1981).

2.2.6 Plant nutrient analysis

General relationships exist between geology and tree nutritional status. Foliar analysis interpretation is a potentially powerful diagnostic tool in evaluating plantation nutrient status, consequently they are often monitored in forestry plantations (Landsberg & Gower 1997). Past foliar nutrient experiments have been based on the following assumptions (Linder 1995):

1. Optimal vitality and conditions for growth can exist only if all essential plant nutrients are present in the correct proportions;
2. The relative proportion of an element to nitrogen is a more important measure than the total elemental content of the element in the leaf;
3. To optimize biomass production in a given climate, all essential minerals should be supplied at a rate which is adjusted to the current mineralization and fixation rates and nutrient demand of the crop; and
4. The optimal proportion between nutrient elements is similar for all higher plants.

All leaves have the same basic function and utilize the same suite of nutrients in the process of photosynthesis. Growth restrictions and mineral deficiencies are detectable by comparing foliar nutrient concentrations to threshold ranges (Tausz 2004). In forestry, the critical level is defined as the foliar nutrient concentration at which yield attains 90% of the potential maximum (Figure 2.2) (Ulrich & Hills 1967).

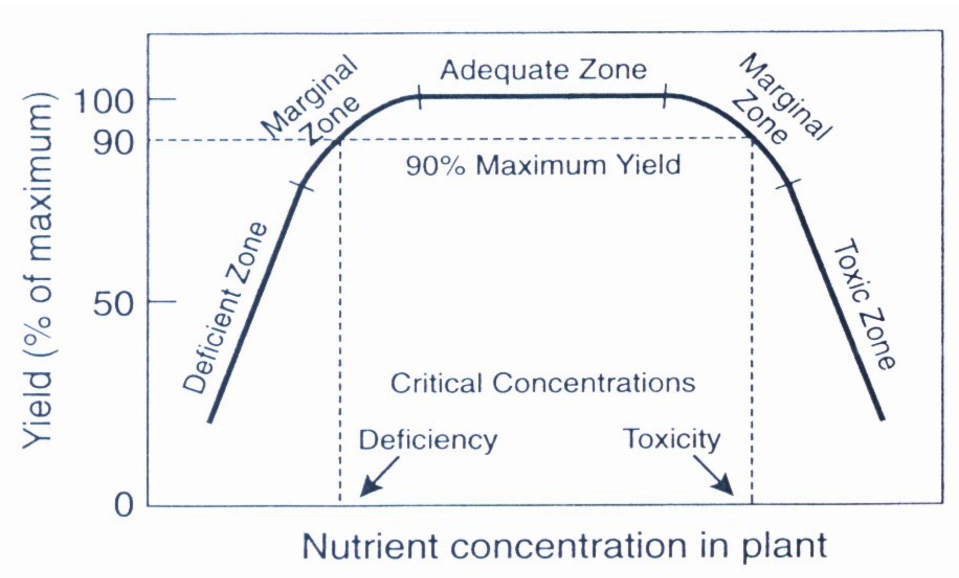

Figure 2.2 Derivation of critical concentrations for diagnosing nutrient deficiency and toxicity in plantation trees (Schutz & de Villiers 1988).

Plant tissue analysis provides a useful measure of the elemental status of plants and is helpful in fertiliser management. Initially single element foliar concentrations were used to establish sufficient or critical levels. Now it is common practice to work with a range of concentrations i.e. from deficiency to excess/toxic concentrations (Figure 2.2) (Sveson & Kimberley 1988, Schutz & de Villiers 1987, Gregoire & Fisher 2004). The actual concentrations corresponding to each foliar nutrient range vary for the different elements and depend on the tree species, tree age, stand density and the specific measure of growth used as a response variable (Gregoire & Fisher 2004). Critical levels are also affected by other factors including climate, season, aspect, altitude, genetic variation, provenance, plant part sampled, moisture content and time of day. Critical levels can thus be misleading (Schutz & de Villiers 1987).

Another shortcoming of the critical levels approach is that only one element can be dealt with at a time and important bi-elemental interactions are missed. The interactions between micronutrients and macronutrients have been reported in various studies (Hill and Lambert 1981). The Diagnosis and Recommendation Integrated System (DRIS), developed in the 1950s provides a method of handling interactions of mineral nutrients by using ratios of foliar nutrient concentrations to calculate indices that diagnose the nutrient status of a plant. The Diagnosis and Recommendation Integrated System assumes that there is an optimal ratio between the elements and departures from that optimum are associated with poorer growth (Sveson and Kimberley 1988). These indices allow for the classification of yield factors in order of limiting importance, and also give an indication of the intensity with which the plant requires a given nutrient (Gregiore & Fisher 2004).

Interpretation of foliar analyses, regardless of method used is difficult because of the large number of external factors which may influence the nutrient levels. The concentration of a mineral nutrient in a leaf is the end result of a number of highly complex processes and interrelated factors (Grey et al. 1979). Foliar analysis has an advantage over soil analysis because the tree integrates all site factors and the chemical content of the foliage reflects the sites nutritional state. The main disadvantages are that nutrient compositions change with season and year and sampling must therefore be standardized to draw accurate conclusions from limited collections. The use of foliar analyses alone often does not give an indication of the amount of a particular element which must be added and should be used in conjunction with soil analyses (Schutz & de Villiers 1987).

3. Materials and Methods

3.1 Location and climate

The permanent sampling plots are located in the Limpopo, Mpumalanga, Eastern and Western Cape Provinces (Figure 1.2). The altitudes of the plots range from 850-1860m. Mean annual temperature ranges from 15 – 20°C with mean annual rainfall ranging from 950-1330 mm. Underlying geologies include dolomite, dolorite, gabbro, granite, shale, sandstone and some undifferentiated basic rock.

3.2 Plantation forest tree species

The plots have been sampled to represent the composition of species used by the forestry company. Eucalypts and pines are used, with the latter being more predominant across all the regions. The Eucalypts used by KFL are *Eucalyptus grandis* and *E. cloeziana*. The pine species used include *P. elliottii, P. patula, P. greggi, and P. elliottii x caribaea.* In this study pine species will be used in the analyses as they are more widely sampled and therefore represent a better dataset for statistical analysis. Only two plots of *P. greggii* have been sampled and it is comparatively not well represented in this dataset (Table 2). Therefore to investigate the species effect *P. elliottii, P. patula* and the hybrid *P. elliottii x caribaea* will be used.

Pinus elliottii grows slightly less rapidly, and hence yields a smaller volume of timber on favourable sites compared to species such as *P. patula* and *P. radiata.* Despite this shortcoming, it is used extensively in South Africa on account of its relative freedom from diseases and pests and its adaptability to an exceptionally wide range of climatic and soil conditions. It thrives best at low to intermediate elevations and in the summer rainfall area it is preferred to *P. patula,* largely because it does not succumb to fungal infection (*Diplodia pinea*) when injured by hail (Poynton 1977)*. P. elliottii* also suffers severe drought stress.

Pinus patula is a timber species of major importance in the cooler, mist belt regions of the summer rainfall areas. This species has proved to be one of the most vigorous and, in certain respects, most dependable of all the conifers that have been used for afforestation in the summer rainfall areas. While ill-suited to very warm or dry regions, and although subject, under certain circumstances, to damage or attack by wind, hail, fungi and insects, it thrives on a great variety of soils and yields a general utility timber free from serious defects and of consistently acceptable quality (Poynton 1977)*. P. patula* is also characterized by high litter accumulation (Dames et al. 2002) and exclusion of competitors when it becomes established.

Pinus elliottii x caribaea is a hybrid of *P. elliottii and P. caribaea. Pinus caribaea* grows more rapidly and yields a larger volume of timber than any other conifer when grown under humid, subtropical to warmer-temperate conditions. Unfortunately, young stands of certain varieties are to some extent marred by an unusually high proportion of badly-formed trees. This problem is compounded by the relatively low density timber produced that is infiltrated with resin making processing difficult (Poynton 1977). The high growth rate has been harnessed together with the good structure, disease resistance and wide environmental tolerance of *P. elliottii* to produce a highly successful hybrid that is slowly phasing out the use of either parent.

3.3 Sampling and analysis

Plots were sampled using the field procedures manual developed by the Mensuration and Modelling Research Consortium that defines reasonable minimum standards for inter-company data sharing (Du Plessis et al. 1997). Further details on site locations and sampling are provided in the manuscript. Soil and foliar samples were analysed for the properties and elements as shown in Table 1 below. The chemical analyses were carried out at the Institute of Commercial Forestry Research in Pietermaritzburg, South Africa. The chemical analyses used can be found in the manual by Donkin, Pearce & Chetty (1993) and Hefferman (1985). Compartment level growth data were captured in the form of forecasted mean annual increment using the ForstatMAI20 model that estimates yields based on site index. MAI is given in cubic meters per hectare per year. All the stand level data can be found in Appendix A. A sub-sample of each soil and foliar sample analysed at the ICFR laboratory is kept for future reference at the laboratory.

Table 1 Summary of soil and foliar analyses.

Soil Property/Element	Foliar Element
Total Nitrogen	Total Nitrogen
Phosphorus	Phosphorus
Exchangeable cations K, Ca, Mg, Na	K, Ca, Mg, Na
Fe & Mn	Cu , Fe, Zn. Mn
Al (ExAcid)	B
Organic Carbon	Total S
pH (KCl & H_2O)	
Al (ExAcid)	

P. elliottii x caribaea, P. patula and *P. elliottii* are found on the three major geologies and will be used to investigate the species effect (Table 2). Table 2 below, gives a summary of the data that will be used in the data analyses to answer the key questions. Some of the plots were selected in 1999 and re-sampled in 2001. New plot selections were also made in 2001 due to losses of plots after 1999 to pests, fire or harvesting. This data includes plots that were re-measured and others were first measured in 2001. *Pinus greggi* is only sampled in twice, on sandstone geology and an undifferentiated basic rock and therefore not represented adequately for this study and data analysis. Data from 1999 and 2001 will be used in the statistical analysis.

Table 2 Number of permanent sampling plots sampled in 1999 and 2001 for foliar and soil analysis.

Species	***Geology***								
	Dolomite		**Granite**		**Shale**		**Other**		**Total Sampled**
	1999	**2001**	**1999**	**2001**	**1999**	**2001**	**1999**	**2001**	
P. greggi			1	1					2
P. elliottii	4	4	9	6	4	4	5	3	39
P. patula	7	7	10	12	5	5	7	6	59
P. elliottii x caribbaea	3	3	3	5	2	2	1	1	20
Total	28		47		22		24		

The chemical analyses results can be found in Appendix A.

3.4 Statistical analyses

The following statistical analyses have been performed to answer the key questions:

- ✓ A principal component analysis was undertaken with pooled pine species data and geological data for all the soil and foliar data collected in 1999 and 2001 to find the variables that best describe productivity observed. The data set is multivariate in character with several complex interrelated dependent predictor variables that are of importance. One of the aims is to encapsulate the many variables into a few summarising variables. The principle component results will be compared to multiple stepwise regression methods. The stepwise regression methods allow for selection of the "best" combination of variables that describe the response variable or a good regression using as few variables as possible. Variables that occur in the all the both regression analyses and the principal component analysis will be considered as good predictors of productivity.
- ✓ ANOVA tests were performed on pine species and used to investigate the geological and species effect.
- ✓ Correlation analyses were used to investigate the relationship between soil properties (i.e. pH, CEC and soil texture) for each of the measured foliar elements.
- ✓ Correlation analyses were used to investigate the relationship between foliar element concentration and the corresponding soil element content.

Only the results where significant differences or relationships were found in each of the statistical tests will be reported. The results and subsequent discussions of this study are presented in the next chapter that is prepared as a manuscript for journal publication. Figure and table caption numbers will be reset in the manuscript.

4. Manuscript for publication

Investigating the use of a suite of foliar and soil parameters as indicators of productivity in short rotation pine plantations in South Africa.

Abstract

The global increased demand for forest products has led to an increase in the area of exotic fast-growing forest plantations. An understanding of nutrient cycling in plantations is essential to enhance their productivity. Sustainable forest productivity involves the managing of nutrients and genetic factors to maximize yields such that they are increasing or non-declining through the maintenance of soil quality and selection of superior tree species and breeds. Komatiland Forests Limited (KFL), a South African forest company, initiated a permanent sampling plot (PSP) programme in 1998, where it monitors over 30 foliar and soil parameters, as well as tree growth parameters. This study utilized a subset of the PSP database to compile a suite of foliar and soil parameters that can be used to better interpret stand productivity in pine plantations. Data from PSPs of pine species *Pinus patula, Pinus elliottii* and the hybrid *Pinus elliottii x caribaea* planted on dolomite, granite and shale were used in the statistical analyses as they were well represented in the dataset. The geological analysis revealed that parent material significantly affects soil organic carbon content, soil exchangeable potassium, soil iron, soil manganese and foliar manganese concentrations. Exchangeable K was found to be low across the geologies ranging on average from 0.08 – 0.11cmol/kg. Potassium is an important macronutrient and its low availability may significantly limit productivity. An accumulative effect was found in foliar concentration of Mn across the geologies and species, with average foliar Mn concentrations being as high as 1086ppm. No statistically significant differences were found at the geological level in soil nitrogen, phosphorus, exchangeable calcium, magnesium & sodium, aluminium, pH or soil texture. Neither were there any significant differences in foliar concentrations of N, P, Ca, Mg, Na, Cu, Fe, Zn, B and S at the geological level of analysis. However, significant correlations were found between soil cation exchange capacity, soil pH and foliar concentration of Zn, Mn, Mg and Ca. *Pinus patula* had significantly higher foliar concentrations of N ($p<0.001$), P ($p<0.001$). Mg ($p=0.001$), B ($p=0.001$) and S ($p<0.001$) compared to the other pine varieties under analysis. However when species x geology interaction analysis was used *P. patula* only had significantly higher foliar concentrations with regard to N ($p<0.001$) and P ($p<0.001$), and lower foliar concentrations of Zn ($p<0.001$) and Na ($p=0.041$) compared to the other pine varieties under analysis. Across the species and geologies, soil acidification resulted in low Ca (0.15-1.6cmol/kg) and Mg (0.1-0.7cmol/kg) availability. Positive and significant correlations were found between foliar and soil concentrations of N ($p=0.022$), P ($p=0.030$), Mg ($p<0.001$) and Ca ($p<0.001$). Productivity of the hybrid was significantly higher than the other two species ($p<0.001$), while *P. elliottii* had significantly lower productivity than *P. patula* ($p=0.001$). Regression models and a principal component analyses revealed that from the dataset of soil and foliar chemical and physical

parameters Mg Soil, CEC, N soil, N foliar, P foliar, K foliar, Cu foliar, B foliar, S foliar, C:N soil, Ca:Al soil, N:Ca foliar, N:K foliar, clay and silt are best correlated with stand productivity.

Introduction

Globally, intensively managed short-rotation forest plantations are becoming the norm in supplying the increasing timber and fibre demands of society. Currently South Africa has approximately 1.52 million hectares managed through intensive silviculture of fast growing exotic species (Louw & Scholes 2002). The core business of forestry is to maximize yields and to ensure sustainable productivity. Forest management tries to ensure that productivity is nondeclining or positive over successive rotations and harvests, while maintaining or enhancing the quality of the soil resource base in perpetuity (Nambiar 1996). Maintaining soil quality is critical as it is the primary source of most mineral nutrients needed for sustainable productivity (Boul 1995).

Plantation productivity has been identified in many policies and standards as a criterion of sustainability (Richardson et al. 1999, Schutz 1982). Forest plantation productivity is reliant on appropriate soil management practices and monitoring. Managers of plantations try to maximize productivity through site-specific management of, among other factors, stand density, selection of superior trees and species, and fertilization (Fox 2000). Optimal nutrient availability makes a significant contribution to the amount of wood and the quality of wood produced. Foresters try to match environments and species (site-species matching) to achieve the maximum potential productivity. Plantation productivity is a function of environmental (i.e. rainfall, temperature, nutrient availability) and genetic factors (Poynton 1977).

Genetic differences have been found to exist in the rates of metabolic processes (e.g. nutrient uptake) of species (Marschner 1986) and this may affect the quality of the litterfall. Soil organic matter is a significant source of plant mineral nutrients, and is largely comprised of litterfall material in plantation ecosystems. Gohlz et al. (2000) found that litter with high nutrient content undergoes rapid rates of decomposition due to the relatively higher water-soluble extractive nutrient content. Pines have also been found to alter the chemical structure of soil by enhancing soil acidity (Scholes & Nowicki 1998). The acidification of soil is associated with the leaching of organic acids generated from slowly decomposing pine litter, and with microbial cycling of nutrients particularly nitrogen, sulphur and the base cations (Scholes & Nowicki 1998). The relative effect of different species depends on factors such as tree growth, relative accumulation rates of base cations, degree of nitrogen fixation, alkalinity of tree litter and the spatial distribution of roots. Acidification of soils may affect the release of nutrients from parent material and from soil organic carbon. Acidification also results in the increase solubility of aluminium. There are three major mechanisms involved in aluminium tolerance (Marschner 1986): (i) exclusion from uptake; (ii) inactivation in the roots or (iii) accumulation in the shoots. Aluminium tolerance is important in the tropics where it was found to be a significant limitation to plant productivity. (Marschner 1986).

Various transfer processes determine the availability and uptake of nutrients e.g. mineralization and selectivity. Within each process, there is a rate limiting step or factor that regulates the release, uptake or storage of mineral nutrients. Factors may not apply equally to all nutrients which may differ in charge, size and mobility.

Komatiland Forests Limited (KFL) is one of the most competitive companies in timber production in South Africa. Management at KFL recognise the importance of genetics and environmental interactions in maximizing productivity. In 1998, KFL initiated a permanent sampling plot (PSPs) programme that monitors soil, foliar and growth parameters. Plots were selected to represent the proportional distribution of the tree species used by the company and to represent the widest possible range of environmental conditions. Plots were selected and marked in established stands of trees already receiving standard silvilcultural treatments. Some of the plots were selected in 1999 and re-sampled in 2001. New plot selections were also made in 2001 due to losses of plots after 1999 to pests, fire or harvesting. Currently the company is monitoring more than 30 soil and foliar parameters in its permanent sampling plot programme. Soil and foliar analysis is very expensive and laborious, but essential for ensuring the long term productivity of plantations. The long term sustainability of soil nutrient supply is of increasing concern in the face of increased demands for forest products, increased intensification, and the reluctance of plantation managers to apply inorganic nutrients to plantation ecosystems due to the environmental and economic constraints involved (Louw & Scholes 2002, Scholes et al. 1995). A range of site-growth studies have revealed that productivity in South African plantations is determined by the site factors controlling nutrient and water availability on a specific site (Louw 1999).

General relationships exist between geology and tree nutritional status. Soil analysis may be used as an aid for evaluating plantation nutritional status. However, the interpretations of the many methods for determining soil nutrient availability and its relationship to tree nutrient status have been met with limited success. Soil analysis may be of less value than foliar analysis for diagnosing the existence and severity of a nutritional problem. However, the use of soil analysis may be useful in correcting a nutrient deficiency detected previously by foliar analysis (Ballard et al. 1971). The nutrient status of a plantation is evaluated by comparing foliar concentrations of nutrients with limiting levels of soil nutrients, with ratios between soil and foliar nutrients and also by using the “Diagnosis and Recommendation Integrated System” (DRIS) (Lambert 1984, Schultz & de Villiers 1988). Interpretation of foliar analysis, regardless of the methods used is difficult because of the large number of external factors which may influence the nutrient levels. The concentration of a mineral nutrient in a leaf or needle is the end result of a number of highly complex processes and interrelated factors (Grey et al. 1979). Foliar analysis has an advantage over soil analysis because the tree integrates all of the site factors. The main disadvantage associated with foliar analysis is that nutrient composition of leaves change with season and year, and sampling time and methods must be standardized to enable accurate conclusions to be drawn from limited collections. The use of foliar analyses alone often does not give an indication of the amount of a particular element which must be added and should be used in conjunction with soil analyses (Schutz & de Villiers 1987).

The purpose of this study was to examine the relationship between foliar nutrient concentrations of short-rotation plantation species and soil chemical and physical characteristics, in order to identify a suite of key foliar and soil indicators for monitoring sustainable productivity.

Materials and Methods

Study sites

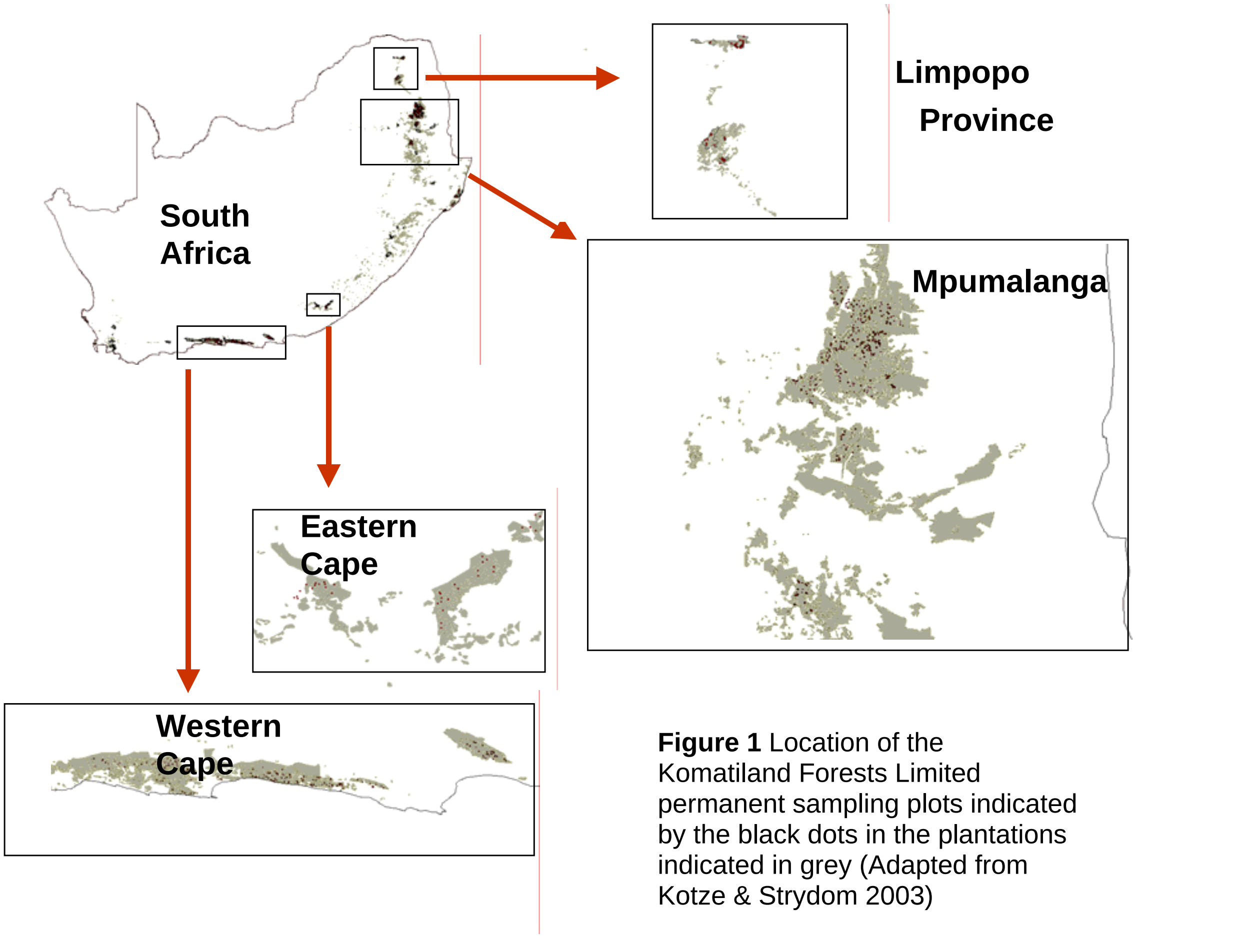

Figure 1 Location of the Komatiland Forests Limited permanent sampling plots indicated by the black dots in the plantations indicated in grey (Adapted from Kotze & Strydom 2003)

The permanent sampling plots are located in the Limpopo, Mpumalanga, Eastern and Western Cape provinces (Figure 1 above). The altitudes range between 850-1860 m. Mean annual temperatures range from 15-20°C with mean annual rainfall ranging between 950-1330 mm. Underlying geologies include dolorite, dolomite, granite, shale, and quartzite. Most of the plantations are found on dolomite, shale and granitic soils. Plantation species include *Eucalyptus grandis, E. cloenziana, Pinus greggi, Pinus elliottii, Pinus elliottii x caribaea* and *Pinus patula.* Most of KFL land is planted to *Pinus elliottii, P.elliottii x caribaea* and *Pinus patula*. These three species will be used in the data analyses (Table 1 below).

Table 1 Number of permanent sampling plots sampled in 1999 and 2001 for foliar and soil analysis.

Species	***Geology***								
	Dolomite		**Granite**		**Shale**		**Other**		**Total Sampled**
	1999	**2001**	**1999**	**2001**	**1999**	**2001**	**1999**	**2001**	
P. greggii			1	1					2
P. elliottii	4	4	9	6	4	4	5	3	39
P. patula	7	7	10	12	5	5	7	6	59
P. elliotti x caribaea	3	3	3	5	2	2	1	1	20
Total	28		47		22		24		

Experimental design

The plots were selected using a random stratification method that incorporated environmental and management variables. The plots are 40 x 40 m in area. Mean annual precipitation, mean annual temperature, geology, soil group and soil depth were environmental variables used in the stratification process. Management variables used for stratification included species and age-class. The tree ages range from 1-11 years. Compartment level growth data were captured in the form of forecasted mean annual increment using the ForstatMAI20 model that estimates yields based on site index. Mean Annual Increment (MAI) is given in $m^3.ha.^{-1}yr^{-1}$.

Soil and foliar sampling and analyses

Soil and foliar sampling took place during July and early August of 1999 and 2001, the same plots were not necessarily sampled in both 1999 and 2001. A topsoil core of 15 cm was taken from 5 points in a plot and bulked. The distribution of samples taken was one at the centre of the plot and the remaining four at random spots approximately 10m away from the central point. At each point the litter was removed with a spade so that no fresh organic matter was incorporated into the soil sample (Kotze & Strydom 2003).

The foliar sampling design was similar to that of the soil sampling. Needle samples were taken from the upper branches of five average sized trees at random within the plot and bulked. In each tree, needles were taken from 3 separate branches in the upper third of the crown where mature needles from last seasons' growth were sampled. These were usually found on the second needle whorl back from the growing tip. Where trees were too large for the upper branches to be removed using a pruning saw, trees were climbed with a tree climbing bicycle.

For continuity and to avoid variability over seasons, care was taken that the same trees were sampled and from the same place in the canopy (Kotze & Strydom 2003).

All soil and foliar analyses were undertaken at the Institute of Commercial Forestry Research (ICFR) in Pietermaritzburg. Soils were analysed to determine total nitrogen, extractable phosphorus (Bray), organic carbon, soil texture, pH, exchangeable cations (K, Ca, Mg, Na), iron, manganese, and aluminium. The needles sampled were analysed to determine concentrations of nitrogen, phosphorus, calcium, magnesium, potassium, sodium, copper, iron, zinc, manganese, boron and sulphur. The chemical analyses used can be found in the manual by Donkin, Pearce & Chetty (1993) and Hefferman (1985).

Data and Statistical analyses

All statistical procedures were performed using STATISTICA 6.0 as well as SAS 9.1. There was no data to indicate within plot variation as all samples were bulked. A principal component analysis was undertaken with pooled pine species data and geological data for all the soil and foliar data collected in 1999 and 2001. ANOVA tests were performed on pine species and used to investigate the geological and species effects. Correlation analyses were used to investigate the relationship between soil properties (i.e. pH, CEC and soil texture) for each of the measured foliar elements. Correlation analyses were also used to investigate the relationship between foliar element concentrations and the corresponding soil element content. Only the results where significant differences or relationships were found in each of the statistical tests will be reported in the results.

Results

1. Foliar elemental content, soil chemical content and variations with geology.

Significant differences were found in soil and foliar chemical analyses at the geological level (Table 2). Soil chemical analyses were found to be significantly different for organic carbon, potassium, iron and manganese. With the exception of manganese, no significant differences were found in foliar concentrations among the geologies (Table 2). The percentage of organic carbon (OC) (Table 2) was found to be significantly lower on granite soils than shale and dolomite (p=0.002), while no significant difference was found between shale and dolomite (p=0.386). Potassium was found to be significantly lower on dolomitic soils than granite (p=0.023) and shale (p=0.014), while no significant difference was found between granite and shale soils (p=0.790). Iron was found to be significantly lower on dolomite than on shale (p=0.015) with no significant difference found between dolomite and granite (p=0.184), and between granite and shale (p=0.295). Soil manganese concentration on dolomite was found to be much higher than on shale and granitic soils (p<0.000). Foliar manganese was found to be lower on granitic soils compared to shale (p=0.042) and dolomite (p<0.000).

Table 2 Selected soil and foliar parameter means of pooled species data found to be significantly different on granite, dolomite and shale.

Parameter	Granite	Dolomite	Shale
Soil OC (%)	3.07 a	3.91 b	4.39 b
Soil K (cmol/kg)	0.08 b	0.04 a	0.11 b
Soil Fe (ppm)	31.20 ab	23.68 a	35.54 b
Soil Mn (ppm)	7.02 b	37.88 a	19.07 b
Foliar Mn (ppm)	424 b	1086 a	876 b

2. Foliar elemental content, soil chemical content and variations with species

There were significant differences found in the soils beneath the different species and also in the needles of the different species (Table 3). Significant differences were found in soil potassium, manganese, and carbon:nitrogen ratios under the species. *Pinus elliottii x caribbaea* had significantly higher potassium than *P. patula* (p=0.002), and a higher carbon:nitrogen ratio compared to *P. elliottii* (p=0.019) in its soils. *P. elliottii had* a significantly higher soil Mn compared to *P. patula* (p=0.037). *P. patula* was found to have significantly higher foliar concentration of nitrogen (p<0.001), phosphorus (p<0.001), magnesium (p=0.001), boron (p<0.0011) and sulphur (p<0.001) compared to the other two pine variants. *P.elliottii x caribaea* was found to have a significantly lower calcium foliar concentration (p=0.003) than the other pine species, while no differences were found between *P. elliottii* and *P. patula.*

Table 3 Soil and foliar parameter means of pooled geological data found to be significantly different under *P. elliottii*, *P. patula* and *P. elliottii x caribaea*.

Parameter	***P. elliottii***	***P. patula***	***P. elliottii x caribaea***
Soil K (cmol/kg)	0.06 a	0.06 a	0.11 b
Soil Mn (ppm)	33.72 b	13.67 a	16.56 a
Soil C:N	9.41 a	12.35 ab	19.12 b
Foliar N (%)	1.29 b	1.69 a	1.23 b
Foliar P (%)	0.09 b	0.13 a	0.09 b
Foliar Mg (%)	0.09 b	0.11 a	0.08 b
Foliar B (ppm)	15.18 b	18.87 a	11.09 b
Foliar S (%)	0.09 b	0.13 a	0.08 b
Foliar Ca (%)	0.26 a	0.25 a	0.18 b

The species x geology interaction ANOVA analysis revealed that *P. patula* had significantly higher foliar nitrogen (Figure 2a) ($p<0.001$) and phosphorus (Figure 2b) ($p<0.001$) among the three tree species. *P. patula* foliar concentrations of sodium (Figure 2d) ($p=0.041$) and Zn (Figure 2c) ($p<0.001$) among the geologies was found to significantly lower compared to the other species. Foliar sodium of *P. elliottii x caribaea* was found to be significantly higher on shale soils (Figure 2d) ($p=0.001$). *P. elliottii x caribaea* had significantly lower foliar calcium compared to the P. e*lliottii* and *P. patula* (Figure 2e) ($p=0.002$).

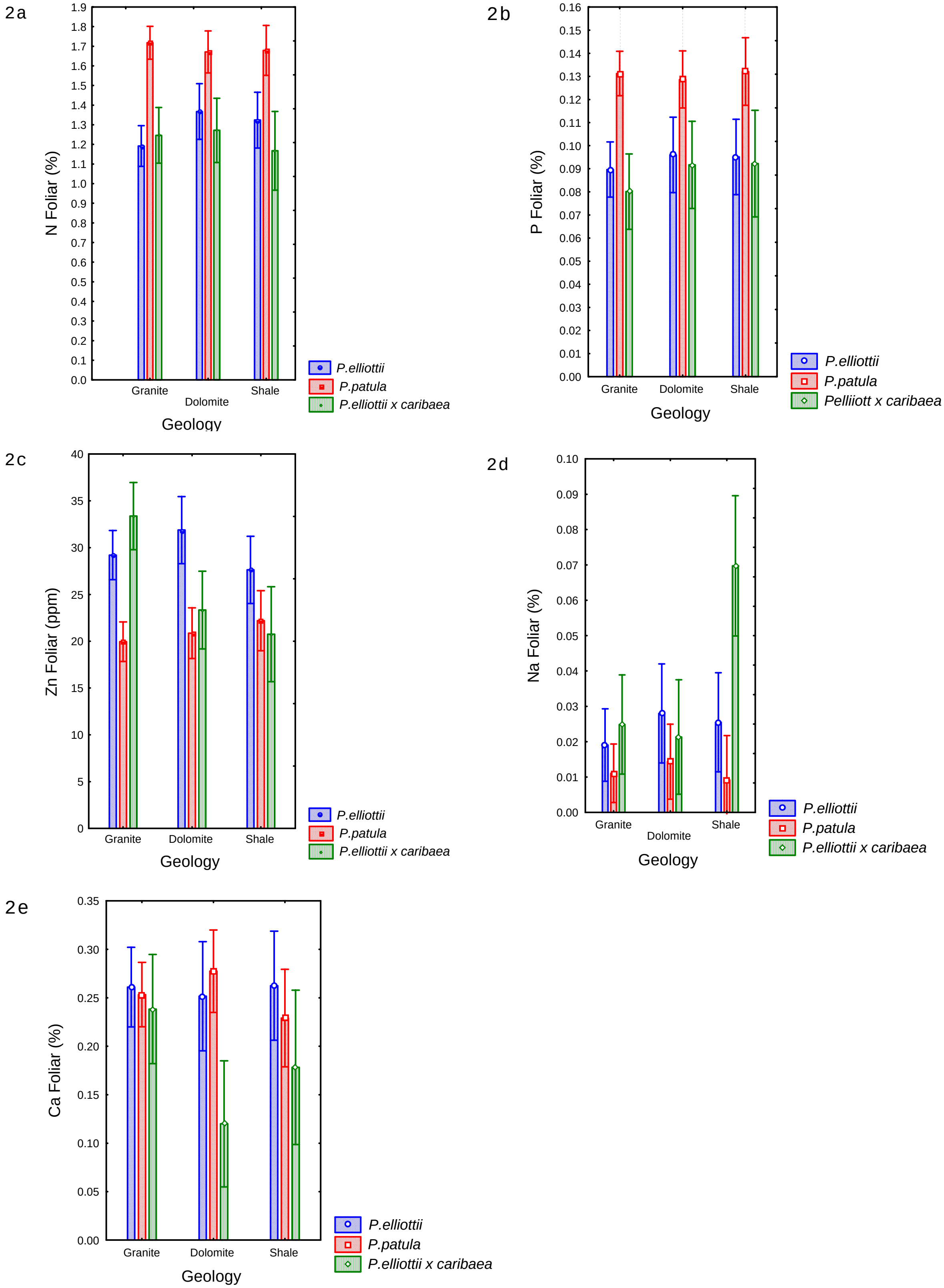

Figure 2 Significant differences found in foliar (a) nitrogen, (b) phosphorus, (c) zinc, (d) sodium and (e) calcium for the *P. patula*, *P. elliottii*, and *P. elliottii x caribaea* on granite, dolomite and shale geologies. Error bars indicate the range of values.

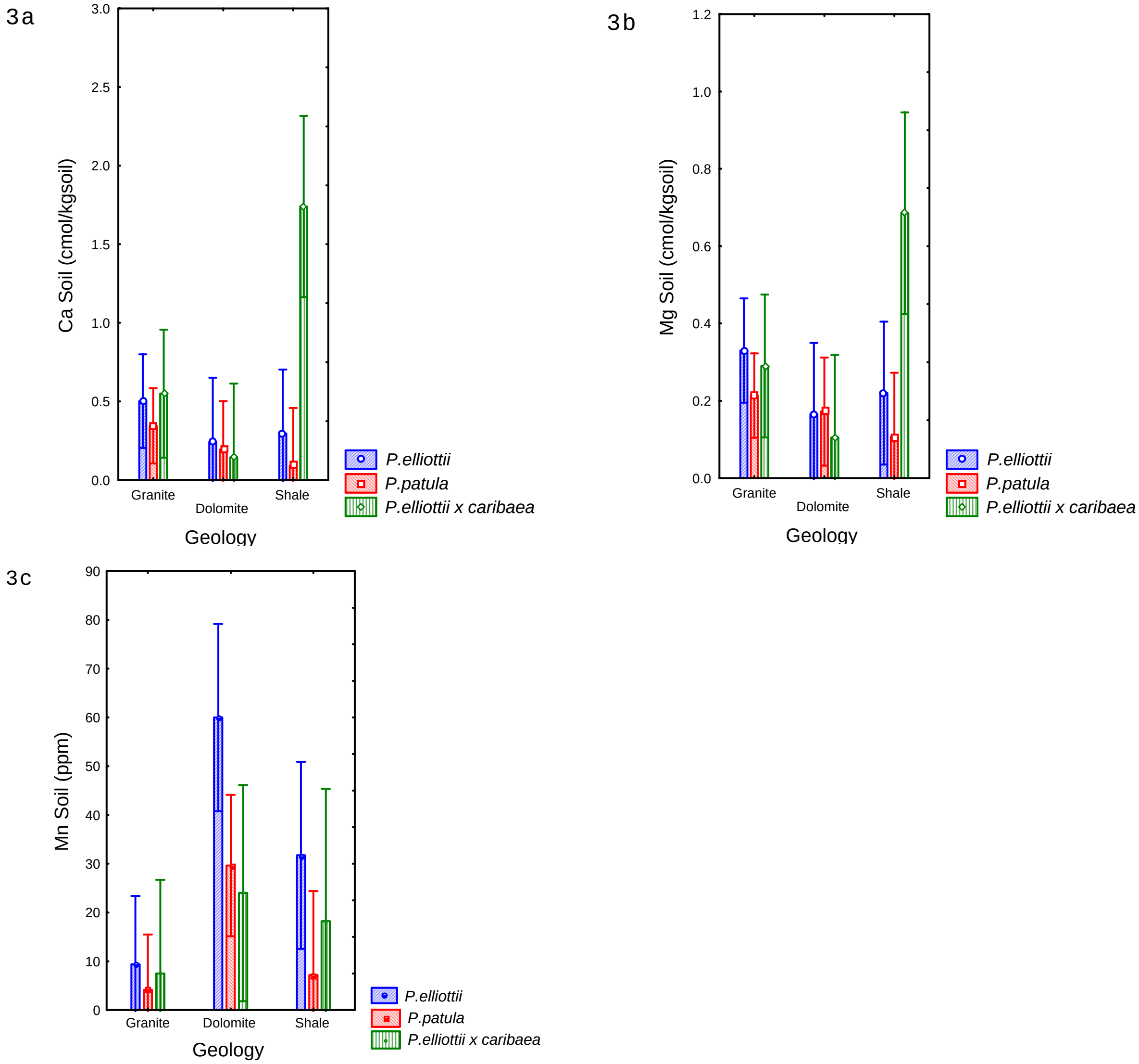

Figure 3 Significant differences found in soil (a) calcium, (b) magnesium and (c) manganese for the *P. patula, P. elliottii*, and *P. elliottii x caribaea* on granite, dolomite and shale geologies. Error bars indicate the range of values.

Significantly higher concentrations were found in the soils under *P.elliottii x caribaea* with regard to calcium (Figure 3a) (p=0.002) and magnesium (Figure 3b) (p=0.023). Manganese on granitic soils was significantly lower across the species and geologies (Figure 3c), except with *P. elliottii and P. elliottii x caribaea* where no significant difference was found, due to high variances. Manganese was significantly lower on granite than on shale soils (p=0.034) and on dolomite soils (p=0,000).

3. Relationships between foliar and soil mineral concentrations and properties

Positive significant relationships exist between foliar and soil elemental concentrations with nitrogen, phosphorus, magnesium and calcium (Table 4). Foliar Zn, Mn, Mg and Ca are correlated to soil pH, CEC and clay in Table 5.

Table 4 Significant results from correlation analyses of foliar and soil elemental content.

Foliar Element	Correlation with Corresponding soil elemental content	
	r	p
Nitrogen	0.208	0.022
Phosphorus	0.197	0.030
Magnesium	0.409	0.000
Calcium	0.432	0.000

Table 5 Significant results of correlation analyses of foliar nutrients and CEC, pH and Clay content.

Foliar Element	Correlation r and p values					
	CEC		pH		Clay %	
	r	p	r	p	r	p
Zinc	0.303	0.001	0.262	0.004	-0.171	0.060
Manganese	0.442	0.000	-0.273	0.002	0.176	0.053
Magnesium	-0.272	0.003	0.389	0.000	-0.080	0.386
Calcium	0.424	0.000	0.364	0.000	0.085	0.352

4. Identifying critical soil and foliar concentration analyses for pine plantation productivity

Significant differences occur for each of the pine species with each being significantly different from the other (Figure 4a) ($p<0.001$). The MAI of the pine species planted on dolomite was found to be significantly higher in productivity when all the species data were pooled ($p<0.001$) (Figure 4b). *P. elliottii x caribaea* was found to have a significantly higher MAI compared to other species-geology combinations ($p<0.001$) (Figure 4c).

Principal component analyses (PCA) indicated that 23 variables can be used to explain 97% of the variance of the data. Regression models produced r^2 values ranging from 0.436 to 0.584. The table below (Table 6) indicates the variables suggested by each model. Variables found in common among the regression models and the PCA were Mg Soil, CEC, N soil, N foliar, P foliar, K foliar, Cu foliar, B foliar, S foliar, C:N soil, Ca:Al soil, N:Ca foliar, N:K foliar, clay and silt. The differences encountered between the forward selection and the backward elimination processes are because neither method takes into account the effect that the addition or deletion of a variable can have on the contribution of other variables. Important variables in the population may appear unimportant in the sample and consequently be omitted from the model, and vice versa (Rawlings et al. 1998). As such using more than one regression analysis to select important variables gives a more robust argument.

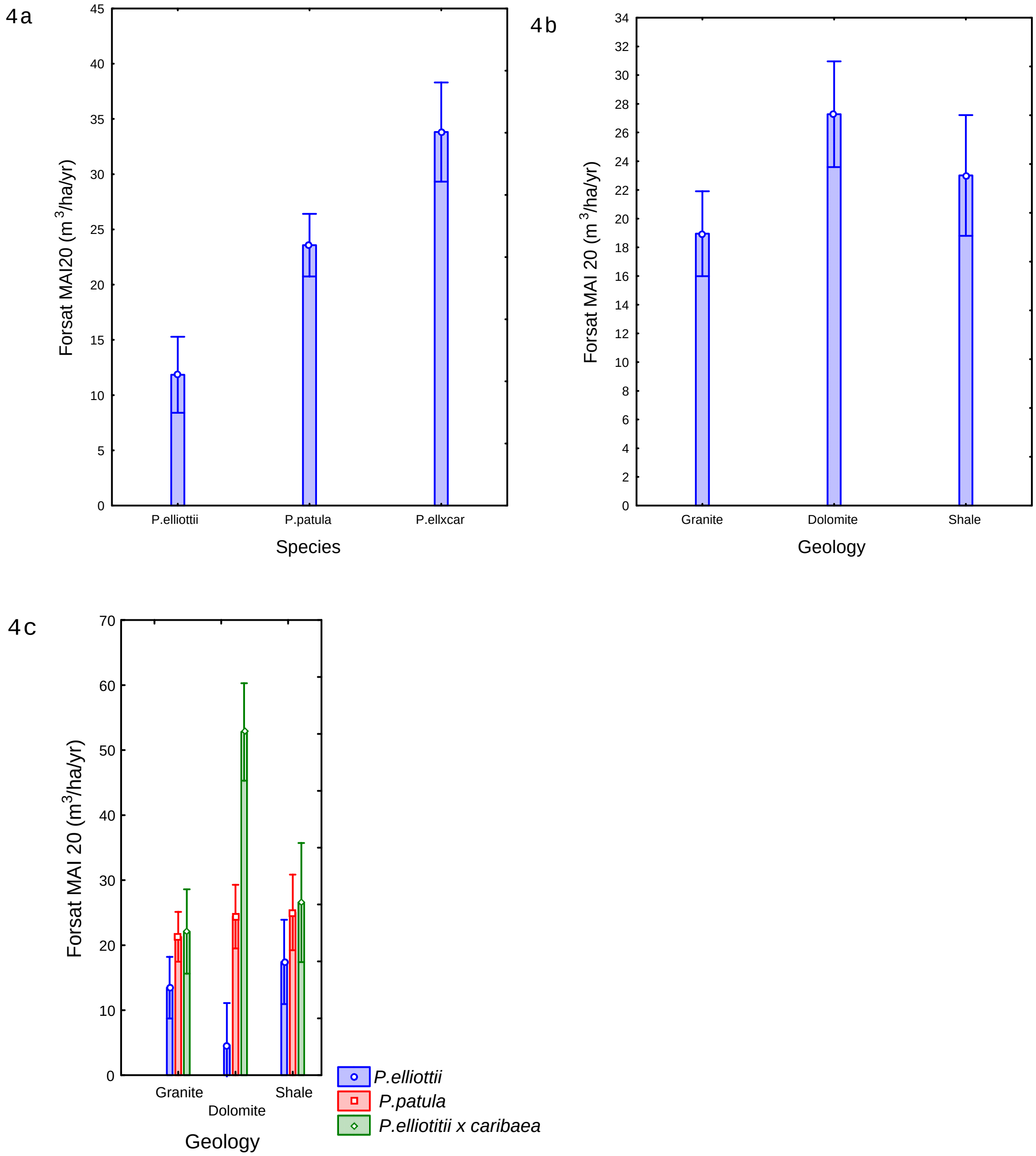

Figure 4 Productivity analyses by (a) species, (b) geology and (c) an interaction analysis. Error bars indicate the range of values.

Table 6 Regression models and Principal Component Analysis Results

	Adjusted R^2 selection	**Forward Selection**	**Backward Elimination**	**PCA**
Best R^2 values	0.571	0.436	0.584	
variables				
pH (KCl)			x	
pH(water)			x	x
Ca Soil				x
Mg Soil	x	x	x	x
K Soil	x		x	
Na Soil			x	x
CEC	x		x	x
EXACID				x
Organic Carbon	x		x	
N Soil	x		x	x
P Soil			x	x
Mn Soil	x		x	
Fe Soil	x	x	x	x
N Foliar	x		x	x
P Foliar	x		x	x
Ca Foliar				
Mg Foliar			x	
K Foliar	x		x	x
Na Foliar	x		x	
Mn Foliar			x	x
Fe Foliar	x	x	x	
Cu Foliar	x		x	x
Zn Foliar				
B Foliar	x		x	x
S Foliar	x	x	x	x
C:N Soil	x	x	x	x
Ca:Al Soil	x		x	x
N:Ca Foliar	x	x	x	x
N:Mg Foliar	x	x	x	
N:K Foliar	x	x	x	x
N:P Foliar	x		x	
Clay	x		x	x
Silt	x		x	x
Sand		x	x	x

5. Discussion

1. The influence of geology on nutrient availability and uptake

The differential concentration of mineral elements within soils can be primarily attributed to pedogenic processes. Activities that may have taken place prior to afforestation may have affected the concentration of mineral elements within the soil. However, no data of soil quality prior to afforestation is provided. Dolomite is a calcareous rock, and is inherently characterised by having low potassium, iron and high manganese (Briar & Lobreaux 1997, Marschner 1986, Tucker & Wright 1990). Dolomite has low cation exchange capacity compared to granite and shale. The mean exchangeable K across the geologies was low ranging from 0.08-0.11 cmol/kg. Potassium was particularly low on dolomite due to its porous nature and low CEC. Low potassium due to acidification of the coniferous forest soils has been reported by Jonsson et al (2003). In a recent review by Grove et al. (2001) they found that the mean exchangeable K in plantations to be 0.19 cmol/kg within a critical range of 0.07-0.46cmol/kg. Potassium is abundant in soils derived from granite (Marschner 1986). Although granitic soils were sampled the most (Table 1) they were found to have lower exchangeable K compared to shale. The higher exchangeable K content in shale soils maybe due to its inherently high clay content and larger surface area to adsorb cations. The low K can be remedied by liming of soils to raise the pH.

In dolomitic soils, half the calcium ions can be replaced by magnesium, iron or manganese (Tucker & Wright 1990). It is likely that these plantations are on dolomite that is predominantly substituted by manganese. The high levels of foliar manganese found on dolomitic soils can therefore be expected because Mn has low complex stability and forms weak bonds allowing for its easy and rapid translocation from roots to shoots. Levels of foliar manganese are high but not unusual. There seems to be an accumulation of Mn in the leaves of all the pine species, not only those growing on dolomitic soils e.g. for a *P. elliottii* PSP planted on shale, although there is a soil concentration of 25ppm, the foliar concentration is 924 ppm. There is no danger of toxicity being reached as a result of Mn as levels of 1000 and 1500 mg/kg are not exceptional (de Ronde etal. 1988).

Agricultural soils may contain 1-5% organic carbon in the top 15 cm (Schnitzer 1991). All the soils across the geologies had mean organic carbon content of between 3.0–4.4%. The significantly lower organic carbon in granitic soils and the low water holding capacity due to lower clay content which compromises productivity. Granite supported the lowest MAI overall (Figure 4b). The low organic carbon content is the result of the combination of low microbial activity due to low water content and low substrate availability due to low productivity.

No statistically significant differences were found at the geological level in soil nitrogen, phosphorus, exchangeable Ca, Mg & Na, aluminium, pH or soil texture. However, it was found that all the soils were acidic with pH < 5. Adaptation to acidic soils requires highly efficient uptake and/or utilization of nutrients, especially phosphorus, calcium and magnesium (Marschner 1986). Pine species are adapted to acidic conditions through associations with mycorrhizae that enhance mineral uptake by increasing the surface area effective in ion absorption (Brundrett 1991, Harley & Smith 1983). Acidic conditions also require tolerance to aluminium. Foliar concentrations of nitrogen, phosphorus, calcium, magnesium, sodium, copper, iron, zinc, boron and sulphur were not found to be significantly different among the geologies. This is because although some foliar nutrient concentrations are positively and significantly correlated to their corresponding soil concentrations (Table 4) internal metabolic processes are more important in determining the uptake of nutrients (Marschner 1986).

2. The influence of species on soil mineral content and foliar nutrient concentration

It has been established in the previous discussion section that soil exchangeable K is low across the geologies. At the species level it was found that the hybrid *P. elliottii x caribbaea* has significantly higher exchangeable K in its soils. However, despite it having a significantly higher soil exchangeable K, it is within the critical range for productivity (Grove et al 2001). On the other hand, soils under *Pinus patula* and *P. elliottii* are below the minimum critical level of 0.7cmol/kg despite being sampled more extensively in granitic soils that are inherently abundant in potassium (Table 3). This may give an indication that K is being lost from soils planted to *P. elliottii* and *P. patula. Pinus patula* is usually planted at high altitudes (Poynton 1977), where surface runoff and leaching can result in significant losses of cations in shallow soils. *P. elliottii* is usually planted to intermediate elevation, on mountain slopes that are prone to erosion and surface run off. This is an indication that K is limiting productivity of these plantation ecosystems. K is essential for many physiological functions such as carbohydrate metabolism, protein synthesis, activation of various enzymes, and growth of meristematic tissues. It is also associated with resistance to certain diseases and is important for fibre production. Potassium has also been found to have direct relationship with growth rate in experiments carried out in Eucalyptus plantations in South Africa (Schönau 1981).

It was established that Mn was significantly higher on dolomitic soils. *P. elliottii* was found to have significantly high levels of foliar Mn even though it was predominantly sampled on granitic soils. However, a *P. elliottii* PSP that was established on dolomite had very high Mn foliar content (i.e. 213 ppm) (Figure 3c) which resulted in the average foliar concentrations being very high for *P. elliottii* (Table 5). Granitic soils are inherently low in manganese (Figure 2c) which is confirmed by the low content across all the species.

The C:N ratios are indicative of microbial activity in relation to mineralization or immobilization of minerals in the soil. Low C:N ratios imply that there is net mineralization. While all soils are undergoing net mineralization, soils under *P. elliottii x caribaea* have the lowest mineralization rates indicated by the high C:N ratio. Most of the *P. elliottii x caribaea* plantations are found on granite (Table 1) support high leaching rates. Pines have been known to form associations with mycorrhizas to increase their surface area and thereby increase the rate of water and nutrient uptake (Dames et al. 2002). Analyses on productivity revealed that granites have lower productivity compared to the other two geologies (Figure 4b). Lower productivity results in less litterfall and lower rates of mineralization unless the litter produced is of superior quality. *Pinus elliottii* may be producing high quality litter. Gohlz et al. 2000 found that there were higher rates of mineralization where high quality litter was produced.

When pooled geological data were used *P. patula* was found to have significantly higher foliar concentrations of nitrogen, phosphorus, magnesium, boron and sulphur. Dames et al. (2002) concluded that the litter layer that accumulates under *P. patula* provides a significant proportion of nutrients particularly of nitrogen, phosphorus and magnesium. These results confirm their findings because when geological data was used as a factorial criterion, foliar concentration was found to be higher in *P. patula* only with regard to nitrogen and phosphorus. Nitrogen and phosphorus foliar contents were found to be significantly correlated to their corresponding soil concentrations regardless of geology (Table 4). For all the species, but particularly for *P. patula,* it appears that they must then directly influence nitrogen and phosphorus availability in soils, while the magnesium, boron and sulphur foliar concentrations are more strongly influenced by other factors such as age, season, and altitude. The trees sampled were in a wide age range from 1 – 10 years old. The trees were sampled in the dormant season which would influence the starch concentrations of the leaves, thereby significantly affecting the concentration of the mineral nutrient concentrations.

Significantly lower foliar calcium concentrations across the geologies for *P. elliottii x caribaea (*Figure 2e) could be the result of an accumulation of organic acids, due to decomposition. Calcium ions are released in alkaline conditions. Foliar calcium has been found to have significant positive relationship with soil pH and CEC (Table 5) and with its corresponding concentration in the soil (Table 4). Therefore the acidification of soils by the pine species will result in a low release of calcium ions into solution and subsequently low foliar calcium concentrations. However, soil calcium and magnesium (Figure 2a & b) was found to be high under *P. elliottii x caribaea* on shale soils. Shales have higher clay content with a correspondingly higher cation exchange capacity

Sodium was found to be significantly higher is needles of the hybrid *P. elliottii x caribaea.* Most of the trees sampled for the hybrid were under 5 years old. Sodium is a beneficial mineral nutrient in that it encourages productivity and may also act as a partial substitute for potassium deficiencies. The hybrid would appear to have a selective mechanism for the uptake of Na that may be partially responsible for its significantly higher productivity (Figure 4).

Zinc is predominantly taken up as a divalent cation. High concentrations of other divalent cations e.g. calcium, will inhibit its uptake (Marschner 1986). This may be the case with regard to the lower foliar Zn concentration in *P. patula.* The foliar concentration of Ca in *P. patula* was found to be significantly higher in Table 3. Zinc also has low solubility and is readily held in the soil by adsorption on exchange positions of clay and organic carbon (hence a negative correlation with clay Table 5) which may result in deficiency (Boardman & McGuire 1990). Zinc is found in its divalent form under acidic conditions, and under these conditions can be lost via leaching (Marschner 1986).

Soil calcium and magnesium levels are significantly higher in the shale soils under the hybrid. However, this has not translated into corresponding significantly higher foliar concentrations. This may be the effect of the predominantly younger hybrid trees having different metabolic requirements compared to the other two species.

Most of the soil variables (N, P, pH, exchangeable Na, Fe, OC and Al) were not significantly different among the geologies. However, all of the foliar nutrient concentrations except for Cu were significantly different among the species. This highlights the need for species-specific nutrient management to maximize productivity. However, these foliar results are confounded by the wide range in the ages of the trees within species which were sampled, which significantly affects foliar concentrations due to the different metabolic requirements at different life-stages of the trees, as well as the higher starch content of leaves in the dormant season when sampling took place.

3. Relationships between foliar and soil mineral concentrations and properties

Foliar concentrations of N, P, Mg and Ca were found to be significantly correlated to their corresponding soil concentrations. Organic matter is the primary source of nitrogen and is a significant source of phosphorus. Organic matter decomposition and mineralization result in the release of organic residue which lowers pH (Scholes & Nowicki 1998) which may result in the immobilization of calcium and magnesium (Marschner 1986, Miller & Donahue 1990). Foresters often increase the soil pH by liming to stimulate the release of cations such as calcium and magnesium. Sanchez-Rodriguez et al. (2002) found significant relationships between foliar calcium and magnesium with soil pH and CEC. However, Sword et al. (1998) found that foliar calcium and magnesium of pines respond differently to different nutrient availability in the soil. The negative correlation of Mg may be due to the competition for absorption sites in acidic soils that have high concentrations of H^+ and NH_4^+ ions (Sanchez-Rodriguez et al. 2002). Manganese is released in acidic conditions and will therefore have a negative correlation with pH.

4. Identifying critical soil and foliar concentration analyses for pine plantation productivity

Figure 4 indicates that strong genetic differences occur in the productivity particularly in the interaction analyses (Figure 4c). Tree species can be seen to perform with varying success across geologies enhancing the importance for industry to optimize site-species selection (Figure 4b & c). Species were found to have a significant influence on the availability of nutrients by modifying soil chemical conditions i.e. acidification. Some inherent geological characteristics influence the soil nutrient availability of certain nutrients. Sword et al. (1998) found that pine productivity and foliar nutrient concentrations were affected by genetics. A range of site-growth studies have revealed that productivity in South African plantations is determined by the site factors controlling nutrient and water availability on a specific site (Louw 1999). However, more conclusive recommendations can be made if the sampling across the species and geologies was extensive (Table 1).

Variables found in common among the regression analyses models and the PCA for the compilation of parameters for monitoring productivity and ecosystem integrity are (Table 6) Mg Soil, CEC, N soil, N foliar, P foliar, K foliar, Cu foliar, B foliar, S foliar, C:N soil, Ca:Al soil, N:Ca foliar, N:K foliar, clay and silt. The use of the results from four models gives a more robust argument for the selection of these variables. Most of the parameters, derived from a dataset with more than thirty variables, are foliar parameters. McMurtrie et al. (1994) also found that foliar nutrient concentrations were significantly related to productivity. However, the main disadvantages of use of foliar nutrient concentrations are that nutrient compositions change with time (season and year) and sampling must therefore be standardized to draw accurate conclusions from limited collections. The use of foliar analyses alone often does not give an indication of the fertilizer requirements when used alone and should be used in conjunction with soil analyses (Schutz & de Villiers 1987). This study has found some significant relationships between soil and foliar mineral nutrient concentrations (Table 4), which may be indicative of nutrients that are or could be limiting to productivity, particularly potassium. However, this list of foliar and soil parameters only describes approximately 50% of the spread of the productivity data. This means that there are other factors such as temperature, rainfall and age of the trees that will also influence the annual stemwood production.

6. Conclusions and Recommendations

Statistical analysis of the pooled species data across the geologies revealed that only three soil variables (soil organic matter, potassium and iron) and one foliar nutrient concentration (manganese) were significantly different among the geologies. However this is confounded by the fact that no soil analysis data prior to afforestation is available for comparison. Of concern were the low potassium concentrations on all the major geologies. Potassium is an important macronutrient and its low availability may be significantly limiting productivity. Silvicultural management can ameliorate these limitations through fertilization with potassium. Lime may also be added to increase the pH and thereby increase the availability of added potassium. Increasing the pH would also effectively increase the availability of calcium and magnesium that were found to be low in the soils but are positively correlated to pH. Nitrogen and phosphorus were found to be significantly correlated to their concentration in the soil. The primary source of nitrogen and phosphorus was found to be in the litter which is influenced by the pine species.

To ensure maximum productivity that is sustainable, forest management must be species- and site-specific. Foliar concentrations, which can be used as an index of uptake, were found to be significantly different among the species. Foliar nutrient concentrations found to be significantly different among the species were nitrogen, phosphorus, calcium, sodium and zinc. *Pinus patula* was found to selectively control its uptake of particular elements particularly nitrogen and phosphorus. The hybrid also had a higher Na foliar concentration, which can be used to partially substitute K under K-limiting conditions. Productivity of the hybrid was significantly higher than the other species possibly because of its ability to compensate Na with K under K-stress. However, this may be confounded by the pooling of species with a wide age range across geologies and species, and the sampling of the trees in the dormant season which does not adequately reflect the nutrient growth requirements of any of the species. The conclusions are further confounded by the uneven sampling across species and geologies.

The PCA and regression models indicate the importance of foliar analyses in maintaining plantation productivity. The r^2 values of ~ 0.49 indicate that although these soil and foliar parameters are important in determining growth, other site variables such as temperature, rainfall and altitude must be taken into consideration for maximum productivity at different sites. Bearing in mind all the confounding factors, (i.e. tree ages, uneven sampling, season variability and other important variables not included in this study e.g. temperature and rainfall) the following variables have shown promise in being well correlated with site productivity: Mg Soil, CEC, N soil, N foliar, P foliar, K foliar, Cu foliar, B foliar, S foliar, C:N soil, Ca:Al soil, N:Ca foliar, N:K foliar, clay and silt.

5. References

1. Albaugh T.J., Lee Allen H., Dougherty P.M., Johnsen K.H., 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *Forest Ecology and Management* 192, 3-19.

2. Allen L. 2001. Silvicultural treatments to enhance productivity. In Evans J (Ed.) *The Plantations Handbook, vol 2,* Black well Science, London, pp. 129-139.

3. Augusto L, Ranger J, Ponette Q, Rapp M., 2000. Relationships between plantation tree species, stand production ad stand nutrient amount. *Annual Forestry Science* 54, 313-324.

4. Baker, F.S. 1950. *The principles of Silviculture.* McGraw-Hill, New York, USA.

5. Ballard R., Jackson D.S., Will G.M., 1971. Correlations between *Pinus radiata* foliage nutrient concentrations and soil tests in New Zealand. New Zealand Plantation Service Reprint No. 547.

6. Barber, S.A., 1995. Soil nutrient bioavailability. A mechanistic approach. 2nd Edition. John Wiley & Sons Inc. New York. USA.

7. Black, C.A., 1957. Soil-plant relationships. John Wiley & Sons, Inc. USA.

8. Boardman R., 1978. Productivity under successive rotations of radiate pine. *Australian Forestry* 4, 177-179.

9. Boardman R,, & McGuire D.O., 1990. The role of zinc in forestry. I. Zinc in plantation environments, ecosystems and tree nutrition. *Forest Ecology and Management* 37, 167-205.

10. Briar J. & Lobreaux S., 1997. Iron transport and storage in plants. *Trends in plant science* 2, 187-193.

11. Brundrett M. 1991. Mycorrhizas in natural ecosystems. *Advances in Ecological Research* 21, 171-313.

12. Buol S.W., 1995. Sustainability of soil use. *Annual Review of Ecology and Systematics* 26, 25-44.

13. Burke I.C., Elliott E.T., & Cole C.V., 1995. Influence of macroclimate, landscape position and management on soil organic matter in agroecosystems. *Ecological Applications* 5, 124-131.

14. Carey M.L., Hunter R., & Andrew I., 1982. *Pinus radiata* plantation floors: factors affecting organic matter and nutrient dynamics. *New Zealand Journal of Forestry Science* 12, 36-48.

15. Chikumbo O., Kotze H., & Hamilton F., 1998. Development of generic yield curve. *Australian Forestry* 61, 127-136.

16. Coleman D.C., Crossley Jr D.A., & Hendrix D., 2004. Decomposition and nutrient cycling In *Fundamentals of Soil Ecology* 2nd Ed. Elsevier Academic Press. USA. P. 187-227.

17. Coyne M., 1999. The nitrogen cycle. In *soil microbiology: an exploratory approach.* International Thomson Publishing Co. USA p.250-259.

18. Dames J.F., Scholes M.C., & Straker C.J., 2002. Nutrient cycling in *Pinus* plantation in Mpumalanga Province, South Africa. *Applied Soil Ecology* 20,211-266.

19. De Ronde C, James D.B., Baylis N.T., Lange P.W., 1988. The response of *Pinus radiata* to manganese application at the Ruitersbos State Forest. *South African Forestry Journal* 146, 26-33.

20. Donkin M.J., Pearce J. & Chetty P.M., 1993. Methods for routine plant analysis in the ICFR laboratories. ICFR, Peitermaritzburg.

21. Du Plessis M., Chiswell K.E., and Morley T., 1997. Criteria for the inclusion of permanent sample plots in the mensuration and modelling research consortium. Version 1. 30pp.

22. Evans J., 1976. Plantations: Productivity and Prospects. *Australian Forestry* 39, 150-163.

23. Evans, J., 1992. Plantation forestry in the tropics. 2nd Edition. Oxford University Press, Oxford. 403p.

24. Evans J., 1999. Sustainability of forest plantations – the evidence. Report commissioned by the Department of International Development. London UK.

25. FAO, 1997. State of the World's Forests – 1997. Food and Agricultural Organization of the United Nations, Rome, 465pp.

26. Federer C.A., Hornbeck J.W., Tritton L.M., Martin C.W., Pierce R.S., & Smith T.C., 1989. Long-term depletion of Calcium and other nutrients in Eastern US forests. *Environmental Management* 13, 593-601.

27. Fox R.T., 2000. Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management* 138, 187-202.

28. Gohlz H.L., Wedin D.A., Smitherman S.M., Harmon M.C., Parton W.J., 2000. Long-tem dynamics of pine and hardwood litter in contrasting environments: towards a global model of decomposition. *Global Change Biology* 6, 751-765.

29. Goncalves J.L.M., Barros N.F., Nambiar E.K.S., & Novais L., 1997. Soil and stand management for short-rotation plantations In *Management of soil, nutrients and water in tropical forests.* ACIAR Monograph No.43 p.379-418.

30. Grey D.C., & Taylor G.I., 1983. Site requirements for commercial afforestation in the Cape. *South African Forestry Journal* 1-3, 35-38.

31. Grey D.C., le Roux J., Schonau A.P.G., 1979. Foliar elements, environmental factors and growth in *Pinus* from the Umzinkulu District, Transkei. *South African Forestry Journal* 111, 24-28.

32. Gregoire N. & Fisher F.R., 2004. Nutritional diagnosis in loblolly pine (*Pinus taeda* L.) established stands using three different approaches. *Forest Ecology and Management* ***in press***

33. Grove T. S., O'Connell A. M., Mendham D., Barrow N. J., & Rance S. J., 2001. Sustaining the productivity of tree crops on agricultural land in south west Australia. Rural Industries Research and Development Cooporation. Australia 79pp.

34. Hanson E.J., Azuma D.L., & Hiserote B.A., 2002. Site index equations and mean annual increment equations for Pacific northwest research station plantation inventory and analysis inventories 1985-2001. United States Department of Agriculture. USA.

35. Harley J.L., & Smith S.E. 1983. *Mycorrhizal symbiosis.* Academic Press, Toronto.

36. Heffernan B., 1985. A handbook of methods of inorganic chemical analysis for forest soils, foliage and water. CSIRO Division of Forest Research, Canberra.

37. Heilman, P. & Norby, R.J., 1998. Nutrient cycling and fertility management in temperate short rotation forest systems. *Biomass and Bioenergy* 14(4), 361-370.

38. Hill J. & Lambert M.J., 1981. Physiology and management of micronutrients in forest trees in Australasia. In *Australian Forest Nutrition Workshop: Productivity in Perpetuity*. CSIRO, Melbourne Australia p93-103.

39. Ingestad T., 1991. Nutrition and growth of forest trees. *Tappi Journal* 57, 55-62

40. Jokela E.J. & Martin T.A., 2000. Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. *Canadian Journal of Forest Research* 30, 1511-1524.

41. Jordan C.F., 1982. The nutrient balance of an Amozonian rain-forest. *Ecology* 63, 647-654.

42. Jorgensen J.R., Wells C.G. & Metz J.L. 1975. The nutrient cycle: Keys to continuous forest production. *Journal of Plantationry* 2, 400-403.

43. Kellman M., Hudson J., & Sanmugadas K., 1982. Temporal variability of atmospheric nutrient influx to a tropical ecosystem. *Biotropica* 14, 1-9.

44. Knoepp J.D., Coleman D.C., Crossley Jr, DA, & Clark J.S. 2000. Biological indices of soil quality: an ecosystem case study of their use. *Forest Ecology and Management* 138, 357-368.

45. Kotze H & Strydom H. 2003. Monitoring site sustainability using a well stratified permanent sample plot programme. Komatiland Forests Research. Nelspruit, South Africa.

46. Lambert, M.J., 1984. The use of foliar analysis in fertilizer research. In: Proceedings of the IUFRO Symposium on Site and Productivity of Fast Growing Plantations, Pretoria, South Africa, pp. 269–291.

47. Landsberg, J.J., & Gower S,T., 1997. Applications of physiological ecology to forest management. Academic Press, Inc. USA.

48. Lal, R., 1991. Soil structure and sustainability. *Journal of Sustainable Agriculture* 1, 67-92.

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

50. Louw J.H., 1999. A review of site-growth studies in South Africa. *South African Forestry Journal* 185:57-65.

51. Louw J.H., & Scholes M., 2002. Forest site classification and evaluation. A South African Perspective. *Forest Ecology and Management* 171, 153-168.

52. Louw J.H., & Scholes M., 2002. The influence of site factors on nitrogen mineralization in forest soils of the Mpumalanga escarpment area: South Africa. *South African Forestry Journal* 193, 47-63.

53. Lynch J.P., & St. Clair S.B., 2004. Mineral Stress: the missing link in understanding how global climate change will affect plants in real world soils. *Field Crops Research* 90, 101-115.

54. McMurtrie R.E., Gohlz H.L., Linder S., & Gower S.T., 1994. Climatic factors controlling the productivity of pine stands: a model-based analysis. *Ecological Bulletin* 43, 173-188.

55. Marschner H., 1986. *Mineral Nutrition of Higher Plants*. Academic Press Inc. London. p 279.

56. Miller H.G., Cooper J.M., Miller J.D., & Pauline O.J.L., 1979. Nutrient cycles in pine and their adaptation to poor soils. *Canadian Journal of Forestry Research* 9, 19-26.

57. Miller R.E., & Donahue R.L., 1990. Soil: An introduction to soils and plant growth. Prentice Hall. Englewood Cliffs, New Jersey, USA.

58. Motavalli P.P., Palm C.A., Elliott E.T., Frey S.D., & Smithson P.C., 1995. Nitrogen mineralization in humid tropical forest soils: mineralogy, texture and measured nitrogen fractions. *Soil Science Society of America Journal* 59, 1168-1175.

59. Morris A.R., 1986. Soil fertility and long term productivity of *Pinus* plantations in Swaziland. PhD University of Reading, England.

60. Mudimeli L., 2003. Komatiland Forests (Pty) Ltd. “The cream of forestry”. Annual Environmental Report 2003. White River Printers, Nelspruit, South Africa.

61. Nambiar E.K.S., 1999. Pursuit of sustainable plantation forestry. *Southern African Forestry Journal* 184, 45-62.

62. Nambiar E.K.S., 1996. Sustained productivity of forests is a continuing challenge to soil science. *Soil Science Society of America Journal* 60, 1629-1642.

63. Nambiar E.K.S., & Sands R., 1993. Competition for water and nutrients in plantations. *Canadian Journal of Forest Research* 23, 1955-1968.

64. Parton W.J., Schimel D.S., Cole C.V., & Ojima D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal* 51, 1173-1179.

65. Payn T.W., Mead D.J., Will G.M., & Hunter I.R., 1995. Magnesium nutrition and dry matter allocation patterns in *Pinus radiata. New Zealand Journal of Forestry Science* 25, 39-48.

66. Ohki K., Boswell FC, Parker MB, Shuma LM, & Wilson DO. 1979. Critical manganese deficiency level of soybean related to leaf position. *Agronomy Journal* 71, 713-716.

67. Powers R.F., 1984. Estimating soil nitrogen availability through soil and foliar analysis In *Forest soils and treatment impacts* Ed E.L. Stone. Department of Forestry, Wildlife and Fisheries, Tennessee, USA.

68. Poynton R.J., 1977. Tree planting in Southern Africa. Vol 1. The pines. Department of Forestry. RSA.

69. Probert M.E., 1976. The composition of rainwater at two sites near Townsville, Queensland. *Australian Journal of Soil Research* 14, 397-402.

70. Rawlings, J.O., Pantula, S.G., and Dickey D. A. 1998. Applied Regression Analysis. A Research Tool.

71. Richardson B., Skinner M.F., & West G., 1999. The role of plantation productivity in defining the sustainability of plantation forests in New Zealand. *Forest Ecology and Management* 122, 125-137.

72. Salisbury, F.B., & Ross C.W., 1992. Plant Physiology. 4th ed. Wadsworth, Belmont, CA.

73. Sanchez-Rodriguez F., Rodriguez-Soalleiro, R., Espanol E., Lopez, C. A., and Merino A. 2002. Influence of edaphic factors and tree nutritive status on the productivity of *Pinus radiata* D. Don plantations in northwestern Spain*. Forest Ecology and Management* 171, 181-189.

74. Schoenholtz S.H., van Miegoet H., & Burger J.A., 2000. A review of chemical and physical indicators of plantation soil quality: challenges and opportunities. *Forest Ecology and Management* 138, 335-356.

75. Scholes R.J., Smith R.E., van Wilgen B.W., Berns J., Evans J., Everard D., Forsyth G.G., Scott D.F., van Tienhoven M., & Viljoen P. 1995. The costs and benefits of plantation forestry In Studies from Mpumalanga, Environmentek (CSIR), Report FOR-DEA-939 Pretoria, 105pp.

76. Scholes M.C. & Nowicki T.E., 1998. Effects of pine on soil properties and process In *Ecology and biogeography of Pinus* Ed. DM Richardson. Cambridge University Press. Chapter 17.

77. Schönau APG. 1981. Seasonal changes in foliar nutrient content of *E. grandis. South African Forestry Journal* 119, 1-4.

78. Schnitzer M. !991. Soil organic matter – the next 75 years. *Soil Science* 151, 41-58.

79. Schutz C.J., 1982. Monitoring the long-term effects of management practices on site productivity in South African Plantationry. *South African Forestry Journal* 120, 3-6.

80. Schutz C.J., & de Villiers J.M., 1987. 6. Foliar diagnosis and fertilizer prescription in forestry – the DRIS system and its potential. *South African Forestry Journal* 141, 6-12.

81. Schultz C.J. & de Villiers J.M., 1988. Foliar diagnosis and fertilizer prescription in plantationry: the DRIS system and its potential. In: Cole, D.W., Gessel, S.P. (Eds.), Plantation Site Evaluation and Long-term Productivity. University of Washington, USA, pp. 34–43.

82. Singh B., 1982. Nutrient content of standing crop and biological cycling in *Pinus* ecosystem. *Forest Ecology and Management* 4, 317-332.

83. Svenson G.A., & Kimberley M.O., 1988. Can DRIS improve diagnosis of nutrient deficiency in *Pinus radiata*. *New Zealand Journal of Forestry Science* 18, 33-42.

84. SwordM.A., Tiarks A. E., and Haywood J. D. 1998. Establishment treatments affect the relationships among nutrition, productivity and competing vegetation of loblolly pine saplings on a Gulf Coastal Plain site. *Forest Ecology and Management* 105, 175-188.

85. Szott L.T., Fernandes E.C.M, & Sanchez P.A., 1991. Soil-plant interactions in agroforestry systems. *Forest Ecology and Management* 45, 127-152.

86. Tausz M, Trummer W, Wonisch A, Goessler W, Grill D, Jimenez M.S., & Morales D. 2004. A survey of foliar mineral nutrient concentrations of *Pinus canariensis* at field plots in Tenerife. *Forest Ecology and Management* 189, 49-55.

87. Thomas R.C., & Miller H.G., 1992. Impact of foliar and soil applications of nitrogen on nutritional status of a young Sitka spruce plantation. *Forest Ecology and Management* 51, 217-225.

88. Tucker ME & Wright VP. 1990. Carbonate Sedimentology. Blackwell scientific publications, London. p 365-382.

89. Turner J, & Lambert MJ. 1988. Soil properties as affected by *Pinus radiata* plantations. *New Zealand Journal of Forestry Science* 18, 77-91.

90. Ulrich A, & Hills F. 1967. Principles and practices of plant analysis in: Hardy, GW et al. (Eds) Soil Test and Plant Analysis. Part II. Soil Science Society of America Special Publication no. 2 pp. 1-24.

91. Will G.M. 1985. Nutrient deficiencies and fertiliser use in New Zealand exotic forests. *New Zealand Forest Service, FRI Bulletin No.* 9.

92. Yarie J, Pulliam W, van Cleve K & Schlentner R. 1994. Carbon and nutrient availability effect on plant nutrient supply for upland plantation sites in interior Alaska. *New Zealand Journal of Forestry Science* 24, 234-252.

93. Zobel B & Talbert J. 1984. *Applied Forest Tree Improvement*. John Wiley and Sons INC. USA.

Appendix A: *Pinus* Permanent sampling plot stand classification.