

**THESIS**

**EFFECTS OF SITE MANAGEMENT ON NUTRITION,  
SUSTAINABILITY AND PRODUCTIVITY IN A  
*EUCALYPTUS GRANDIS* STAND IN SOUTH AFRICA**

by

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## **DECLARATION**

I declare that this thesis, submitted for the degree of Doctor of Philosophy at the University of the Witwatersrand is the result of my own investigation, unless acknowledged to the contrary in the text. This thesis has not been submitted for any degree or examination to any other university.

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Ben du Toit

## ABSTRACT

The findings presented in this thesis are a sub-set of data taken from the Karkloof Project experiment conducted by the author, and situated in the Midlands of KwaZulu-Natal, South Africa. The Karkloof Project is a case study of the effects of intensive site management operations during the inter-rotational period on nutrition, sustainability and productivity of a short-rotation, commercial *Eucalyptus grandis* plantation in South Africa. It focusses primarily on (a) the nutrient capital, nutrient fluxes and nutritional sustainability of the system, and (b) the availability of growth resources (nutrients and water) and their effect on the eco-physiological processes governing productivity from planting up to three years of age. Site management treatments included slash removal, slash addition, slash retention, fertilization, slash burning and slash disturbance through mechanised harvesting operations. All treatments barring the first two listed above mimicked common operational practices in the region at representative intensities. The experiment is situated at an altitude of 1260 m on an acid, humic ferralsol with a clayey texture and receives an average annual rainfall of 950 mm.

The effects of nutrient removal through harvesting operations, slash management or slash burning were examined in relation to estimates of readily plant-available nutrient pools in the system. The nutrient contents in various pools of the system, namely the soil, the forest floor, and the above- and below-ground biomass were determined through sampling and chemical analysis. The removal of individual nutrient elements through harvesting plus slash burning was calculated for a regime of one planted crop followed by two coppice crops. In this regime, slash burning (if used) and fertilization are normally only implemented immediately before replanting. The combined losses of harvesting and burning (averaged per crop cycle) amounted to 13, 25, 11, 5 and 3% of the readily available pools for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg), respectively. The system is thus well buffered against the depletion of most macronutrients over the short term. Despite this fact, the cumulative effect of nutrient removal through successive rotations could add up to substantial amounts over long periods of time. Nutrients removed from the system need to be replenished to ensure sustained productivity. The comparatively large percentage loss of P is small in actual quantity (ca. 20 kg ha<sup>-1</sup> per crop cycle) and is commonly mitigated to some degree by recommended fertilization practices. Losses of Mg are very small relative to available Mg pools. However, N, K and Ca losses are not replenished under current management regimes and management will need to deal with this to ensure long-term sustainability. Adequate and sustainable supplies of nutrients to tree crops could be ensured

by implementing some of the following strategies: Wood-only harvesting, slash conservation, fertilization and intercropping or cover-cropping with N-fixing species. The latter two options will require a more thorough investigation, followed by implementation on a site-specific basis.

A more comprehensive evaluation of the nutritional short- and long-term sustainability of the *Eucalyptus grandis* plantation system was made after estimating the magnitude of the major nutrient fluxes. Nutrient pools in the forest floor and biomass (above- and below-ground) were assessed by destructive sampling. The size of nutrient pools in the soil that approximate to readily available and potentially available fractions were estimated from chemical extractions, and an approximate nutrient input-output budget was constructed. The study has shown that large nutrient pools occur in the forest floor and below-ground biomass when compared to most short-rotation eucalypt cropping systems globally. The readily available pools of K, Ca and Mg in the soil are moderately large (466 to 771 kg ha<sup>-1</sup>) when compared to similar systems in the tropics (Brazil & Congo). The potentially available nutrient pools are particularly rich in potassium (2.5) and magnesium (1.1 t ha<sup>-1</sup>). This indicates that the system is well buffered against base cation depletion in the short and long term. Estimates of nutrient fluxes revealed that fertilization and mineral weathering constitute small inputs, while atmospheric deposition makes a major contribution to the N, K, Ca and Mg inputs in the system. Sizeable nutrient losses were caused by slash burning (N), leaching (Ca & Mg), and both wood harvesting and firewood collection (N, K & Ca). The management regime and intensity of operations both have a pronounced effect on nutrient fluxes to and from the system, and hence, the net balance of the budget was calculated for different management regimes at representative intensities. Net fluxes were positive or near zero for several elements in the absence of firewood collection or slash burning and changed to losses of between ca. 6 to 20 kg ha<sup>-1</sup> a<sup>-1</sup> per individual nutrient when slash burning was incorporated in the regime. Despite the increases in nutrient loss with more intensive management, the indices of nutritional sustainability indicated a resilient system with respect to nutrition.

Nutritional sustainability has been gauged by other researchers using the ratio (nutrient export in harvesting)/(available nutrient pool size). An index of nutritional stability (pINS) is proposed, based on the negative logarithm of the ratio (net nutrient loss)/(nutrient pool) where the nutrient pool can be readily available soil pools or (long term) potentially available system pools. Although this index has intensive data requirements, it evaluates management intensity effects as well as the “buffer capacity” of the system more rigorously than previously proposed indices.

The effects of intensive site management operations on leaf area index (LAI), aboveground woody

biomass (WB) development, and stand growth efficiency were intensively monitored from establishment to half-rotation age. Stand LAI development responded strongly and significantly to the site management treatments imposed at establishment. Responses were driven by nutrient supply, but were apparently limited by a severe drought after establishment. At 1.3 years, LAI in the slash removal treatment reached 2.1 compared to 4.5 following fertilization or slash burning. Treatments also significantly affected above-ground WB development, which ranged from 53.6 (slash removal) to 64.9 (fertilization) and 65.8 t ha<sup>-1</sup> (slash burning) at 3.5 years. Biomass allocation to roots, and stand growth efficiency (*i.e.* WB increment per unit of LAI) did not differ significantly between treatments (although the canopy quantum efficiency per unit of absorbed radiation varied amongst treatments). We conclude that the fast-growing treatments produced more WB because of the more rapid development of maximum LAI. The observed response mechanism shows the importance of optimum nutrient supply during the period before LAI peaks. It *suggests* that, in water stress environments, measures aimed at increasing nutrient availability after peak LAI has been reached are less likely to yield substantial growth responses.

The effects of treatments on the production ecology of the stand were evaluated. We calculated the carbon distribution in the standing biomass from allometric relationships. Fine root turnover and litterfall measurements were determined using sequential coring techniques and litter traps, respectively, and these data were used to construct a full model of biomass allocation among stand components. Differences in nutrient availability to young trees, brought about by the most extreme site management treatments, produced several small but significant changes in the elements of the production ecology over the three year monitoring period: Absorbed photosynthetically active radiation (APAR) increased from 210 to 247 Mmol photons ha<sup>-1</sup>, apparent canopy quantum efficiency ( $\alpha$ ) from 0.026 to 0.029 mol C (mol photon)<sup>-1</sup>, and the fraction of carbon allocated to stem wood from 32.7% to 35.6% of net primary production. The magnitudes of these individual responses collectively described the increase in net primary productivity and the Type 1 timber volume response obtained. The biggest changes occurred in APAR, in contrast to published studies from higher rainfall environments where  $\alpha$  dominated.

The description of stand growth in production ecology terms has increased our knowledge of the stand's response mechanism to increased nutrient availability under water limiting conditions. As such it is relevant for researchers working in the field of site management and fertilization research as well as for managers implementing recommended silvicultural practices. In addition, the index of nutritional sustainability that was developed in this study may be useful in assessing short-and long term nutritional sustainability under a variety of management scenarios.

## DEDICATION

*I dedicate this thesis to the memory of my beloved brother*

*François du Toit*

*1962 - 2005*

*He was my friend, loyal supporter and motivator, my confidant and soul mate.*

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## LIST OF TERMS AND ABBREVIATIONS

$\alpha$	Canopy quantum efficiency
$\eta_w$	Partitioning coefficient to woody biomass
ACRU	An agrohydrological model, developed by the School of Bioresources, Engineering and Environmental Hydrology at the University of KwaZulu-Natal
AGB	Above-ground biomass
ANOVA	Analysis of variance
APAR	Absorbed photosynthetically active radiation
CIFOR	Centre for International Forestry Research
dbh	Diameter at breast height
$E_r$	Reference potential evaporation
GE	Growth efficiency
GPP	Gross primary production
LAI	Leaf area index
n.d.	Not determined
NPP	Net primary production
n.s.	Not significant
PAR	Photosynthetically active radiation
pINS	Index of nutritional sustainability (This index is used with the subscripts RA and POT, which denotes readily available and potentially available nutrient pools, respectively).
PSI	Plantation stability index
TDR	Time domain reflectometry
WB	(Above-ground) woody biomass
WUE	Water use efficiency
YAP	Years after planting

# CHAPTER 1

## 1 General introduction

### 1.1 FOREST MANAGEMENT, CUSTODIANSHIP AND RESEARCH

Tree-based systems, and more specifically managed forests (be they natural or man-made) have always fascinated me. To be the manager and custodian of a system which includes living organisms that are mostly much larger (and sometimes also older) than oneself, does indeed carry responsibility and requires dedication, especially if such systems cover large areas of land. This responsibility becomes more pertinent in the global ecological perspective when one considers the reliance of man on trees and tree based products, and the importance of healthy, functional ecosystems. In theory, a manager and custodian of forest ecosystems should be able to optimise production of a certain product (be it timber or fibre or a variety of non-timber forest products) through proper management strategies, without compromising future production potential of the site or system. The important question is: do we (the scientific / forest management community), really understand the forest systems under our custodianship well enough to make informed decisions?

### 1.2 SUSTAINED FOREST PRODUCTIVITY AND ITS IMPORTANCE IN INDUSTRIAL PLANTATIONS OF SOUTH AFRICA

The management of natural forests for conservation purposes, rather than commercial timber production is increasingly gaining momentum worldwide. In most industrialised (and many developing) countries with suitable climates, the rate of forest exploitation has been decreased following the establishment of industrial forest plantations to meet wood and fibre needs of a growing population. This places an increasing responsibility on plantation forestry to produce increasing volumes from a relatively small land base (Schönau, 1991). Industrial plantation forestry worldwide (and certainly also in South Africa) is under pressure to maintain high levels of productivity and at the same time demonstrate that its management practices are ecologically sustainable and beneficial to society at large (Brown, *et al.*, 1997; Nambiar, and Brown, 1997; Evans, 1999a).

The fact that large parts of the southern African sub-continent has a dry climate, means that productive forests can only be established on a limited land base. Natural forests and savanna

woodlands occupy a mere 0.5% and 19% of the South African land base, respectively (Owen and Van der Zel, 2000). Most of the closed-canopy forests in the country, as well as sizable portions of the savanna woodland are managed primarily for conservation purposes, resulting in many sectors of the economy being reliant on a highly productive and sustainable plantation forestry industry.

Industrial plantation-based forestry currently covers an area of approximately 1.4 million hectares in South Africa. It produces 19 million m<sup>3</sup> of timber per annum, and the wood-based products derived from this industry accounts for approximately 9% manufacturing output of the country. The area under *Eucalyptus* plantations in South Africa exceed 540 000 ha and plantations of this genus are mainly grown on short rotations for pulpwood, mining timber and pole production. *Eucalyptus grandis* (Hill ex Maiden) is the most important plantation hardwood species in the country, occupying an area of 311 000 ha (FSA, 2002 and 2003).

Afforestation on the eastern seaboard of South Africa has taken place mainly in grassland ecosystems (Acocks, 1953). These systems have been modified to support eucalypt plantations and it needs to be established whether they will remain sustainable in this modified state. In addition, the productivity of short-rotation eucalypt plantations in South Africa is high (especially if the climatic constraints are taken into consideration), and this is mainly a result of intensive site management practices at time of establishment (Schönau *et al.*, 1981; Schönau, 1984; Schönau, 1989; Herbert and Schönau, 1989 & 1990; Herbert, 1996; Little *et al.*, 1996; Little *et al.*, 1997; Smith *et al.*, 2000; Smith *et al.*, 2001b; du Toit *et al.*, 2004; Smith *et al.*, 2005). Intensive site management operations represent an increased ecological risk profile, e.g. soil degradation or nutrient depletion risks (Nambiar, 1996; Smith *et al.*, 2005). The research contained in this thesis was initiated to increase our understanding of the effects of intensive site management on the productivity and sustainability of a representative eucalypt plantation system in the study area.

### **1.3 THE THESIS IN CONTEXT OF THE KARKLOOF PROJECT AND THE CIFOR EXPERIMENTAL NETWORK**

At the time when this project was contemplated, Southern African forestry had already made several strides toward implementing site-specific silviculture. Several authors have studied the effects of site factors on growth and/or species choice (Joubert, 1965; Grey, 1987; Schafer, 1988a & 1988b; Schutz, 1990; Louw, 1991; Schönau and Aldworth, 1991; Noble *et al.*, 1991; Louw, 1995 & 1997). Most of these studies were of an empirical nature, trying to identify those variables that correlated well with forest production potential.

Local studies have also dealt with the effects of silvicultural operations (site management) on plantation productivity: A silvicultural regime of intensive site management has been pioneered by South African researchers such as Beard (1951 and 1957) and Schönau (1984 and 1989) and their colleagues that followed. This regime consists of appropriate slash management and site preparation techniques (Norris, 1995; Smith *et al.*, 2000; Rolando *et al.*, 2002), water planting where necessary (Viero *et al.*, 2002), fertilization at time of establishment (Herbert and Schönau, 1989 & 1990; Herbert, 1996; du Toit and Carlson, 2000; du Toit, 2002a; du Toit and Oscroft, 2003), followed by intensive weed control up to canopy closure (Little *et al.*, 1997; Little, 1999; Little and van Staden, 2003), and this regime has since become standard practice in southern African eucalypt plantations. Very few, if any, silvicultural tending operations are carried out from canopy closure until clear felling, since fertilization and vegetation management practices after canopy closure have not yet been proven to be generally cost effective under water-limiting conditions commonly experienced in the study area (Little and Rolando, 2002).

However, a process-based understanding of the effects of some of these operations on site productivity is still lacking. It follows that the scientific community do not fully understand the mechanism whereby growth resource availability was affected by site management treatments, or what the impacts of intensive site management were on sustained productivity (Kimmins, 1994). The Karkloof Project experiment was conceptualised around this time: it would be a process-based experiment, focussing on the effects of early, intensive silviculture in eucalypt plantation systems in South Africa and its effects on long-term sustainability. At the same time, the Centre for International Forestry Research (CIFOR) started a trial series in tropical and sub tropical climates entitled "Site Management and Productivity in Tropical Plantation Forests" (Tiarks *et al.*, 1998). The Institute for Commercial Forestry Research was formally co-opted as a research partner in the CIFOR Network. The Karkloof project thus became part of a network of international trials focussing on the effects of site management on productivity and sustainability in plantation forests. It was designed to contain some treatments that are comparable to other sites in the network and also to address specific research questions pertaining to productivity and sustainability of short-rotation hardwood forestry in the KwaZulu-Natal (KZN) Midlands.

This thesis focusses on some of the key questions that we tried to answer as part of the greater Karkloof Project, as shown in Figure 1.1 and discussed in more detail in section 1.4. Several other processes were studied as part of the Karkloof Project, but these fall outside the scope of this thesis.

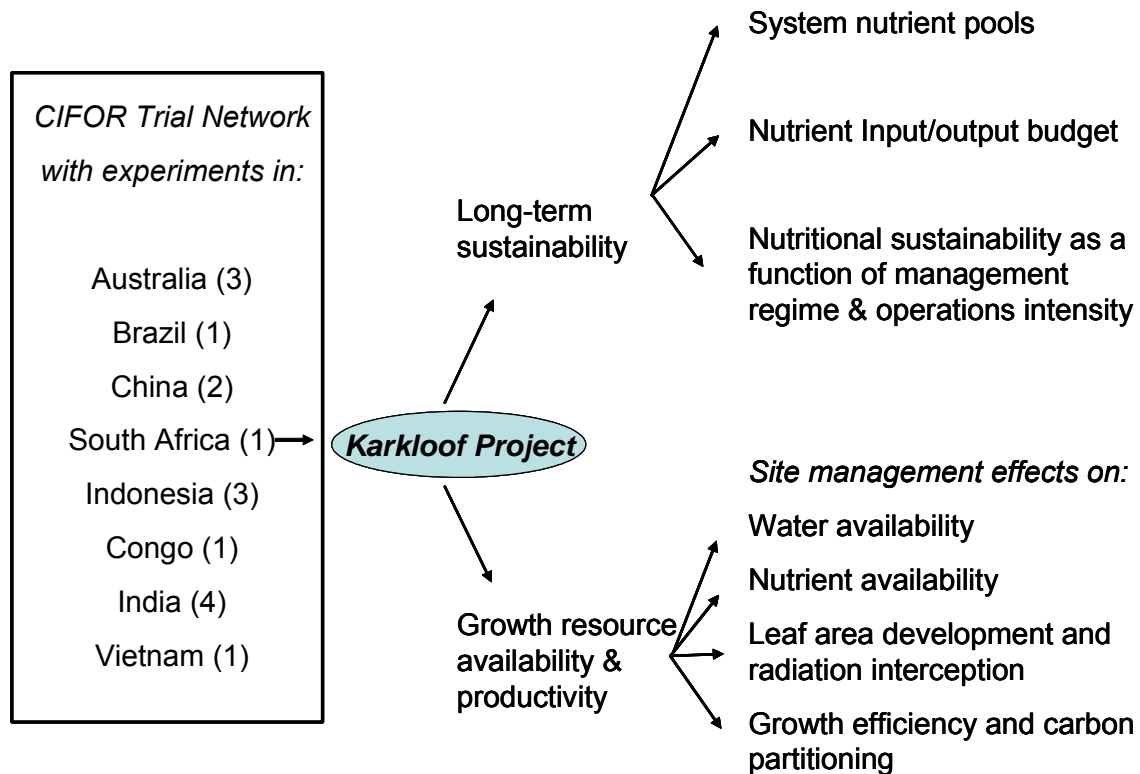


Figure 1.1 Schematic diagram placing the components of this thesis in context with the Karkloof project Experiment and the greater CIFOR network on 'Site management and productivity in tropical forest plantations'.

#### 1.4 STUDY APPROACH

The KwaZulu-Natal Midlands are used extensively for growing short-rotation eucalypt pulpwood crops. Site management operations (harvesting, harvest residue management, slash burning, fertilization and vegetation management) are used to varying degrees in the inter-rotational period and these potentially affect the availability of growth resources and the nutrient capital. We used these operations as well as slash manipulations (designed to create a large nutritional gradient) as treatments in a case study (The Karkloof Project) to develop an understanding of the effects of site management on nutrition, sustainability and productivity of a representative *Eucalyptus grandis* plantation system. The specific objectives of the research effort (A-D) were:

***Developing an understanding of the effects of site management operations on nutrient losses and nutrient capital in a eucalypt plantation system representative of the KwaZulu-Natal Midlands.***

- A To quantify nutrient losses due to harvesting and burning operations of representative intensity, and to compare the relative magnitude of these to other systems where quantitative data exist.
- B To quantify net nutrient losses from a typical eucalypt plantation system (Karkloof case study) under varying site management systems and place this in context to (i) total system nutrient pools and (ii) plant-available nutrient pools to enable an assessment of the nutritional sustainability of the system.

***Developing an understanding of the effects of site management operations on short-term nutrient dynamics and its effect on the production ecology of the re-established crop.***

- C To describe stand response to treatments affecting the availability of growth resources in terms of leaf area index and growth efficiency (also termed foliar efficiency).
- D To develop an understanding of the net primary production of the stand in response to treatments in terms of fundamental eco-physiological processes, i.e. radiation interception, canopy quantum efficiency and partitioning of assimilated carbon.

## **1.5 THESIS STRUCTURE**

A short literature review (Chapter 2) and a description of the site conditions and experimental treatments (Chapter 3) are provided to give the reader the necessary background. These chapters draw from preliminary progress reports that had previously been published. The research findings contained in this thesis were initially prepared as two pairs of scientific papers dealing respectively with nutritional sustainability and the effect of growth resource availability on stand productivity. These publications were incorporated into this thesis with minimal modifications: The nutrient losses in burning and harvesting operations of representative intensity are discussed in Chapter 4. A conceptual approach to judge the nutritional sustainability of forestry systems is presented in Chapter 5, based on a case study of the Karkloof project experiment. The effect of growth resource availability on leaf area development and stand growth efficiency is presented in Chapter 6. Finally (in Chapter 7), the physiological processes of light absorption, canopy quantum efficiency and

carbon partitioning are quantified for the system in question. Chapter 8 provides a general discussion of the findings and is used to reflect on the implications of the published findings for management and research.

# CHAPTER 2

## 2 General Literature review

### 2.1 SUSTAINABLE FOREST MANAGEMENT

Sustainable forest management has been defined as the management of the economic, social and biological components of the forest in such a way that it will continue to be productive in perpetuity (Toman and Ashton, 1996; Helms, 1998). This is often referred to as the “triple bottom line” by managers. However, there are two controversies surrounding the definition above:

The first point of controversy centres on the measurement of the triple bottom line. Economic success (e.g. financial statements) and indicators of social benefits (e.g. job creation, recreational use of forest land) are arguably, relatively easy to measure. Measurement of sustainability relating to the biological or ecological component is more difficult to gauge. The trend in plantation productivity over successive rotations is a practical measure of biological sustainability, and an important reference point. It is usually assessed through sequential measurement plots (e.g. Herbert, 1984; Squire *et al.*, 1979 and 1985) or matched plots of different rotations (e.g. Morris, 1986; Evans, 1996 and 1999b). The maintenance of current yields in terms of products and services from a forest has been described by Evans (1999a) as sustainability in the ‘narrow sense’. However, it may have several disadvantages because it is essentially based on tree growth and does not necessarily take ecosystem processes into consideration (Morris and Smith, 2002; Smith *et al.*, 2005). Responses to site management operations could also be masked by genetic improvements or climatic variability (Smith *et al.* 2005). An understanding of management impacts on the ecological processes that drive productivity is required to comprehensively assess ecological sustainability in the broader sense (Smith *et al.* 2005). The measurement of these processes is complex and requires well designed, controlled experimentation (e.g. Bouillet *et al.*, 2000; Gonçalves *et al.*, 2004c; Nzila *et al.*, 2004; Smith *et al.*, 2005).

The second point of controversy is linked to predictive ability and the timespan of the definition of sustainability. Constanza (1996) argued that any system has a finite lifespan. Any system that remains functional for the expected lifespan could only really be labelled ‘sustainable’ retrospectively. Constanza (1996) therefore prefers to see sustainability as a *prediction* of a set of conditions that could ensure system survival for its expected lifespan. The concept of striving for a

set of conditions that are *most likely* to preserve the integrity and production potential of the system has been proposed by several authors. Broadly speaking, the degree of alignment between (often limited) ecological capability of the system and the intensity of management plus social and economic benefits is seen as an indicator of the likelihood of sustainability (Kaufmann and Linder, 1996; Nambiar and Brown, 1997).

On an operational level, some practical goals need to be set that will incorporate the triple bottom line as well as the essence of sustainability in its broader sense. Nambiar (1996) proposed that plantation management should strive to: (1) achieve a non-declining trend in productivity, *while preserving or enhancing the quality of the soil resource base*, (2) avoid adverse effects on the environment, and (3) ensure that the enterprise remains viable and benefits the local people and economy. [Own phrasing and own emphasis, after Nambiar, 1996].

The social and economic sustainability falls outside the scope of this thesis, as it is essentially concerned with the ecological or biological components of sustainability. For this reason, the remainder of the section on sustainability in this literature review will focus on the ecological component.

## **2.2 INTENSIVE PLANTATION MANAGEMENT**

The global need for fast-growing plantations to meet future demands for wood and fibre (and to conserve natural forests) has been high on the socio-political agenda since the 1970's and 1980's (Gessel, 1984). In many countries, vast areas of plantations have been established since that time, the total global plantation area current being approximately 140 million hectares (FAO, 2000). Most of the plantations of the world have much greater productivity than natural forests, with plantation forests commonly outperforming natural forests by an order of magnitude (Brown *et al.*, 1997). The high productivity of man-made plantations is due to several factors, a very important factor being intensive stand and site management (Schönau, 1984; Schönau, 1989; Birk and Turner, 1992; Gonçalves *et al.*, 1997; Gonçalves *et al.*, 2004b). With increasingly intensive management aimed at maximum productivity, the sustainability of plantations in the broader sense may be at risk, as the following examples show: Increased removal of biomass from forests (through greater volumes of timber, whole-tree harvesting; firewood collection, de-barking off site or partial removal of the slash) greatly increases the nutrient removal from the site which may result in base cation stripping and acidification of the soil (Morris, 1986; Musto, 1992, du Toit, 1993; Judd, 1996; Herbert, 1996; Fölster and Khanna, 1997; Dovey and du Toit, 2004; Nzila *et al.*, 2004; Gonçalves *et al.*, 2004a).

Intensive cultivation and certain slash management practices may deplete the labile pool of organic matter in soils, leading to increased nutrient loss, decreased biological activity and a degradation of soil physical properties (Attiwill and Leeper, 1987; Gonçalves *et al.*, 2004a; Gonçalves *et al.*, 2004b). Slash burning may be practised to minimise the risk of wildfire, to improve access for replanting, to stimulate nutrient release and recycling, but this practice will increase nutrient losses through oxidation, volatilization and carries with it the increased threat of wind or water erosion losses, especially on steep terrain (Beard, 1951 & 1961; Sherry 1953, 1954, 1961 & 1964; Morris, 1986; Fölster and Khanna, 1997; Fisher and Binkley, 2000; Gonçalves *et al.*, 2004a). Intensive mechanised harvesting systems may impact negatively on soil physical properties and soil erosion potential (Fölster and Khanna, 1997; Smith *et al.*, 1997; Smith, 1999; Smith, 2000; Smith *et al.*, 2001a; Smith 2003; Smith and du Toit, 2005).

The preservation of water and soil quality is essential to ensure sustainable forest ecosystems (Raison, 1984; Nambiar, 1999a). More specifically, an understanding of the interplay between water and nutrient availability to tree crops is pivotal to ensure the achievement and maintenance of high yields (Gonçalves *et al.*, 1997; Binkley *et al.*, 1997). One key component of soil quality is concerned with nutritional sustainability. Fölster and Khanna (1997) identified three areas needing further research to ensure the nutritional sustainability of plantation systems globally: (a) the effect of site management operations on N and P dynamics; (b) the interplay between base cation availability (i.e. the equilibrium between nutrients held on the cation exchange complex and those in the soil solution, as well as the contribution of mineral weathering), and the uptake into the biomass, and (c) to develop models on the landscape scale that could assist in assessing nutrient fluxes and pools in ecosystems (including soil pools).

### **2.2.1 Nutrient input / output fluxes and nutrient pools**

Nutrients are present in several pools in forest ecosystems, varying in size, e.g. the soil, the living biomass and the forest floor. The movement of nutrients between pools can be described by nutrient fluxes (Fisher and Binkley, 2000; Ranger and Turpault, 1999, Scholes and Scholes, 1999). Some fluxes involve transfers within the biomass (biological cycling) while others involve non-living components. For example, mineral weathering will release nutrients into the soil solution. A biological example could be litterfall from trees: nutrients are added to the forest floor, and when the litter has decomposed, the nutrients move into various soil pools from where plants can take it up. The entire nutrient cycling process in forests has been termed biogeochemical cycling (Fisher and Binkley, 2000). The nutrient pools in an ecosystem may differ greatly in their availability to

plants (Attiwill and Leeper, 1987; Binkley and Hart, 1989; Stewart *et al.*, 1990). Some nutrient pools constitute a source of readily available nutrients (e.g. the soil exchange complex) whereas nutrients in other pools may be largely unavailable to plants (e.g. specifically adsorbed P or heavy fraction organic matter). Knowledge of both nutrient pool sizes and nutrient fluxes are important to fully understand ecosystem nutrition, nutritional constraints on production, and sustainability of systems.

Biogeochemical cycling is best described by accurate budgets of nutrient input and output fluxes. However, these data are extremely time-consuming and resource hungry to gather and is therefore limited to very few sites around the globe. Furthermore, it is often difficult to estimate the “potentially plant available” pools of nutrients in soils - various techniques have been proposed, e.g. for soil nitrogen and phosphorus (Binkley and Hart, 1989; Stewart *et al.*, 1990). Despite the difficulties and pitfalls, it is still informative to compare the net loss (or gain) of nutrients under specific management regimes to either total or plant available soil pools, e.g. the “plantation stability index” measure proposed by Fölster and Khanna (1997). Such an approach will shed light on the relative vulnerability of a system to nutrient depletion.

The three major mechanisms of nutrient input into ecosystems are atmospheric deposition, mineral weathering and symbiotic N fixation (Fisher and Binkley, 2000). In managed ecosystems, inputs from fertilization also need to be taken into account. Of the macronutrients, inputs of the elements Ca, Mg, K and P originate chiefly from mineral weathering, while N and Sulphur (S) are predominantly from atmospheric sources (Likens *et al.* 1977). Atmospheric inputs of N and S in industrialised areas are often higher than background levels (Reuss *et al.* 1987), however, even in rural areas, inputs through this pathway can still be substantial. For example, Laclau (2001), working near Pointe-Noire, Congo, measured atmospheric input rates of N, P, K Ca and Mg to be 10.1, 0.7, 6.5, 8.2 and 3.3 kg ha<sup>-1</sup> a<sup>-1</sup>. Mean values of wet deposition for South African rural deposition rates, calculated by Scholes and Scholes (1999) from four study sites, amounts to 6.0, 4.4, 7.7 and 2.3 kg ha<sup>-1</sup> a<sup>-1</sup> for N, K, Ca and Mg, respectively. Bruinzeel (1991) reviewed the rates of nutrient release in tropical and subtropical sites and estimated the ranges of weathering rates for K, Ca and Mg to be 9-21, 5-15 and 3-10 kg ha<sup>-1</sup> a<sup>-1</sup>, respectively. Binkley and Giardina (1997) listed estimates of symbiotic N fixation rates in tropical ecosystems which mostly fell in the range of approximately 50 to 150 kg ha<sup>-1</sup> a<sup>-1</sup>. These values are large when compared to potential inputs made by non-symbiotic (free living) N fixers (Son, 2001). Nutrient inputs into systems from atmospheric sources or weathering can make a significant contribution to the total budget. Despite the fact that some inputs (such as those from mineral weathering) are difficult to quantify, an

estimate of its contribution should be taken into account in nutrient budget calculations.

The major nutrient outputs from ecosystems include harvesting, losses through burning, erosion and leaching (Ranger and Turpault, 1999; Scholes & Scholes, 1999). In a review of forest ecosystems in warm temperate areas of the USA and Australia, Bruijnzeel (1991) concluded that harvesting and slash burning are responsible for the major nutrient losses in these ecosystems. Nutrient outputs through harvesting depend on the amount (Judd, 1996; Gonçalves *et al.*, 1997) and type (Johnson *et al.*, 1982) of biomass material. Waring and Schlesinger (1985) cite examples to show that nutrient losses in stemwood harvests in several northern hemisphere studies are usually less than atmospheric inputs over the rotation period. Turner and Lambert (1986) and Richards and Charley (1983), working on eucalypt systems, showed that nutrient losses through harvesting of the stem wood only, is usually relatively small by comparison to ecosystem pools. However, larger losses can occur when whole tree harvesting is practised or where slash burning takes place under specific environmental conditions (Morris, 1986; Fisher and Binkley, 2000). Nutrient losses through fires depend on the fire intensity and fire return interval. Losses of nutrients can occur as a result of oxidation, volatilisation, particle loss through convection, and also accelerated erosion or leaching following the event (Fisher and Binkley, 2000; Waring and Schlesinger, 1985). Very large losses of nutrients have been recorded as a result of wildfires (Leitch *et al.*, 1983; Van Wyk, 1985; Scott and van Wyk, 1990) or due to the burning of large loads of harvesting residue under unfavourable climatic and site conditions (Sherry, 1954 & 1964; Morris, 1986; Allan and Carlson, 1998; Fisher and Binkley, 2000).

Leaching losses can increase following clear felling as a result of decreased evapotranspiration and increased quantities of water percolating through the soil. Furthermore, a lower level of nutrient uptake by plants will be coupled to an increased level of nutrient release through microbial action after clear cutting (Waring and Schlesinger, 1985; Smethurst and Nambiar, 1990; Fisher and Binkley, 2000). Nutrient losses will be exacerbated if short rotations are used (Fölster and Khanna, 1997) since relatively greater amounts of nutrient-rich materials are removed and since more clear felling operations (followed by increased leaching) will take place per unit of time.

### **2.2.2 Nutrient supply to trees**

Site management operations such as slash manipulation, burning, fertilization, soil tillage or disturbance can strongly affect the nutrient availability to trees (Gonçalves *et al.* 1997; Fölster and Khanna, 1997). The nutrients considered to be most limiting in plantation forestry world wide are N

and P (Cromer *et al.*, 1993b; Grove *et al.*, 1996; Nambiar and Brown, 1997; Fisher and Binkley, 2000). Fertilizer trial responses show that N and P frequently limit the growth of plantation forests of southern Africa (Herbert and Schönau, 1990; Herbert, 1996; du Toit *et al.*, 2001; du Toit and Oscroft, 2003).

Trees take up large quantities of N into the biomass, which means that the rate of nitrogen supply to tree stands is often strongly correlated to tree growth (Gonçalves *et al.* 1997; Fife and Nambiar, 1997; Fisher and Binkley, 2000;). Fölster and Khanna (1997) described mineralization as the rate-limiting step to N supply for tree stands because of low supply rates or lack of synchrony with stand needs. A low rate of N supply often limits growth in established forests. N mineralization usually increases after clear felling, but the period of re-establishment is characterised by a low demand for N (Smethurst and Nambiar, 1990; Gonçalves *et al.* 1997; Fölster and Khanna, 1997).

Kimmins (1972) concluded that the degree of destabilisation of the nutrient cycle following clearcutting and slash burning depends on: (1) The ability of other plants to utilize resources after clearcutting, (2) degree of soil disturbance, (3) slash burning or conservation (4) rate of successional change and (5) the size of the clearfelled area. Managers should aim to minimize harvesting impacts and speed up stand development so that nutrient aggradation can start as soon as possible (Richards & Charley, 1983). The observations listed above underscores the importance of understanding the nutrient dynamics after clearfelling as this is the time when nutrient release is not always matched by uptake (Smethurst and Nambiar, 1990). The fact that microbes release and remobilise N, makes the process of N mineralization difficult to quantify (Fisher and Binkley, 2000).

Nitrogen availability to trees can be gauged by several laboratory techniques (Binkley and Hart, 1989). Many authors prefer to study N mineralization rates in field, so as to avoid artificial conditions created in laboratory studies (Waring and Schlesinger, 1985; Raison *et al.*, 1987; Fölster and Khanna, 1997; Carlyle *et al.*, 1998; Fisher and Binkley, 2000). Several models have been developed to predict the rate of N mineralization in field (O'Connell and Rance, 1999; Gonçalves and Carlyle, 1994; Paul *et al.*, 2002). Most models recognise the effect of microbial substrate, temperature and soil water content as the main drivers of N mineralization. Nitrogen availability to trees can also be gauged indirectly from the rate of uptake by the standing crop (Laclau *et al.*, 2003).

### 2.2.3 The eco-physiological basis of plantation productivity

The scientific community has made a lot of progress during the last two decades in the quest for understanding the eco-physiological basis of forest productivity. From an eco-physiological perspective, forest productivity can be described as the amount of radiation absorbed by vegetation and the efficiency by which this energy is converted to fix carbon dioxide through photosynthesis (Linder, 1985; Gholz and Lima, 1997; Landsberg and Gower, 1997). The process of photosynthesis is governed by radiation energy, temperature, water and nutrient supply, atmospheric CO<sub>2</sub> concentration, and plant factors (such a genotype and tissue age) (Landsberg and Gower; 1997; Gholz and Lima, 1997). However, for a given species on a given site, production effectively hinges on three main factors that can be manipulated: (a) the quantity of absorbed, photosynthetically active radiation (APAR), which is a mainly a function of latitude and leaf area index (LAI), (b) the water availability on the site, which is essentially governed by rainfall, evapotranspiration and soil water storage potential, and (c) the nutrient supply of the site, which is primarily a function of the nutrient pools and the rate of nutrient release or mineralization. High levels of available nutrients, coupled to adequate levels of soil moisture will yield plantations with large LAI's which will increase levels of APAR as well as the efficiency with which light energy is converted to fix carbon, and hence, increase growth (Brix 1983; Waring, 1983; Linder, 1985; Cromer *et al.*, 1993a; Landsberg and Gower, 1997; Landsberg and Waring, 1997; Fife and Nambiar, 1997; Albaugh *et al.* 1998; Carlyle, 1998; Bergh *et al.* 1999; Jokela and Martin 2000; Giardina *et al.* 2003, Binkley *et al.* 2004). The percentage of the fixed carbon that is channelled into stem wood biomass will also increase with increasing water and nutrient availability (Linder and Rook 1984; Keith *et al.* 1997; Misra *et al.* 1998; Hunter 2001; Stape 2002; Giardina *et al.*, 2003).

The issues of forest productivity and ecological sustainability share some common ground: the manipulation of ecological processes driving productivity also impacts on long-term sustainability (Kimmins, 1994), although the short-term effect may differ from the long terms effects. An example is the effect of burning which usually increases nutrient loss when measured over the longer term, but can be the cause of a large increase in the short-term availability of nutrients to tree stands which could boost production. It is thus informative to link an understanding of the effect of site management on nutritional sustainability with the eco-physiological response mechanism of the stand (specifically the effects on carbon sequestration, carbon partitioning and nutrient cycling) (Stape, 2002; Nzila *et al.*, 2004; Mendham *et al.*, 2003; O'Connell *et al.*, 2004; Gonçalves *et al.*, 2004c). Such an understanding will elucidate how changes in resource availability (brought about

by intensive site management) is utilised by the plantation system, and how this, in turn, affects the growth and carbon cycling in the system which has feedback mechanisms to nutrient cycling and soil fertility levels.

## CHAPTER 3

### 3 Site Description and Experimental Treatments

#### 3.1 GENERAL SITE DESCRIPTION

##### 3.1.1 Experimental location and site history

The Karkloof Project experiment is located near Howick in the Midlands of the KwaZulu-Natal (KZN) province, South Africa ( $29^{\circ} 24' S$  and  $30^{\circ} 12' E$ ) (Figure 3.1). The site lies on gently undulating terrain at 1260 m above sea level. The site is well suited to *E. grandis* and is highly representative of commercial eucalypt stands in the KwaZulu-Natal Midlands in terms of site index, climate, soil properties and historical land use.

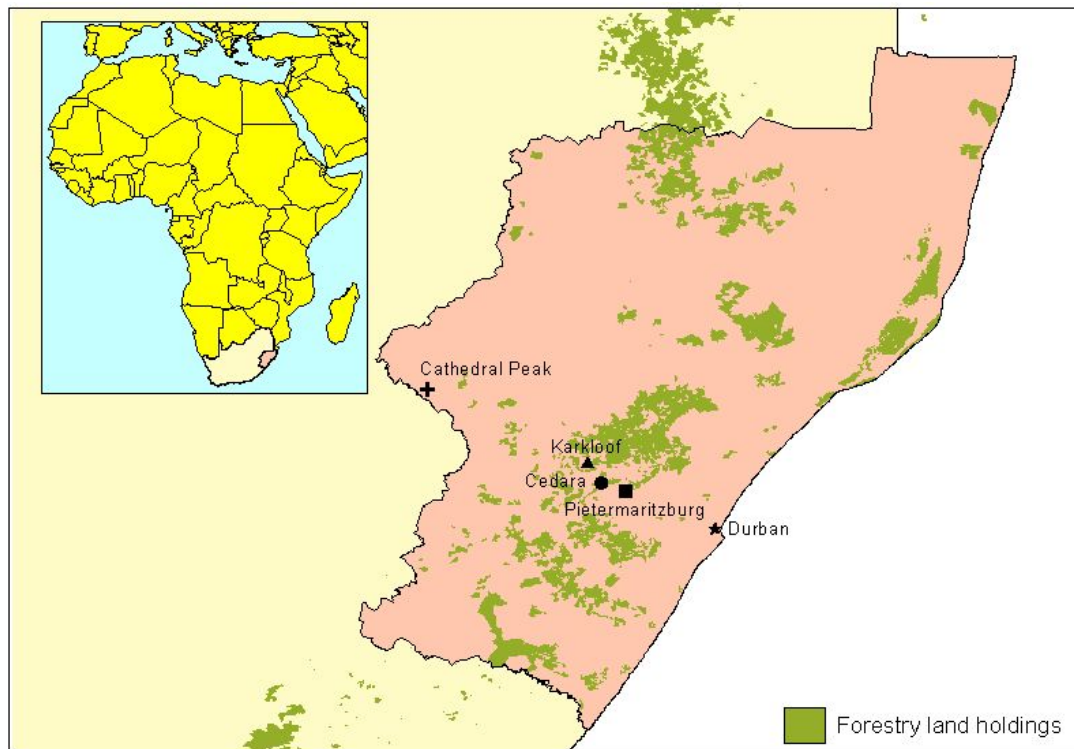


Figure 3.1. Location of the Karkloof trial in the Midlands of KwaZulu-Natal province, South Africa.

### 3.1.2 Long-term climatic data

Long-term historic climatic data are presented in Table 3.1 for the project site (interpolated from various sources) and for the Cedara Agricultural College (a full weather station with long-term historical data, situated approximately 17 km from the site).

Table 3.1 Estimated long-term historical climatic data for the Karkloof experimental site based on adjacent recording stations.

Site	Karkloof Project	Cedara Agricultural College
Latitude	29° 24' S	29° 32' S
Longitude	30° 12' E	30° 17' E
Altitude	1260 m asl	1067 m asl
Mean annual rainfall	ca. 950 mm <sup>1</sup>	877 mm
Rainfall concentration index	51% <sup>2</sup>	-
Mean annual temperature	ca. 15.2°C <sup>3</sup>	16.2°C
Radiation (monthly min-max)	-	15.9 - 27.8 MJ.m <sup>-2</sup> .day <sup>-1</sup>

<sup>1</sup> Mean value of seven stations recording only rainfall, located within a 5 km radius from the site with a mean recording period of 28.7 years;

<sup>2</sup> Based on the Methodology of Markham (1970) as cited in Schulze (1997);

<sup>3</sup> Value estimated from adiabatic lapse rate for KZN (5°C per 1000 m increase in altitude).

Estimates of mean monthly rainfall and reference potential evaporation from an open water surface ( $E_r$ ) have been calculated for the site, using the ACRU Model (Schulze *et al.*, 1995). These values are presented in Figure 3.2 with the monthly value ( $0.3 \cdot E_r$ ) to demonstrate the approximate duration of the water deficit period and the “moisture growing season” on the site, according to the FAO method cited by Schulze (1997). Our results show that the mean start of the moisture growing season falls on day 244 (Julian calendar, *i.e.* 1 September) and the mean end falls on day 105 (*i.e.* 15 April). The average duration of the moisture growing season is 226 days. A pronounced period of water deficit prevails over the winter months (May to August – Figure 3.2). Mean monthly minimum and maximum temperatures are shown in Figure 3.3. The long-term mean monthly minima for the coldest month (June) and the warmest month (January) are 3.7 °C and 14.8 °C while the corresponding maxima are 19.0 °C and 25.0 °C. Light frost events occur sporadically during most winters and episodic snowfalls occur in the region on sites with altitudes over 1150 m (Gardner and Swain, 1996).

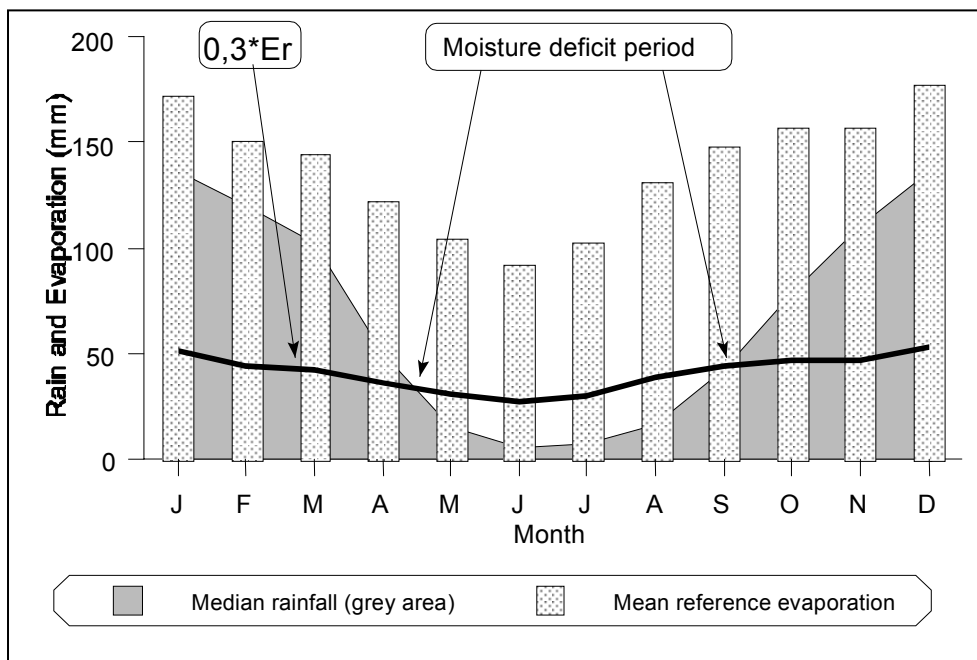


Figure 3.2 Mean monthly values for evaporation ( $E_r$ ), rainfall ( $P$ ) and the value  $0.3 \cdot E_r$  (dark line) at the site (the moisture growing season occurs where  $P > 0.3 E_r$ , i.e. Sept.-April).

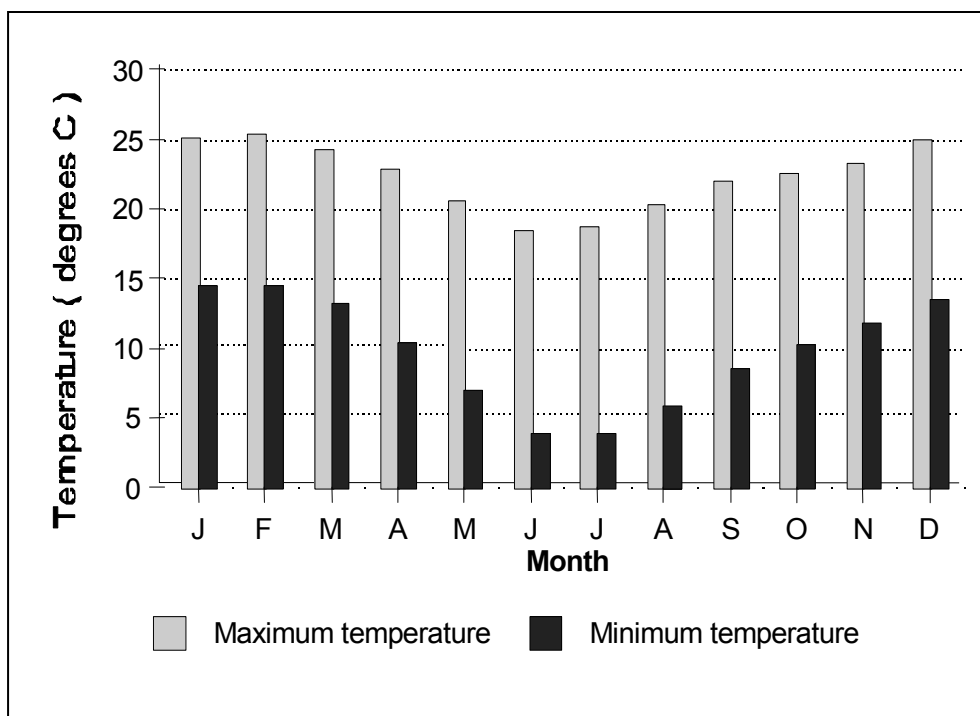


Figure 3.3 Mean monthly minimum and maximum temperatures at the site.

### 3.1.3 Soils of the KwaZulu-Natal Midlands and the Trial Site

The sites suitable for forestry in the Midlands of KZN are dominated by highly weathered soils derived principally from sedimentary rocks (shale, sandstone and mudstone), with igneous (dolerite) intrusions. An area with a relatively uniform soil profile and uniform stand characteristics (in terms of stocking and tree size distribution) was selected for the location of the actual trial site. The soil at the trial site is derived from a mixture of Jurassic dolerite and shale of the Ecca group. It has a humus-rich, clayey A horizon (zero to 0.2 m depth) overlying a yellow-brown clayey B<sub>1</sub> horizon (0.2 to 0.4 m), and a red clayey B<sub>2</sub> horizon which grades into weathered shale at approximately 0.9 m depth, on average (Figure 3.4). The weathered shale layer exceeds 5 m in depth, and is colonised by roots to a limited degree along fractured surfaces (own observations from pit profile and road cuttings). A generalised and representative soil profile with key sets of descriptive data per horizon is shown in Table 3.2. The soil is described as a Kranskop 1100 (Soil Classification Working Group, 1991) and would be classified as a Humic Ferralsol under the FAO classification. The soils in this group do not have a well defined macro-structure since the clay minerals are dominated by 1:1 clays and sesquioxides. The soil has a low bulk density and a well developed micro-structure, which ensure that it is stable, porous and well drained with a rapid infiltration rate (Smith *et al.*, 1997; du Toit *et al.*, 2000; du Toit *et al.*, 2004). The potential for P fixation is high due to the clay type (Bainbridge *et al.*, 1995).

Table 3.2 Soil characteristics at the trial site.

Horizon	Depth (m)	Texture class	Particle size analysis (%)			pH (KCl)	Organic carbon (%)
			Clay	Silt	Sand		
A	0.2	Clay	68	19	13	3.98	6.97
B <sub>1</sub>	0.4	Clay	68	14	18	4.09	3.27
B <sub>2</sub>	0.8	Clay	68	8	24	4.62	1.53
C	0.95	Silty clay	50	24	25	4.21	0.48

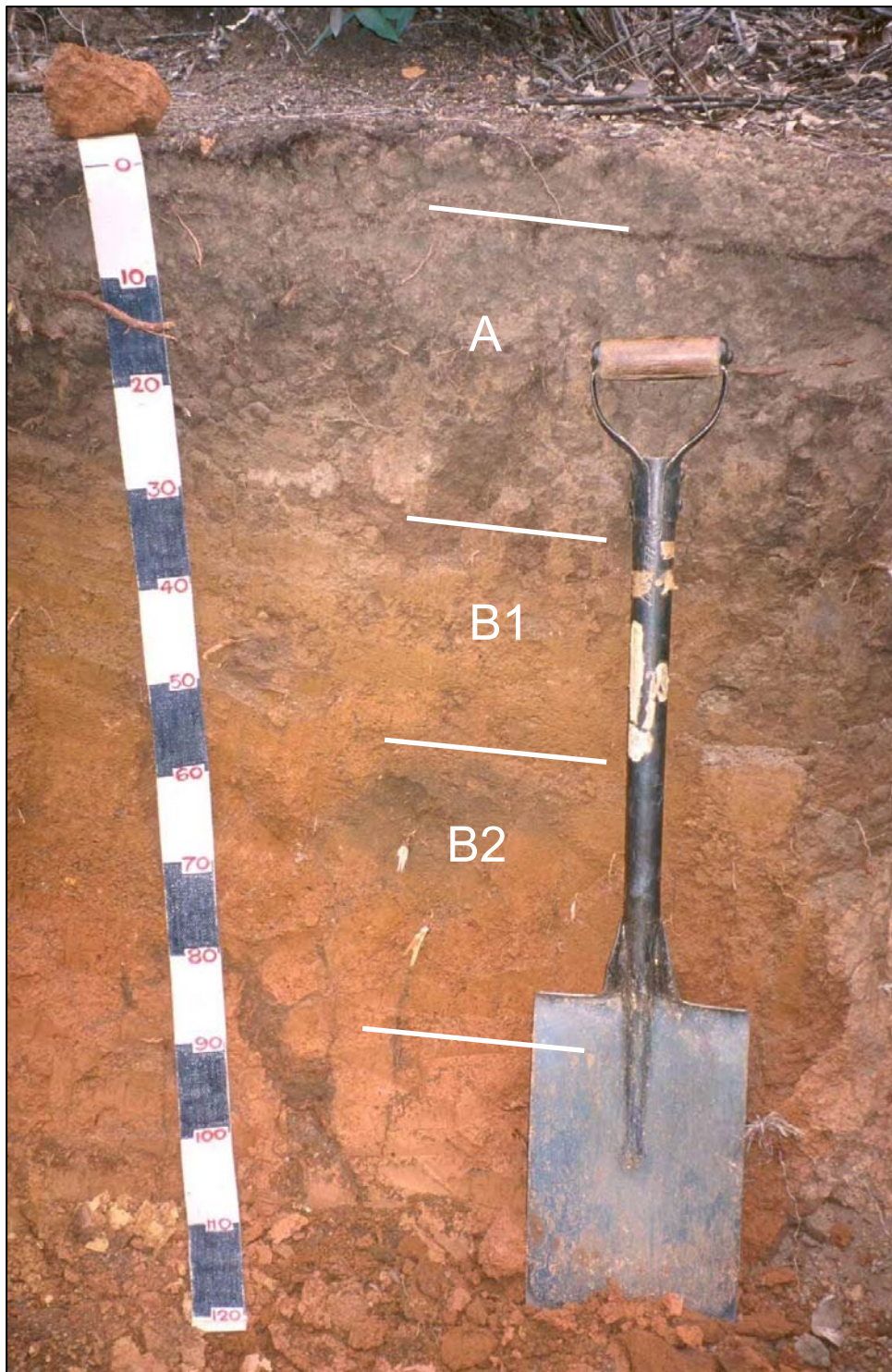


Figure 3.4. Soil profile showing the humic A, yellow-brown apedal B1 and reddish brown apedal B2 horizons, as well as the saprolitic material (weathered shale). Some overburden from the excavation is visible above the spade top.

### 3.2 HISTORY OF THE SITE AND THE STANDING CROP

*Eucalyptus grandis* (the Flooded gum) is a fast-growing, evergreen tree native to Australia. It has large dark green ovate leaves in the juvenile stage, which become more slender and lanceolate in shape with age. It has an open, spreading crown and is capable of rapidly forming a dense canopy in plantations under suitable establishment conditions (Poynton 1979; Boland *et al.* 1997). The tree has been planted extensively in the subtropical and warm temperate zones of the summer rainfall area of South Africa.

The natural vegetation on the study site was *Themeda* grassland until the site was afforested during 1964 with *Eucalyptus grandis*. After the initial tree crop was harvested in 1973, the stumps were allowed to coppice three times (1973, 1982 and 1991). The fourth and final crop from the originally planted stumps was seven years old and management staff had estimated its mean annual increment as  $21 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$  when it was clear felled in 1998. We calculated the utilizable standing volume as  $162 \text{ m}^3 \text{ ha}^{-1}$  at clear felling, using the Shumacher and Hall equation with Coetzee's (1992) coefficients for short-rotation *E. grandis* (cited in Bredenkamp, 2000), which would suggest a mean annual increment of  $23.1 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ . It is common practice in eucalypt stands in the region to allow for one or two coppice crops in addition to the initially planted crop. It is less common to allow a third coppice crop to grow to maturity, as was the case on this site. Standard recommendations for coppice shoot reduction were most likely followed. According to this procedure, coppice shoots are reduced to 2 or 3 stems per stool when mean shoot height is 4 m and are then reduced to 1 or 2 stems per stool (depending on stool mortality) when mean shoot height is 8 m (Stubblings and Schönau, 1980). A spacing of 2.44 x 2.44 m was used in the original stand giving an initial stand density of 1680 stems  $\text{ha}^{-1}$ . The standing crop was clear felled in December 1998 and site management treatments were implemented.

### 3.3 EXPERIMENTAL DESIGN

Before clear felling the existing crop, plot locations for the planned experiment were demarcated to ensure that vehicular traffic could be kept off the measurement plots during the harvesting operation. The area of each of the plots was  $1715 \text{ m}^2$  of which the inner  $286 \text{ m}^2$  was used as measurement plots (6 x 8 rows of trees at an initial spacing of 2.44 x 2.44 m). The randomised block design chosen consisted of 32 plots (8 treatments in 4

replications) and is annotated as black squares in Figure 3.5. Six of the eight treatments were implemented in 1999 and these are described in this thesis. The remaining two treatments (coded with symbols C and X on Figure 3.5) were earmarked for future use in subsequent rotations of trees on this long-term experimental site. A number of additional monitoring plots (white annotations in Figure 3.5) were also demarcated around the replicated experiment (i.e. in the virgin grassveld, in zones impacted by vehicular traffic, in the mature crop of eucalyptus, and in a block planted to *Acacia mearnsii* which was earmarked for future crop rotation studies). These additional monitoring plots were established for comparative purposes (du Toit *et al.* 2000) and do not form part of the work described in this thesis.

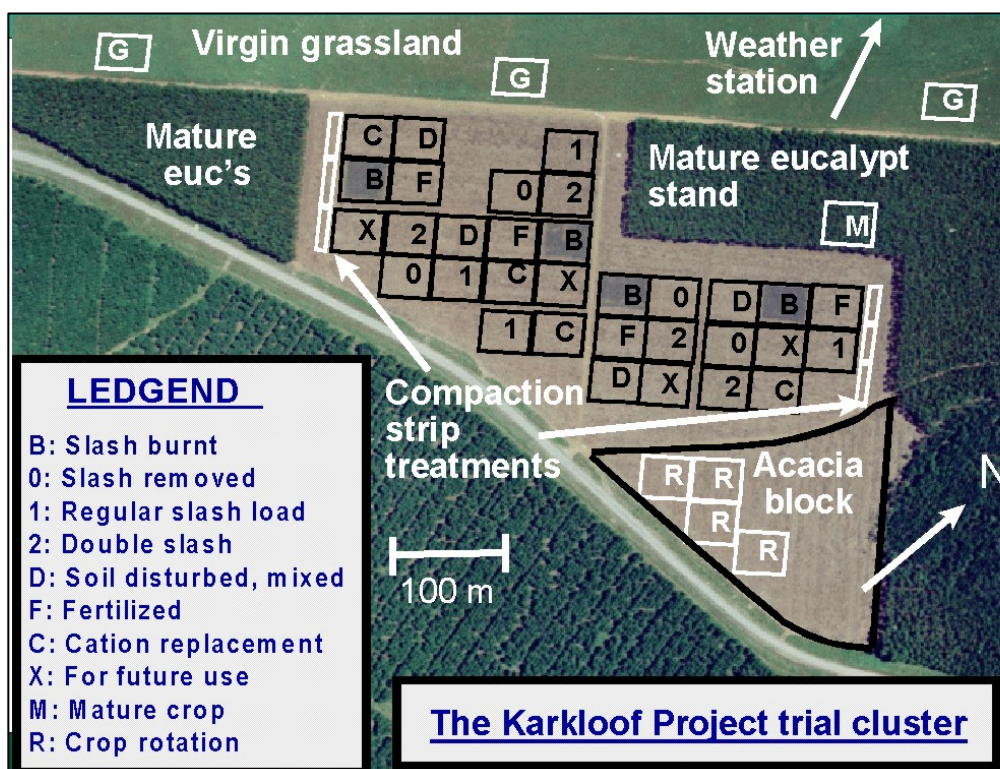


Figure 3.5 Annotated aerial photograph of the main trial site (black grid) and adjacent monitoring plots (white blocks).

### 3.3.1 Treatments

The following treatments were chosen for implementation:

**0S Slash removal:** All harvesting residue (including bark, branches and foliage) and litter layer manually removed from the plot. Partly decomposed material in the forest floor remained on site.

**1S Regular slash load:** Harvesting residue retained and broadcast on the plot.

*Note: 1S is regarded as the control treatment.*

**2S Double slash :** Material from the 0S plot deposited on top of existing slash load.

**SB Slash burning:** Harvesting residue burnt in a medium intensity fire.

**SD Topsoil disturbance:** Slash disturbed and mixed with soil through mechanical loading and stacking of timber with a 3-wheeled loader.

**SF Fertilization:** Regular slash load, followed by the application of 16.6 kg nitrogen (N) + 33.3 kg phosphorus (P) + 0.7 kg zinc (Zn) per hectare in localised positions near seedlings at time of planting.

Treatments 0S, 1S and 2S were aimed at creating a wide range in nutrient pool sizes. Treatments SD, SB and SF were used to simulate site management operations at representative intensities, and these treatments were all superimposed onto plots that initially had a regular slash load (similar to treatment 1S). The treatments are shown pictorially in Figure 3.6



Figure 3.6. Karkloof project treatments: (left column, from top) slash removal, regular slash, double slash; (right column, from top) topsoil disturbance, fertilization and slash burning.

### 3.4 SITE PREPARATION AND TREATMENT IMPLEMENTATION

In the 0S (slash removal) treatments, the bulk of the freshly fallen (L) layer was manually raked up into piles and transferred to the 2S (double slash) treatments. Old tree stools were treated with herbicide (a glyphosate/triclopyr mix) between one and 14 days before clear

felling (the 'basal frill treatment') described by Little *et al.* (2000b). Excessive coppice re-growth was not desirable as it would have necessitated several coppice control operations and would have altered the nutrient dynamics on site. During December 1998, plots were demarcated and all trees felled by chainsaw and debarked manually. Timber was stacked in rows outside the plots. In the SD treatments, a 3-wheeled loader with grapple was used to pick up all logs. This operation mimicked a loading operation since the loader travelled in a zig-zag fashion across virtually the entire plot (only the borders of the outer plots were not impacted). The 25 t forwarder was only allowed to travel in a predetermined path on the outsides of the two lines of stacked timber. No vehicular traffic was allowed in the plots, except for the topsoil disturbance treatments. The harvesting residue was raked up in the slash removal treatments and transferred to the double slash treatments. Internal firebreaks were cleaned between replications as well as around the plots where the slash was burnt. The slash was burnt during the early morning of a single day in a medium intensity fire. Mean hourly air temperature over the period of burning rose from 14.9 to 26.1°C, and wind speed ranged from 0.3 to 2.2 m s<sup>-1</sup> (*i.e.* 1 – 8 km hr<sup>-1</sup>). The relative humidity decreased from 99 to 57% over the same period.

### **3.5 RE-ESTABLISHMENT, FERTILIZATION AND WEED CONTROL**

Genetically improved seed of *E. grandis* was collected from trial EB 011K, of Sappi (Pty) Ltd. and seedlings were raised in containerised planting trays in the nursery. The original spacing (1680 stems ha<sup>-1</sup>) was maintained when the site was pitted for replanting, as optimum economic returns on sites of moderate to low productivity (such as the trial site) can be obtained with a *final* stocking of approximately 1500 stems ha<sup>-1</sup> (Coetzee, 1995). Seedlings were planted on 3-4 February 1999, following substantial rains (44.6 mm on 1-3 February). Seedlings were planted in small notch pits and treated with two litres of a synthetic pyrethroid pesticide drench (0.5 ml of Deltamethrin 5% suspension concentrate per litre of water). Mortality rate was assessed at 20 and 43 days after planting and dead trees replaced (blanked). Blanking amounted to 2.49% overall. Eucalypts were fertilized with 90 g of Mono-ammonium phosphate (MAP+Zn) per tree (16.6 kg N + 33.2 kg P + 1.1 kg Zn ha<sup>-1</sup>). The fertilizer was applied as a spot treatment 15 cm from the seedling. Fertilizer application rates were based on recommendations from previous experiments (du Toit 1995) but using slightly higher rates as suggested for eucalypts on soils rich in organic matter (du Toit 1998). The few coppice shoots that sprouted were removed manually. Weeds were controlled by spot-

spraying with glyphosate. Only one weed control operation was necessary in the first nine months after planting.

The stocking for each treatment at two years of age is shown in Figure 3.7. Despite the generally high level of survival (90 %), some plots had fairly high mortality. The stocking in the four replications of treatment 2S were 805, 1050, 1260 and 1540 stems ha<sup>-1</sup>. The mortality was ascribed to a combination of the micro-topography in specific replications and unfavourable microclimatic conditions in the planting pits resulting from large slash loads with subsequent frost pocket formation (du Toit *et al.*, 2000). It was feared that differences in stocking may confound the response to treatment in the 2S treatment as it may affect growth response (e.g. the leaf area, growth efficiency and biomass partitioning of trees). For this reason, statistical analysis and interpretation of results in Chapters 6 and 7 focus only on the remaining five treatments with adequate stocking.

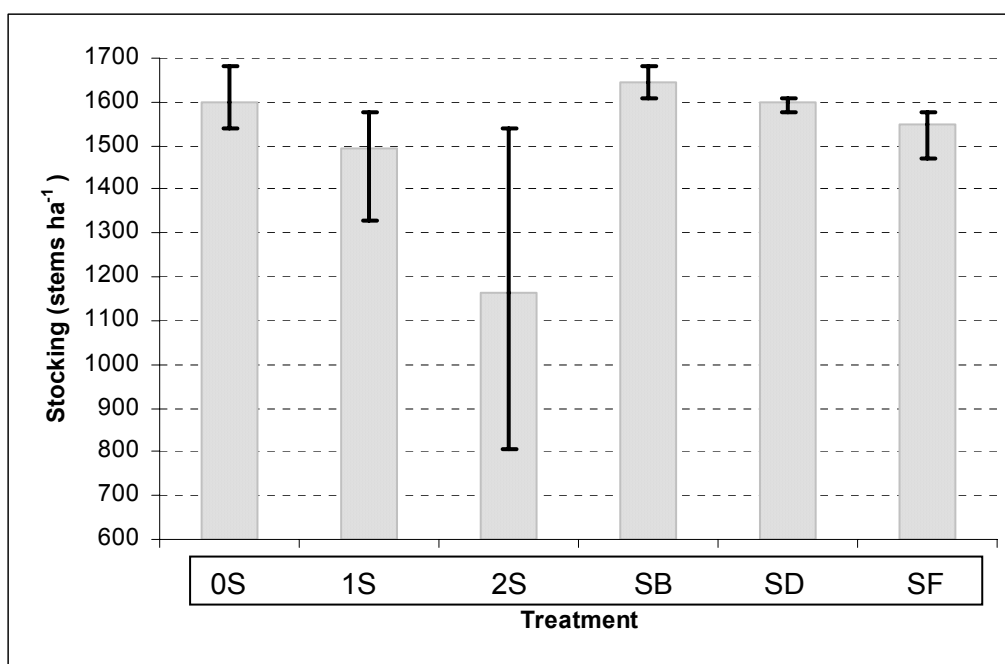


Figure 3.7. Stocking across treatments at two years of age. The range in stocking across replications are shown as vertical bars.

## **3.6 ADDITIONAL DATA COLLECTION**

The collection of additional data pertaining to specific research objectives, namely nutrient pool data, estimates of nutrient fluxes, climatic variables, soil water, growth, leaf area and biomass development, litterfall, root turnover, growth efficiency and canopy quantum efficiency are described in detail in the specific materials and methods sections of chapters 4 to 7.

### **3.6.1 Climatic and soil water data**

A full weather station was erected at the Karkloof Project site and became operational during August 1998, ca. six months prior to trial establishment. It recorded the hourly maximum and minimum air temperature, relative humidity, solar radiation, rainfall, wind speed and direction. Variations in topsoil water content were monitored through a network of loggers and time domain reflectometry (TDR) sensors installed during February and May 1999 and comprise two CR10 loggers and 15 CS615 soil water sensors. These sensors have been placed in two of the four replications, and measure the soil water contents at a depth of 0.15 m. Variations in soil water content in the deeper layers were monitored initially on weekly and later on monthly intervals with a neutron moisture meter. Readings obtained from both sets of measurements were calibrated using gravimetric samples.

### **3.6.2 Nutrient pool, biomass and growth data**

The focus of chapters 6 and 7 of this thesis is on the effects of intensive site management at time of establishment on the nutrition and growth of a young eucalyptus stand (from planting to three years of age). However, some of the key properties (e.g. LAI and biomass development) have been measured beyond three years of age. These data are shown in Appendix 5. Some early growth responses are shown in Figures 3.8 and 3.9. The trial was earmarked for monitoring for a full rotation (8 years), but was unfortunately badly damaged by snowfall and subsequent breakage at 5.5 years of age (Figure 3.10). Notwithstanding this fact, a large body of data had been gathered, and plans are in an advanced stage to re-implement this trial so that long-term responses can be measured over successive rotations (du Toit and Dovey, 2004).



(a)



(b)

Figure 3.8. Early responses in leaf area development, photographed at (a) 4 and (b) 12 months of age from approximately similar vantage points. In the foreground of both pictures, treatment SF of replication 3 is on the left, treatment OS of replication 4 on the right, and a section of the mature crop is visible in the background.



(a)



(b)



(c)

Figure 3.9. The trial at (a) 2.8 and (c) 4.5 years after planting, photographed from approximately similar vantage points. Image (b) shows the leaf area at 4.5 years of age.



Figure 3.10. Extensive breakage of stem tops and bending of trees, photographed on 7 September 2004, following a snowstorm the day before.

## CHAPTER 4

### 4 Effect of site management operations on the nutrient capital of a eucalypt plantation system in South Africa <sup>1</sup>

#### 4.1 INTRODUCTION

Site management operations carried out during the inter-rotational period in forest plantations (harvesting, slash management and other silvicultural operations at time of establishment) have a potentially large impact on the productivity and long-term sustainability of forest stands, especially if short rotations are used (Fölster and Khanna, 1997; Fisher and Binkley, 2000; Gonçalves *et al.* 1997; Nambiar, 1999b). In the South African commercial hardwood context, large growth responses have been documented in empirical field trials or groups of trials as a result of the implementation of silvicultural operations that affect nutrient and water supply to trees. These operations include soil cultivation (Smith *et al.*, 2000; Smith *et al.*, 2001b), fertilization (Herbert and Schönau, 1989 & 1990; Herbert, 1996), management of competing vegetation and harvesting residue (Little, 1999; Little *et al.*, 1996; Little *et al.*, 2000a) and harvesting operations impacts (Smith, 2000).

Despite this large body of evidence regarding growth responses to early, intensive silviculture in southern African plantations (Schönau, 1984 & 1989), the processes that govern the responses obtained are not entirely understood, making extrapolation of experimental results difficult. Furthermore, little is known about the impact of management operations on either the nutrient capital or the nutrient dynamics in the system. This chapter deals with the initial changes in the nutrient capital of the various nutrient pools of the system, brought about by six inter-rotational site management operations.

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## 4.2 MATERIALS AND METHODS

The details of the study site and experimental treatments have been given in Chapter 3. Immediately after site selection, samples were collected in the mature crop, forest floor and soil to determine the nutrient capital before implementation of harvesting treatments. One set of samples per biomass component was used to quantify nutrient capital before harvesting, since no treatments had been implemented at that stage.

### 4.2.1 Nutrient capital in biomass, forest floor and soil before harvesting

The nutrient capital was determined in four components of the plantation system: the above-ground biomass, the roots (including stumps), the forest floor and the soil. The following methods were used to estimate nutrient content in each component:

*Above-ground biomass.* Before harvesting, diameter at breast height (dbh) of 1335 trees was measured on the selected experimental area. The dbh distribution was divided into 18 equal (in terms of tree number per hectare) class intervals and one tree was randomly selected from the mid-point of each class for destructive sampling. The sample trees were felled, de-branched and cross cut into 2.5 m sections which were debarked on site. Wood and bark disk samples were taken at each of the 2.5 m sections to determine nutrient and moisture content of utilizable wood and stripped bark. Leaves and capsules were removed from the branches. Sample tree biomass was then divided into the following components: utilizable stem wood (> 70 mm thin end diameter as measured over bark), the bark removed from utilizable wood, stem top with bark, dead branches, live branches in categories > 30 mm and < 30 mm diameter, respectively, capsules of the current and previous growing season and leaves. For each fraction of the standing biomass, wet mass was determined on the full sample in the field, and at the same time, representative sub-samples were collected so that moisture and nutrient contents could be determined in the laboratory. The mass of individual sample tree components was regressed against dbh (Appendix 1). The regression estimates of the biomass components for each of the original 1335 measured trees were determined and summed to provide estimates of biomass per unit area of land. The methods used to analyse plant material are described by Kalra and Maynard (1991). The dried material was ground, dry ashed and dissolved in 0.6 M HCl, filtered and diluted to an appropriate level with de-ionised water. Concentrations of Ca and Mg were determined by

atomic absorption spectroscopy while flame emission spectroscopy was used for K. The concentration of P was determined spectrophotometrically (molybdenum blue method). N was determined by the Kjeldahl procedure with selenium as a catalyst (Nicholson, 1984). The nutrient concentration of each biomass component per class was multiplied by the estimated biomass of that component to determine the nutrient content.

*Below-ground biomass.* The diameters of 200 stumps were measured at ground level and stratified into three classes. A stump at the midpoint of each class was selected at three random locations adjacent to the demarcated trial area so as to minimise damage to the site upon stump and root excavation. The excavated area around each stump was equal to the dimensions of the original spacing (2.44 by 2.44 m) and was dug to a depth of 1 m. The soil profile was stratified into three layers (0.0 to 0.2 m; 0.2 to 0.6 m and 0.6 to 1.0 m). The deepest horizon excavated consisted of a mixture of the subsoil and the uppermost layer of saptrolite below the mineral soil. The mass of fine roots (diameter < 1 mm) was not determined in this study. A soil coring device with a volume of 1.274 dm<sup>3</sup> was used to collect four root samples per horizon to estimate medium root mass, i.e. roots between 1 and 10 mm in diameter. The soil in the entire 2.44 by 2.44 m block was then excavated and sieved through a 10 mm mesh sieve to separate soil clods from the root and stump fractions > 10 mm in diameter. These fractions were separated into coarse and very coarse fractions (smaller and greater than 100 mm diameter, respectively), by sawing. The stump was separated from the roots by sawing at the soil surface level. All root samples and stumps were air-dried and weighed. Sub-samples were then oven dried for moisture and nutrient content determinations. Only the average mass and nutrient content of the three samples were reported, as it was not possible to gauge the variability with only three basic samples.

*The forest floor.* The mass and nutrient content of the forest floor before harvesting was determined by collecting 18 random samples with a ring sampler of 0.30 m diameter. To allow for differences in nutrient content due to differences in degree of decomposition, the samples were separated into fine, medium and coarse fractions. The fine fraction consisted of material passing through a 2 mm sieve, representing the humus fraction (H-layer), as defined by Fisher and Binkley (2000). The medium and coarse fractions made up the L-layer (a clear F-layer could not be discerned). After sieving, each fraction was oven dried and weighed separately. The loads of material were reported as ash-free masses in each case to circumvent potential problems with soil contamination during sampling at the litter/soil interface.

*Soil.* Soil samples were taken at three depths (0 - 0.2, 0.2 - 0.4 and 0.4 – 0.6 m) which correspond closely to the soil horizons identified. At each plot, four samples of the A horizon (bulked) and one sample each of the B1 and B2 horizons were collected for analysis. The samples were air dried and ground to pass through a 2 mm sieve. Soil pH was determined in both water and 1 M KCl using a soil solution ratio of 1:2.5 in each case. Exchangeable cations were extracted in 1 M ammonium acetate at pH 7 and their concentrations were determined with atomic absorption spectroscopy. Extractable acidity was determined by titration after extraction with 1 M KCl. Organic carbon was estimated using the Walkley-Black method of wet oxidation (Nelson and Sommers, 1996). Total N was determined by the Kjeldahl method (Bremner, 1996). After dispersion and ultrasonic treatment, particle size was determined by sieving (coarse fractions) and the pipette method (fine fractions) (Gee and Bauder 1986). Available P was estimated by extracting with Bray-2 solution (0.03 M  $\text{NH}_4\text{F}$  in 0.1 M HCl) (Bray and Kurtz 1945) and P content was determined colorimetrically (molybdenum blue). Mean soil bulk density in each horizon was determined from sixteen undisturbed soil core samples per horizon. Readily available pools of nutrients in the soil were estimated as follows: Exchangeable fractions were used for the base cations (Ca, Mg and K) and Bray-2 extractable levels for P. Available N was estimated as 2% of total N (after Fisher and Binkley, 2000). These numbers were scaled up to a hectare value using the volume of soil (up to the weathered saprolite at 0.9 m depth) and the bulk density.

#### **4.2.2 Harvesting and treatment implementation**

The standing tree crop on the experimental site was clear felled using conventional practices, *i.e.* trees were de-barked in field and only utilizable timber (stem wood > 70 mm diameter over bark) was removed. The treatments (section 3.3) were implemented as described in sections 3.4 and 3.5.

In treatments 0S, 1S, 2S and SB, two sets of three slash samples each were collected per plot by cutting out squares of 0.071 m<sup>2</sup> with a chainsaw. Samples were separated into size fractions in the same way as for the forest floor described earlier. The fine, medium and coarse fractions originating from all three samples within the same set were bulked before chemical analysis to determine macronutrient content. Slash loads were reported as ash-free masses as for the forest floor. In treatment SB, the residual ash was sampled 14 days after burning using a ring sampler with a diameter of 0.30 m. Two sets of three ash samples

each were collected per plot. The samples within the same set were bulked before chemical analysis. The analysis followed the same procedure as for an ashed biomass sample (see section on above-ground biomass). The differences in mass and macronutrient capital between the double slash, single slash and slash burning treatments were analysed using a standard ANOVA procedure after performing an appropriate transformation on the dependent variables. Means and standard errors tabulated for these nutrient pools are the original (untransformed) data.

The impact of treatments on nutrient capital (removals from and additions to the system) were calculated as follows: (a) harvesting losses were calculated as the nutrient removal in stem wood as estimated from sample trees, (b) losses from slash burning were measured as the difference between the pre and post-burn slash, (c) slash addition was estimated as the difference between the double slash and regular slash load, while slash removal was taken as the same numerical value with a negative sign, and (d) additions through fertilization were scaled up from the actual quantity applied per tree. Planted eucalypt crops are commonly managed as coppice crops for two crop cycles following the original planted crop (usually referred to as “plant + 2” in southern Africa). Under this regime, the burning of slash will only take place every third harvesting cycle since coppice crops are not subjected to burning. Actual burning losses (measured after clearfelling the coppice stand) and theoretical losses under the “plant + 2” regime are presented.

### **4.3 RESULTS**

Basic soil properties are listed in Table 4.1. The mass of each of the nutrient pools and the macronutrient capital contained therein are presented in Table 4.2. The nutrient capital in components other than the soil and root pools has been altered considerably through the implementation of treatments. Nutrient capital after treatment implementation is listed in Table 4.3, with a summary of nutrient losses due to harvesting and slash burning. The estimated losses of nutrients due to harvesting and slash burning have been expressed as a percentage of the total of all components (i.e. plant available nutrients in soil + nutrients in biomass and forest floor) (Table 4.3).

Table 4.1. Selected soil properties recorded prior to trial establishment. Means are printed in bold and standard errors of the mean are shown in parentheses.

Depth (cm)	Bulk density (Mg m <sup>-3</sup> )	pH in KCl	pH in H <sub>2</sub> O	C		C:N	P (mg kg <sup>-1</sup> )	Exchangeable cations				Sum of Bases	Extr. Acidity	ECEC
				(g kg <sup>-1</sup> )	(g kg <sup>-1</sup> )			Ca	Mg	K	Na			
0-20	<b>0.97</b> (0.02)	<b>3.94</b> (0.03)	<b>4.33</b> (0.03)	<b>66.5</b> (1.3)	<b>3.2</b> (0.1)	<b>21.3</b> (0.6)	<b>2.75</b> (0.20)	<b>0.43</b> (0.04)	<b>0.64</b> (0.04)	<b>0.16</b> (0.01)	<b>0.23</b> (<0.01)	<b>1.46</b> (0.09)	<b>3.25</b> (0.09)	<b>4.71</b> (0.10)
20-40	<b>1.21</b> (0.02)	<b>4.23</b> (0.03)	<b>4.87</b> (0.04)	<b>42.3</b> (1.3)	<b>1.8</b> (0.1)	<b>23.7</b> (0.6)	<b>0.94</b> (0.09)	<b>0.33</b> (0.04)	<b>0.56</b> (0.03)	<b>0.11</b> (0.01)	<b>0.21</b> (0.01)	<b>1.20</b> (0.07)	<b>1.48</b> (0.21)	<b>2.68</b> (0.23)
40-60	<b>1.35</b> (0.04)	<b>4.40</b> (0.03)	<b>5.13</b> (0.03)	<b>23.5</b> (1.0)	<b>1.2</b> (<0.1)	<b>20.4</b> (0.8)	<b>0.34</b> (0.07)	<b>0.31</b> (0.03)	<b>0.55</b> (0.03)	<b>0.09</b> (0.01)	<b>0.21</b> (0.01)	<b>1.16</b> (0.05)	<b>0.81</b> (0.12)	<b>1.97</b> (0.12)

Table 4.2. Nutrients contained in various ecosystem components. Soil nutrient pools are estimates of plant-available nutrients (salt-exchangeable base cations, Bray-2 P and 2% of Kjeldahl soil N).

Component	Mass	N	P	K	Ca	Mg
	----- All values in kg ha <sup>-1</sup> -----					
Foliage	5266	91	5	31	44	15
Capsules	3278	26	3	26	22	7
Branches & stem tops	25707	63	5	66	77	29
Bark	9859	30	3	31	109	35
Stem wood #	90604	101	13	67	63	19
Stumps	15200	36	3	8	23	4
Roots	69500	199	16	76	158	29
Forest floor	69600	1045	28	105	530	121
A horizon (0-0.2 m)	1940 x 10 <sup>3</sup>	124*	5	120	167	151
B1 Horizon (0.2-0.4 m)	2420 x 10 <sup>3</sup>	87*	2	104	159	165
B2 Horizon (0.4-0.9 m)	6750 x 10 <sup>3</sup>	162*	3	241	416	455
<b>Totals</b>						
Total standing biomass	134714	311	27	220	315	105
Crown+bark+forest floor	113710	1255	43	258	782	208
Sum of soil horizons	11110 x 10 <sup>3</sup>	373*	10	466	742	771
Total all components	11399 x 10 <sup>3</sup>	1964	84	874	1768	1030

Notes:

# The stem wood has a mass of 90600 kg ha<sup>-1</sup> and a mean density of 509 kg m<sup>-3</sup>. If we calculate the utilizable volume from these numbers, we obtain an estimate of 178 m<sup>3</sup> ha<sup>-1</sup>. The estimate obtained for standing timber volume using the Shumacher and Hall equation yields a value of 162 m<sup>3</sup> ha<sup>-1</sup> which is 9% lower.

\* The readily plant-available N in the soil horizons has been estimated as 2% of the total organic N pool in each layer (see discussion).

Table 4.3. Effects of management operations on the nutrient capital in various pools of the system. Values in parentheses are standard errors of the means. Mean values for slash loads within the same column followed by the different letters are significantly different ( $p < 0.05$ ).

Treatment/operation	Mass	N	P	K	Ca	Mg
	----- All values in kg ha <sup>-1</sup> -----					
<b>Slash loads</b>						
Double slash	153 200 <sup>a</sup>	1378 <sup>a</sup>	67 <sup>a</sup>	275 <sup>a</sup>	1413 <sup>a</sup>	286 <sup>a</sup>
<i>Standard error (double slash)</i>	(7 038)	(150)	(5)	(26)	(152)	(15)
Regular slash	116 527 <sup>b</sup>	1044 <sup>b</sup>	53 <sup>a</sup>	193 <sup>b</sup>	823 <sup>b</sup>	201 <sup>b</sup>
<i>Standard error (regular slash)</i>	(7 262)	(46)	(3)	(13)	(42)	(6)
Burnt slash	31 415 <sup>c</sup>	604 <sup>c</sup>	27 <sup>b</sup>	96 <sup>c</sup>	747 <sup>b</sup>	151 <sup>c</sup>
<i>Standard error (burnt slash)</i>	(2 935)	(51)	(2)	(7)	(80)	(16)
<b>Management removals</b>						
Utilizable stem wood	90604	101	13	67	63	19
(as % of the available pool)	n.d.	5	15	8	4	2
Losses through slash burning	85112	440	26	97	76	50
Average effect of burning 1 in 3 cycles	28371	147	9	32	25	17
(as % of the available pool)	n.d.	7	10	4	1	2
<b>Management additions</b>						
Additional slash	36673	334	14	82	590	85
(% of total pool in system)	n.d.	17	17	9	33	8
Fertilization	151	17	33	0	1	2
(% of total pool in system)	n.d.	1	39	-	<1	<2

n.d. = not determined.

## 4.4 DISCUSSION

### 4.4.1 The soil and its readily available nutrient pools

The soil has formed under conditions of intensive weathering and leaching, which has resulted in a strongly acidic soil with low effective CEC at ambient pH (Table 4.1). The exchange complex is dominated by acid cations in the A and B1 horizons. The exchangeable Ca and K levels are low when compared to mean values of other shale-derived forestry soils in South Africa (ICFR, 1998). Interestingly, the exchangeable Mg levels in all soil layers are higher than that of Ca, and Na occupies a significant portion of the sum of base cations. Mineralogical analysis (data not shown) suggests that small quantities of illite-type clays exist in the profile, which could explain the comparatively high levels of Mg on the exchange complex. The soil is rich in organic matter throughout the profile (Table 4.1). The C:N ratio of 21 in the A horizon is moderately high when compared to values

between 10 and 13 that have been recorded in tropical soils by Bouillet *et al.* (1999), Gonçalves *et al.* (2000) and Hardiyanto *et al.* (2000), and values ranging from 15 to 25 obtained in warm-temperate areas of Australia (Adams and Attiwill, 1986; O'Connell *et al.*, 2000). A topsoil C:N ratio of 21 suggests a modest rate of N mineralization and very low rates of nitrification (Attiwill and Leeper, 1987). The low levels of extractable P (Bray-2) indicate that the quantity of readily plant-available P is small. The highly weathered clays on the eastern seaboard of South Africa generally have high P-fixing capacities (Bainbridge *et al.*, 1995).

The total soil nutrient pool constitutes a large reservoir of nutrients, but only a fraction can be considered to be readily available to plants. The total organic N pool contained in the soil is in excess of 16 t ha<sup>-1</sup> (du Toit and Scholes, 2002), however, a fair portion of that pool would be made up of relatively inert N compounds that do not effectively contribute to N nutrition (Attiwill and Leeper, 1987). A degree of uncertainty exists with respect to the fractions of total N that can be considered as potentially available to plants. Binkley and Hart (1989) showed that the methods used to estimate available N tend to emphasise specific components of the N pools in soils. However, due to the complexity of the different N pools, no single, accurate measure is available to assess the readily available N in soils. On a broad level, Fisher and Binkley (2000) estimated that one to three percent of the total N pools in soils are made available to plants per annum. We have estimated the short-term available N as 2% of the total soil N for the purposes of this study, accepting that it is a fairly coarse approximation. The Bray-2 solution could be considered a very mild extractant for soil P; thus the estimated available soil P pool of 10 kg ha<sup>-1</sup> could represent an underestimate of the actual plant-available P in the soil. The so-called "forest accessible P" fraction (i.e. the sum of repeated extractions with Bray-1 solution, after Stewart *et al.*, 1990) has been calculated for this soil as 83 kg ha<sup>-1</sup> (du Toit and Scholes, 2002). The soil store makes up the greatest pool of available Ca, Mg and K in the system. It also holds relatively large quantities of readily available N despite the fact that it is a small fraction of the total soil N pool.

#### **4.4.2 Biomass and nutrient pools in eucalypt plantation systems**

The nutrient capital contained in various components of the biomass in this study has been compared to data on *Eucalyptus grandis* stands and eucalypt hybrid coppice crops published by Birk and Turner (1992); Bradstock (1981); Herbert (1996); Negi and Sharma

(1985) and Tandon *et al.* (1988). The eucalypt plantation systems used for comparison varied in age from 5 to 12 years. The techniques used to estimate the biomass of components in the above-mentioned studies differed on minor points, such as the specific criteria to define utilizable wood and mass of the wood allocated to the categories: bole, stem tops and branches. Despite these small anomalies, general conclusions can still be drawn from the data. Above-ground biomass of the Karkloof study amounted to 135 t ha<sup>-1</sup>, while that of other short rotation systems ranged from approximately 52 to 196 t ha<sup>-1</sup>. As tree stands mature, the portion of above ground biomass held in the crown will decrease relative to that portion contained in the stem wood. For example, the percentage of biomass held in the tree crowns in stands studied by Bradstock (1981) decreased from 30% in a 5-year-old stand to around 10% in 11 and 12-year-old stands. The Karkloof stand had a large proportion of biomass within the crown, considering its age. This can be explained by the relatively high stand density (1461 stems ha<sup>-1</sup>) (du Toit *et al.*, 2000). The average tree size was still relatively small when the stand reached seven years of age (mean dbh was 13.4 cm). The utilizable wood fraction in small sized timber is usually less than that of larger sizes. Stem wood amounted to 91 t ha<sup>-1</sup> in the Karkloof study, with wood mass in the published studies ranging from approximately 30 to 147 t ha<sup>-1</sup>. These findings for *E. grandis* in the Karkloof study are similar to the idealised curves published by Judd (1996) for eucalypts in general. Nutrient losses through specific harvesting practices in the Karkloof study (such as stem wood or whole tree harvesting) would thus be comparable in magnitude to existing estimates of harvesting losses published by the authors referred to at the beginning of this section. The non-utilized fraction of the above-ground biomass (crown plus bark) constitute 68, 54, 70, 80 and 82 % of the above-ground nutrient contents of N, P, K, Ca and Mg, respectively. This emphasises the importance of harvesting only the utilisable wood to minimise nutrient losses. Nutrient contents in the crown plus bark fractions are similar to data published by Herbert (1996) for 7-year-old eucalypt stands in South Africa. However, the K, Ca and Mg content in the stem wood of this study is lower than that reported for fast-growing eucalypt species across five sites on the South African Highveld (Herbert, 1996). This is probably due to the higher mean base cation content in soils of the five sites used in the Highveld study (Herbert and Robertson, 1991; Herbert, 1996). The root and stump biomass measured in the Karkloof study amounted to 69.5 and 15.2 t ha<sup>-1</sup>, respectively, which sums to 84.7 t ha<sup>-1</sup> (Table 4.2). The large root and stump masses are due to the three coppice crops. Root mass data presented by Tandon *et al.* (1988) and Negi and Sharma (1985) ranged from 13.4 to 46.2 t ha<sup>-1</sup>, with the coppice crops having greater root masses than planted crops. The root biomass represents a large store of nutrients (especially N, P

and Ca) which will not be affected by harvesting and site management operations. This nutrient store is much larger than published accounts for similar crop systems in warm climates (Vogt *et al.*, 1997).

#### **4.4.3 Nutrient capital in the forest floor**

The mass of the forest floor in the Karkloof study site amounts to 69.6 t ha<sup>-1</sup>. The forest floor loading in tropical systems rarely exceed 20 t ha<sup>-1</sup>, while upper ranges listed for temperate systems sometimes exceed 100 t ha<sup>-1</sup> (O'Connell and Sankaran, 1997). The forest floor load in the Karkloof experiment is thus more closely aligned to the temperate forests than tropical forests, despite its latitude. The decomposition of organic matter in the forest floor is affected by several factors, of which moisture and temperature have large influences. O'Connell (1990) explained more than 90% of the variation in litter decomposition rate by relating it to temperature and moisture of the litter. Woods and Raison (1983) achieved similar results by using the time period above a moisture threshold and mean monthly temperature. The Karkloof study site has relatively low temperatures in winter, combined with a period of very low rainfall that stretches over approximately four to five months, on average (du Toit *et al.*, 2000). These conditions certainly contribute to the large build-up of mass in the forest floor. Large forest floor masses have also been recorded in pine plantations planted at high altitude sites in southern Africa (Schutz, *et al.*, 1983; Morris, 1986; Schutz, 1990). The forest floor contains large quantities of N, P and Ca relative to system totals in Table 4.2 (where total system nutrients are defined as nutrients in biomass plus forest floor plus readily available nutrients in the soil). Nitrogen, P, K, Ca and Mg in the forest floor constitute 53, 33, 12, 30 and 12 percent of system totals, respectively. These data illustrate the extent of the N, P and Ca lock-up in the forest floor that is effectively unavailable to the trees. A large portion of the locked-up nutrients can be made available to trees through acceleration of the decomposition process (e.g. through slash burning or operations that fragment and mix soil and slash either intentionally or as a side effect).

#### **4.4.4 Nutrient capital and site management effects**

Nutrient pools and litter mass in double, regular and burnt slash (Table 4.3) were all significantly different ( $p < 0.05$ ) barring two cases: the differences between P pools (double and regular slash treatments) and Ca pools (regular and slash burning treatments) were only weakly significant ( $p < 0.10$ ). However, when the impact of treatments is put into perspective

by expressing it as a fraction of the entire available pool defined earlier, it is considerably smaller in magnitude (Table 4.3). The slash removal and double slash treatments are important for inter-trial comparisons and were implemented to create a steep gradient in nutrient capital between treatments in the experiment, however, they do not represent regular operational conditions. This discussion will focus on the treatments that simulate commonly used management operations (burning, wood only harvesting and fertilization). Nutrient losses due to slash burning will depend strongly on the fire intensity and the resulting quantity of fuel consumed (Fisher and Binkley, 2000, Neary *et al.*, 1999). Fire intensity can be broadly classified by examining the degree of forest floor consumption by fire: high intensity fires will burn all above-ground litter, medium intensity fires will consume most of the undecomposed (L) and some of the humus (H) layer, whereas light intensity fires will scorch but not consume the H layer (de Ronde, 1990; Neary *et al.*, 1999). Judging by the degree of slash consumption, most slash burns implemented locally in short-rotation eucalypt crops would fall into the medium intensity class, which is broadly the same intensity of fire that was chosen for implementation in the Karkloof trial. The loss of nutrients in the medium intensity fire at the site is therefore deemed a fair estimate for controlled burning under favourable climatic and fuel moisture conditions. Uncontrolled wildfires, such as those described by van Wyk (1986), Scott and van Wyk (1990) and Leitch *et al.* (1983) or burning of large slash loads under unfavourable conditions (Morris, 1986) would obviously result in much larger nutrient losses. Burning losses in Table 4.3 have been estimated from the difference in nutrient contents in the forest floor immediately before and after the burning operation. Forest floor samples were collected 6 days before burning and ash samples 14 days after burning. Four rainfall events measuring more than 5 mm per day were recorded in the 14-day period from burning until ash sampling, and these totalled 31 + 7 + 6 + 7 mm. The trial site is located on level land, which contributed to the fact that erosion of ash after rainfall (surface wash) was confined to undetectable levels during the weeks following burning and re-establishment (field observations by technical staff). However, it is likely that some portion of the nutrients in the ash (notably the more mobile nutrients such as K) could have washed into the soil, in which case the calculated nutrient losses due to burning will represent an overestimate of the true losses. A fraction of the particulate losses of nutrients are also not likely to have been transported far away from the site, thus mitigating the measured impact of nutrient loss on the plantation scale. It is unlikely that nutrients and organic matter were lost from the mineral soil horizons as a result of this fire, since the H layer of the forest floor was not entirely consumed. This usually happens in high intensity fires, leading to additional nutrient losses from the mineral soil.

The loss of N through burning ( $440 \text{ kg ha}^{-1}$ ) constitutes 42% of the N pool in the regular slash load. Under similar fire conditions, N losses on sites with smaller forest floor layers are expected to be less. Values ranging from 200 to  $300 \text{ kg ha}^{-1}$  (38 to 61%) have been recorded in eucalypt stands managed for sawtimber (du Buisson, 2003), while 200 -  $350 \text{ kg N ha}^{-1}$  was lost through slash burning in short-rotation stands of *E. globulus* in Western Australia (Mendham *et al.*, 2003). Morris (1986) recorded a loss of  $1183 \text{ kg N ha}^{-1}$  (54% of the slash N pool) with a hot burn in Swaziland after clear felling a *Pinus patula* stand. This is expected since N loss has been shown to increase strongly with increases in fire intensity (Hough, 1981; Fisher and Binkley, 2000). The average burning loss of N per rotation in a “plant + 2” system was estimated to be in the order of  $150 \text{ kg N ha}^{-1}$  (Table 4.3), which is larger than the harvesting losses per rotation. The combined losses of N through harvesting and slash burning (ca.  $250 \text{ kg N ha}^{-1}$  per rotation) constitutes only one percent of the total N pool in this system. However, the combined impact on the plant-available pool (Table 4.3) constitutes a loss of approximately 13%. Despite the N loss being well buffered by the large soil N pool, the loss of N through slash burning and harvesting is not replaced by current fertilization practices. On the other hand, relatively high levels of atmospheric N deposition have been recorded in the region (van Wyk, 1990). An approximate input-output budget of the system has been constructed (Chapter 5) showing that the net N loss in a “plant + 2” regime including slash burning is in the order of  $20 \text{ kg ha}^{-1} \text{ a}^{-1}$ .

Approximately  $26 \text{ kg P ha}^{-1}$  was lost through burning in this study, which constitutes 49% of the P pool in slash (Table 4.3). Harwood and Jackson (1975) recorded a loss of  $10 \text{ kg P ha}^{-1}$  (18%) after a relatively cool burn in a mixed forest dominated by *Eucalyptus regnans*. It differed from our study in that more than 80% of the material on the site was woody debris (with low nutrient contents), the forest floor load was smaller ( $40 \text{ t ha}^{-1}$ ) and the burn was less intense (judging by the material remaining after fire). The available P pool in our system is much smaller than that of N and the macronutrient cations, as is the case in most eucalypt plantations (Herbert, 1996; Judd, 1996). The removal of 13 and  $9 \text{ kg P ha}^{-1}$  through harvesting and slash burning amounts to 15 and 10% of the estimated available P in the “plant + 2” system. The inherently low available P status of the highly weathered soils in the KZN Midlands region, coupled to the fairly substantial portion of P that is removed in harvesting and/or slash burning, appears to be the main reason for the consistent response to P fertilization recorded in other empirical fertilization experiments (summarised by Herbert, 1996) in the region over the last four decades. Despite the fact that harvesting and slash

burning losses of P make up substantial fractions of the available P pool in the system, the actual quantity of P lost through slash burning or harvesting is small, which means that it can be replaced relatively easily by fertilization. The inputs of P in the form of a “starter” fertilizer in this experiment ( $33 \text{ kg P ha}^{-1}$ ) would apply to planted crops but not to coppice crops. An average of  $11 \text{ kg P ha}^{-1}$  per cycle in a “plant + 2” regime would mitigate the estimated loss of  $21 \text{ kg P ha}^{-1}$  through burning and harvesting. Localised applications are used in all P fertilizing operations in the region, which means that P fixation is minimized. Even when some P fixation occurs, a substantial part of the P losses will be offset by fertilization.

Table 4.2 shows that a relatively large soil pool exists for K ( $466 \text{ kg ha}^{-1}$ ) and that a total of  $258 \text{ kg ha}^{-1}$  is held in the non-utilized pools (forest floor + tree crown + bark). In contrast to Ca and Mg, K is easily lost from the slash by leaching (Mackensen *et al.*, 1996). Over a period of approximately five months after clear felling, the K levels in the slash had decreased to  $193 \text{ kg ha}^{-1}$  (Table 4.3), which is less than the quantity estimated for K in the non-utilized biomass (Table 4.2). It is assumed that leaching of K from the non-decomposed slash is responsible for the bulk of this discrepancy. The bulk of the leached fraction is expected to end up in the soil pool and would thus not be lost from the system. Losses of K as a consequence of slash burning amounts to approximately  $97 \text{ kg ha}^{-1}$  (i.e. 38% of the K pool initially present in the slash - Table 4.2). The loss of K could have been overestimated because of leaching losses after the fire, as discussed earlier. In Harwood and Jackson’s (1975) study cited earlier,  $51 \text{ kg ha}^{-1}$  K was lost through burning. The average loss in the order of  $100 \text{ kg K ha}^{-1}$  per rotation in the “plant + 2” regime due to slash burning plus harvesting is reason for some concern. Recommended fertilizer mixtures on the bulk of the soils in the region contain either zero or low levels of K (Herbert, 1996; ICFR, 2000) since the application of K does not always yield economic growth responses. K release from non-exchangeable sources needs to be monitored to be able to gauge the severity of the threat posed by K removal in current management regimes.

The available pool of Ca in the soil amounts to  $742 \text{ kg ha}^{-1}$  (Table 4.2) while that of the conventional (single) slash load totals  $823 \text{ kg ha}^{-1}$  (Table 4.3). The Ca contained in the slash makes up a substantial fraction of the potentially available Ca in the system. The expression of Ca removals in harvesting as a fraction of only the soil-available Ca would overestimate the impact of Ca removal by a large margin for this site. Low intensity fires usually have a small impact on the Ca pools due to the stability of Ca at high temperatures (Fisher and Binkley, 2000). An estimated  $76 \text{ kg Ca ha}^{-1}$  was lost through slash burning, compared to 100

kg ha<sup>-1</sup> in the study of Harwood and Jackson (1975). It is clear from Table 4.3 that either harvesting of stem wood or slash burning had small impacts on the Ca pool in the “plant + 2” system, the combined mean loss per rotation due to harvesting and slash burning amounting to 89 kg ha<sup>-1</sup> per rotation. Removal of the bark (109 kg Ca ha<sup>-1</sup>) or partial removal of the harvesting residue through firewood collection would have a much greater impact on Ca in the system than the effect of wood harvesting alone (if these practices occurred). Although it is not very difficult to replace the Ca, this is not being done under the current fertilizer regimes where highly concentrated fertilizer sources (such as ammonium phosphates) are preferred in place of superphosphates or rock phosphates, both of which contain substantial amounts of Ca (e.g. Table 4.3). Applications of Ca in the form of lime (CaCO<sub>3</sub>) should be used with caution since excessive liming may raise the pH to undesirable levels and thus depress growth (Herbert, 1996). Applications of about 0.5 t ha<sup>-1</sup> of industrial gypsum (ca. 23% Ca) every rotation would theoretically offset Ca losses over that period without unfavourable effects on the soil reaction. This treatment still needs to be tested experimentally.

In the case of Mg, the highest proportion occurs in the soil-available pool with a total value of 771 kg ha<sup>-1</sup> out of a value of 1030 kg ha<sup>-1</sup> for the system (Table 4.2). In contrast to the high levels of Ca, the Mg pool in the slash following conventional harvesting contains only 201 kg ha<sup>-1</sup> (Table 4.3). The Mg lost through burning amounted to 50 kg ha<sup>-1</sup>, compared to a figure of 37 kg ha<sup>-1</sup> reported by Harwood and Jackson (1975). In the local “plant + 2” system, wood harvesting and slash burning remove 19 and 17 kg t ha<sup>-1</sup> per rotation, respectively, which is less than 2% of the system pool in each case. It follows that the Mg pool is well buffered against losses due to slash burning or harvesting by virtue of the large soil-available pool.

#### **4.5 CONCLUSIONS**

Threats to the nutritional sustainability of a plantation system can be comprehensively assessed if the magnitudes of the following processes are known: (a) net nutrient gains or losses from the system (e.g. Ranger and Turpault, 1999) (b) the size of the nutrient pools in the system (e.g. du Toit and Scholes, 2002; Fölster and Khanna, 1997) and (c) the impact of operations on short-term nutrient dynamics (Gonçalves *et al*, 1997). The results presented in this paper allows for a comparison of the system nutrient capital with some of the major nutrient inputs and outputs that are under direct control of the forest manager (harvesting,

slash burning and fertilization). The quantities of N, K, Ca and Mg removed through stem wood harvesting plus slash burning in a “plant + 2” regime range between 3 and 13% of the pool used to approximate “available nutrients in the system”. The corresponding figure for P is 25%, but the quantity is much smaller. Nutrient depletion (through commonly used harvesting and slash burning practices) does not pose an immediate threat to the nutritional sustainability of the system. However, it is important to acknowledge that nutrient losses do occur and that the losses incurred over several rotations will add up to a substantial amount over a time scale of centuries or more.

The replenishment of nutrients still needs to be addressed to ensure sustainable production in the long-term. Under current management practices, only P losses are partly offset by fertilization. Nitrogen losses are small when trees are debarked on site and slash is not burnt. In areas where substantial amounts of N have been lost (e.g. through repeated slash burning or through wildfires), N could potentially be replaced through biological N fixation. The use of crop rotation systems (even on a periodic basis) holds promise to offset N losses from the system. The very good growth of eucalypt crops on land previously planted to an N-fixing species such as *Acacia mearnsii* (Pennefather and MacGillivray, 1971; Schönau and Pennefather, 1975) demonstrates the potential of crop rotation systems. Research is needed to compare the losses of K to atmospheric inputs and the release of non-exchangeable sources, in order to formulate replenishment strategies. Although Ca losses are easy to replenish (and generally not very costly), this is not currently part of the management regime. An understanding of the long-term effect of management operations on nutrient losses from the system can be used (a) to modify current silvicultural management regimes, or (b) recommend nutritional supplements on a site-specific basis, so as to ensure high levels of forest productivity on a sustainable basis.

## CHAPTER 5

### 5 Nutritional Sustainability of *Eucalyptus* Plantations: a case study at Karkloof, South Africa <sup>2</sup>

#### 5.1 INTRODUCTION

Industrial forestry in southern Africa faces several challenges to remain viable in the long term. Three of the important challenges that are shared with other enterprises around the globe revolve around: (1) Achievement and/or maintenance of high levels of production and quality to remain economically competitive; (2) timber production on a basis that is demonstrably sustainable from an ecological perspective; and (3) socio-political equity and stability. The concept of promoting the economic, ecological and social aspects of sustainable forest management has been embraced by several industrial forestry concerns in southern Africa through the process of certification, to a point that South African forestry can be regarded as a world leader in forest certification (Edwards, 2000).

In order to manage plantation forests on an ecologically sustainable basis it is necessary to understand the effect of operations on the supply of resources that drive photosynthesis, and hence, growth. These drivers are incoming radiation, the carbon dioxide concentration of the atmosphere, temperature conditions as well as soil water and nutrient availability (Waring and Schlesinger, 1985). On a given site, little can be done to change ambient levels of radiation, carbon dioxide concentration or temperature (although the quantity of intercepted radiation may be manipulated indirectly, through changes in the availability of soil water and nutrients). However, soil water and nutrient availability can be manipulated through site management operations and this will impact on current forest productivity. Equally important, site management operations may also affect the long term capability of the site to supply water or nutrients. This process, the sustained supply of nutrients to forest trees is central to the concept of ecological sustainability and forms the basis of this chapter.

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<sup>2</sup> Published in Southern African Forestry Journal 195:63-72. One set of original numbers (forest floor nutrient contents) was miscalculated in the original paper (erroneously adjusted to ash-free mass) and some of the values for soil and biomass nutrient pools were adjusted slightly upon inclusion of additional sample points. Collectively, these adjustments resulted in small changes to subsequent calculations and tables, but these were small enough that they did not significantly alter the conclusions that had been drawn in the paper. The corrected values appear in this thesis.

The nutritional sustainability of plantation systems can be evaluated in several ways, most of which can be divided into two categories: (a) studies that deal with the short-term nutritional requirement of the crop as it matures (i.e. the required rate of nutrient supply for optimal and sustained crop growth (e.g. Fisher and Binkley, 2000 ; Fölster and Khanna, 1997) and (b) nutrient budgets that deal with the net balance of nutrient inputs to and outputs from a system, but ignoring the transformations within the system (Ranger and Turpault, 1999). Both approaches focus on valid mechanisms to evaluate the sustainability of systems.

Nutrients are stored in various pools in ecosystems, such as the standing biomass, the forest floor, the soil exchange complex and in soil minerals. Some of the pools constitute a source of nutrients that is readily available to plants (i.e. accessible over a time-scale of months) whereas other (potentially available) pools have nutrient reserves that could become available to plants over a time scale ranging from years to decades (Attiwill and Leeper, 1987). Nutrients locked in pools that turn over on a time scale of hundreds to thousands of years (e.g. the organic fraction referred to as “dauerhumus” by the above-mentioned authors) can be treated as effectively unavailable to plants. Nutrient fluxes occur between these pools (intra-system), and nutrient fluxes can also occur as gains and losses from the system as a whole (inter-system fluxes) (Fisher and Binkley, 2000). From an ecological sustainability perspective, there is a need to understand both inter-system and intra-system nutrient fluxes since the flux from both types may affect nutrient supply to trees. For example, large net losses of nutrients from a system will eventually deplete reserves, but immobilization of nutrients within a system pool can also render these nutrients unavailable for tree use. This paper focusses on the inter-system transfers, i.e. the net gain or loss of nutrients from an ecosystem.

Terrestrial ecosystems naturally lose nutrients over time, mainly to marine systems. In terms of geological time, terrestrial systems are replenished, for example, by the input of nutrient-rich rock from volcanic activity. While it is natural for terrestrial systems to lose nutrients, rate of loss and the size of the pools where nutrients are stored will determine the stability of a particular system. It can be informative to compare the net loss and transfer of nutrients in a system to evaluate the stability of that system over the long-term. This paper will present data from a eucalypt plantation case study examining the magnitude of nutrient loss from the system and the relative size of the nutrient pools. An existing index of sustainability will be evaluated and compared to a proposed new index, using principles of pools and fluxes as described above.

## **5.2 MATERIALS AND METHODS**

### **5.2.1 Nutrient capital in biomass, forest floor and soil pools before harvesting**

The nutrient capital was determined in four components of the plantation system: (1) Nutrients in the standing biomass, the below-ground biomass, and the forest floor were determined by conventional methods of destructive sampling, separation of different tissues, drying and chemical analysis of the nutrient concentrations. The detailed methodology has been described in section 4.2.1. (2) Soil samples were taken at three depths, corresponding to the soil horizons identified. At each of 20 sampling pits, four samples of each of the A , B1 and B2 horizon were collected and bulked for analysis, yielding 60 samples in total after bulking. The samples were air dried and ground to pass through a 2 mm sieve. Nutrient contents of the soil were divided into three pools on the basis of different extractions which gives an approximation of what is available to plants (Table 5.1). The pools are: (a) total nutrient pool, (b) pool that is potentially plant available in the long term, and (c) readily available pool. Nutrient transfer processes between readily available and potentially available pools are complex and fall beyond the scope of this Chapter.

### **5.2.2 Nutrient fluxes in the Karkloof system**

Nutrient losses that vary according to management and have the potential to be large (i.e. harvesting, firewood collection and slash burning) have been estimated from data collected at the Karkloof study site. All the fluxes were calculated for a 21 year eucalypt crop system (one planted crop followed by 2 coppice crops, each 7 years in duration) and expressed on an annual basis. A planted crop followed by two coppice crops is representative of management practices on the majority of eucalypt growing sites in the KZN Midlands. Little (unpublished) demonstrated that volume production in planted and first rotation coppice crops can be of similar magnitude provided that the stump survival and number of remaining shoots approximate that of the original crop. It is assumed that slash burning takes place only before re-planting and fertilizer is not applied to coppice crops, which is in line with current management practice. Harvesting losses were taken as the nutrient removal in stem wood. Losses with slash burning were taken as the difference between the pre- and post-burn slash load and nutrient contents. Fertilizer input was calculated from standard fertilizer recommendations developed by ICFR and widely implemented in hardwood forestry in KZN (ICFR, 2000; du Toit and Carlson, 2000). Atmospheric deposition data were obtained from

Cathedral Peak research catchment near the town of Winterton (van Wyk, 1990), approximately 100 km northwest of the study site<sup>3</sup>.

Table 5.1. Chemical extraction procedures used to determine fractions of nutrients in the soil that corresponds approximately to readily plant-available, potentially plant available and total nutrient pools.

Element	Procedure to estimate readily available pool	Procedure to estimate potentially available pool	Procedure for total pool
N	Anaerobic incubation <sup>1</sup>	N in particulate organic matter <sup>4</sup>	Kjeldahl <sup>8</sup>
P	Bray 2 method <sup>2</sup>	Forest accessible P <sup>5</sup>	XRF <sup>9</sup>
K	Exchangeable <sup>3</sup>	Nitric acid extraction <sup>6</sup>	XRF
Ca	Exchangeable	Mehlich extractant <sup>7</sup>	XRF
Mg	Exchangeable	Nitric acid extraction	XRF

- 1 Anaerobic incubation for 1 week at 40 °C (after Keeney, 1982)
- 2 10 minute extraction using 0.03 M NH<sub>4</sub>F & 0.05 M HCl in a soil: solution ratio of 1:30.
- 3 Extraction in 1 M ammonium acetate and determined with atomic absorption spectroscopy.
- 4 N content of particulate organic matter obtained through particle size fractionation (after Cambardella and Elliott, 1992)
- 5 Sum of 6 sequential extractions of 10 minutes each using Bray-1 extractant in a soil-solution ratio of 1:30 (Stewart *et al.*, 1990). P content determined colorimetrically (molybdenum blue).
- 6 Method for non-exchangeable K (Helmke and Sparks, 1996) used for elements Mg and K.
- 7 Extracted with 0.05 M HCl & 0.05 M H<sub>2</sub>SO<sub>4</sub> (Helmke and Sparks, 1996).
- 8 Kjeldahl total N determination (Bremner, 1996) pp 1103-1108.
- 9 XRF analysis. The basic XRF methodology is summarised by Karathanasis and Hajek (1996) while the specific procedure used in this study is described in Wilson (2002).

Several nutrient fluxes that are comparatively smaller in magnitude than most of the fluxes described above have not been monitored at the Karkloof study site. These fluxes were estimated from other study sites under similar land use, terrain and soils. Leaching losses were taken from volume-weighted nutrient contents in measurements of streamflow for a catchment at Cedara, which is 77% afforested with pines (Simpson, 1991) and which has

<sup>3</sup> In South Africa, electricity is generated mainly by coal burning power stations that are situated in the north-east of the country. The emissions from these power stations are rich in N compounds. The movement of air masses over the sub-continent gives rise to slightly elevated levels of atmospheric N deposition, even in rural areas that are not adjacent to point sources.

parent material and soils that are similar to the Karkloof trial site. Sediment yields (mass) collected in the study of Simpson (1991) were multiplied by the total nutrient content (Table 5.1) in the topsoil at the Karkloof trial site to estimate the quantities of nutrients lost through erosion. No published information on mineral weathering rates could be found for shale-derived soils in the area. The data from Owens and Watson (1979), derived from granitic catchments in Zimbabwe, was used to estimate weathering. Inputs through N fixation have not been taken into account since there are no symbiotic N fixers in the system, and the contribution of free-living N fixers are not likely make substantial inputs judging from reviews on the topic, e.g. Son (2001).

### **5.3 RESULTS AND DISCUSSION**

#### **5.3.1 Nutrient pools in system components**

The biomass components of the system (foliage, branches, stem and roots) have been described previously by du Toit (2003) and only a brief summary is given here: Both the above-ground biomass of the standing crop (134 t ha<sup>-1</sup>) and the nutrient losses through specific harvesting intensities were comparable in magnitude to existing estimates of *Eucalyptus grandis* stands and eucalypt hybrid coppice crops with rotation ages from 5 to 12 years (Birk and Turner, 1992; Bradstock, 1981; Herbert and Robertson, 1991; Herbert 1996; Negi and Sharma, 1985; and Tandon *et al.*, 1988). The standing crop differs from published results in that: (a) the crown biomass makes up a large portion of the total biomass, which is mainly attributable to high stem densities (1461 stems ha<sup>-1</sup>), (b) the root plus stump biomass contributes approximately 38% of the total biomass (du Toit, 2003), which has been attributed to repeated coppicing, and (c) the mass of the forest floor in the Karkloof study site is considerable (70 t ha<sup>-1</sup>), which is thought to be chiefly attributable to the cold and dry winters which would slow down the rate of decomposition (du Toit, 2003).

The soil nutrient pool constitutes a large reservoir of nutrients but only a fraction can be considered potentially plant available. Table 5.2 shows the nutrient pools contained in the various system components. Binkley and Hart (1989) regard anaerobic incubation techniques to be useful estimates to compare short-term N availability in soils. The quantity of N liberated through this technique over 7 days of incubation (and after subtracting the mineral N already present in the sample) were determined for the three major horizons at the Karkloof trial site. These have yielded values of 29.5, 20.6 and -2.2 µg g<sup>-1</sup> for horizons A,

B1 and B2, respectively. The small negative values obtained for the B<sub>2</sub> horizon indicates net short-term immobilization of N. The A and B1 horizon values equate to a readily available N pool of 105 kg ha<sup>-1</sup>, which constitutes approximately 1% of the total N contained in these horizons. This is much smaller than the tentative estimate of 2 % used before (du Toit, 2003 & Chapter 4). Fisher and Binkley (2000) report results where anaerobic extractions yielded 2.8% of the total N in the soil. A large portion of the soil N pool turns over so slowly that it plays a minor role in plant nutrient supply. Active soil carbon turns over within a one year timespan, slow (less labile) carbon at the 10 to 100 year scale and passive soil C (so-called “dauerhumus”) at the 1000 year time scale (Attwill and Leeper, 1979). The N contained in lighter fractions of organic matter (active plus slow carbon) can be estimated by several techniques (Binkley and Hart, 1989). In this study, the particulate organic matter fraction (Cambardella and Elliott, 1992) was sieved out and then subjected to total N determination to estimate the potentially available soil N pool. This pool amounted to approximately 5% of the total soil N. The potentially available N of soils on the Brazilian Cerrado has been estimated as 5 to 15 % of total soil N through repeated mineralization studies (Gonçalves *et al.* 2001). Our estimates of both the readily and potentially available N pools are conservative. More research is needed to develop or test rapid laboratory techniques whereby the (long term) potentially available soil N can be estimated. The total soil N pool (Table 5.2) is fairly large by most southern African standards, due to the high organic matter content in all horizons, specifically the topsoil. Neither the available nor the total pools of P are large (Table 5.2), mainly because of the shale parent material that has undergone considerable weathering. It is interesting to note that the estimate of potentially available soil P (obtained through sequential extractions) is considerably greater than the estimate of readily available P (obtained through single extraction). In the original methodology (Stewart *et al.*, 1990), the quantity of P extracted diminished with repeated extractions to reach a low asymptote by the fifth or sixth extraction for the particular soil used. In the current study, a clear asymptote was not reached after six extractions, suggesting that a fraction of the P potentially available to forest trees still remained undetected. The value reported in Table 5.2 is based on six sequential extractions as in the original methodology, which is probably a conservative estimate of the forest accessible P.

Potassium is known to exist in four distinct pools in soils: the soil solution, an exchangeable fraction, fixed K (also-called interlayer K), and a structural pool (Helmke and Sparks, 1996). The so-called interlayer K (potentially available pool) can make a substantial contribution to the long-term supply of K to crops (Brady and Weil, 1999). This scenario also holds true for

the Karkloof site (Table 5.2), where the readily available pool is the smallest but the potentially available pool is the largest of the base cation macronutrients. The total K pool in the soil is extremely large and this is probably due to the presence of micaceous material in the soil and shale parent material. The same applies to a lesser extent for Mg. Exchangeable fractions of Ca and Mg are similar, but the same cannot be said for their potentially available and total pools, with long term supplies of Ca being comparatively small.

Table 5.2. Nutrients contained in various components of the Karkloof system. The terms available, potential & total refer to different nutrient pools in the soil as defined in Table 5.1.

System component	Nutrient pools (all values in kg ha <sup>-1</sup> )				
	N	P	K	Ca	Mg
Biomass (a)	546	46	304	496	138
Forest floor (b)	1 045	28	105	530	121
Readily available soil nutrients (c)	105	10	466	742	771
Potentially available soil nutrients (d)	782	83	2 466	862	1 130
Total soil nutrients (e)	18 664	4 710	326 350	2 920	50 150
System potential (a+b+d)	2 373	157	2 875	1 888	1 389
System total (a+b+e)	17 881	4 784	326 759	3 946	50 409

### 5.3.2 Nutrient fluxes

There are four major pathways through which nutrient inputs are made to terrestrial ecosystems (atmospheric deposition, mineral weathering, nitrogen fixation and anthropogenic inputs, e.g. fertilization). Lateral fluxes (such as colluvial movement and lateral drainage), as well as the fluxes attributable to the movement of fauna are of secondary importance in most ecosystems (Ranger and Turpault, 1999). The four potentially major pathways of nutrient loss are biomass removal, burning, erosion and nutrient leaching beyond the rooting zone. Immobilization of biomass in the forest floor will also remove nutrients from the plant-available pool in the soil, but strictly speaking, it does not constitute a loss from the system as a whole (Ranger and Turpault, 1999).

The flux rates for mineral weathering, non-symbiotic N fixation, leaching and atmospheric deposition in the Karkloof system are all estimates from other (comparative) systems and therefore, the data in Table 5.3 are presented as an **approximate** input/output budget. Furthermore, all fluxes used in calculations have been applied to nutrient movements at the forest compartment scale. However, some of the source data (e.g. erosion and leaching)

originated from studies at a catchment scale. There is potential to increase the accuracy of the input-output budget (in terms of additional measurements at the site and in terms of more appropriate scales of measurements) since the Karkloof experiment is a long-term trial. Atmospheric inputs make up between 82 and 95% of the total inputs of N, K, Ca and Mg in Table 5.3, which underscores the importance of having reliable estimates for this flux. The relatively small magnitude of the weathering and leaching fluxes for most nutrients mean that the full budget is unlikely to be affected materially in the case of an over- or underestimate for these processes. Exceptions to this statement are the leaching losses of Ca and Mg.

Many of the potentially large fluxes are highly dependent on land management operations and – regimes and changes in these will impact on nutritional sustainability. This implies that the input-output budget should be evaluated for specific management scenarios in order to be meaningful. All fluxes listed in Table 5.3 reflect operations at fairly representative intensities. High intensity disturbances (such as wildfires, for example) will have a much greater impact on the system. The net fluxes of nutrients in the Karkloof system has been estimated for 3 commonly used operations regarding harvesting residue (Table 5.4). Guthrie *et al.*, (1978) lists several input-output budgets from forests in North America and Australasia. Compared to these, base cation losses estimated for the more intensive management options in the Karkloof system (Table 5.4) are relatively minor. Table 5.4 shows that under conservative management operations (option X), N, P and Ca experience net gains while losses of Mg are small. This picture changes for specific nutrients when changes are made to the management regime.

Table 5.3. Approximate nutrient input-output budget for the Karkloof system.

Process	Site	Nutrient flux (kg ha <sup>-1</sup> year <sup>-1</sup> )					Reference
		N	P	K	Ca	Mg	
Weathering	Mean of 2 granitic catchments, Zimbabwe	0.0	n.d. 0.2	1.9	1.7	0.3	Owens and Watson (1979) Fey, cited in Scholes & Scholes (1999)
Atmospheric deposition	KwaZulu-Natal, SA (Rural)	15.2	1.0	8.6	20.7	4.5	van Wyk (1990)
N fixation	From non-symbiotic (free-living) organisms	?	0.0	0.0	0.0	0.0	---
Fertilization	Recommended application for SA eucalypts on humus-rich clays (coppice crops not fertilized)	0.9	1.0	0.0	<0.1	0.1	ICFR (2000)
Leaching	Pine plantation on shale, Cedara, KZN	1.0	0.1	2.3	8.0	7.3	Simpson (1991)
Erosion	Sediment yield: Cedara pine catchment, KZN Nutrient content: Karkloof, KZN	0.2	<0.1	0.5	<0.1	0.2	Calculated from Simpson (1991) for sediment yield and this paper (nutrient concentration)
Harvesting	7 year-old <i>E. grandis</i> , Karkloof, SA	14.4	1.9	9.6	9.0	2.7	du Toit (2003)
Other biomass removals	Firewood collection (75% of branch mass), Karkloof, SA	6.8	0.5	7.1	8.3	3.1	du Toit (2003)
Slash burning	Medium intensity fire, Karkloof, SA	21.0	1.3	4.6	3.6	2.4	du Toit (2003)

Table 5.4. Net nutrient fluxes estimated for the Karkloof eucalypt plantation system under three representative management regimes. The total cycle (planted crop followed by two coppice crops) is set at 21 years in duration for the calculations.

Management regime *	Nutrient flux (kg ha <sup>-1</sup> a <sup>-1</sup> )				
	N	P	K	Ca	Mg
Planted crop + double coppice, no burning (X)	0.4	0.2	-1.9	5.5	-5.3
Planted crop + double coppice & firewood collection after clear felling (Y)	-6.3	-0.4	-9.0	-2.7	-8.4
Planted crop + double coppice, slash burnt (Z)	-20.6	-1.1	-6.5	1.9	-7.8

\* It is difficult to obtain accurate statistics on the implementation of management regimes, but it appears that roughly equal proportions of sites in the KZN Midlands are managed according to options X and Z. Option Y does not have reliable estimates as it is highly specific to individual contractors operating on specific plantations within regions.

Firewood collection removes sizeable quantities of N, K and Ca (Table 5.3). The net result for option Y is moderately small losses of N, K and Mg (Table 5.4). Slash burning impacts most heavily on the N budget (Table 5.3). This results in fairly large losses of N and moderately small losses of K and Mg when option Z is implemented.

The net loss of N in option Z could potentially be replaced by additional fertilization but this will increase silvicultural cost margins. The net loss in P is more than an order of magnitude smaller than that of N for management scenario's Y and Z, which is in step with the approximate relative size of the biologically active portion of the two elemental pools. The P losses can easily be replaced by fertilization at minimal cost since they are very small. The lack of response in P output from the system with burning has been noted by other authors. For example, Van Wyk (1985) found little change in P output in streamwater following a wildfire in a *P. patula* stand while the corresponding N outputs increased with 2 orders of magnitude.

Table 5.4 shows a net loss of K and Mg for all management regimes listed but a net gain for Ca in options X and Z. A general trend, indirectly indicating a net loss of base cations has been inferred from paired sample plot studies (grassland and eucalypt plantations) collected by du Toit (1993) and Musto (1992) in KwaZulu-Natal. These studies showed a reduction in exchangeable Ca, Mg and K for soils under plantation forestry (pine, eucalypt and wattle) when compared to adjacent natural grassland. These studies suggest that the net gain reported for Ca in this study (chiefly due to high estimates for atmospheric inputs in Table 5.3) may be an overestimate. Despite the measurable effect of base cation

stripping, Ca and Mg can be replaced without incurring excessive cost (based on current prices of gypsum and agricultural liming materials). Replacement of K will be somewhat more costly.

### **5.3.3 Nutritional sustainability of plantation systems and its estimation**

The resilience of a system will depend to a large degree on the net flux in relation to the size of the bio-available pool. Where pool sizes are large, the system will be more buffered against short-term nutrient losses. Furthermore, many fluxes are variable in time and space and also vary with respect to management intensity. With small nutrient pools, the variability in fluxes will cause large variations in system stability estimates between (and even within) management units. In contrast, a relatively large nutrient pool will mean that variation in the net flux of nutrients will have a less pronounced impact on the stability of the system as a whole, resulting in easier management.

Several authors have compared the nutrient export from study sites with available soil reserves. A summary of these studies has been presented by Fölster and Khanna (1997), who proposed a simple Plantation Stability Index (PSI), where  $PSI_{(\text{stem wood})} = (\text{Nutrients in stem wood}) / (\text{nutrients in soil})$ . They point out that the soil nutrient pool estimates should be standardised for this measure to be useful in comparing system stability across sites. They proposed that nutrient quantities be calculated for a soil depth of 1 m and that standard extraction procedures be used. However, the aforementioned authors concede that methods to analyse nutrient fractions are comparable for some nutrients (e.g. exchangeable bases) but differ widely for others (available P). The PSI is a useful first approximation and can easily be applied to a wide range of conditions because of its simple data requirements. However, with respect to nutrient removal, it only takes harvesting into account, and there is limited scope to accommodate the intensity of harvesting operations. The data in Table 5.4 showed that the net nutrient flux is strongly influenced by the management regime. The importance of understanding the effects of operations with differing intensities had also been discussed. For these reasons, a new index of nutritional sustainability is proposed, using the ratio of (net nutrient loss) : (nutrient pool). The values obtained for the above-mentioned ratios may be very small for certain ecosystems. The proposed Index of Nutritional Sustainability (INS) is therefore expressed as the negative logarithm of the above-mentioned ratio, and hence, is abbreviated as  $p(\text{INS})$ , as shown here:

$$p(\text{INS}) = -\log_{10} \left( \frac{\text{Net annual nutrient loss}}{\text{Nutrient pool}} \right)$$

Where:

(a) The net annual nutrient loss from the system is determined by the input-output budget for management systems and intensities currently in use, and

(b) An appropriate nutrient pool is chosen: The readily available soil pool (Table 5.2) will yield an index of short-term nutritional sustainability [denoted  $p(\text{INS})_{\text{RA}}$ ], while an index of long-term nutritional sustainability [denoted  $p(\text{INS})_{\text{POT}}$ ] will be obtained by using the potentially available system pool described in Table 5.2.

(c) NOTE: Since publication of this index, feedback was received by the senior author commenting on the usefulness of presenting the index on a log scale. The author concedes that a simple ratio will suffice and that the log scale could be omitted.

In cases where a net nutrient flux is positive, i.e. the system is gaining in that element, the  $p(\text{INS})$  value cannot be calculated and is simply reported as a net nutrient gain. The system is thus sustainable for the specific management regime and operational intensities tested. A  $p(\text{INS})$  value of 1, 2 and 3, respectively, indicates that the net nutrient loss, is 10, 100 or 1000-fold smaller than the nutrient pool used in the calculation. What would be a reasonable norm to evaluate the  $p(\text{INS})$  values obtained? Any system where the net annual nutrient loss under the existing management regime exceeds 10% of the readily available nutrient pool should raise some concern. A minimum  $p(\text{INS})_{\text{RA}}$  value of 1 is therefore tentatively proposed as a norm to evaluate system stability in the short term. The index based on readily available nutrients cannot be linked to a potential lifespan of the system as the readily available pools are constantly replenished by potentially available pools, the dynamics of which are complex.

Since the net nutrient flux rate is expressed per annum, the  $p(\text{INS})_{\text{POT}}$  value would be a **theoretical** estimate of the number of years it will take to deplete a chosen long-term pool (when expressed as a power of base 10). This estimate should not be made for short-term pools as they are continually being replenished from the long-term pools at rates that may be different to the rates of depletion, and hence, any such calculation would be misleading. With respect to long term evaluations, systems where the net nutrient loss will not erode the potentially available nutrient pool within a century could arguably be regarded as nutritionally sustainable. In such a scenario, there would be ample time to re-assess nutrient pools (say) 50 years hence to verify original theoretical estimates, and secondly, there would be ample time to take ameliorative action or change the management regime if necessary. A  $p(\text{INS})_{\text{POT}}$  value of 2 is therefore proposed as a norm for evaluating long-term nutritional sustainability. Both  $p(\text{INS})_{\text{RA}}$  and  $p(\text{INS})_{\text{POT}}$  norms are proposed as early warning

systems, i.e. systems with lower values could even remain highly productive in the foreseeable future. However, values below the norms will indicate that either current management regimes or operational intensities (or both) may need to be adjusted to ensure sustained productivity. It should be stressed that the soil nutrient pools (RA and POT) in the index constitute coarse estimates of nutrient availability, and could be subjected to large errors in estimation. The pINS index should thus be used primarily as an early warning system, rather than a definite statement of the level of nutritional sustainability. Two indices of sustainability (PSI and the new p(INS)) have been calculated for short rotation eucalypt systems where data sets were easily obtainable (Table 5.5): The Congolese site is located on sandy soils on an extremely infertile coastal plain (Bouillet *et al.*, 1999) while the Brazilian site is representative of a large body of light to medium-textured forest soils on the Brazilian Cerrado with moderately low fertility (Gonçalves *et al.* 1999).

Table 5.5. Plantation stability indices and indices of nutritional sustainability for the Karkloof case study and selected sites in a CIFOR<sup>4</sup> experimental network. The negative logarithm of the Index of Nutritional Sustainability [p(INS)] is calculated from the ratio of net nutrient losses to nutrient pools where pools can be (a) readily available soil pools (RA), or (b) potentially available system pools (POT), as described in Table 5.2.

<b>Plantation Stability Indices (Fölster &amp; Khanna, 1997)</b>	N	P	K	Ca	Mg
PSI <sub>(stem wood)</sub> Karkloof System <sup>A</sup>	n.d.	0.62	0.17	0.10	0.03
PSI <sub>(stem wood)</sub> Itatinga, Brazil <sup>B</sup>	n.d.	0.69	0.88	0.24	0.21
PSI <sub>(stem wood)</sub> Kondi, Congo <sup>C</sup>	n.d.	n.d.	0.83	0.49	0.44
<b>Proposed short term index of nutritional sustainability : p(INS)<sub>RA</sub></b>					
p(INS) <sub>RA</sub> Karkloof, SA <sup>A</sup>	1.22	1.42	1.72	2.43	1.96
p(INS) <sub>RA</sub> Kondi, Congo <sup>D</sup>	n.d.	n.d.	Gain <sup>E</sup>	Gain <sup>E</sup>	2.88
<b>Proposed long term index of nutritional sustainability : p(INS)<sub>POT</sub></b>					
p(INS) <sub>POT</sub> Karkloof, SA <sup>A</sup>	2.57	2.61	2.51	2.84	2.22

n.d = not determined

<sup>4</sup> The experimental network entitled "Site Management and Productivity in Tropical Plantation Forests" is conducted by several research partners in tropical and semi-tropical locations under the umbrella of CIFOR (Centre for International Forestry Research, Bogor, Indonesia).

- A = Karkloof system under management regime Y (refer Table 5.4);
- B = Calculated from Gonçalves *et al.*(1999);
- C = Calculated from Bouillet *et al.* (1999): management roughly similar to regime Y (Table 5.4)
- D = Calculated from Laclau (2001) and Bouillet *et al.* (1999);
- E = Net budget showed nutrient gain (system stable), pINS thus not calculated.

The PSI values listed in the top half of Table 5.5 expresses the harvesting losses (stem wood only) of each base cation as a fraction of the exchangeable pool for that nutrient, calculated to 1 m soil depth. Losses of K equivalent to approximately 83 - 88% of the exchangeable K pools are recorded in a single harvest at Kondi and Itatinga. The percentage losses for the Karkloof site are much lower (i.e the system is more stable) than that of the other short-rotation eucalypt systems listed in Table 5.5. The difference is particularly striking with respect to K, and to a lesser extent, Mg and Ca. This can be ascribed to a large reservoir of exchangeable base cations in the subsoil at Karkloof.

The middle section of Table 5.5 lists short-term indices of nutritional sustainability for two sites with available data on roughly similar management regimes. Under moderately intensive management practices (short rotation harvesting + firewood collection but no slash burning), the values for the index  $p(INS)_{RA}$  in the Karkloof system lies in the range of approximately 1.2 to 2.4. These data show that the net losses under current management constitute fairly small fractions of the readily available nutrient pools, indicating a very stable short-term scenario. This finding is in step with the low PSI value (indicating a stable system), for the three macronutrient cations, as described above. However, the two indices of plantation sustainability (PSI and pINS) yield markedly different results for the Congolese study site. The PSI values suggests severe base cation losses (especially for K), whereas, in fact, the net flux shows that the system experiences a net gain in K and Ca, and small net losses of Mg (Table 5.5; Laclau, 2001). This system is particularly unstable for the element N, which has a net loss of  $23.7 \text{ kg ha}^{-1} \text{ a}^{-1}$  (Laclau, 2001) and a small readily available soil N pool, judging by *in situ* N-mineralization studies (UR2PI, 2001). The critically low supply of readily available N in the Congolese system is supported by evidence of significant responses to added nitrogen in Congolese fertilizer trials on similar site types (UR2PI, 2001). Modifications to the management regime that will impact on the net nutrient flux (e.g. the inclusion of slash burning) will have a dramatic impact on the  $p(INS)_{RA}$  values at Kondi due to the small pool sizes for all nutrients. It is advisable to evaluate net fluxes rigorously, and to test a range of management scenarios when evaluating the sustainability of sites with small nutrient pools, such as Kondi. It follows that

the pINS approach, although it has more intensive data requirements, is deemed more suitable than the existing PSI method to evaluate nutritional sustainability. One of the important reasons for the difference is the fact that net fluxes differ substantially from harvest losses alone. For example, P losses in harvesting (Karkloof system) is largely offset by fertilization and atmospheric inputs (Table 5.3) while, on the other hand, net Mg losses are much greater than harvesting exports, mainly due to leaching (Table 5.3).

Evaluation of the long-term sustainability of a system can be done by inspecting  $p(INS)_{POT}$  values (Table 5.5, bottom). The  $p(INS)_{POT}$  values for the Karkloof system using management scenario Y (refer Table 5.4), varies between 2.2 (Mg) and 2.8 (Ca). The high values for  $p(INS)_{POT}$  is indicative of a well buffered and stable system in the long term. Net losses for all nutrients are small and potentially available nutrient pools are large. The weakest link in the system (Mg) is theoretically sustainable for at least 200 years if the management regime is maintained (i.e. no ameliorative action).

The pINS system can also be used to evaluate changes in the management regime. When slash burning is practised (scenario Z, Table 5.4), the  $p(INS)$  values for N and P are most strongly affected: The  $p(INS)_{RA}$  values for N and P decrease to levels of 0.7 and 1.0, respectively, while the  $p(INS)_{POT}$  indices for N and P both drop to approximately 2.1. All indices remain above the proposed critical threshold values, except the  $p(INS)_{RA}$  value for N.

The concept of  $p(INS)$  which has been developed in this study has application for a wider range of conditions with respect to sustainable forest management since many of the input parameters are available or can be determined relatively easily. The concept has the following advantages: (a) It uses net nutrient fluxes, (b) it can be adapted for short- and long-term nutrient supply by using readily available or potentially available nutrient pools, (c) it takes account of actual, representative intensities of all operations, and (d) it can be used to construct scenarios with different management regimes and operational intensities. The fact that it has more intensive data requirements is not insurmountable since: (a) soil pools can be estimated with fairly elementary analytical techniques in routine laboratories, (b) nutrient fluxes for many of those factors that are usually large (e.g. harvesting and burning losses) can be obtained from existing or past experiments while many countries support atmospheric deposition monitoring networks, and (c) processes that have small fluxes which are difficult to measure do not make a large impact on the index and can be approximated from other systems in similar environments.

## 5.4 CONCLUSIONS

Standing biomass of the crop in the Karkloof case study is comparable to other warm temperate and tropical systems. It follows that nutrient losses in harvesting would be comparable if similar volumes of wood are harvested. Soil, below ground biomass and forest floor pools are all greater than that listed for comparable systems in the tropics and in warm temperate zones. Specific chemical extractions were proposed to estimate the size of readily and potentially available nutrient pools of systems. Net nutrient fluxes estimated for the Karkloof system showed that nutrient loss is highly dependent on management. The fluxes for P were small in magnitude relative to other macronutrients for all regimes tested. N, P and Ca showed the greatest variability in net fluxes when the management regime is changed.

Indices that compare the net balance of nutrient fluxes with readily available and potentially available system nutrient pools have been developed. These indices of nutritional sustainability (dubbed p(INS)) are more rigorous than conventional indices since they take the intensity of management practices into account, along with all other fluxes. This set of indices evaluates both the short-term and long-term potential of the system to be nutritionally sustainable under given management regimes and intensities. However, the indices have intensive input data requirements.

The  $p(INS)_{RA}$  and  $p(INS)_{POT}$  values indicate the Karkloof system to be stable compared to other studies on short-rotation eucalypt crops under moderately intensive management regimes. The p(INS) index was used to evaluate the nutritional impact of more intensive management regimes. The system was found to be fairly resilient with respect to most macronutrients, even with increased nutrient losses due to slash burning. However, the index suggested that N losses may need to be replenished with additional inputs to ensure sustainability if slash burning is implemented.

## CHAPTER 6

### 6 Effect of site management on leaf area, biomass development and stand growth efficiency of a young stand of *Eucalyptus grandis* in South Africa <sup>5</sup>

#### 6.1 INTRODUCTION

The fact that intensive site management operations during the inter-rotational period affects the availability of growth resources to tree stands have been shown through literature studies (Chapter 2) and original data for the Karkloof experimental site (Chapters 4 and 5). This chapter deals specifically with the response mechanism of a stand of trees to such changes in growth resource availability.

Operations that increase the availability of water and nutrients in forest stands have the potential to increase wood production. The mechanism for this response is the stand's ability to capture incoming radiation and the efficiency by which this energy is used to convert CO<sub>2</sub> into woody biomass (WB) (Linder 1985; Linder 1987; Landsberg and Hingston 1996; Ericsson *et al.* 1992, Binkley *et al.* 2004). In practical terms, we hypothesised that the response can manifest as (a) an increased leaf area, or (b) an increased stand growth efficiency (*i.e.* above-ground WB production per unit of leaf area) (Waring 1983). This chapter explores the nature of the relationship between leaf area, above-ground WB and coarse roots with changing levels of available soil water and nutrients (brought about by site management treatments), and subsequently reflects on the implications of these effects for the management of commercial forests.

#### 6.2 EXPERIMENTAL DESIGN AND TREATMENTS

The design and layout of the experimental program has been described in Chapter 3. All treatments were kept weed free until canopy closure.

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<sup>5</sup> Published in Canadian Journal of Forestry Research 35(4):891-900. (The contribution of the second author to this paper centered around the measurement of leaf area index and soil moisture as well as the analysis of these data sets).

### 6.3 MATERIALS AND METHODS

Climatic data were collected using an automatic weather station (AWS). The reference evapotranspiration from a short grass surface was calculated using the Penman-Monteith equation (Monteith 1965). Soil water retention characteristics were determined at matric potentials ranging between saturation and wilting point. We used a tension table apparatus (Smith and Thomasson 1974) for high matric potentials and a pressure plate apparatus (Klute 1986) for matric potentials from -100 to -1500 kPa. Soil water content in the field experiment was measured with time domain reflectrometry (TDR) sensors (model CS615; Campbell Scientific Africa, Stellenbosch, South Africa), placed at 15 cm depth. Four sensors were used per treatment (two per plot in replications 1 and 3). Permanent wilting point in this soil was estimated from the soil retention curve as 25.2% volumetric soil water content. This level was used to normalise the readings from all TDR sensors in the first dry winter period (the soil water was drawn down to near wilting point and remained at that level for more than 30 days across all treatments). Small differences between treatments were recorded in soil water content during the first growing season (Appendix 2). However, for the bulk of the remaining observation period, soil water levels were remarkably similar between treatments at a given point in time, and hence, mean values across treatments are presented.

The development of woody tissues and other biomass components over time was determined by destructive harvesting of  $20 \pm 3$  trees at 0.3, 0.5, 0.8, 1.0, 1.8 and 3.0 years after planting (YAP). An additional sample of 12 trees was harvested at 3.5 YAP. Fresh wet mass of the foliar and woody components were determined separately for destructive samples in field. Sub-samples were oven dried to constant mass at 65 °C in preparation for nutrient analysis and were weighed to convert fresh sample mass to oven dry mass. The term woody biomass (WB) is used throughout this chapter to refer to above-ground woody biomass. Coarse root samples (diameter > 2 mm) were collected from the 20 sample trees at 3.0 YAP. The area occupied by each sample tree (2.44 \* 2.44 m) was divided in four quadrats. The soil in one such quadrat was excavated in layers to a depth of 60 cm and sieved to obtain the coarse roots (Q). The taproot (TR) was excavated separately to the same depth. The coarse root mass associated with the tree was estimated as  $4Q + TR$ , and was reported on an ash-free basis to eliminate potential errors arising from soil contamination. Coarse root mass and WB of destructive sample trees were regressed against diameter at breast height (dbh) and total tree height, and the models explaining the

largest portion of the variation were used to estimate individual tree WB. Individual tree estimates were summed per plot and scaled up to a hectare basis.

Sub-samples from the four bulk foliar samples per treatment were analysed for nutrient concentration according to the methods described by Kalra and Maynard (1991). The dried material was ground, dry ashed and dissolved in 0.6 M HCl, filtered and diluted to an appropriate level with de-ionised water. Concentrations of calcium and magnesium were determined by atomic absorption spectroscopy while flame emission spectroscopy was used for potassium (K). The concentration of phosphorus was determined spectrophotometrically (molybdenum blue method). The concentration of N was determined by the Kjeldahl procedure with selenium as a catalyst (Nicholson 1984). Nutrient accretion into the foliar and woody tissues was calculated as the product of the nutrient concentration (mean of four sample trees per treatment) and the dry mass of that component per plot. Nutrient accretion in the above-ground WB is the sum of foliar and woody components at each age, and periodic values were obtained by difference.

The specific leaf area was determined by scanning sub-samples of leaves with a Li-Cor™ 3200 area meter (Li-COR Inc., Lincoln, Nebraska) before oven drying. The leaf area indices (LAI's) for the treatments were determined using two different techniques during stand development. From planting up to 1.3 years of age, the leaf area of individual trees (destructive samples) was regressed against tree height (tree height and canopy length were virtually identical during this period, as the canopy had not started to lift from below). The regressed leaf areas of individual trees per plot were summed and divided by the ground area to determine LAI.

After canopy closure (1.8 to 3.5 YAP), plant area index was estimated with optical methods using two Li-Cor™ plant canopy analysers in remote mode. All measurements were taken on windless days, under uniform sky conditions, and with the sun at a low angle (Li-Cor 1992). The relationship between plant area index and LAI varied with age. Relationships appropriate to the stand age class (developed from Dovey and du Toit 2005) were used to convert LAI from plant area index readings at different intervals between 1.8 and 3.5 years of age.

For this chapter, the stand growth efficiency (GE) is defined as the periodic increase in above-ground WB ( $\text{t ha}^{-1} \text{a}^{-1}$ ) per unit leaf area (after Brix 1983; Waring 1983; Albaugh *et al.* 1998; Jokela and Martin 2000). Leaf area index rather than leaf mass was chosen as

the indicator of the photosynthetic capacity of the stand, since it is related to absorbed photosynthetically active radiation (Linder 1985; Landsberg and Hingston 1996) and since specific leaf area is not constant in developing stands (Linder 1985; Sands *et al.* 1992; Cromer *et al.* 1993a and 1993b; Osório *et al.* 1998; Job *et al.* 2003). Measurement periods were of unequal length, making it necessary to express GE on an annual basis. Since leaf area was increasing, the average value of LAI over the observation period was used. Levels of GE were depicted on graphs at the midpoint of each observation period.

Data for nutrient accretion, LAI, WB and GE were analysed with a standard one-way analysis of variance (ANOVA) procedure using Genstat® for Windows™ (Lane and Payne 1996). We made sure that the basic assumptions of ANOVA were not violated, by following the guidelines described by McConway *et al.* (1999).

## 6.4 RESULTS

The mass of slash on the site after harvesting amounted to 116.5 t ha<sup>-1</sup> on average, of which approximately 40% (by mass) was from the harvesting residue and 60% from the forest floor. This large build-up of material on the forest floor has been ascribed to a combination of dry and cold conditions during winter (du Toit, 2003). The oven-dry mass and nutrient content for slash management treatments are shown in Table 6.1. Slash burning markedly reduced the quantities of N, P and K in the remaining ash, but the total amounts of Ca and Mg were affected to a lesser degree. Slash removal strongly reduced levels of all elements, especially Ca.

Table 6.1. Mean values for slash dry mass and nutrient content after implementing three slash management options that formed part of treatments (adapted from du Toit, 2003).

Treatment	Dry mass	N	P	K	Ca	Mg
		----- All values in kg ha <sup>-1</sup> -----				
1S (Regular slash)	116527	1044	53	193	823	201
0S (Slash removal)	79854	710	39	111	233	116
SB (Slash burning)	31415	604	27	96	747	151

Note: Treatments 1S, SD, and SF had regular slash loads, similar to treatment 1S.

Foliar nutrient concentrations and nutrient accretion in WB (Table 6.2) were monitored to reflect differences in plant-available nutrients between treatments. Nutrient accretion in treatment 0S was significantly lower than the control (1S) for virtually all elements across

all monitoring periods as shown in Table 6.2. On the other extreme, the uptake of N and P in the fertilization treatment remained significantly superior to that in the control for the entire first year. Nutrient accretion in treatments 1S, SD and SB remained statistically similar during mid-winter (0.25 to 0.50 YAP). However, by 0.75 YAP, the trees in the SB and SD treatments had already taken up significantly more K and Ca than those in the control (1S). Finally, by 1.0 YAP, the nutrient accretion in treatment SB was significantly superior to that in the control for all elements in Table 6.2.

Table 6.2. Nutrient accretion in the above-ground biomass of treatments for specific intervals during the first year of growth.

Event Number	Period (years)	Time of year (month)	Nutrient	Treatment (kg ha <sup>-1</sup> )					mean	LSD*
				0S	1S	SD	SB	SF		
1	0.00 - 0.25	Feb – Apr	N	0.56 <sup>a</sup>	1.37 <sup>c</sup>	1.43 <sup>c</sup>	1.07 <sup>b</sup>	1.76 <sup>d</sup>	1.24	0.25
			P	0.03 <sup>a</sup>	0.08 <sup>c</sup>	0.07 <sup>bc</sup>	0.06 <sup>b</sup>	0.10 <sup>d</sup>	0.06	0.02
			K	0.18 <sup>a</sup>	0.49 <sup>c</sup>	0.47 <sup>c</sup>	0.34 <sup>b</sup>	0.46 <sup>c</sup>	0.39	0.08
			Ca	0.11 <sup>a</sup>	0.25 <sup>c</sup>	0.25 <sup>bc</sup>	0.21 <sup>b</sup>	0.29 <sup>c</sup>	0.22	0.04
			Mg	0.11 <sup>a</sup>	0.30 <sup>c</sup>	0.27 <sup>bc</sup>	0.23 <sup>b</sup>	0.29 <sup>c</sup>	0.24	0.05
2	0.25 - 0.50	May – Jul	N	0.61 <sup>a</sup>	2.51 <sup>b</sup>	2.15 <sup>b</sup>	2.18 <sup>b</sup>	3.26 <sup>c</sup>	2.14	0.72
			P	0.04 <sup>a</sup>	0.15 <sup>b</sup>	0.15 <sup>b</sup>	0.16 <sup>b</sup>	0.22 <sup>c</sup>	0.14	0.04
			K	0.14 <sup>a</sup>	0.62 <sup>b</sup>	0.46 <sup>b</sup>	0.52 <sup>b</sup>	0.95 <sup>c</sup>	0.54	0.20
			Ca	0.13 <sup>a</sup>	0.67 <sup>cd</sup>	0.45 <sup>b</sup>	0.53 <sup>bc</sup>	0.83 <sup>d</sup>	0.52	0.16
			Mg	0.10 <sup>a</sup>	0.43 <sup>b</sup>	0.38 <sup>b</sup>	0.43 <sup>b</sup>	0.57 <sup>c</sup>	0.38	0.13
3	0.50 - 0.75	Aug – Oct	N	2.09 <sup>a</sup>	4.59 <sup>bc</sup>	6.12 <sup>bc</sup>	6.41 <sup>bc</sup>	7.23 <sup>c</sup>	5.29	2.47
			P	0.11 <sup>a</sup>	0.29 <sup>b</sup>	0.33 <sup>bc</sup>	0.38 <sup>bc</sup>	0.45 <sup>c</sup>	0.31	0.15
			K	0.52 <sup>a</sup>	1.42 <sup>b</sup>	2.41 <sup>c</sup>	2.37 <sup>c</sup>	2.19 <sup>bc</sup>	1.78	0.79
			Ca	0.31 <sup>a</sup>	0.67 <sup>a</sup>	1.44 <sup>b</sup>	1.68 <sup>b</sup>	1.35 <sup>b</sup>	1.09	0.51
			Mg	0.43 <sup>a</sup>	1.05 <sup>b</sup>	1.59 <sup>bc</sup>	1.92 <sup>c</sup>	1.74 <sup>c</sup>	1.35	0.61
4	0.75 - 1.00	Nov – Jan	N	20.50 <sup>a</sup>	39.60 <sup>b</sup>	42.00 <sup>b</sup>	51.50 <sup>c</sup>	52.00 <sup>c</sup>	41.12	8.19
			P	1.04 <sup>a</sup>	2.08 <sup>b</sup>	2.33 <sup>b</sup>	3.20 <sup>c</sup>	3.04 <sup>c</sup>	2.34	0.51
			K	7.89 <sup>a</sup>	15.37 <sup>b</sup>	16.29 <sup>bc</sup>	19.39 <sup>c</sup>	18.79 <sup>c</sup>	15.55	3.30
			Ca	5.47 <sup>a</sup>	12.68 <sup>b</sup>	17.97 <sup>c</sup>	15.82 <sup>c</sup>	22.97 <sup>d</sup>	14.98	3.13
			Mg	6.15 <sup>a</sup>	13.88 <sup>b</sup>	15.36 <sup>bc</sup>	18.68 <sup>c</sup>	18.08 <sup>c</sup>	14.43	3.65

Note: Values within rows followed by the same letter are not significantly different a  $p < 0.05$ .

\*Least significant difference at  $p = 0.05$ .

Cumulative monthly data for rainfall and for evapotranspiration were recorded for each growth year (August to July). The rainfall for each of the four years (August to July) totalled 618, 1003, 810 and 1013 mm compared to the long-term average of 918 mm. Cumulative evapotranspiration over the same periods totalled 1262, 1159, 1130 and 1189 mm. The first year of the project (1998-1999) was abnormally dry in the late summer with relatively high evapotranspiration levels. In addition, the winter period was unusually dry and long; the period with monthly rainfall less than 20 mm spanned six months during the winter of

1999 compared to only three months during the following two seasons. In strong contrast, the second year (1999-2000) had above-average rainfall with relatively low evapotranspiration rates.

Figure 6.1 shows the volumetric soil water content over the monitoring period with lines indicating the soil water contents at -10, -1000, and -1500 kPa of tension. Despite the fact that soil moisture was very similar between treatments, large differences existed between years, specifically with regard to the duration of the water stress period during each dry (winter) season. Another important difference between seasons was the level of soil moisture in the wet season. The low rainfall towards the end of the first summer led to a rapid depletion of soil moisture (Figure 6.1). During the second growing season (1999–2000), soil water was held at less negative tensions and the soil water content regularly exceeded field capacity after large rainfall events. The large differences in LAI that existed between treatments during the second growing season did not give rise to meaningful differences in soil moisture, apparently because soil water was available in such abundant supply during this time.

Tree survival immediately after planting was generally very good and was similar between treatments. The average stocking for plots on the trial site was 1582 stems ha<sup>-1</sup>. The development of LAI in the treatments is shown in Figure 6.2. The duration of the dry winter periods, where soil moisture decreased to tensions more negative than -1000 kPa, appeared to have a pronounced influence on the development of LAI in the treatments. Leaf area index developed slowly during the dry winter period of 1999 (0.5 to 0.7 YAP in Figure 6.2). The onset of spring rains in October 1999, coupled with higher temperatures, triggered rapid growth in leaf area (0.7 YAP). The above average rainfall in the second growing season kept the soil moist (Figure 6.1) and allowed trees in the fast-growing treatments (SB, SF, SD and 1S) to develop LAI values in excess of 4 by the end of that season (1.4 YAP in Figure 6.2). Within the group of fast-growing treatments, SB was significantly superior to 1S (control) from 0.5 to 1.8 YAP, whereas SF was significantly greater than the control from 0.8 to 1.0 YAP. Trees in the SD group had a slightly higher leaf area than those in the control group for long periods of time, but this difference was never significant. On the other extreme, LAI development in treatment 0S was significantly slower than in all other treatments, reaching a value of approximately 2.1 by the end of the second summer season (Figure 6.2). The difference in LAI between 0S and the other treatments remained highly significant ( $p < 0.001$ ) from 0.3 to 2.1 YAP, and it was still significant ( $p < 0.05$ ) at 2.3 YAP.

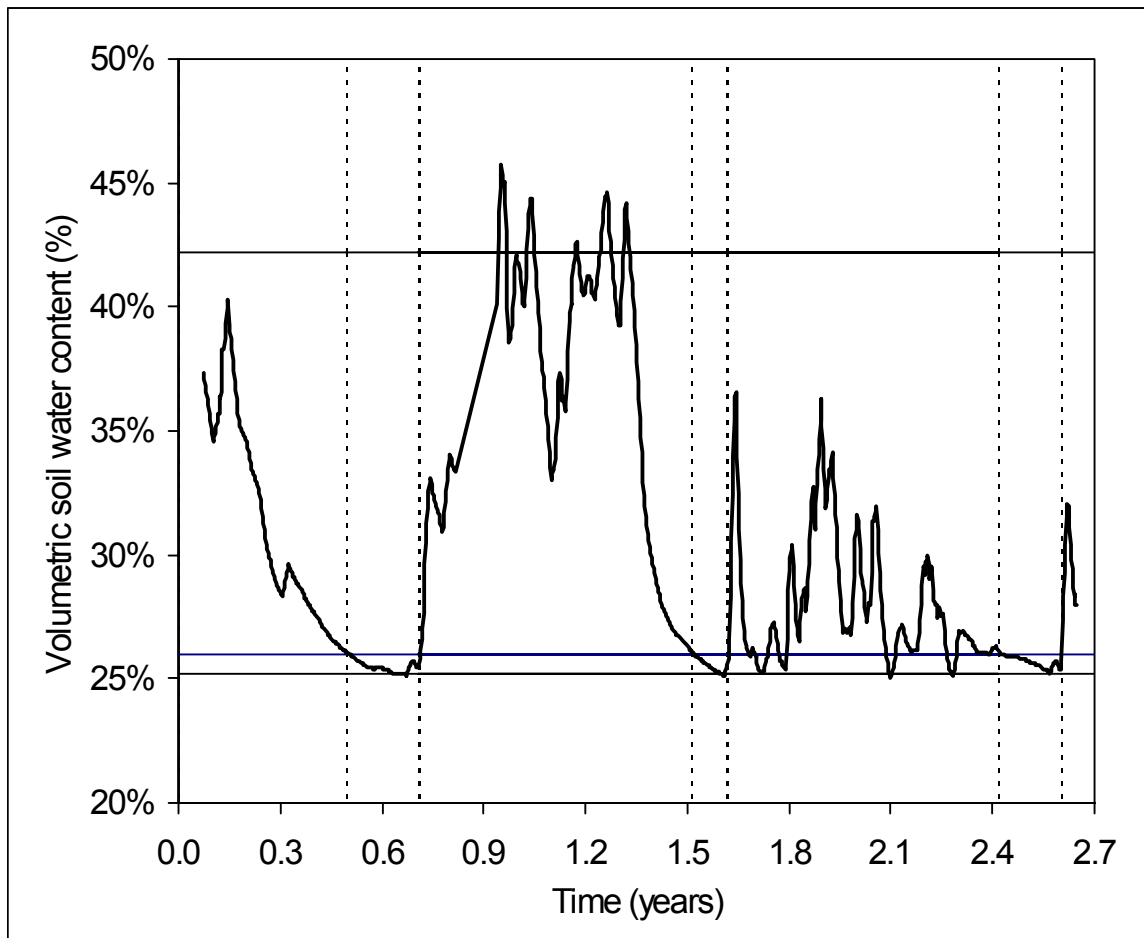


Figure 6.1. Mean soil water content across treatments at 0.15 m depth from time of planting until 2.7 years of age. The volumetric soil water contents at field capacity (42.2%), -1000 kPa tension (26.0%) and wilting point (25.2%) are shown as horizontal lines on the graph. The three pairs of vertical lines indicate the onset and the end of each of the first three dry winter periods, where soil moisture was held at tensions more negative than -1000 kPa for more than 30 consecutive days.

The LAI in treatment 0S finally reached a maximum of 3.95 at 2.3 YAP (approximately 400 days after the fast-growing treatments reached or exceeded that level). The last substantial rainfall event of the third growing season lasted three days and ended on 2 May 2001, when 12 mm was recorded. The LAI of most treatments were still virtually unaffected by the dry conditions when measured at 2.3 YAP (27 days after the last significant rainfall event). Intense water stress set in at approximately 2.4 YAP (Figure 6.2), *i.e.* 63 days after the last rains, when the soil water contents dropped below 26%. The dry conditions in the third winter (this time of fairly average duration, *i.e.* 106 days) caused LAI to decline sharply in all treatments. No significant differences were detected between treatments from this point forward. LAI again increased in the fourth growing season (2.6 to 3.2 YAP), but

this peak was lower than that of the third summer (Figure 6.2).

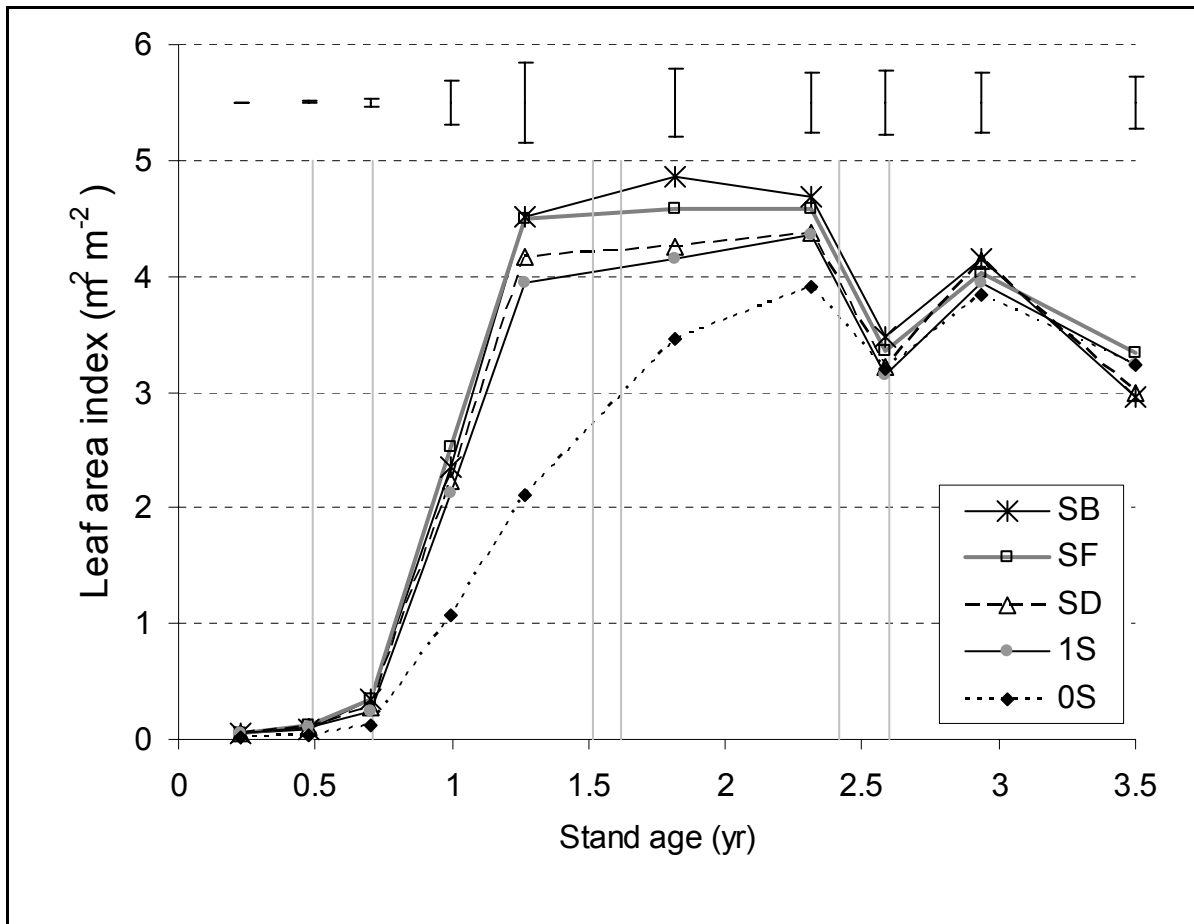


Figure 6.2. Development of leaf area index up to 3.5 years of age. The least significant difference ( $p=0.05$ ) is shown as an error bar for each measurement event. The three pairs of grey vertical lines indicate the onset and the end of each of the first three dry winter periods as defined in Figure 6.1.

The development of the WB (mass of the stem wood plus bark and branches) over time is shown in Figure 6.3. The values for treatment 0S were significantly ( $p<0.001$ ) lower than in all other treatments for all measurement events recorded (Figure 6.3). This was expected, given the slow development of LAI in that treatment. A significant “block effect” was observed in the WB data towards the end of the observation period (2.7 to 3.5 YAP), with replications 1 and 2 having greater WB than replications 3 and 4. A summary of the ANOVA for WB from 1.8 to 3.5 YAP is shown in Table 6.3. In all treatments, WB was slow to develop initially, since early tree growth favours the development of leaves and roots. However, from the onset of the second growing season WB increased at exponential rates

in all treatments (Figure 6.3). The slopes of the lines showing WB increment over time for individual treatments all decreased after 2.1 YAP, but then increased again slightly from 2.6 YAP (Figure 6.3). As expected, these fluctuations coincided with the decline in LAI observed in all treatments during the third winter, and its subsequent increase thereafter (Figure 6.2). The rate of increase in WB for the 0S treatment diverged from the other treatments from 0.3 YAP (Figure 6.3); however, from 2.1 YAP, the WB increment lines for all treatments run in parallel. Here again, the WB development mirrors the fact that LAI, the main driver of growth rate, had converged to similar levels in all treatments and remained similar, despite seasonal fluctuations. Coarse root mass at 3.0 YAP is shown in Figure 6.3. The ratio of coarse root mass to WB at 3.0 YAP was not significantly different between treatments, ranging from 21.7% (0S) to 21.0% (SF and SB).

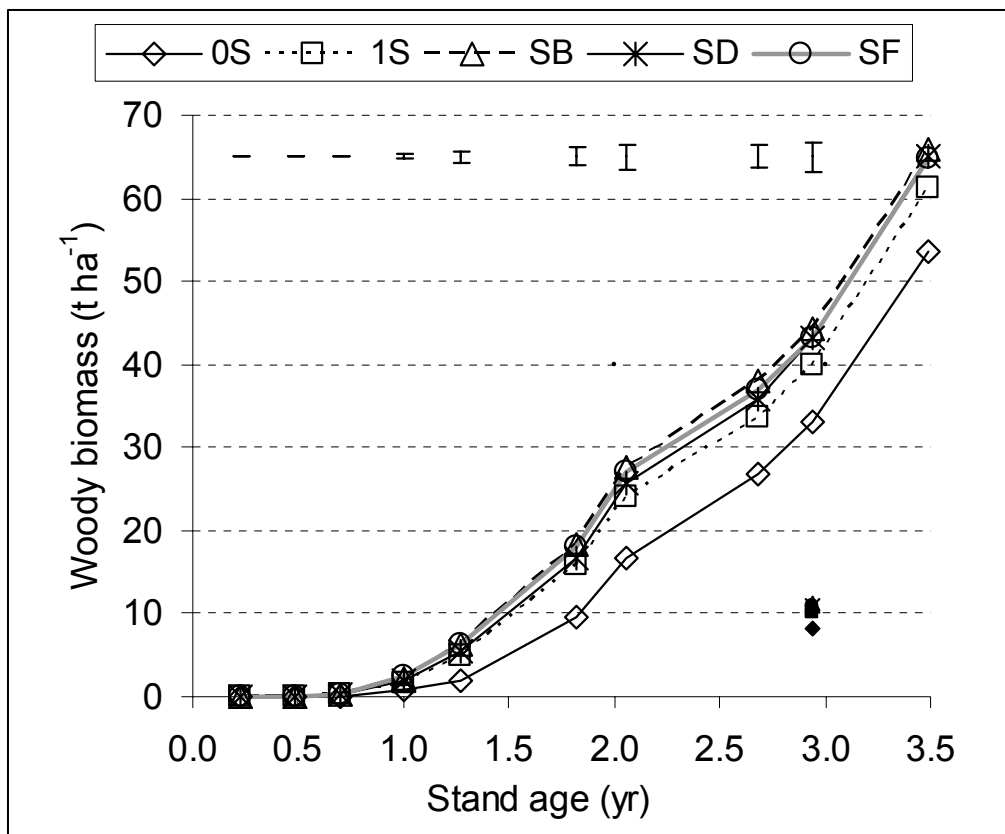


Figure 6.3. Development of above-ground woody biomass during the first 3.5 years after planting (Open symbols linked by lines) and coarse root biomass at 3.0 years (filled symbols without lines, bottom right corner). The least significant difference for the above ground data ( $p=0.05$ ) is shown as an error bar for each measurement event.

Fluctuations in the periodic stand GE (periodic WB increment per unit leaf area) are shown in Figure 6.4. During the principal period of canopy development (0.0 – 1.3 YAP), levels of GE were generally lower than in the third growing season. This is an expected result, as trees shift from initially allocating large portions of carbon to developing canopies and roots to gradually allocating increasing portions of carbon to stem wood. The GE for treatment 0S was consistently lower than for treatments SD, SB and SF (Figure 6.4). The difference between the fastest growing treatment (SB) and the slowest (0S) was significant during this entire period. Some tree mortality occurred during the first winter in the control treatment. The net effect was that the leaf area of the plots recovered more rapidly than the WB increment. This explains the very low levels of GE in the control at the end of the first winter. The stand GE curves for treatments changed markedly after canopy closure. Treatment 0S recorded significantly greater GE than the fast growing SB treatment during the last two measurement intervals (Figure 6.4).

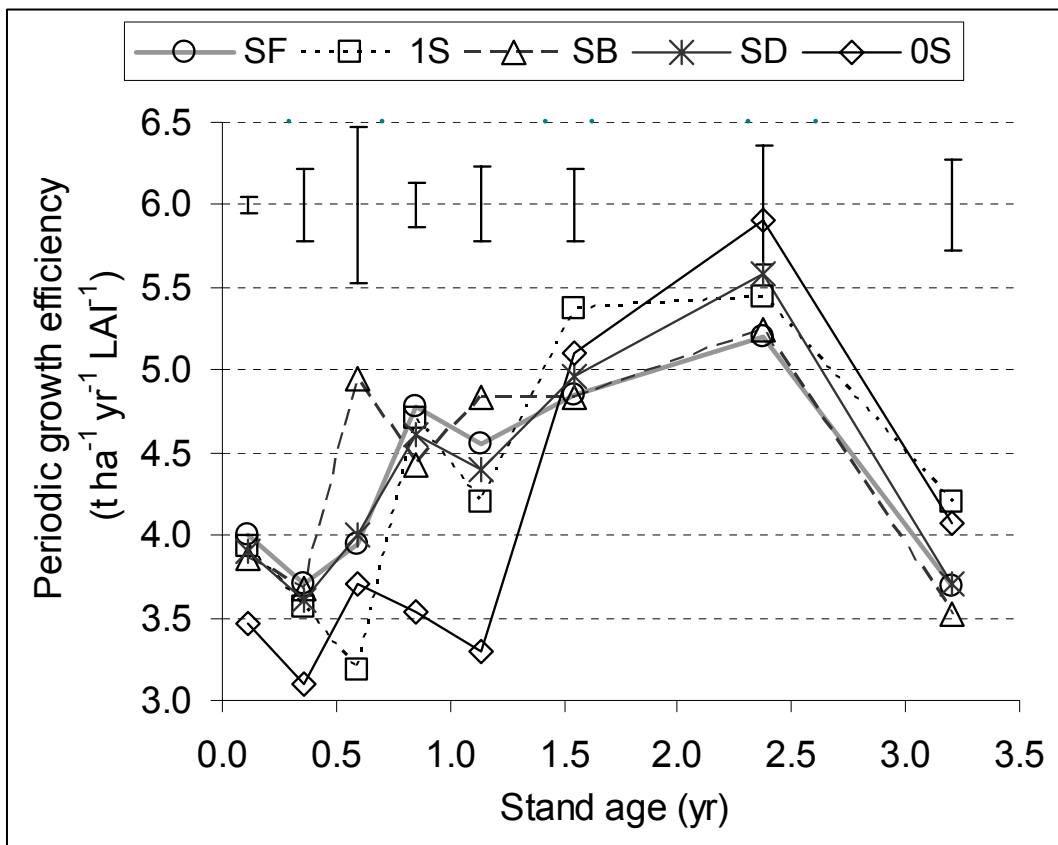


Figure 6.4. Periodic stand growth efficiency, *i.e.* periodic woody biomass increment per unit leaf area, from planting to 3.5 years of age. The least significant difference ( $p=0.05$ ) is shown as an error bar for each measurement event.

The fraction of dry matter production allocated to WB varies amongst trees of different size and age classes (Ledig 1983; Cromer and Jarvis 1990). Significant differences in GE between treatments (Figure 6.4) may also be attributed (at least in part) to trees being at different physiological phases of development at specific times. The fact that LAI in 0S peaked 400 days after the fast-growing treatments (Figure 6.2) may have resulted in it reaching maximum GE considerably later than the other treatments (Figure 6.4). To rule out the effect of the physiological development phase and the differences in time span of individual measurement events, we calculated the mean values of LAI and GE. (Measurement intervals were of unequal length, and this was taken into account in the calculation of the true annual mean values). These mean annual values of LAI differed significantly between treatments (Table 6.4). Although the GE differed significantly between treatments at specific time intervals in our study, the mean values were statistically similar (Table 6.4).

Table 6.3. Summary of analysis of variance results showing mean squares for woody biomass (WB) in Mg ha<sup>-1</sup> from 1.8 to 3.5 years of age.

Source of variation	Degrees of freedom	Stand age (years)				
		1.8	2.1	2.7	3.0	3.5
Replication	3	3.58 <sup>n.s.</sup>	11.63 <sup>n.s.</sup>	21.32*	26.21*	46.89*
Treatment	4	52.36***	77.97***	81.24***	83.38***	101.98***
Residual	12	2.70	4.62	5.54	7.09	11.07
Total	19					

Note: ns, not significant; \*,  $p < 0.05$ ; \*\*\*,  $p < 0.001$ .

Table 6.4. Mean annual values for leaf area index (LAI) and stand growth efficiency (GE) calculated over three years of growth.

Treatment	Mean E (t ha <sup>-1</sup> a <sup>-1</sup> LAI <sup>-1</sup> )	Mean L (m <sup>2</sup> m <sup>-2</sup> )
0S	4.59 <sup>a</sup>	2.35 <sup>a</sup>
1S	4.70 <sup>a</sup>	2.85 <sup>b</sup>
SB	4.58 <sup>a</sup>	3.11 <sup>c</sup>
SD	4.66 <sup>a</sup>	2.96 <sup>bc</sup>
SF	4.56 <sup>a</sup>	3.08 <sup>bc</sup>

Note: Values in columns followed by the same letter are not significantly different at  $p < 0.05$ .

## 6.5 DISCUSSION

### 6.5.1 Growth resource availability

Historic climatic data (du Toit *et al.* 2000) shows that rainfall at the site is strongly seasonal and that both the intensity and duration of dry winter periods are highly variable. Severe drought (annual rainfall < 650 mm), as experienced in the present study, has a probability of 0.04 of occurring in a given year at this site (Kunz and Smith 2001). A block effect observed in the WB data (Table 6.3) exists between groups of adjacent replications (1 and 2 versus 3 and 4), and appears to be linked to differences in the soil parent material and soil depth. The soil in replications 1 and 2 has a higher incidence of doleritic intrusions in the predominantly shale parent material and is slightly deeper than the soil in replications 3 and 4. The block effect may be an indication of gradients in resource availability that exist across the experimental site, despite being located in a single compartment of the plantation. The fact that we observed the same treatment responses in two groups of replications that differed significantly in WB growth, suggest that our results may have wider applicability to other sites in the region.

The dynamics of nutrient supply with varying stand age has been described by Miller (1995). This paper also highlighted the need for a significant nutrient supply from the soil in a young stand. Our treatments created large gradients in total nutrient quantities (Table 6.1), but this gradient was not the only driver of nutrient uptake into the biomass. It appears that plant-available nutrient fractions differed between treatments and across time, judging by soil analyses (Appendix 3), as well as differences in foliar nutrient concentrations (Appendix 4) and nutrient accretion into above-ground tissues (Table 6.2). Slash removal significantly decreased the availability of macronutrients relative to the control, whereas fertilization significantly increased it (specifically for N and P). There were no significant ( $p < 0.05$ ) differences between treatments with respect to foliar macronutrient concentration at 0.25 and 0.5 YAP (with mean levels for N, P and K at 0.5 YAP being 3.03%, 0.15% and 0.66%, respectively). Spring rains for 1999 started during October 1999, and the nutrient concentrations responded immediately with highly significant ( $p < 0.001$ ) differences for N, P, K and Ca between treatments in the November sample (0.75 YAP; Appendix 4). The nutrient uptake values (being the product of biomass and nutrient concentration) responded somewhat slower than the concentrations themselves (Table 6.2). Differences in nutrient availability between 1S and SB (which had been apparent since treatment

implementation) manifested as significant differences in nutrient accretion only toward the end of the first year. It appears that the dry (and cold) winter conditions limited nutrient uptake across all treatments and prevented differences in nutrient availability from manifesting in terms of nutrient accretion. Fertilization would increase nutrient availability through direct supply. Other studies have also shown that burning (Romanyà *et al.* 1994; Fisher and Binkley 2000) and topsoil disturbance (Smith and du Toit, 2005) indirectly increase nutrient availability, at least temporarily. Removal of the forest floor or harvesting residue from a site constitutes a loss of nutrient capital from that system and, in addition, has been shown to negatively affect the rate of nutrient mineralization in the topsoil (Gonçalves *et al.* 2000).

### 6.5.2 Leaf area and growth

With adequate supplies of growth resources, *E. grandis* stands are capable of rapid canopy expansion and height growth. Coetzee (1994) showed one-year top height<sup>6</sup> to range from 2.1 to 5.5 m for various site productivity classes of *E. grandis* in South Africa. Height growth of 3 to 6 m in the first year has been documented by Gonçalves *et al.* (2000) in Brazil. However, we only achieved height growth ranging from 1.7 m (0S) to 2.8 m (SF) and a LAI ranging from 1.1 to 2.5 across treatments at that age. Stand growth rates may be constrained by reductions in the availability of growth resources (water, nutrition, light) or planting of a species under unfavourable climatic conditions for that species. In the present study, the site is climatically suited to *E. grandis* (Boland *et al.* 1997). Light *per se* is seldom a strong limiting factor at our latitude (for example, average solar radiation for February and March 1999 averaged 19.0 and 18.2 MJ m<sup>-2</sup> day<sup>-1</sup>, respectively). However, light capture is reduced when LAI is too small to absorb adequate quantities. Nutrient supply was generally good (Appendix 4) and was increased in treatments SB, SD and SF. A periodic decrease in the specific leaf area (SLA) (from approximately 17 to 10 m<sup>2</sup> kg<sup>-1</sup>) was brought about during the first season (Job *et al.* 2003), which is typical of water stress (Osório *et al.* 1998). We conclude that the development of leaf area in all treatments (Figure 6.2) was severely curtailed by the dry conditions during the first growing season (Figure 6.1).

The response in LAI for treatments SB and SF during the second summer season was mainly driven by increases in nutrient supply (0.75 and 1.00 YAP in Table 6.2) since rainfall was present in abundance, and prolonged, significant differences in soil moisture levels

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<sup>6</sup> Top height in this text is defined as the mean height of those 20% of trees in the population that have the largest diameters at breast height.

between these treatments could not be detected during this time (Figure 6.1). Cromer *et al.* (1993a,b) and Hunter (2001) both observed strong responses in the leaf area (or leaf mass) of young stands of *E. grandis* with increasing levels of fertilization. From 1.8 to 2.3 YAP, the LAI of the fast-growing treatments (SB, SF, SD and 1S) remained relatively constant around a level of 4.5. Linder (1985) showed that LAI for eucalypts in Australia usually peaks at values of approximately 5 to 6, since (theoretically) light interception at these values already exceeds 90%. From a tree perspective, the building of leaf area is resource hungry, and any increases in LAI from this high base will result in small gains with respect to light harvesting. This relationship explains why the LAI approached, but never exceeded 5 in our experiment (where soil water was limiting). Smethurst *et al.* (2003) presented data for *Eucalyptus nitens* plantations where LAI exceeded a value of 6, but this only occurred on high rainfall sites subjected to high levels of multiple fertilizer applications.

In general, LAI can be expected to reach a maximum in developing stands, and after canopy closure it commonly declines, reaching an equilibrium value for an extended period of time (Beadle, 1997). As described by Linder (1985), this decline in LAI coincides with the decrease in SLA which is a function of the physiological age of the trees (Sands *et al.* 1992). The third growing season experienced fairly average rainfall conditions, however, the soil water content (Figure 6.1) remained at low levels. The inability to recharge the soil to field capacity is apparently due to the high levels of LAI in all treatments (Figure 6.2), which maximised the actual evapotranspiration during the third growing season. The leaf area for any eucalypt stand on the study site is also expected to vary seasonally because of the pronounced dry season commonly experienced in winter. Seasonal fluctuations of LAI around an equilibrium value are common in eucalypt forests in seasonally dry climates (Beadle 1997). An LAI of 3.2 was determined on the study site by destructive harvesting in the original mature crop before re-establishment (du Toit *et al.* 2000). This value (determined during August 1998) was taken as a realistic estimate of the lower end of the range of “equilibrium” LAI values for this specific stand. Values of LAI across treatments ranged from 3.2 to 3.5 (third winter) and from 2.9 to 3.3 (fourth winter), which is in close agreement with the mature crop value.

The absolute difference in WB between the extreme treatments (OS and SB) at three years amounts to approximately 11 t ha<sup>-1</sup> (Figure 6.3). Fertilization of eucalypts at establishment is highly likely to yield significant growth responses in short rotations (8 to 10 years) under most site conditions in and around the study area. Schönau (1983) listed a variety of trials from the same region, where responses in wood production ranged between 18 and 70 t

ha<sup>-1</sup> on a 10-year rotation, with generally slightly lower N and P fertilizer doses than in our trial on similar soils. A significant growth response to fertilization at planting was documented for a stand of *E. grandis* growing on the same soil type and on the same plantation as our current trial (du Toit and Freimond 1994). They reported an increase of 47 m<sup>3</sup> ha<sup>-1</sup> (approximately 22 t ha<sup>-1</sup>) of utilizable timber at seven years of age, while we recorded a non-significant improvement with fertilization in the Karkloof experiment. We conclude that the potential magnitude of the response to those treatments that increased nutrient supply to young trees (most notably SB and SF) has not been realised. This was apparently caused by low levels of soil water, which inhibited rapid leaf area development.

The mean level of GE in our study (4.6 t ha<sup>-1</sup> a<sup>-1</sup> LAI<sup>-1</sup>) remained relatively constant amongst treatments that manipulated stand nutrition (Table 6.4). Smethurst *et al.* (2003) reported levels of GE ranging from 3 to 5 t ha<sup>-1</sup> a<sup>-1</sup> LAI<sup>-1</sup> for 5 to 7 year old *E. nitens* plantations in Tasmania. Giardina *et al.* (2003) studied the effects of fertilization at four years of age in a stand of *Eucalyptus saligna* in Hawaii. From their data, we calculated stand GE as 2.1 and 3.1 t ha<sup>-1</sup> a<sup>-1</sup> LAI<sup>-1</sup> for control and fertilization treatments, respectively. Jokela and Martin (2000), working in *Pinus taeda* and *Pinus elliotii* in Florida, USA, showed that GE declined strongly as the plantation aged from 7 to 16 years. An age related decline may explain the fact that we, (in a trial with young trees on a dry site) recorded higher levels of GE than the aforementioned eucalypt studies (wetter sites but mid rotation age classes).

Several authors showed that GE can be strongly affected by resource availability (Brix 1983; Albaugh *et al.* 1998; Bergh *et al.* 1999; Jokela and Martin 2000; Giardina *et al.* 2003, Binkley *et al.* 2004). In contrast to the aforementioned results, Cromer *et al.* (1993a) found a linear relationship between net primary production (or WB increment) and LAI in stands of *E. grandis* up to three years of age, which was constant for unfertilized and heavily fertilized treatments. In cases where one resource is strongly limiting, GE may be limited to low levels despite large increases in the availability of another group of growth resources. For example, Stoneman *et al.* (1996) found no significant response in growth efficiency<sup>7</sup> of an unthinned stand of *Eucalyptus marginata* following large N and P fertilizer inputs. However, GE was significantly improved by fertilization after thinning in that study. The authors ascribed this response to an alleviation of water stress. The non-significant differences in GE between treatments in our study (despite significant differences in stand

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7 Defined in that study as the basal area increment per unit leaf area

nutrition) could have been caused by the overriding effect of water stress, or by the diminishment over time of the nutrient gradients created by the treatments.

### 6.5.3 Implications for research and management

Silvicultural treatments that increase the availability of growth resources can affect stand growth in several ways. They may lead to (a) increased leaf area (Brix 1983; Linder 1985; Linder 1987; Linder *et al.* 1987; Turnbull *et al.* 1988; Nambiar 1990; Ericsson *et al.* 1992; Cromer *et al.* 1993a; Jokela and Martin 2000; Stape 2002; Smethurst *et al.* 2003), (b) increased photosynthetic efficiency (Waring 1983, Linder and Rook 1984; Fife and Nambiar 1997; Stape 2002; Giardina *et al.* 2003), (c) changes in allocation of carbon to plant parts (Ledig 1983; Linder and Rook 1984, Keith *et al.* 1997; Misra *et al.* 1998; Hunter 2001; Stape 2002; Giardina 2003). Some authors have also reported an increased conversion of light energy into above-ground biomass or WB (Brix 1983; Linder 1987; Linder *et al.* 1987; Landsberg and Hingston 1996; Stoneman *et al.* 1996; Albaugh *et al.* 1998), *i.e.* combining factors (b) and (c) above. Stand GE, as defined in our study, is likewise most closely aligned with combined factors (b+c).

The mechanism of response to changes in resource availability in our experiment is clear: We found large changes in LAI (factor a), but no significant change in mean GE (factors b+c). The fractions of biomass contained in the coarse roots at 3.0 YAP were similar between treatments. In addition, Nkosana (2002), studying fine root (< 2 mm diameter) turnover in this experiment, found large seasonal variations, but could not demonstrate significant differences between treatments. We conclude that treatment responses through factor (c), *i.e.* changes in the allocation of assimilates to roots, do not apply in our study. If there were no significant changes in factors (b+c) or (c), it follows that there were probably no changes in factor (b) either. Strong responses to early development of LAI, similar to what we saw in our trial, were reported by Turnbull *et al.* (1988) and Cromer *et al.* (1993a).

At the fundamental level, forest production can be determined from the product of the intercepted photosynthetically active radiation (PAR) and the radiation utilisation coefficient (Landsberg and Hingston 1996). It is difficult to obtain reliable measurements of intercepted PAR in crops before and during canopy closure because of variations in the canopy structure and the light extinction coefficient (Dovey and du Toit, 2005). On a practical (forest management) level, the use of LAI and GE, as defined earlier, presents

useful surrogates. Forest production can be taken as approximately driven by LAI and GE (Waring 1983).

The fact that increases in LAI (rather than changes in GE) drove increases in the production of woody fibre, has some implications for management on similar sites (unthinned, short rotation crops on fairly fertile sites). It has been argued that the level of LAI peaked and will probably stabilise at a lower level, reflecting the soil water availability of the site. This implies that the period immediately after re-establishment (when the soil profile has been recharged with water and actual evapotranspiration has not yet peaked) is most conducive to boosting the development of LAI (first and second growth seasons in our study). Treatments that can potentially improve immediate nutrient availability to the tree (e.g. burning, fertilization, tillage or soil disturbance) are highly likely to have the greatest impact on leaf area development (and hence also on growth in general) during this early period. This hypothesis supports the responses in production obtained through a combination of several empirical studies testing intensive silvicultural operations in young, short-rotation hardwood crops around South Africa, described by Schönau (1984, 1989) and Herbert and Schönau (1989 and 1990). Leuning *et al.* (1991) and Cromer *et al.* (1993a,b) also emphasise that optimum nutrition has a potentially large impact on growth through its effect on early development of SLA, and on the photosynthetic efficiency, *specifically in young stands*. It is likely that improved nutrition (e.g. fertilization) of unthinned stands after canopy closure will have a less marked effect on LAI (because of limitations with respect to soil water), as was found in the study of thinned stands by Stoneman *et al.* (1986). In unthinned, short-rotation crops where soil water availability is generally limiting, we hypothesise that the window of opportunity for increasing the productivity falls in the early stages of development, before soil water limitations constrain leaf area development.

## 6.6 CONCLUSIONS

Leaf area development over the first two years responded strongly to a nutrient availability gradient brought about by site management treatments imposed at time of establishment. Slash burning or fertilization accelerated LAI development, and slash removal slowed it down. The GE (WB produced per unit leaf area) differed temporally between treatments, but the mean values were statistically similar over the first three years of growth. The magnitude of the response (between 9 and 11 t ha<sup>-1</sup> of WB) was smaller than that recorded in other fertilizer trials, and this was attributed to the abnormally severe winter drought at the end of the first growing season. Rapid deployment of the maximum leaf area in

treatments (and rapid SLA recovery after the drought), rather than increases in stand GE, resulted in the observed increases in wood production. In unthinned, short-rotation eucalypt stands, treatments that increase nutrient availability to plants are most likely to yield responses in young stands when soil water availability is usually sufficient for developing canopies. Any treatments that increase nutrient availability (e.g. fertilization) are therefore less likely to yield large responses if applied after culmination of leaf area development or during severe droughts. Our study shows that continuous monitoring of LAI is needed to obtain reliable estimates in areas with strong seasonal and inter-annual rainfall variations.

## CHAPTER 7

### 7 Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of *Eucalyptus grandis* in South Africa <sup>8</sup>

#### 7.1 INTRODUCTION

The advances with empirical research on early, intensive silviculture in South Africa has been discussed in Chapter 1. Despite this knowledge, a lack of a process-based understanding of tree growth in response to growth resource availability is currently constraining research efforts to increase productivity in a sustainable way. Increasingly site-specific and operation-specific silvicultural regimes are needed to optimally manage the supply of growth resources (du Toit *et al.*, 2000). A comprehensive, physiologically-based understanding of the response mechanism of the stand to changes in resource availability is needed. This will enable the extrapolation of experimental results (Binkley *et al.*, 2004; du Toit and Dovey, 2005) and facilitate the refinement and implementation of best operating practices on a site-specific basis.

In Chapter 6, the growth of tree stands (and their responses to changes in resource availability) has been described in the simple terms of leaf area and growth efficiency. A more comprehensive explanation (usable in physiological growth models) would require that growth be described in terms of absorbed radiation, canopy quantum efficiency and biomass partitioning (Landsberg and Gower, 1997; Landsberg and Waring, 1997). The growth rates of trees are essentially governed by the quantity of absorbed photosynthetically active radiation (APAR) and the efficiency with which this radiation is utilised to convert atmospheric CO<sub>2</sub> to carbohydrates (Linder, 1985; Landsberg and Gower, 1997; Stape, 2002; Giardina *et al.*, 2003; Binkley *et al.*, 2004). The quantity of carbon assimilated (after respiration losses have been subtracted), is termed the net primary production (NPP) (Landsberg and Gower, 1997). Changes in the availability of growth resources can modify the quantity of absorbed PAR (through changes in leaf area), the canopy quantum efficiency ( $\alpha$ ) and the allocation of carbon to different plant parts (Linder and Rook, 1984; Landsberg and Waring, 1997; Landsberg and Gower, 1997; Albaugh *et al.*, 1998; Bergh *et al.* 1999; Jokela and Martin 2000; Stape, 2002; Giardina *et al.*, 2003;

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Binkley *et al.* 2004; du Toit and Dovey, 2005). We consider the terms allocation and partitioning (in the context of describing the dynamic apportionment of NPP or assimilated carbon) as synonymous in this chapter, and we use the term distribution to describe the quantity of biomass contained in various parts of a standing crop of trees at a given point in time.

Several papers have been published on carbon distribution among biomass components of eucalypt stands worldwide (Bradstock, 1980; Tandon *et al.*, 1988; Herbert, 1996; Misra, 1998; Hunter, 2001; Laclau *et al.*, 2000; Xu *et al.*, 2002), among many others. However, fewer studies have linked this with allocation to transient components, e.g. fine root production and litterfall, and even fewer have included estimates of above- and below ground plant respiration to calculate a stand-level carbon budget (Stape, 2002; Giardina *et al.*, 2003). There is also limited information on the effects of changes in resource availability in eucalypt stands on respiration losses (Giardina *et al.*, 2003). The partitioning of carbon, fixed during photosynthesis, is imperfectly understood (Landsberg and Gower, 1997; Gholtz and Lima, 1997) and therefore, further research should focus on measuring whole-forest fluxes of carbon and water. An improved physiological understanding of carbon partitioning at the stand level could facilitate extrapolation of trial results and decision-making in forest management (Gholz and Lima, 1997; Binkley *et al.*, 2004; du Toit and Dovey, 2005), especially through the use of process-based models (Waring, 2000; Mäkelä *et al.*, 2000; Corbeels *et al.*, 2001 and 2002; Coops and Waring, 2001; Dye, 2001; Esprey, 2001; Landsberg *et al.*, 2001; Sands and Landsberg, 2002; Almeida *et al.*, 2003; Almeida *et al.*, 2004; Binkley *et al.*, 2004).

Experimentation with growth resource manipulation (varying the supply of water, nutrients, light and CO<sub>2</sub> concentration) has been done on trees of varying age classes (and on eucalypts in particular). A number of papers have been published to demonstrate that seedlings (Cromer and Jarvis, 1990; Kirschbaum *et al.*, 1992) and tree stands (Keith *et al.*, 1997; Albaugh *et al.*, 1998; Misra, 1998; Berg *et al.*, 1999; Hunter, 2001; Stape, 2002; Giardina *et al.*, 2003) can vary their carbon allocation patterns as a result of changes in the availability of growth resources. Most of these experiments included treatments that resulted in very large and prolonged changes in resource availability, e.g. greenhouse trials with widely differing growth conditions, fertilizer field trials testing large, repeated additions of nutrients, or water and nutrient optimisation experiments. While these experiments have demonstrated that changes in partitioning may occur, it is not certain whether similar changes will take place under less intensive site management treatments commonly used

in industrial forestry. Data will be presented to illustrate the production ecology of *E. grandis* subjected to common silvicultural treatments, and to quantify the allocation of the NPP in the young stand. We will demonstrate how changes in growth resource availability affect APAR,  $\alpha$ , and the partitioning of NPP to above-ground woody parts ( $\eta_w$ ).

## **7.2 MATERIALS AND METHODS**

### **7.2.1 Site, stand and experimental design**

The details of the site, the stand, the experimental design and the trial implementation procedures have been discussed in detail in Chapter 3.

### **7.2.2 Determination of stand volume and standing biomass**

Tree growth measurements (tree survival, tree diameter and tree height) were conducted at three monthly intervals during the first two growing seasons and six monthly thereafter. Volume was calculated by the equation developed for *E. grandis* short-rotation crops by Coetzee, 1992 (cited in Bredenkamp, 2000). The development of woody tissues and other biomass components over time were determined by destructive harvesting of  $20 \pm 3$  trees at 0.3, 0.5, 0.8, 1.0, 1.8 and 3.0 years after planting (YAP). Fresh wet mass of the foliar and woody components were determined separately for destructive samples in field. Sub-samples were oven dried to constant mass and weighed to correct for moisture content. Coarse root samples (roots with diameter  $> 2$  mm) were collected for the 20 sample trees at three YAP. The area occupied by each sample tree ( $2.44 * 2.44$  m) was divided in four quadrats. The soil in one such quadrat was excavated to a depth of 60 cm and sieved to obtain the coarse roots (A). This depth was chosen since a study of root distribution patterns in the previous crop (du Toit *et al.*, 2004) showed that the bulk of the root biomass was located in the upper soil horizons. The taproot was excavated separately to the same depth (B). The coarse root mass associated with the tree was estimated as  $4*A + B$ , and was reported on an ash-free basis to eliminate potential errors arising from soil contamination. Allometric relationships were developed to estimate the biomass of tree components in the coarse root and above-ground biomass (AGB) samples (leaves, branches, stem bark and stem wood) from diameter at breast height (dbh) and total tree height. Individual tree component biomass were estimated from these relationships, summed per experimental plot and reported on a land area basis.

### 7.2.3 Estimation of transient biomass components

#### 7.2.3.1 Litterfall.

Foliar and woody litterfall were collected in litter traps on a monthly basis as soon as the first signs of leaf fall could be observed at 14 months of age (unpublished field log file). Eight litter traps were used per treatment, each trap measuring 1.2 \* 1.2 m in size (to facilitate the capture of large woody material). Foliar and woody components in monthly samples were separated, oven dried at 65 °C until constant mass was obtained, and weighed.

#### 7.2.3.2 Fine roots

Nkosana (2002) collected monthly samples of fine roots (< 2 mm diameter) with a coring device in the top 30 cm of soil during the period 1.6 to 2.6 years after planting (YAP). Fine root turnover has been estimated for this site, using monthly soil core collections of fine roots after the methodology presented by Santantonio and Grace (1987). The individual treatments (n=4 for monthly observations) were not significantly different, but showed some spikes in the data due to individual outliers (Nkosana, 2002). For these reasons, average values across treatments were used to calculate fine root turnover. These estimates for root production in early summer, late summer and winter seasons of the measurement period (1.6 to 2.6 YAP) were extrapolated to the crop for the period from 0.8 to 3.0 YAP. Fine root turnover immediately following planting (small trees prior to canopy closure) could not be estimated with confidence, but was assumed to make up a small portion of the cumulative fine root turnover during the first three years of stand growth.

#### 7.2.3.3 Other removals

The consumption of foliage by heterotrophs was assumed to be negligible since *E. grandis* is an exotic tree with relatively few pests and browsers in this country and hence suffers little biological damage in the study region (Midlands of KwaZulu-Natal). The very small seeds could potentially fall through the litter traps mesh, but this was not a factor in our study since the trees are not sexually mature and have not produced any capsules or seed during the study period.

#### 7.2.4 Light absorption, photosynthesis and NPP

Daily solar radiation data were collected with an automatic weather station on site. The solar radiation data were converted to photosynthetically active radiation using the approximate conversion under average sunlight conditions given by Landsberg and Gower (1997) as  $1\text{W m}^{-2} \approx 2.2 \mu\text{mol of photons m}^{-2} \text{sec}^{-1}$ . The development of leaf area index for treatments in this trial was published previously (du Toit and Dovey, 2005). The exponential relationship between light absorption and leaf area index (Beer-Lambert law) was used to estimate the quantity of PAR absorbed by the stand in each treatment (after Linder, 1985; Sands and Landsberg, 2002). We used a non-constant value for the extinction coefficient ( $k$ ) since Dovey and du Toit (2005) found  $k$  to vary with the stage of physiological development in young stands of *E. grandis*. The values used for  $k$  at ages < 2.0, 2.6 and 3.0 YAP were 0.55, 0.48 and 0.42. Values of  $k$  for the days in between these ages were linearly interpolated between point data.

The canopy quantum efficiency ( $\alpha$ ) can be estimated from the following equation (Landsberg and Waring, 1997):

$\alpha = \text{GPP} / \text{APAR}$ , where

GPP is measured in mol of C per unit area and APAR in mol of photons per unit area.

If we assume a constant, unit-less fraction to scale NPP to GPP, namely 1/0.47 (Waring *et al.*, 1988), and assume that 1 mol C is equivalent to 24 g dry matter (Sands and Landsberg, 2002); we can calculate  $\alpha$  from the data that we have obtained, as follows:

$\alpha = \text{NPP} / (24 * 0.47 * \text{APAR})$ , where

NPP = Net primary production ( $\text{t ha}^{-1}$ )

APAR = Absorbed photosynthetically active radiation ( $\text{Mmol ha}^{-1}$ )

$\alpha$  = Canopy quantum efficiency ( $\text{mol C (mol photon)}^{-1}$ ).

#### 7.2.5 Statistical analysis

The data on stand volume, litterfall, fine and coarse roots, above-ground biomass components, NPP, APAR  $\alpha$  and  $\eta_w$  were all calculated on a plot basis. The differences between treatments (across the four replications) were analysed with the standard ANOVA

procedure in Genstat® for Windows™ (Lane and Payne 1996). The statistical analyses followed the guidelines described by McConway *et al.* (1999), to ensure that the basic assumptions of ANOVA were not violated.

## 7.3 RESULTS

### 7.3.1 Treatment response in terms of volume growth

Figure 7.1 shows the volume growth of the treatments over time. There are no statistically significant differences between the fast growing treatments (1S, SD, SF and SB). However, treatment 0S had significantly lower volume than all the other treatments at all measurement events from 1.0 to 3.0 years of age. An average volume in the fast-growing treatments of  $70 \text{ m}^3 \text{ ha}^{-1}$  at three years of age can be considered a moderate growth rate by South African hardwood standards (Coetzee, 1999). Considering that the trial is located on a site with moderate productivity potential (du Toit *et al.*, 2000), and that it had experienced a short, but severe drought at establishment (du Toit and Dovey, 2005), the recorded growth rate was very good. The difference in utilisable timber volume between treatment 0S and the fast growing treatments varied between 18 and  $29 \text{ m}^3 \text{ ha}^{-1}$  (approximately 7 to  $12 \text{ t ha}^{-1}$ ) at three years of age, which is smaller than responses obtained in similar treatments on comparable sites (Schönau, 1983; du Toit and Dovey, 2005). The two best treatments (SB and SF) had supplied near optimum levels of nutrients during the early growth phase, judging by foliar nutrient concentrations and nutrient uptake rates (du Toit and Dovey, 2005): For example, N and P concentrations in treatment SF were 3.28% and 0.19%, respectively at 0.7 YAP, while the corresponding concentrations in treatment 0S were 2.69% and 0.13%. However, the trial experienced intense water stress during a dry period (0.3 to 0.7 YAP), which resulted in soil water being held at tensions more negative than -1000 kPa for 78 consecutive days (du Toit and Dovey, 2005). This led du Toit and Dovey (2005) to conclude that water stress was the major factor limiting the magnitude of the response in this experiment.

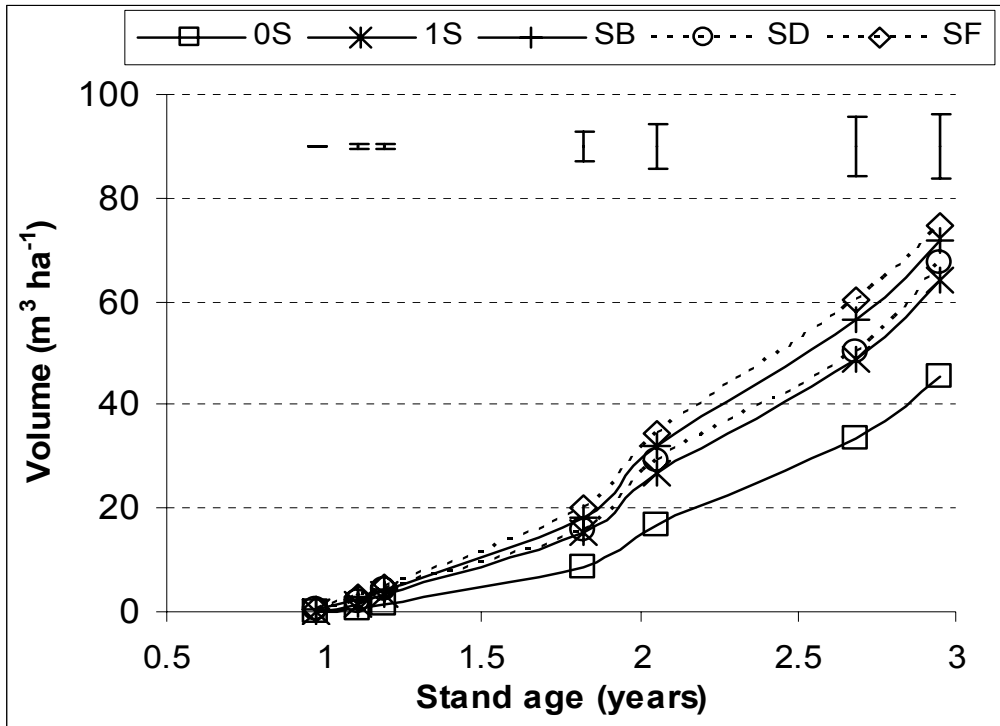


Figure 7.1. Development of utilizable stem volume from 0 to 3.0 years of age. Values more closely spaced than the vertical bars are not significantly different ( $p=0.05$ ).

### 7.3.2 Allocations to transient biomass components

Cumulative values for foliar and woody litter fall are shown in Table 7.1. When expressed on an annual basis, the average litterfall of foliar and woody components across all treatments amounts to 5.5 and 0.8 t ha<sup>-1</sup>, respectively. The differences in foliar and total litterfall between treatment 0S and the remaining treatments were only weakly significant ( $p<0.10$ ). However, the difference was consistent throughout the monitoring period. Cumulative litterfall in treatment 0S over the reported period amounted to 82% of the mean of the other treatments (Table 7.1).

Table 7.1. Cumulative litterfall from 1.67 to 3.04 years after planting as well as mean and peak levels of leaf area index. Numbers within rows followed by the same letter superscript are not significantly different at  $p < 0.10$ .

Litterfall component	Treatment				
	0S	1S	SD	SF	SB
Foliar components (t ha <sup>-1</sup> )	6.56 <sup>a</sup>	7.59 <sup>b</sup>	7.90 <sup>b</sup>	7.66 <sup>b</sup>	8.11 <sup>b</sup>
Woody components (t ha <sup>-1</sup> )	0.80 <sup>a</sup>	1.10 <sup>a</sup>	1.31 <sup>a</sup>	1.17 <sup>a</sup>	1.11 <sup>a</sup>
Total litterfall (t ha <sup>-1</sup> )	7.36 <sup>a</sup>	8.69 <sup>b</sup>	9.21 <sup>b</sup>	8.83 <sup>b</sup>	9.22 <sup>b</sup>
Mean LAI (m <sup>2</sup> m <sup>-2</sup> )	2.35 <sup>a</sup>	2.85 <sup>b</sup>	2.96 <sup>bc</sup>	3.08 <sup>bc</sup>	3.11 <sup>c</sup>
Peak LAI (m <sup>2</sup> m <sup>-2</sup> )	3.84	4.36	4.38	4.58	4.86

There were no significant differences between treatments for the live root mass and the root necromass, respectively (Nkosana, 2002). The mean root production, averaged from 16 core samples across treatments, was bi-modal, with peaks in early summer (November) and again in late summer (April). Fine root production during the dry, cold winter was minimal. The mean fine root production observed during the early summer, late summer and winter periods (calculated from Nkosana, 2002; du Toit - unpublished root decay data) is shown in Table 7.2 (**bold print**). It is likely that root growth would have followed the same seasonal pattern in the unmeasured seasons for the period following canopy closure (bottom section of Table 7.2). However, fine root production would probably have been less than the seasonal estimates in the very young crop before canopy closure as the trees were very small at this age (mean tree height in the trial was 0.71 and 1.59 m, respectively, at 0.4 and 0.8 YAP). We can therefore estimate the fine root turnover in the 0-30 cm soil layer for the period 0.8 to 3.0 YAP as a cumulative number of approximately 7.0 t ha<sup>-1</sup>. We used this value as a conservative estimate of fine root turnover for the entire period as it was not realistic to estimate fine root turnover for the period from planting up to 0.8 YAP from the original data collected by Nkosana (2002) that had been determined under bigger trees in a closed canopy stand. The actual fine root turnover for the entire period from planting to three years of age would thus be slightly greater than our conservative estimate (Table 7.2).

Table 7.2. Observed (Bold entries, calculated from Nkosana, 2002) and estimated seasonal and cumulative fine root production from 0.0 to 3.0 years.

Period	Stand age (years)	Canopy closure	Observed, estimated or uncertain	Fine root production (Mg ha <sup>-1</sup> )
Late summer 1999	0.2	No	Uncertain, likely to be a small number	<< 1.0 (?)
Winter 1999	0.5	No	Uncertain, likely to be a small number	< 0.1 (?)
Early summer 1999	0.8	Partial	Estimated (80% of early summer value)	1.4
Late summer 2000	1.2	Yes	Estimated (late summer value)	1.0
Winter 2000	1.5	Yes	Estimated (winter value)	0.1
<b>Early summer 2000</b>	<b>1.8</b>	<b>Yes</b>	<b>Observed</b>	<b>1.7</b>
<b>Late summer 2001</b>	<b>2.2</b>	<b>Yes</b>	<b>Observed</b>	<b>1.0</b>
<b>Winter 2001</b>	<b>2.5</b>	<b>Yes</b>	<b>Observed</b>	<b>0.1</b>
Early summer 2001	2.8	Yes	Estimated (early summer value)	1.7
Feb1999–Feb 2002	0 to 3		Observations and estimates	Approx. 7.0

### 7.3.3 Allocations to biomass components with slow turnover rates

The dry mass estimates of various components of the stand (foliage, branches, bark, stem wood and coarse roots) at three years of age are shown for each treatment in Figure 7.2. The dry mass across treatments follows exactly the same pattern as the utilisable volume growth presented earlier. The 0S treatment recorded the lowest stand biomass while the SD, SF and SB treatments had very similar levels of stand component masses and total biomass. The biomass of all individual components in treatment 0S was significantly smaller than the remaining treatments. There were no significant differences between treatments SD, SF and SB for any of the components shown in Figure 7.2. The relative contribution of each of the biomass components in the stand was contrasted to published accounts of *E. grandis* stands at a comparable developmental stage (AGB ranging from 45 to 67 t ha<sup>-1</sup>) in Table 7.3. Biomass distribution was expressed as a fraction of AGB (and not total biomass) since not all comparable studies included root estimates.

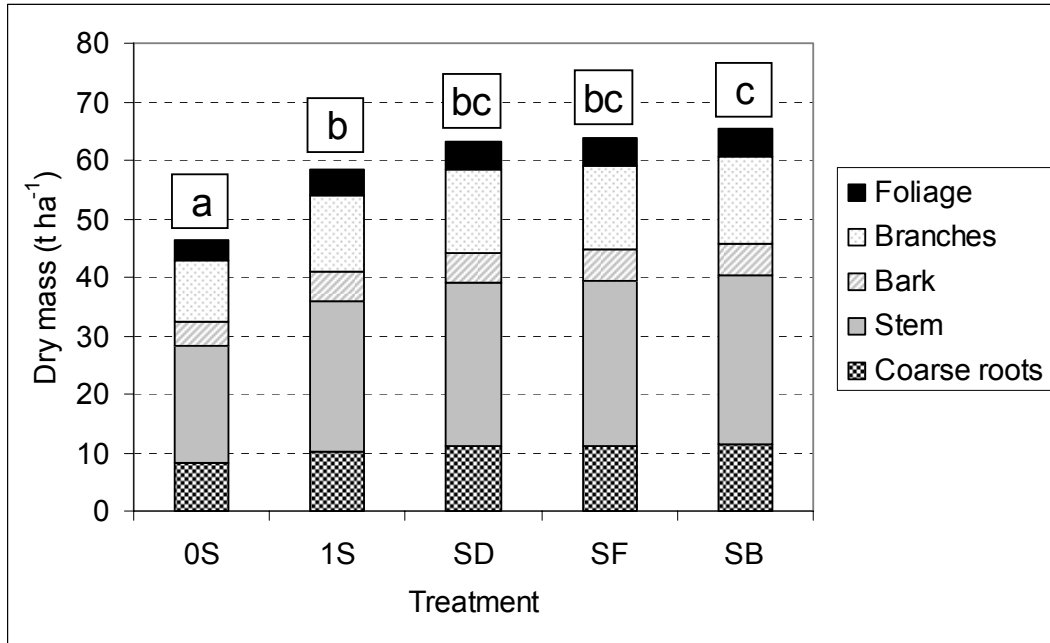


Figure 7.2. Biomass distribution in various stand components. Columns headed by the same letter code are not significantly different at  $p < 0.05$ .

Table 7.3. Biomass distribution of stand components as percentages of the above-ground biomass.

Data source	Karkloof Experiment					<i>E. grandis</i> literature			
	0S	1S	SD	SF	SB	Campion <i>et al.</i> (2005) <sup>a</sup>	Hunter (2001) <sup>b</sup>	Bradstock (1981)	Tandon <i>et al.</i> (1988)
Site and treatment	0S	1S	SD	SF	SB				
Stand density (stems ha <sup>-1</sup> )	1601	1505	1610	1549	1645	1250	2500	1080	1700
Age (Years)	3	3	3	3	3	4	3	5	3
Above ground biomass AGB (Mg ha <sup>-1</sup> )	38.2	48.2	52.1	52.8	54.0	67.0	45.5	52.2	56.3
Foliage/AGB (%)	9.0	9.0	8.9	8.9	8.9	7.0	14.7	8.6	4.7
(Branch+bark)/AGB (%)	38.9	37.6	37.4	37.3	37.3	34.3	27.5	33.1	27.2
Stem/AGB (%)	52.1	53.4	53.7	53.8	53.7	58.7	57.8	58.3	68.2
Coarse roots/AGB (%)	21.7	21.1	21.1	21.0	21.0	7.7 <sup>c</sup>	n.d.	n.d.	15.0

<sup>a</sup> Values for the unfertilized control treatment.

<sup>b</sup> Average values given across all treatments which included irrigation and fertilization gradients.

<sup>c</sup> The coarse root mass was recovered by excavating a limited soil volume and values is therefore an underestimate of total coarse root mass.

The biomass contained in foliage, woody components and roots at 3.0 years of age (Figure 7.2) was added to the biomass allocated to components with rapid turnover, *i.e.* litterfall (Table 7.1) and fine root turnover (Table 7.2), to form a complete synthesis of NPP partitioning in the Karkloof trial system. The allocation to components (a) foliar plus leaf fall; (b) coarse roots plus fine root turnover, and (c) above-ground WB plus woody litterfall are discussed in this paragraph as absolute values and are expressed as percentages of the total NPP in Table 7.4. Foliar NPP of the 0S treatment ( $10.0 \text{ t ha}^{-1}$ ) was significantly lower than that of the faster growing treatments, which varied between  $11.9$  and  $12.9 \text{ t ha}^{-1}$  (Figure 7.2 and Table 7.1). However, the percentage of the NPP allocated to foliar tissues was statistically similar across all treatments (Table 7.4). Cumulative woody litterfall contributed only 2.4%, on average, of the total NPP of woody tissues in this young crop. We observed significant differences in total (above-ground) woody NPP between treatments, with  $35.5 \text{ t ha}^{-1}$  in treatment 0S,  $45.0 \text{ t ha}^{-1}$  in 1S and the remaining treatments ranging from  $48.8$  to  $50.3 \text{ t ha}^{-1}$  (Figure 7.2 and Table 7.1). The total root NPP followed the same pattern, with treatment 0S ( $15.3 \text{ t ha}^{-1}$ ), being significantly smaller than the remaining treatments ( $17.2$  to  $18.3 \text{ t ha}^{-1}$ ) (Figure 7.2 and Table 7.2). It was interesting to note, however, in treatment 0S that the fraction of NPP allocated to roots was significantly greater, and the percentage allocated to above-ground WB was significantly smaller than the remaining treatments (Table 7.4).

Table 7.4. Total biomass allocation to foliar, woody and below-ground components during the three year monitoring period. Numbers within rows followed by the same letter superscript are not significantly different at  $p < 0.05$ .

Biomass component	Description	Portion of NPP (%)				
		0S	1S	SD	SF	SB
Foliage	Standing foliage mass + foliar litter	16.4 <sup>a</sup>	16.1 <sup>a</sup>	15.8 <sup>a</sup>	15.5 <sup>a</sup>	15.9 <sup>a</sup>
Woody parts	Stem, branches, bark + woody litter	58.5 <sup>a</sup>	60.8 <sup>b</sup>	61.5 <sup>b</sup>	61.8 <sup>b</sup>	61.7 <sup>b</sup>
Roots	Coarse roots + fine root production	25.1 <sup>a</sup>	23.2 <sup>b</sup>	22.7 <sup>b</sup>	22.7 <sup>b</sup>	22.5 <sup>b</sup>
Stem wood	Commercially utilized stem wood	32.7 <sup>a</sup>	34.8 <sup>b</sup>	35.3 <sup>b</sup>	35.6 <sup>b</sup>	35.6 <sup>b</sup>

#### 7.3.4 Leaf area development and absorbed PAR

Radiation at the study site varies between monthly averages of 15.9 and 27.8 MJ m<sup>-2</sup> day<sup>-1</sup> (du Toit *et al.*, 1999). Cumulative daily radiation at the study site over the three-year period totalled 17.6 GJ m<sup>-2</sup>. Leaf area development in the trial was slow at first, due to the unusually dry conditions from 0.3 to 0.7 YAP referred to earlier. However, leaf area index developed extremely rapidly during the second summer season, reaching values > 4 in the fast growing treatments (Table 7.1; du Toit and Dovey, 2005). After canopy closure, the LAI levels in all treatments converged to similar levels which followed a pattern dictated chiefly by soil water supply (*i.e.* it increased slightly during the wet summers and decreased during the dry winters) (du Toit and Dovey, 2004; du Toit, and Dovey, 2005). Large differences in LAI between treatments, especially in the developmental phase, resulted in significant differences in radiation interception. The annual and cumulative levels of APAR are shown in Table 7.5, alongside estimates of NPP and canopy quantum efficiency ( $\alpha$ ).

Table 7.5. Estimates of photosynthetically active radiation absorbed by treatments and canopy quantum efficiencies for the period 0 to 3 years of age. Numbers within rows followed by the same letter superscript are not significantly different at  $p < 0.05$ .

Treatment	Period	0S	1S	SD	SF	SB
APAR (Mmol photons ha <sup>-1</sup> )	Year 1	12.1 <sup>a</sup>	21.1 <sup>b</sup>	22.5 <sup>bc</sup>	25.0 <sup>c</sup>	23.6 <sup>bc</sup>
	Year 2	91.1 <sup>a</sup>	107.3 <sup>b</sup>	109.0 <sup>b</sup>	111.3 <sup>b</sup>	111.4 <sup>b</sup>
	Year 3	106.5 <sup>a</sup>	109.1 <sup>ab</sup>	109.0 <sup>ab</sup>	110.8 <sup>b</sup>	111.4 <sup>b</sup>
APAR (Mmol photons ha <sup>-1</sup> )	Cumulative years 0 to 3	209.7 <sup>a</sup>	237.4 <sup>b</sup>	240.4 <sup>bc</sup>	247.1 <sup>c</sup>	246.4 <sup>bc</sup>
NPP <sup>a</sup> (t ha <sup>-1</sup> )		60.8 <sup>a</sup>	74.1 <sup>b</sup>	79.3 <sup>bc</sup>	79.7 <sup>bc</sup>	81.6 <sup>c</sup>
$\alpha$ [mol C (mol photon) <sup>-1</sup> ]		0.026 <sup>a</sup>	0.028 <sup>b</sup>	0.029 <sup>b</sup>	0.029 <sup>b</sup>	0.029 <sup>b</sup>

<sup>a</sup> Indicates the cumulative total of standing biomass plus litterfall plus fine root turnover  
 $\alpha$  = Canopy quantum efficiency

## 7.4 DISCUSSION

### 7.4.1 Volume growth

The poor growth in the 0S treatment was attributed to a decrease in the nutrient supply rate relative to other treatments (du Toit and Dovey, 2005). The decrease in volume

development of treatment 0S relative to the fast-growing treatments only occurred during the establishment phase, due to a slower rate of development in leaf area index (du Toit and Dovey, 2005). The leaf area index of all treatments converged to similar values by 3 YAP. The mean growth efficiency (GE; stem wood production per unit of leaf area) over the first three years of growth was not significantly different between treatments, despite large differences in nutrient availability (du Toit and Dovey, 2005). This finding suggests that current annual volume increment between treatments will also remain similar from year three onward, since the differences in nutrient and water supply between treatments are likely to become even smaller. The difference in response between 0S and the fast growing treatments can thus be described as a Type 1 response (after Snowdon and Waring, 1984; Snowdon, 2002), since it does not cause a sustained improvement in volume growth, but merely enhances the stage of stand development.

#### **7.4.2 Litterfall**

The bulk of the cumulative litterfall in all treatments are made up by foliar elements. A large portion of the branch mass remains on the tree as dead branches after the leaves had fallen (visual observations), which explains why the litter is dominated by foliar elements in young, developing stands. The average foliar litterfall estimated for the measurement period expressed *per annum*, ranged from 4.79 (0S) to 5.92 (SB) (calculated from Table 7.1). Dye *et al.* (2004) recorded annual foliar litterfall rates of between 2.4 and 3.0 t ha<sup>-1</sup> for two groups of *E. grandis* plantations in coastal Zululand, South Africa. Turner (1986) documented annual foliar litterfall rates ranging from 4.23 to 5.46 for the same species in New South Wales, Australia, while Bernard-Reversat *et al.* (2001) measured values of 4.31 and 6.84 for eucalypt hybrids grown from seedling crops in Congo. Keith *et al.* (1997) recorded an annual foliar litterfall rate of 2.9 t ha<sup>-1</sup> under *E. pauciflora* in temperate Australia. The period of litterfall reported in this document co-incides with the period of very active tree height growth resulting in the “lifting” of the canopy. LAI in the fast growing treatments already exceeded 4.0 at the onset of the litterfall measurement period but lagged behind in treatment 0S. From 2.5 years of age, LAI’s amongst all treatments started to converge at a common, but lower level of approximately 3.3 (du Toit and Dovey, 2005). The greatest litterfall rates have been recorded in the fast-growing treatments, which experienced the greatest decrease in LAI from 1.6 to 3.0 years (Table 7.1; du Toit and Dovey, 2005). This may explain why we recorded fairly high annual foliar litterfall rates for the fast-growing treatments (*i.e.* our rates are comparable to the higher end of the spectrum of the cited literature). The foliar litterfall up to 3.0 years of age made up a large

fraction of the total foliar allocation (approximately 64% to 66%, depending on treatment), emphasising the importance of the litter as a carbon sink and as a nutrient cycling pathway.

### 7.4.3 Fine root production

Fine root production peaked in early summer and late summer/autumn, which roughly coincided with the peak litterfall periods. The observed annual production of fine roots during one year (in the period after canopy closure) was  $2.8 \text{ t ha}^{-1}$  (Table 7.2). Working on *E. globulus* in Portugal, Fabiao *et al.* (1985) estimated fine root production to be at least  $6.0 \text{ t ha}^{-1}$ , using root ingrowth bags. Using the data of Keith *et al.* (1997), we estimated fine root dry mass production in their control and fertilized *E. pauciflora* stands to be approximately  $4.5$  and  $3.4 \text{ t ha}^{-1}$ , respectively (allowing for 47% respiration loss for the below-ground tissues, as estimated independently by the authors, subtracting coarse root biomass, and assuming a biomass C content of 50%). Lee and Jose (2003) recorded fine root production values of  $2.21$  and  $1.44 \text{ t ha}^{-1}$ , respectively, for stands of cottonwood and pine in South-eastern USA. Santantonio and Santantonio (1987) estimated the fine root turnover in *P. radiata* in New Zealand to be  $1.9$  and  $2.2 \text{ t ha}^{-1}$  in thinned and unthinned plots, respectively. Our fine root production estimate of  $2.8 \text{ t ha}^{-1} \text{ a}^{-1}$  falls in between the cited studies, being slightly greater than the estimates for pines and cottonwood, but slightly lower than the estimate for *E. pauciflora*. Our fine root production estimates are much lower than the value of  $> 6 \text{ t ha}^{-1}$  obtained by Fabiao *et al.* (1985) for *E. globulus* in Portugal, using root ingrowth bags. The lower estimate from the corer method is expected, as root ingrowth bags could artificially boost fine root production following increases in nutrient availability from the disturbed soil in the sleeve. Such potential increases using the root ingrowth technique are admitted by Fabiao *et al.* (1985) and have also been demonstrated by Nkosana (2002). However, it is likely that we have underestimated fine root turnover in the first growing season. Although the trees were very small at that age, the abnormally dry conditions may have increased fine root death in winter, followed by an increase in allocation to fine roots to rebuild the fine root biomass after the onset of the first spring rains.

No significant treatment differences could be detected for live and dead fine root mass (Nkosana, 2002), which allowed us to pool data across treatments when estimating fine root production. While there may have been subtle differences in fine root production, it was not possible to detect these with the methods used. It is important to note that the absolute values for fine root production are coupled to different values for the total NPP across treatments. When the fine root production is expressed as a fraction of the NPP per

treatment (Table 7.5), it is clear that treatment differences exist. According to this calculation, fine root production constituted 11.5% of the NPP in treatment 0S, but only 8.6% of the NPP in treatment SB. A decrease in the fraction of carbon allocated to fine roots with increases in resource availability has been documented in several forest stands (Keith *et al.*, 1997; Albaugh *et al.*, 1998; Stape, 2002; Giardina *et al.*, 2003).

#### 7.4.4 Biomass distribution in the standing crop

The foliage makes up a comparatively large portion of the biomass in the young trees in our study (8.9 to 9.0% of the above-ground biomass) (Table 7.3). This fraction usually decreases with increasing plantation age, since the WB will increase while leaf mass may remain roughly constant in closed canopy stands or decrease slightly (Laclau *et al.*, 2000; Judd, 1996). The contribution of the leaf mass to the above-ground biomass in a 7-year old stand of *E. grandis* (the previous crop on the same study site) was 3.8% (du Toit *et al.*, 2000). The treatments in our study held 37 to 39% of the AGB in the bark plus branch fractions. The branch plus bark mass is commonly expressed as a fraction of the above-ground woody biomass for modelling purposes (Landsberg and Waring, 1997). When expressed in this way, the bark plus branch fraction made up between 41 and 43% of the WB in our study. In an age-series study on the same plantation, Job *et al.* (2003) showed that the bark plus branch fraction decreased from approximately 58% in a one year-old stand to 19% in an eleven year-old stand of *E. grandis*. The stem wood mass makes up a comparatively small percentage of the AGB at this young age (between 52.1 and 53.8%). Note that non-utilised stem tops (< 7 cm diameter over bark) were excluded from the stem mass but added to the branch mass for the purposes of our study. The stem mass of *E. grandis* plantations in other studies at comparable stages of development constituted between 58 and 68% of the total biomass (Table 7.3). We detected significant differences in coarse root mass between treatments. Average annual coarse root production varied from 2.8 (0S treatment) to 3.8 t ha<sup>-1</sup> (SB treatment) (Figure 7.2). Expressed as a fraction of the AGB, the coarse root mass in our study ranged between 21.0% and 21.7%, which is slightly greater than that found by Tandon *et al.* (1988). The Karkloof study site has a markedly drier climate than the site at the latter study, which may explain the greater fraction allocated to roots. The fraction reported by Champion *et al.* (2005) was much lower as only a limited soil volume was excavated. Keith *et al.* (1997) found that coarse root mass of a mature *E. pauciflora* stand constituted approximately 22% of the above-ground biomass.

The portion of biomass contained in each structural component remained remarkably similar across treatments in our study. Ranges for structural components were very narrowly distributed around the mean: foliage (0.1%) branches and bark (1.6%); stem wood (1.6%) and coarse roots (0.7%). The biomass contained in each component was strongly related to tree size (represented by dbh), irrespective of treatment. The narrow ranges explain why the treatment effect in the allometric relationships developed for scaling-up purposes was non-significant in all cases. Our results agree with those documented by Birk and Turner (1992). They studied the response of 9.25 year-old *E. grandis* plantations to fertilization (single or repeated applications), weeding and insecticide treatments. Their treatments resulted in significant differences in the biomass of individual tree components, however, the ratio between above-ground biomass components remained similar. Hunter (2001) tested the effects of irrigation and fertilization on tree growth and biomass partitioning. The main effect of fertilization resulted in significant increases in stembark and branches, but the percentage of biomass allocated to woody tissues or foliage remained virtually constant. However, there are also a number of studies that demonstrated shifts in biomass ratio's following specific treatments. In Hunter's (2001) study, irrigation resulted in a substantial increase in stemwood and stembark. In addition, there was a shift in the partitioning of AGB reserves; allocation to foliage increased from an average of 13.4 % in two heavily irrigated treatments, up to 17.2% in the control treatment. Misra *et al.* (1998) showed how, in a young (0.8 to 2.8 year-old) *E. nitens* crop, there was a significant reduction in the portion of dry mass allocated to coarse roots following heavy, repeated fertilization with N and P.

#### **7.4.5 NPP partitioning**

The amount of biomass partitioned to roots make up 22.5 to 25.7% of the total NPP (Table 7.4). Other studies contrasted the total above- and below-ground carbon allocation (Keith *et al.*, 1997; Stape, 2002; Giardina *et al.*, 2003). In these studies below-ground allocation constituted between 23 and 40% of total GPP, depending on site and growth resource availability. The below-ground estimates for the cited studies included allocation of C to mycorrhizae, which could not be measured in our study. This may be one of the reasons why our estimates fall in the lower end of the range for below-ground C allocation.

We also evaluated shifts in the partitioning of NPP in the system as a whole, brought about by changes in resource availability. The data in Table 7.4 show that no significant differences could be detected in the portion of NPP allocated to foliar tissues, although the absolute foliage mass produced in the fast growing treatments was greater than in the 0S

treatment (Table 7.1 and Figure 7.2). However, there was a significant shift in allocation from woody to root biomass in treatment 0S relative to the fast-growing treatments. The changes in NPP as well as the allocation of NPP to foliar, woody or root tissues were calculated from comparable studies on eucalypts, using respiration rates estimated by the authors. We thus contrasted our NPP data (*E. grandis*) with that of a stand of *E. pauciflora* (Keith *et al.*, 1997); *E. saligna* (Giardina *et al.*, 2003) and *E. grandis x urophylla* (Stape, 2002). The only study in this group that showed little change in NPP following treatment was the mature *E. pauciflora* stand. Its response to fertilization consisted of an increase in above-ground NPP at the expense of root NPP. The three young stands responded to changes in growth resource availabilities with significant changes in total NPP. The stand on a very infertile site (*E. saligna*) responded with very large increases in the absolute values of NPP allocated to foliage and WB. It appears that virtually the entire increase in NPP following fertilization was channelled to above-ground tissues. The net effect was a decrease in the fraction of NPP partitioned to roots and an increase in the fraction allocated to woody tissues. The fraction allocated to foliage remained fairly constant. In the *E. grandis x urophylla* stand, irrigation overcame a resource constraint that appears to be intermediate in its severity, relative to the *E. saligna* and *E. grandis* sites (judging by the non-irrigated rainfall quantity and the size of the NPP response). The increase in soil water resulted in a large increase in woody NPP, and moderate increases in foliar and root NPP (absolute values). This pattern represented a substantial shift from the fraction of NPP allocated to both foliage and roots in favour of woody tissues. Finally, in our study with *E. grandis* on a fertile soil (by forestry standards), the 0S treatment had a moderate impact on nutrient availability while the effect of other treatments were either small or had a short duration. The only treatment that had a significant impact on NPP was 0S, where it was reduced relative to other treatments. Decreases in NPP allocated to roots, wood and foliage varied between 20 and 40% in absolute terms. The larger decrease in woody NPP over that of roots represents a modest but significant shift in fractional allocation from woody to root NPP, with the foliar allocation fraction remaining constant (Table 7.4).

#### **7.4.6 APAR and estimates of canopy quantum efficiency**

The calculation of GPP and  $\alpha$  depends on the accuracy of the assumption that NPP is a constant fraction of GPP across all treatments. While it has been shown that the portion of GPP that is respired may change across large gradients of tree age or size (Mäkelä and Valentine; 2001), it is unlikely that it will change considerably among treatments during the short duration of our study. Other studies have found the ratio of NPP:GPP to be relatively

constant (Ryan *et al.*, 1996; Waring *et al.*, 1998; Giardina *et al.*, 2003), despite large gradients in resource availability.

Due to the slow initial leaf area development, levels of APAR were low during the first year. Leaf area development in the OS treatment was significantly slower than the others (du Toit and Dovey, 2005), which explains the significantly lower values for APAR in this treatment. Treatment differences were most striking during year 1 (Table 7.5). The estimates for  $\alpha$  over the three-year period ranged between 0.026 and 0.029 for the treatments in our experiment (Table 7.5). The OS treatment had a significantly lower canopy quantum efficiency than the other treatments. Estimates of canopy quantum efficiency obtained in ecosystem-level studies on eucalypts range from 0.027 to 0.060 (Küppers *et al.*, 1986, Wong and Dunin, 1987; Stape, 2002; Giardina, 2003). The higher values in the range were obtained in studies where large quantities of irrigation water and/or fertilizer were applied to treatments. A value of 0.03 mol C (mol photon)<sup>-1</sup> was suggested for use as a general value for forest systems in the 3-PG model (Landsberg and Waring, 1997), based on the results obtained in pine plantations, as well as deciduous and evergreen forests. Our estimates for  $\alpha$  are very close to the values suggested by Landsberg and Waring (1997) and are similar to unfertilized treatments in *E. saligna* (Giardina *et al.*, 2003) and non-irrigated *Eucalyptus grandis* x *urophylla* hybrids under average rainfall conditions in the study of Stape (2002). The parameter  $\alpha$  has been shown to be very sensitive in process-based models such as 3-PG (Esprey *et al.*, 2004), underscoring the importance of reliable values for this parameter.

Changes in the availability of light, water and nutrients are within the scope of the plantation manager. Extreme changes in any one of these three growth resources may cause large and significant changes in biomass partitioning to stand components, e.g. light – Little *et al.* (2002); water – Hunter (2001), Stape (2002); nutrition – Misra (1998), Hunter (2001) Giardina *et al.* (2003). However, most of the treatments described above effected extreme changes in resource availability over prolonged periods of time. Commonly used operational treatments (mimicked in our trial) resulted in significant (but smaller) changes to  $\alpha$ . The smaller magnitude in our trial appears to be due to shorter duration of the treatment effects and/or the less extreme changes in resource availability.

#### **7.4.7 Relative contribution of increases in APAR, $\alpha$ and $\eta_w$ to wood production**

The production ecology equation states that forest production is a function of the supply of

growth resources, the portion of the resources captured by stands and the efficiency of resource use to fix atmospheric CO<sub>2</sub> into biomass (Binkley *et al.*, 2004). We have measured two sets of variables that describe the relative contribution of each factor in the production ecology equation. The percentage change (relative to the control treatment) for NPP and mean values for LAI, growth efficiency (GE), APAR,  $\alpha$  and  $\eta_w$  are shown in Table 7.6. Our values for  $\alpha$  and  $\eta_w$  show an increase with increasing nutrient supply. We can thus concur with Stape (2002); Giardina *et al.* (2003) and Binkley *et al.* (2004) that increased use of growth resources at the stand level, leads to increases in the efficiency of resource use. However, our treatments, being less intensive than the studies cited above, yielded more modest responses. The only treatment in our experiment that brought about significant differences from the control (1S) in terms of APAR,  $\alpha$  and  $\eta_w$ , and consequently to stem mass, was 0S. All the treatments commonly used in industrial forestry had no significant effect on mean values for LAI, APAR,  $\alpha$  and  $\eta_w$  under the prevailing conditions at the site. The differences between the slowest growing and fastest growing treatments are also tabulated in absolute and relative terms in Table 7.6. The relative change in factors that govern wood production was similar amongst treatments, and their relative magnitude was proportional to the change in NPP for that factor. The treatment differences in NPP can be explained by the two parameter sets in Table 7.6 (set A represents a pragmatic approach to describe wood production (after Brix, 1983; Waring, 1983), and set B describes a physiologically-based approach (after Landsberg and Gower, 1997; Landsberg and Waring 1997; Binkley *et al.*, 2004). Using set A, du Toit and Dovey (2005) showed that the differences in woody mass production at three years of age was brought about by changes in mean LAI and that mean GE remained relatively constant (Table 7.1 and Table 7.6). However, data presented for set B in this paper show small but significant differences in  $\alpha$  (Table 7.5). It is clear that sets A and B measure approximately equivalent parameters: LAI (set A) is a surrogate for APAR (set B) while the product of  $\alpha$  and  $\eta_w$  (set B) is approximately equivalent to GE (set A). However, there are important differences in the two sets: Any increase in LAI is not always met with an equivalent increase in APAR, due to the increased shading of leaves with increasing LAI as described by the Lambert-Beer law (Linder, 1985). This explains why the difference between SB and 0S yielded a 31% increase in LAI but only an 18% increase in APAR. Another important difference is the efficiency parameters in the two sets: the GE measures woody mass production per unit of LAI, while  $\alpha$  expresses C assimilation per unit of APAR. This explains why no significant differences could be detected in GE, while we have reported small but significant changes in  $\alpha$  in this paper. While set B describes the physiological response more accurately, the data in set A is also useful for our understanding of the system. For example, it

emphasises the fact that the difference between 0S and SB stemmed from a disproportionately large (31%) increase in LAI, which only achieved an 18% gain in APAR (*i.e.* the stand had to expand its LAI by that margin to achieve a moderate increase in APAR).

Table 7.6. Two parameter sets describing changes in the production ecology of the stand as brought about by treatments.

Parameter set		Change relative to the control treatment (1S)				Largest treatment difference (SB-0S)	
		0S	SD	SF	SB	Absolute	Relative
	NPP	-18%	7%	8%	10%	14.3 t ha <sup>-1</sup>	24%
A	LAI*	-18%	9%	4%	8%	0.73 units	31%
	GE*	-2%	-3%	-1%	-3%	-0.03 t ha <sup>-1</sup> a <sup>-1</sup> LAI <sup>-1</sup>	-1%
	APAR	-12%	2%	4%	4%	37.4 Mmol photons ha <sup>-1</sup>	18%
B	$\alpha$	-7%	6%	3%	6%	0.004 mol C (mol photon) <sup>-1</sup>	13%
	$\eta_w$	-4%	1%	2%	1%	0.025	5%

\* Calculated from du Toit and Dovey, 2005

Despite the small differences between the two approaches to describe wood production, they are in agreement on the response mechanism of the stand, namely that the increase in light capture was the major contributor to increased woody production, rather than changes in efficiency or allocation. The difference in NPP between the most extreme treatments (0S and SB) was 14.3 t ha<sup>-1</sup>, which represents a difference of 24%. The overall effect was brought about by decreases in APAR,  $\alpha$  and  $\eta_w$  of approximately 18%, 13% and 5%. Giardina *et al.* (2003) measured a 13% increase in APAR and a 33% increase in  $\alpha$  following fertilization in a stand of *E. saligna* under high rainfall conditions. Stape (2002) documented improvements in APAR (7%),  $\alpha$  (33%), as well as a shift of 8% in allocation from below- to above ground WB, following irrigation treatments of *Eucalyptus grandis* x *urophylla* hybrids in Brazil. Both studies increased the supply of the most limiting resource (nutrients or water) while the other resources were present at relatively high levels of supply. The response was dominated in both cases by the contribution of  $\alpha$  to the increase in NPP, while the contribution of APAR was small. Improvements in NPP in the Karkloof study stemmed largely from improvements in APAR, particularly during the latter half of

year one and the whole of year two, when moisture supply was plentiful and the canopy was in a developing phase (du Toit and Dovey, 2005). We also found increases in  $\alpha$ , but these were modest compared to the cited studies. Our experiment is located in a comparatively low rainfall area with prolonged dry periods in winter, leading to periodic water stress (du Toit and Dovey, 2005). It is highly likely that soil moisture limited  $\alpha$  through increased vapour pressure deficit during dry periods. The increases in  $\eta_w$  with increasing resource availability could be associated (at least in part) by increases in wood density which is commonly observed with increase in resource availability of short-rotation eucalypt stands (Wilkins, 1990; Cromer *et al.*, 1998; Little, 1999; du Toit *et al.*, 2001; du Toit and Drew, 2003).

## 7.5 IMPLICATIONS FOR MANAGEMENT AND PLANNING

The quantity of radiation and the concentration of CO<sub>2</sub> at a given site cannot be changed by management, however, the quantity of APAR, as well as soil water and nutrient supply can strongly be manipulated through silvicultural operations. The treatments used in this trial closely resemble silvicultural treatments at time of establishment and our trial site is highly representative of forestry sites in the region. The responses obtained are therefore highly applicable to short-rotation eucalypt plantations in the region, and has the following implications for planning and management:

Our study corroborates the general finding (Binkley *et al.*, 2004) that increases in growth resource availability and use (chiefly light and nutrients in our case) will lead to increased efficiencies of resource use at the stand scale. However, the rainfall at our site and in our region is only moderately high, with high pan evaporation rates (du Toit *et al.*, 1999), which means that one growth resource (water) is seldom in plentiful supply. This also implies that, as the stand develops its leaf area, soil water will increasingly constrain stand resource use efficiency since the stand will then be able to transpire at maximum rates. Our study differed from comparable results obtained in eucalypts, namely that resource capture (*i.e.* increases in APAR), and not resource use efficiency, was the most important component of the response in wood production. The window of opportunity to increase chiefly resource capture (light) but also the efficiency of use, is thus in the early developmental phase. This finding agrees with an analysis of the growth efficiency (du Toit and Dovey, 2005), and it underscores the importance of early silvicultural management (appropriate slash management, weed control and early fertilization) in short rotations crops on sites with moderate to low rainfall. (Broad scale irrigation of plantations is definitely not an option in our region due to higher priority needs of a water-scarce country and due to economic

considerations). Growth modellers involved in management planning will need to take the moderate (but temporary) increases in APAR and  $\alpha$  into account as it has been shown that wood production estimates in process models are sensitive to these variables. However, it appears that the partitioning coefficients are relatively insensitive to the degree of change in growth resource availability brought about by commonly used treatments.

# CHAPTER 8

## 8 General discussion and conclusions

### 8.1 NUTRITIONAL SUSTAINABILITY OF FOREST PLANTATIONS

The importance of maintaining the integrity of soil biology and nutrient supply processes as well as water quality to ensure sustained productivity has been stressed in Chapter 2. Tree stands that are healthy and fast growing are usually associated with sound (and sometimes sustainable) forest management. However, an increase in forest productivity over successive rotations is not a guarantee that the ecological processes supporting ecosystem integrity are not being degraded. It is possible that management interventions (e.g. genetic improvements, accurate site:genotype matching or site preparation activities) may mask the effects of certain negative impacts such as soil erosion, soil compaction or nutrient depletion (Smith *et al.*, 2005). Measures to increase production may bring about increased demands on growth resources. It is likely that intensively managed plantations (in general) will pose a greater threat to long-term ecological sustainability than stands managed at lower intensities (Schönau, 1991). From the literature review and data presented in Chapter 5, it is apparent that biomass harvesting and slash burning may be responsible for the greatest nutrient losses in most plantation systems. It is also clear that the nutritional impacts of site management regimes need to be assessed in the light of the type of operations included in the overall management regime *and* their respective intensities. The literature abounds with data on the effects of high intensity operations (whole tree harvesting and wildfires or hot burns). This is also the case in southern Africa (Van Wyk, 1985; Morris, 1986; Allan and Carlson, 1998; Scott and van Wyk, 1990). The case study presented in Chapter 4 shows that wood-only harvesting has a moderate effect on nutrient removal. The effect of slash burning with moderate intensity fires in the case study substantially increases N and P losses, but the system remains fairly well buffered against nutrient depletion with respect to base cations. If nutrient input to the system is taken into account (Chapter 5), the losses of N and P through slash burning and harvesting does not constitute a major threat to the Karkloof system. Fire is often excluded from plantations due to its potential effect on sustainability (Norris, 1995; du Toit *et al.*, 2003). Recent drives to obtain certification have forced many foresters to exclude the use of fire from their plantations entirely, apparently (partly) in reaction to published examples of the impacts of fires of high intensity. However, the complete exclusion of fire may lead to the

buildup of fuel loads which poses a very large risk in the event of a wildfire (De Ronde, 1990; du Toit *et al.*, 2003). Preventing the judicious, pro-active use of fire may also lead to increased costs, thus impacting on the economic sustainability of the system. The generation of more data sets testing the effects of management operations at representative intensity will yield a more objective assessment of their nutritional impacts. This will allow the forester to use certain management tools (such as fire), provided that it is used at an appropriate intensity. Simply put: In forest management, it is not just what you do, it is also how you do it. In specific situations, it may be more beneficial to manage the intensity of operations (such as burning), rather than to exclude them entirely and run the risk of predisposing the plantation to a serious risk of wildfire.

The literature review in section 2.2 concluded with research requirements as put forward by Fölster and Khanna (1997). They emphasised the importance of understanding the impacts of site management on nutrient pools and fluxes (nutrient dynamics) and expressed the need for models that could assess these on the landscape scale. A comprehensive understanding of the effect of site management on nutrient dynamics and its potential effects on the system over time scales of centuries or more is an extremely complex question to answer. Several case studies will be necessary to extrapolate such results with confidence to the landscape scale in any forest region of the globe. The value of such research is immense and should be encouraged, however, it would be prohibitively expensive to conduct such experimentation across several site types and management regimes globally. The index of nutritional sustainability (pINS) puts forward a compromise: it sacrifices some accuracy (being an index and not consisting of absolute numbers), but allows the user to obtain a useful index of several site and soil types within a short time frame, which will enable extrapolation with relative confidence to the greater regional scale. It has application in the identification and mapping of plantation systems that are sensitive to nutrient depletion on the landscape scale. It also allows the manager to test several scenarios (inclusion/exclusion of operations at more than one intensity) and then to formulate appropriate management regimes and codes of practice.

One example will suffice: The reality in southern Africa is that many people depend on fuelwood for their daily energy requirements (Schönau, 1991). Fuelwood is the source of approximately 51% of the cumulative domestic energy use in South Africa (Geldenhuys, 1999). Allowing local people to collect branchwood from the plantations for fuel or charcoal manufacture may amount to an increased nutrient loss from plantations, but it does improve the social benefits of the plantation to local communities. Using the pINS system,

a manager could make a reasonably objective assessment of the potential impact of such a decision on the nutritional sustainability of the system for the site types in question. The manager may also decide to increase levels of fertilizer input to compensate for losses incurred from branchwood collection. It is hoped that the pINS index, used as a scenario generating tool, will facilitate sustainable forest management, ensuring nutrient conservation without incurring excessive cost and with maximum benefits to the community at large.

Two factors in the pINS assessment systems compel the author to issue a word of caution: The first issue is that the system does not accommodate the dynamic equilibrium that exists between readily available and (long-term) potentially available nutrient pools in the system. This is a very complex process and should be addressed in long term studies of nutritional sustainability. The second issue revolves around the estimates that are available from local studies for nutrient fluxes. Four of the fluxes described in the pINS system are usually large and will generally have the biggest influence on the net rate of nutrient loss or gain: additions by atmospheric deposition and fertilization, as well as losses through biomass harvesting or burning<sup>9</sup>. These fluxes (three of which are also highly variable depending on operational intensity), can be estimated for most regions in South Africa with an acceptable degree of accuracy for the purposes of pINS. A reasonable body of data exists to gauge nutrient losses from biomass removal at a range of harvesting intensities (Dovey, 2005). There are comparatively fewer local studies documenting losses through slash burning at representative intensities, with a greater number of studies that documented the effects of high intensity fires (Chapter 4). Nonetheless, the abovementioned data should enable estimation of usable values (at various classes of management intensity) for burning and harvesting losses in eucalypt plantation systems. However, the values for erosion and leaching need to be used with circumspection. The numbers currently available in South Africa generally stem from catchment studies in plantations under fairly conservative management. Leaching and erosion case study data (e.g. from runoff plots) will be superior (in terms of accuracy) to catchment data, but the former is seldom available. Furthermore, substantial changes to the management regime could strongly alter erosion and leaching estimates, and currently available catchment data do not allow us to make this assessment. The numbers used in the pINS assessment (Chapter 5) and currently available in South Africa thus implicitly assume conservative levels of management that would not result in excessive erosion losses. If this is not the case, e.g. if burning and soil cultivation is practised after clearfelling on steep slopes as

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<sup>9</sup> If symbiotic N fixation is present in the system, e.g. when a leguminous tree crop is planted, this flux will also have a very pronounced effect on the input-output budget and hence, the pINS index.

described in the experiments of Sherry (1953; 1954; 1961 & 1964), the erosion and leaching losses need to be adjusted using more appropriate data. We must stress here that despite the word of caution above, excessive erosion losses resulting from careless management are currently the exception, not the norm in SA plantations. With over 75% certification in local plantations, and with very strict controls on monitoring water quality as part of the certification process, excessive erosion losses are simply not tolerated by management.

## **8.2 THE MECHANISM OF STAND RESPONSE TO INCREASED RESOURCE AVAILABILITY**

In section 2.2.3, we tentatively stated that an understanding of the eco-physiological mechanism of stand response to changes in growth resource availability could improve our understanding of the constraints to production, and the measures that can realistically be implemented to increase productivity. It could also explain the feedback mechanisms that any response may have on nutrient cycling and soil fertility levels. We suggested that this knowledge should assist us in the extrapolation of trial results and the design of new experimental procedures and trials. The literature shows that nutrient limited environments (with adequate and well distributed seasonal water supply) are likely to yield large responses in LAI, canopy quantum efficiency and partitioning to WB with increases in nutrient supply (Stape, 2002; Giardina *et al.*, 2003; Binkley *et al.*, 2004). These will be the sites where nutrient manipulation (through site preparation, slash management or fertilization) will yield the largest returns on investment. In stark contrast, the results presented in Chapters 6 and 7 have indeed improved our understanding of the response mechanism of the system to increased nutrient availability under water limiting conditions (which is very common in southern Africa). The latter systems apparently have a small capacity for response, which will probably manifest through a temporary increase in LAI (and hence APAR) but little change in growth efficiency (or canopy quantum efficiency and partitioning to WB). This would suggest a small window of opportunity to boost growth in young tree stands before peak leaf area levels are reached and water becomes limiting (Chapters 6 and 7). The type I responses (Snowdon, 2002) that have been described in many empirical fertilizer trials with short rotation hardwoods (ICFR, 1985 and 1992) supports this deduction. However, with the current data, we cannot prove this hypothesis conclusively since the treatments that increased nutrient availability did so primarily in the early phase of the trial. The limited response in terms of canopy quantum efficiency is most likely due to forced stomatal closure under moisture stress caused by xylem pressure

potential or VPD (Gholtz and Lima; 1997; Landsberg and Waring, 1997; Landsberg and Gower, 1997). The small impact on partitioning is likely to be due to channelling of carbon into roots to search for water. It can also be that a large quantity of fixed carbon is lost in seasonally dry environments when fine roots die back and excessive leaf drop occurs. To ensure that this hypothesis is more conclusively tested, the author and co-workers have established an experiment on a site adjacent to the Karkloof experiment where nutrition will be optimised (a) during the canopy development, (b) after canopy closure and (c) throughout the rotation. This experiment is currently (December 2005) one year old and its response is being carefully monitored as it will determine the focus of future fertilization research (applications to either young stands or semi-mature stands).

It may also be useful to consider the stand response in terms of water use efficiency (WUE). It is important to realise at the outset that the WUE is a measure of NPP (or other production-related variables) per unit of water used, which is not directly comparable to canopy quantum efficiency (which expresses NPP per unit of APAR). We cannot generate WUE data from the Karkloof experiment since measurements of actual water use had not been made. We will thus persist with data from other experiments in our discussion. Moderate drought stress in tree stands usually causes partial stomatal closure which apparently limits water loss but diminished photosynthesis only by a small margin (Kallarackal and Somen, 1997; Ares and Fownes, 2000). This evidence suggests that the WUE (at the scale of the leaf) in drought-stressed trees may be greater than that of unstressed trees. However, Dye (2000) presented evidence to show that water use efficiency at the stand level (expressed in terms of stem wood production per unit of rainfall) may be greatest in stands with ample water supply [Kwambonami (high rainfall) versus Baynesfield (low rainfall) experimental plots]. The mechanism contributing to this result could possibly be an increased partitioning of fixed carbon to tissues other than stem wood in the drought stressed plantations, a point also supported by evidence presented by Binkley *et al.* (2004).

The information on the response mechanism to increased nutrient supply in water limited environments has benefits for physiological growth modelling. Most process based growth models simulate eco-physiological processes in that they use the quantity of APAR as the primary driver of growth. In addition, the efficiency by which light energy is converted to fixed carbon, also strongly influences forest productivity. For example, the canopy quantum efficiency has been shown to be one of the most sensitive parameters in the physiological growth model 3-PG (Esprey *et al.*, 2004). Measures of LAI, APAR, GE,  $\alpha$  and  $\eta_w$  over

several years are rare for plantation systems in southern Africa. The estimates of  $\alpha$  in forest stands can be obtained from intensive process measurements of photosynthesis and light interception at various scales in space and time. For example, Wallin *et al.* (2001) compared CO<sub>2</sub> exchange at the shoot, tree and ecosystem level, using shoot cuvettes, whole tree chambers and eddy covariance techniques. They found some problems when scaling up to from the shoot to the ecosystem level, mainly due to periods of low coupling between the canopy and the atmosphere. In our study, estimates of  $\alpha$  was not based on gas exchange techniques, but was calculated after quantifying the carbon budget and by calculating APAR from radiation data and LAI over time. The fact that our (indirect) method yielded expected results for the system in question (compared to data published by Küppers *et al.*, 1986; Wong and Dunin, 1987 and Stape, 2002) strengthens the reliability of the sets of published estimates.

Local experiments with short-rotation eucalypts that manipulate the availability of growth resources at time of establishment (fertilizer, site preparation and vegetation management experiments) have shown a decrease in the time taken for the trees to “capture” the site (e.g. Herbert and Schönau, 1990; Little *et al.* 1997). Although these trials do not have leaf area data, some of them have data on the development of the canopy size (e.g. Noble, 1992; Schumann, 1992) which is related to leaf area. Uncertainties regarding leaf area development in southern African plantations are clearly evident from the lack of published data on this topic. We have measured the LAI of the developing tree stand from planting until the stand was badly damaged by snowfall at 5.5 years of age (Chapter 6 and Appendix 5), enabling the calculation of APAR when coupled to radiation data. These data is useful as a benchmark of the dynamic changes in LAI and APAR over time as a function of resource availability in short rotation eucalypt stands in South Africa.

Few data sets exist on the effect of resource availability on biomass partitioning in eucalypt plantations, and even fewer deal with stands during the early phase of development. Our data have shed some light on the partitioning of biomass in a developing stand of *E. grandis*. Under the conditions that prevailed during the experiment, biomass partitioning patterns were altered to a modest degree by the treatments imposed, when averaged over the three year period (Chapter 7). However, it is indeed possible that we failed to detect the magnitude of the change in partitioning patterns over very short time scales. For example, the early drought experienced in the trial may have temporarily increased biomass partitioning to below ground tissues, but our measurements of root growth commenced too late to monitor this facet of growth. It was also interesting to observe the very rapid

increase in LAI during the second summer season with abundant water supply. It appears that this “flush” was also brought about by a strong, but temporary change in biomass partitioning patterns during the second summer season. However, when viewed over the whole rotation, it appears that partitioning coefficients will not be affected significantly under current management regimes employed in short-rotation eucalypt stands (which may include topsoil disturbance through harvesting, slash burning or fertilization at establishment). It follows that partitioning coefficients used for modelling purposes in industrial plantations will probably only need adjustment when extraordinary silvicultural inputs are made.

### **8.3 CONCLUSIONS**

Four specific goals were listed in section 1.4, and these were grouped under two main themes. The achievement of these goals would support a detailed understanding of the effects of site management operations on nutrient fluxes, nutritional sustainability and productivity of a typical KZN eucalypt plantation system. The study components reported in chapters 4 to 7 of this thesis describes how these goals were attained. Results obtained enabled us to explain the stand response mechanism to increased nutrient availability under conditions of moderate to strong soil water stress. The results also allowed us to construct an index that is useful to assess both short and long-term nutritional sustainability under varying site management scenarios.

## REFERENCES

- Acocks, J.P.H., 1953. Veld types of South Africa. Botanical survey memoir no. 28., Government Printer, Pretoria, South Africa. 192pp.
- Adams, M.A. and Attiwill, P.M., 1986. Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. I: Nutrient cycling and nitrogen turnover. *Plant Soil* 92:319-339.
- Albaugh, T.J., Allen, H.L., Dougherty, P.M., Kress, L.W. and King, J.S. 1998. Leaf Area and Above- and Belowground Growth Responses of Loblolly Pine to Nutrient and Water Additions. *For. Sci.* 44(2):317-328.
- Allan, R. and Carlson, C., 1998. Report on trial SP96/03: an investigation into the re-establishment of severely burnt sites. *ICFR Bulletin 10/98*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Almeida, A.C., Maestri, R., Landsberg, J.J. and Scolforo, J.R.S. 2003. Linking process-based and empirical forest models in *Eucalyptus* plantation in Brazil. In: Amaro, A., Tomé, M. (eds.) *Modelling Forest Systems*. CABI, Portugal, pp. 63-74.
- Almeida, A.C., Landsberg, J.J., Sands, P.J. and Ambrogi, M.S., Fonseca, S., Barddal, S.M., Bertolucci, F.L. 2004. Needs and opportunities for using a process-based model as a practical tool in *Eucalyptus* plantations. *For. Ecol. Manage.* 193:167-178.
- Ares, A. and Fownes, J. H., 2000. Productivity, nutrient and water-use efficiency of *Eucalyptus saligna* and *Toona ciliata* in Hawaii. *For. Ecol. Manage.* 139:227-236.
- Attiwill, P.M. and Leeper, G.W., 1987. *Forest Soils and Nutrient cycles*. Melbourne University Press, Victoria, Australia. 202pp.
- Bainbridge, S.H., Miles, N., Praan, R. and Johnston, M.A., 1995. Phosphorus sorption in Natal soils. *South Afr. J. Plant Soil* 12(2):59-64.

- Beadle, C.L. 1997. Dynamics of leaf and canopy development. In Nambiar, E.K.S., and Brown, A.G. (eds). *Management of soil, nutrients and water in tropical plantation forests*. ACIAR Monograph no 43, pp169-212.
- Beard, J.S., 1951. An experiment on burning in Wattle Silviculture. *J. South Afr. For. Assoc.* 20:53-77.
- Beard, J.S., 1957. A manual of Wattle growing. The Natal Tanning Extract Company Limited, South Africa.
- Beard, J.S., 1961 . Further evidence of burning versus non-burning in wattle silviculture. *J. South Afr. For. Assoc.* 38:7-10.
- Bergh, J., Linder, S., Lundmark, T. and Elfving, B. 1999. The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. *For. Ecol. Manage.* 119:51-62.
- Bernhard-Reversat, F., Loumeto, J.J. and Laclau, J.P., 2001. Litterfall, litter quality and decomposition changes with eucalypt hybrids and plantation age. In: Bernhard-Reversat, F. (Ed). *Effect of exotic tree plantations on plant diversity and biological soil fertility in the Congo Savanna: with special reference to eucalypts*. Center for International Forestry research, Bogor, Indonesia, pp23-29.
- Binkley, D. and Giardina, C., 1997. Nitrogen fixation in tropical plantation forests. In: Nambiar, E.K.S. and Brown, A.G., (eds). *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 297-337.
- Binkley, D. and Hart, S.C., 1989. The components of nitrogen availability assessments in forest soils. *Advances Soil Sci.* 10:57-112.
- Binkley, D., O'Connell. A.M. and Sankaran, K.V., 1997. Stand development and Productivity. In Nambiar, E.K.S. and Brown, A.G. (eds.). *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 419-442.

- Binkley, D., Stape, J.L. and Ryan, M.G. 2004. Thinking about efficiency of resource use in forests. *For. Ecol. Manage.* 193:5-16.
- Birk, E., and Turner, J., 1992. Response of flooded gum (*E. grandis*) to intensive cultural treatments: biomass and nutrient content of eucalypt plantations and native forests. *For. Ecol. Manage.* 47:1-28.
- Boland, D.J., Brooker, M.I.H., Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnston, R.D., Kleinig, D.A. and Turner, J.D. 1997. *Forest Trees of Australia*. CSIRO Publishing, Australia, p 362.
- Bouillet, J.P, Nzila, J.D., Ranger, J., Laclau, J.P and Nizinski, G., 1999. *Eucalyptus* plantations in the equatorial zone on the coastal Plains of the Congo. In: Nambiar, E.K.S., Cossalter, C., and Tiarks, A. (eds). *Site management and productivity in tropical plantation forests: Workshop Proceedings 16-20 February 1998, Pietermaritzburg, South Africa*. Center for International Forestry Research, Bogor, Indonesia, pp 13-21.
- Bouillet, J.P., Nzila, J.D., Laclau, J.P. and Ranger, J. 2000. Effects of site management in *Eucalyptus* plantations in equatorial zone on the coastal plains of the Congo. In: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds). *Site Management and Productivity in Tropical Plantation Forests*. Center for International Forestry Research, Indonesia, pp 11 – 20.
- Bradstock, R., 1981. Biomass in an age series of *Eucalyptus grandis* plantations. *Australian For. Res.* 11:111-127.
- Brady, N.C. and Weil, R.R., 1999. *The nature and properties of soils*. 12<sup>th</sup> Edition. Prentice-Hall, London, 881 pp.
- Bray, R.H. and Kurtz, L. T., 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.* 59:39-45.

- Bredenkamp, B. 2000. Volume and mass of logs and standing trees. In: Owen, D.L. (ed). *South African Forestry Handbook*. Vol. 1 pp 167-174. V&R Printers, Pretoria, South Africa.
- Bremner, J. M. 1996. Chapter 37. Nitrogen-total. In Bartels, J. M., (Managing ed.) *Methods of soil analysis. Part 3. Chemical methods*. Soil Sci. Soc. Am. Book series No. 5. Soil Sci. Soc. Am., Madison, Wisconsin, USA, pp 1103-1108.
- Brix, H. 1983. Effects of thinning and nitrogen fertilisation on growth of Douglas-fir: relative contribution of foliage quantity and efficiency. *Can. J. For. Res.* 13:167-175.
- Brown, A.G., Nambiar, E.K.S. and Cossalter, C., 1997. Plantations for the tropics - their role, extent and nature. In Nambiar, E.K.S. and Brown, A.G. (eds). *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 339-378.
- Bruinzeel, 1991. Nutrient input-output budgets of tropical forest ecosystems: A review. *J. Tropical Ecol.* 7:1-24.
- Cambardella, C.A. and Elliott, E.T., 1992. Particulate soil organic matter across a grassland cultivation sequence. *Soil Sci. Soc. Am. J.* 56:777-783.
- Campion, J.M., Nkosana, M. and Scholes, M.C., 2005. Biomass and N and P pools in above- and below-ground components of an irrigated and fertilised *Eucalyptus grandis* stand in South Africa. *Submitted for publication to Australian Forestry*.
- Carlyle, J.C., 1998. Relationships between nitrogen uptake, leaf area, water status and growth in an 11-year-old *Pinus radiata* plantation in response to thinning, thinning residue, and nitrogen fertiliser. *For. Ecol. Manage.* 108:41-55.
- Carlyle, J.C., Nambiar, E.K.S. and Bligh, M.W., 1998. The use of laboratory measurements to predict nitrogen mineralization and nitrification in *Pinus radiata* plantations after harvesting. *Can. J. For. Res.* 28 (8):1213-1221.

- Coetzee, J. 1994. The development of top height with age for application to short rotation, non-thinning crops of *E. grandis*. *ICFR Bulletin 9/94*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Coetzee, J. 1995. Factors influencing the decision on initial espacement in the case of short rotation crops. *ICFR Bulletin 5/95*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Coetzee, J., 1999. Growth prediction for short-rotation *E. grandis* crops. *ICFR Bulletin 9/99*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Constanza, R. 1996. Defining Sustainability. In Miller, G. and Tyler, J. (eds). Living in the environment. Principles, Connections and Solutions. Ninth edition. Wadsworth Publishing Co., California, USA.
- Coops, N.C. and Waring, R.H. 2001. Estimating maximum potential site productivity and site water stress in the Eastern Siskiyou using 3-PGPjss. *Can. J. For. Res.* 31:143-154.
- Corbeels, M, McMurtrie, R.E. and O'Connell, A.M. 2001. Modelling the effects of harvest residue management on soil nitrogen supply in short rotation Eucalyptus plantations in Southwestern Australia. *Proceedings of the international workshop 'Models for the sustainable management of temperate plantation forests' held in Bordeaux, France, 7-9 September 2000 as a satellite activity of the 7th EFI annual conference in Lisbon, Portugal, 2-4 September 2000*. EFI-Proceedings. 2001, No.41: 71-80.
- Corbeels, M., O'Connell, A.M., McMurtrie, R.E., Grove, T.S. and Mendham, D.S. 2002. Modelling changes in nitrogen mineralisation following conversion of improved pasture to eucalypt plantation. *Agronomie*. 22(7-8): 801-815.
- Cromer, R.N., and Jarvis, P.G. 1990. Allocation of dry matter in *Eucalyptus grandis* seedlings in response to nitrogen supply. *Aust. J. Plant Physiol.* 17:503-515.
- Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A., and Brown, M. 1993a. Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *For. Ecol. Manage.* 62:211-230.

- Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A., and Brown, M. 1993b. Response to nutrients in *Eucalyptus grandis*. 2. Nitrogen accumulation. *For. Ecol. Manage.* 62:231-243.
- Cromer R N, Balodis V, Cameron D, Garland C P, Rance S and Ryan P. 1998. *Eucalyptus grandis* fertiliser trials: growth, wood properties and kraft pulp yield. *Appita J.* 51:45-49.
- De Ronde, C., 1990. Impact of prescribed fire on soil properties - Comparison with wildfire effects. In: Goldammer, J.G., and Jenkins, M.J. (eds). *Fire and ecosystem dynamics: Mediterranean and Northern perspectives*. SPB Academic publishing, The Hague, Netherlands, pp127-136.
- Dovey, S.B., 2005. Simple ratios to estimate biomass components and nutrient contents in mature stands of some important commercial plantation species. *ICFR Bulletin 13/2005*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Dovey, S.B. and du Toit, B., 2004. Nutrient distributions in black wattle at four ages on three sites with the effects of harvesting practices. *ICFR Bulletin 07/2004*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Dovey, S.B. and du Toit, B., 2005. Calibration of LAI-2000 canopy analyser with leaf area index in a young eucalypt stand. *Trees Structure Function* online publication: Digital Object Identifier (DOI - 10.1007/s00468-005-0038-y).
- du Buisson, S.S., 2003. The Impact of post-harvesting residue burning on environmental sustainability in the Northern Timbers plantations, Tzaneen. Unpublished paper submitted in partial fulfilment of the requirements for the M.S.A. degree, Centre for Sustainable Agriculture, University of the Free State, Bloemfontein.
- du Toit, B. 1993. Soil acidification under forest plantations and the determination of the acid neutralising capacity of soils. Unpublished M.Sc. Thesis, University of Natal.

- du Toit, B., 1995. Guidelines for the fertilization of Pine, Eucalypt and Wattle Plantations in the Summer Rainfall Areas of South Africa. *ICFR Bulletin 10/95*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- du Toit, B., 1998. Initial responses of *E. dunnii* to fertilization and timing of fertilizer applications on a highly leached sandstone-derived soil of the Inanda form. *ICFR Newsletter*, August 1998:13-15. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- du Toit, B., 2002a. Wattle Nutrition. In: Dunlop, R. W. and MacLennan, L., (eds.). *Black Wattle: The South African Research Experience*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. Chapter 6, pp 47-64.
- du Toit, B., 2002b. Long-term ecological sustainability of wattle plantations. In: Dunlop, R. W. and MacLennan, L., (eds). *Black Wattle: The South African Research Experience*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. Chapter 14, pp 135-144.
- du Toit, B. 2003. Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa. *Southern Afr. For. J.* 199:15-25.
- du Toit, B. and Carlson, C., 2000. Fertilisation of commercial forest stands. In Owen, D. (ed). *South African Forestry Handbook*. Vol.1. Southern African Institute of Forestry, V&R Printers, Pretoria. pp 102-105.
- du Toit, B. and Dovey, S.B., 2004. Response of a South African eucalypt plantation to changes in soil nutrients and soil water levels brought about by early, intensive silvicultural management operations. (As yet Unpublished) *Proceedings of the 6<sup>th</sup> CIFOR Workshop: Site Management and Productivity in Tropical Plantation Forests, Piracicaba, Brazil, 22-24 November 2004*.
- du Toit, B. and Dovey, S.B., 2005. Effect of site management on leaf area, biomass development and stand growth efficiency of a young stand of *Eucalyptus grandis* in South Africa. *Can. J. For. Res.* 35(4):891-900.

- du Toit, B. and Drew, D., 2003. Effects of fertilising four eucalypt hybrid stands at planting on wood density, screened pulp yield and fibre production. *ICFR Bulletin 22/2003*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- du Toit, B., and Freimond, S. 1994. Fertilizing trees at planting. In MacLennan, L. (ed). *ICFR Ann. Res. Rep. 1994* Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, pp. 74-84.
- du Toit, B. and Oscroft, D., 2003. Growth response of a eucalypt hybrid to fertilisation at planting across five site types in Zululand. *ICFR bulletin 21/2003*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- du Toit, B. and Scholes, M.C., 2002. Nutritional sustainability of *Eucalyptus* plantations: A case study at Karkloof, South Africa. *Southern Afr. For. J.* 195:63-72.
- du Toit, B., Smith, C., Carlson, C., Esprey, L., Allan, R. and Little, K., 1999. Eucalypt and pine plantations in South Africa. In Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds). *Site management and Productivity in tropical plantation forests. Workshop Proceedings, 16-20 February 1998, Pietermaritzburg, South Africa*. Center for International Forestry Research, Bogor, Indonesia. pp. 23-30.
- du Toit, B., Esprey, L.J., Job, R.A., Fuller, G. and Dovey, S., 2000. Effects of Site Management in *Eucalyptus grandis* plantations in South Africa. In Nambiar, E. K. S., Tiarks, A., Cossalter, C. and Ranger, J. (eds). *Site Management and Productivity in Tropical Plantation Forests. Workshop Proceedings 7-11 December 1999, Kerala, India*. Center for International Forestry Research, Bogor, Indonesia. pp 21-30.
- du Toit B, Arbuthnot A, Oscroft D and Job R A. 2001. The effects of remedial fertiliser treatments on growth and pulp properties of *Eucalyptus grandis* stands established on infertile soils of the Zululand Coastal Plain. *Southern Afr. For. J.* 192:9-18.
- du Toit, B., Fuller, G., Champion, J, McNamara, L and du Plessis, M. 2003. Proceedings of the workshop: Slash management and slash burning in South African Forests: Issues and research needs. *ICFR Bulletin 08/2003*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

- du Toit, B., Dovey, S.B., Fuller, G.F. and Job, R.A., 2004. Effects of Harvesting and Site Management on Nutrient Pools and Stand Growth in a South African Eucalypt Plantation. In Nambiar, E.K.S., Ranger, J., Tiarks, A., and Toma, T. (eds). *Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003*. Center for International Forestry Research, Bogor, Indonesia. pp 31-43.
- Dye, P.J., 2000. Water use in South African Eucalyptus plantations: a review. *Southern Afr. For. J.* 189:17-26.
- Dye, P.J., 2001. Modelling growth and water use in four *Pinus patula* stands with the 3-PGpjs process-based model. *Southern Afr. For. J.* 191:53-63.
- Dye P.J., Jacobs, S. and Drew, D., 2004. Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *For. Ecol. Manage.* 193:197-218.
- Edwards, M. 2000. The South African Forest Sector at a glance. Unpublished address to the Forest Owners association, South Africa, November 2000.
- Ericsson, T., Rytter, L., and Linder, S. 1992. Nutritional dynamics and requirements of short rotation forests. *In Ecophysiology of short rotation forest crops*. In Mitchell, C.P., Ford-Robertson, J.B., Hinkley, T., and Sennerby-Forsse, L. (eds). Elsevier Science Publishers Ltd.; Barking; UK, pp. 35-65.
- Esprey, L.J., 2001. The evaluation of drought risk of *Eucalyptus grandis* using a process-based model. *ICFR Bulletin 12/2001*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Esprey, L.J., Sands, P.J. and Smith, C.W., 2004. Understanding 3-PGpjs using a sensitivity analysis. *For. Ecol. Manage.* 193:235-250.
- Evans, J. 1996. The sustainability of wood production from plantations: evidence over three successive rotations in the Usutu Forest, Swaziland. *Commonwealth For Rev* 75: 234-239.

- Evans, J. 1999a. Sustainability of Forest Plantations: The Evidence. Department for International Development, London, 64 pp.
- Evans, J. 1999b Sustainability of plantation forestry: Impact of species change and successive rotations of pine in the Usutu Forest, Swaziland. *Southern Afr. For. J.* 184: 63-70
- Fabiao, A., Persson, H.A. and Steen, E., 1985. Growth dynamics of superficial roots in Portuguese plantations of *Eucalyptus globulus* Labill. studied with a mesh bag technique. *Plant Soil.* 83:233-242.
- FAO, 2000. Global forest resources assessment 2000. Food and Agriculture Organisation of the United Nations, Rome, Italy. [internet: [www.fao.org/forestry/fra2000](http://www.fao.org/forestry/fra2000); accessed 2 January 2006].
- Fife, D.N. and Nambiar, E.K.S., 1997. Changes in the canopy and growth of *Pinus radiata* in response to nitrogen supply. *For. Ecol. Manage.* 93:137-152.
- Fisher, R. F. and Binkley, D., 2000. Ecology and management of forest soils. Third edition. John Wiley & Sons, Inc., New York. 489pp.
- Fölster, H. and Khanna, P. K., 1997. Dynamics of nutrient supply in plantation soils. In: Nambiar, E.K.S. and Brown, A.G., (eds.) *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 339-378.
- FSA, 2002. The South African Forestry and Forest Products industry 2002. Forestry South Africa, Rivonia, South Africa.
- FSA, 2003. Forestry and Forest products industry Facts and Figures 1979/80 to 2002/03. Published by Forestry South Africa, Rivonia, South Africa. ([www.forestry.co.za](http://www.forestry.co.za)).
- Gardner, R.A.W. and Swain, T-L. 1996. Snow damage to timber plantations in KwaZulu-Natal during July 1996 and subsequent species recommendations. *ICFR Bulletin* 8/96. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, 12p.

- Gee, G.W. and Bauder, J.W., 1986. Particle size analysis. In: Klute, A. (ed.) *Methods of Soil Analysis. Agronomy monograph no. 9, Part 1*. American Society of Agronomy, Madison, Wisconsin, USA, pp 383-411.
- Geldenhuys, C.J., 1999. Requirements for improved and sustainable use of forest biodiversity: examples of multiple use of forests in South Africa. *Forests in focus: Proceedings forum, Biodiversity - Treasures in the World's forests, 3-7 July 1988*. pp 72-82.
- Gessel, S.P., 1984. Site productivity. In Grey, D.C., Schönau, A.P.G. and Schutz, C.J. (eds). *Proc. IUFRO Symposium on site and productivity of fast-growing plantations. Pretoria and Pietermaritzburg, South Africa, 30 April -11 May 1984*. Volume 1, pp 433-439.
- Gholz, H.L. and Lima, W.P., 1997. The ecophysiological basis for productivity in the tropics. In: Nambiar, E.K.S. and Brown, A.G., (eds). *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 213-246.
- Giardina, C.P., Ryan, M.G. and Binkley, D. 2003. Primary production and carbon allocation in relation to nutrient supply in a tropical experimental forest. *Global Change Biol.* 9:1438-1450.
- Gonçalves, J.L.M, and Carlyle, J.C. (1994). Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. *Soil Biol. Biochem.* 26: 1557-1564.
- Gonçalves, J. L. M., Barros, N. F., Nambiar, E. K. S. and Novais, R. F., 1997. Soil and stand management for short-rotation plantations. In: Nambiar, E.K.S. and Brown, A.G., (eds.) *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 379-417.

- Gonçalves, J.L.M., Poggiani, F., Stape, J.L., Serrano, M.I.P., Mello, S.L.M., Mendes, K.C.F.S., Gava, J.L. and Benedetti, V., 1999. Eucalypt plantations in the humid tropics: São Paulo, Brazil. In: Nambiar, E. K. S., Cossalter, C. and Tiarks, A. (eds). *Site Management and Productivity in Tropical Plantation Forests. Workshop Proceedings, 16-20 February 1998., Pietermaritzburg, South Africa*. Center for International Forestry Research, Bogor, Indonesia, pp 5-12.
- Gonçalves, J. L. M., Serrano, M.I.P., Mendes, K.C.F.S. and Gava, J.L., 2000. Effects of site management in a *Eucalyptus* plantation in the humid tropics: São Paulo, Brazil. In: Nambiar, E.K.S., Tiarks, A., Cossalter, C, and Ranger, J., (eds.) *Site management and productivity in tropical plantation forests: a progress report. Workshop Proceedings, 7-11 December 1999, Kerala, India*. Center for International Forestry Research, Bogor, Indonesia, pp 3-9.
- Gonçalves, J.L.M., Mendes, K.C.F.S. and Sasaki, C.M., 2001. Mineralização de Nitrogênio em ecossistemas florestais naturais e implantados do estado de São Paulo. (English title = Nitrogen mineralisation in natural and forest plantation ecosystems of São Paulo State). *Viçosa, Revista Brasileira de Ciência do Solo* 25(3):601-616.
- Gonçalves, J.L.M., Stape, J.L., Benedetti, V., Fessel, V.A.G. and Gava, J.L., 2004a. An evaluation of minimum and intensive soil preparation regarding fertility and tree nutrition: In Gonçalves, J.L.M., and Benedetti, V. (eds) (Translator: McNabb, K). *Forest Nutrition and Fertilization*. Instituto de Pesquisas e Estudos Florestais, Piracicaba, SP, Brazil. Chapter 2, pp 15-64.
- Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Smethurst, P. and Gava, J.L., 2004b. Silvicultural effects on the productivity and wood quality of eucalypt plantations. *Forest Ecol Manage.* 193:45-61.
- Gonçalves, J.L.M., Gava, J.L. and Wichert, M.C.P., 2004c. Sustainability of wood production in eucalypt plantations of Brazil. In Nambiar, E.K.S., Ranger, J., Tiarks, A., and Toma, T. (eds). *Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003*. Center for International Forestry Research, Bogor, Indonesia. pp 3-14.

- Grey, D.C., 1987. A study of the relationship between environmental factors and mensurational parameters in *P. radiata* (D.Don.). Unpublished PhD thesis. University of Stellenbosch. 130pp.
- Grove, T.S., Thomson, B.D. and Malajczuk, N., 1996. Nutritional physiology of eucalypts: Uptake, distribution and utilization. In: Attiwill, P. M. and Adams, M. A. (eds.) *Nutrition of eucalypts*. CSIRO, Australia. pp77-108.
- Guthrie, H.B., Attiwill, P.M. and Leuning, R., 1978. Nutrient cycling in a *Eucalyptus obliqua* (L'Herit) forest. II: A study in a small catchment. *Australian J. Bot.* 26:189-201.
- Hardiyanto, E.B. Ryantoko, A. and Anshori, S. 2000. Effects of site management in *Acacia mangium* plantation at PT. Musi Hutan Persada, South Sumatra, Indonesia. In: Nambiar, E.K.S., Tiarks, A., Cossalter, C, and Ranger, J., (eds.) *Site management and productivity in tropical plantation forests: a progress report. Workshop Proceedings, 7-11 December 1999, Kerala, India*. Center for International Forestry Research, Bogor, Indonesia, pp 41-49.
- Harwood, C.E. and Jackson, W.D., 1975. Atmospheric losses of four plant nutrients during a forest fire. *Australian For.* 38(2):92-99.
- Helmke, P.A. and Sparks, D.L., 1996. Chapter 19. Lithium, Sodium, Potassium, Rubidium and Cesium. In Bartels, J. M., (Managing Ed.) *Methods of soil analysis. Part 3. Chemical methods*. Soil Sci. Soc. Am. Book series No. 5. Soil Sci. Soc. Am., Madison, Wisconsin, USA: 551-574.
- Helms, J.A. (Ed), 1998. *The Dictionary of Forestry*. The Society of American Foresters and CABI publishing, Wallingford, UK.
- Herbert, M.A., 1984. Variation in the growth of and responses to fertilizing Black Wattle with nitrogen, phosphorus, potassium and lime over three rotations. In: Grey, D.C., Schönau, A.P.G., Schutz, C.J. and Van Laar, A.. *IUFRO symposium on site productivity of fast growing plantations, Pretoria and Pietermaritzburg, 30 April-11 May 1984. Vol 2*, pp 907-920.

- Herbert, M.A., 1996. Fertilisers and eucalypt plantations in South Africa. In: Attiwill, P. M. and Adams, M. A. (eds). *Nutrition of Eucalypts*. CSIRO Publishing, Australia. pp 303-325.
- Herbert, M.A. and Robertson, M.A., 1991. Above-ground biomass composition and nutrient content for *Eucalyptus* species in the south-eastern Transvaal. In: Schönau, A.P.G. (ed.) *Intensive Forestry: The role of eucalypts. Proceedings of IUFRO symposium, Durban, South Africa, 2-6 September 1991*, Vol. 2, pp 662-674.
- Herbert, M.A. and Schönau, A.P.G. 1989. Fertilising commercial forest species in southern Africa: Research progress and problems (Part 1 ). *South Afr. For. J.* 151 : 58-70.
- Herbert, M.A. and Schönau, A.P.G. 1990. Fertilising commercial forest species in southern Africa: Research progress and problems (Part 2). *South Afr. For. J.* 152: 34-42.
- Hough, W.A., 1981. Impact of prescribed fire on understory and forest floor nutrients. U.S. Department of Agriculture, Forest Service Research Note SE-303.
- Hunter, I. 2001. Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis*, *Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertilizer, at 3 years of age, in southern India. *For. Ecol. Manage.* 144:189-199.
- ICFR, 1998. Annual Research Report 1998. (Ed. MacLennan, L.). Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, pp 134-136.
- ICFR, 2000. Fertilizer recommendations for Commercial Hardwood species in South Africa. *ICFR Innovations 2000/02*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, 4 pp.
- Job, A., du Toit, B., and Esprey, L.J. 2003. Estimating selected input parameters for 3-PG using above-ground biomass data collected from an age series of *Eucalyptus grandis* in KwaZulu-Natal, South Africa. *ICFR Bulletin 15/2003*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

- Johnson, D.W., West, D.C., Todd, D.E., and Mann, L.K., 1982. Effects of sawlog vs. Whole-tree harvesting on the nitrogen, phosphorus, potassium and calcium budgets of an upland mixed oak forest. *Soil Sci. Soc. Am. J.* 46:1304-1309
- Jokela, E.J. and Martin, T.A. 2000. Effects of ontogeny and soil nutrient supply on production, allocation and leaf area efficiency in loblolly and slash pine stands. *Can. J. For. Res.* 30:1511-1524.
- Joubert, G.P.J., 1965. Die verband tussen opstandsbonniteit van *Pinus radiata* en grondeienskappe. Unpublished MSc Thesis, University of Stellenbosch. 45pp.
- Judd, T.S., 1996. Simulated nutrient losses due to timber harvesting in highly productive eucalypt forests and plantations. In: Attiwill, P.M and Adams, M.A. (eds.) *Nutrition of eucalypts*. CSIRO Publishing, Australia. pp 249-258.
- Kallarackal, J. and Somen, C.K., 1997. An ecophysiological evaluation of the suitability of *Eucalyptus grandis* for planting in the tropics. *For. Ecol. Manage.* 95:53-61.
- Kalra, Y.P. and Maynard, D.G., 1991. Methods manual for forest soil and plant analysis. *Inf. Rep. NOR-X-319*, Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.
- Karathanasis, A.D. and Hajek, B.F., 1996. Elemental Analysis by X-Ray Fluorescence Spectroscopy. In Bartels, J. M., (Managing ed.) *Methods of soil analysis. Part 3. Chemical methods*. Soil Sci. Soc. Am. Book series No. 5. Soil Sci. Soc. Am., Madison, Wisconsin, USA pp 161-223.
- Kaufmann, M.R. and Linder, S., 1996. Tree Physiology research in a changing world. *Tree Physiol.* 16:1-4.
- Keeney, D. 1982. Nitrogen-availability indices. In: Page, A., Miller, R., and Keeney, D., (eds.) *Methods of soil analysis, Part 2, Chemical and microbiological properties*. Am. Soc. Agron. Madison, Wisconsin, USA: 711-734.

- Keith, H., Raison, R.J. and Jacobsen, K.L. 1997. Allocation of carbon in a mature eucalypt forest and some effects of soil phosphorus availability. *Plant Soil* 196:81-99.
- Kimmins, J.P., 1972. The ecology of forestry: the ecological role of man, the forester, in forest ecosystems. *For. Chronicle* 48:301-307.
- Kimmins, J.P., 1994. Identifying key processes affecting long-term site productivity. In: Dyck, W.J, Cole, D.W. and Comerford, N.B. (eds). *Impacts of forest harvesting on long-term productivity*. Chapman & Hall, London, pp 41-80.
- Kirschbaum, M.U.F., Bellingham, D.W., and Cromer, R.N. 1992. Growth analysis of the effect of phosphorus nutrition on seedlings of *Eucalyptus grandis*. *Aust. J. Plant Physiol.* 19:55-66.
- Klute, A. 1986. Water retention: laboratory methods. In: *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Agronomy Monograph 9, 2<sup>nd</sup> Ed.* In: Klute, A. (ed). Am. Soc. Agron. & Soil Sci. Soc. Am., Madison, WI, USA. pp. 635-662.
- Kunz, R., and Smith C.W. 2001. An initial assessment of drought risk for the forestry areas in the summer rainfall region of southern Africa. *ICFR Bulletin 15/2001*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Küppers, M., Wheeler, A.M., Küppers, B.I.L., Kirschbaum, M.U.F., Farquhar, G.D., 1986. Carbon fixation in eucalypts in the field. Analysis of diurnal variations in photosynthetic capacity. *Oecologia*. 70:273-282.
- Laclau, J.P., 2001. Dynamique du fonctionnement mineral d'une plantation d'Eucalyptus: Effets du reboisement sur un sol de savanne du littoral congolais; consequences pour la gestion des plantations industrielles. PhD. Thesis, Institut National Aronomique Paris-Grignon, France.
- Laclau, J.P., Bouillet, J.P. and Ranger, J., 2000. Dynamics of biomass and nutrient accumulation in a clonal plantation of *Eucalyptus* in Congo. *For. Ecol. Manage.* 128:181-196.

- Laclau, J.P., Deleporte, P., Ranger, J., Bouillet, J.P. and Kazotti, G., 2003. Nutrient dynamics throughout the rotation of Eucalyptus clonal stands in Congo. *Ann. Bot.* 91:879-892.
- Landsberg, J.J and Gower, S.T. 1997. Applications of Physiological Ecology to Forest Management. Academic Press, New York.
- Landsberg, J.J. and Hingston, F.J. 1996. Evaluating a simple radiation/dry matter conversion model using data from *Eucalyptus globulus* plantations in Western Australia. *Tree Physiol.* 16:801-808.
- Landsberg, J.J. and Waring, R.H. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.* 95:209-228.
- Landsberg, J.J., Johnsen, K.H., Albaugh, J., Allen, H.L. and McKeand, S.E. 2001. Applying 3-PG, a simple process-based model designed to produce practical results, to data from Loblolly pine experiments. *For. Sci.* 47:43-51.
- Lane, P.W. and Payne, R.W. 1996. Genstat® for Windows™, an introductory course. Lawes Agricultural Trust, Rothamstead Experimental Station, U.K.
- Ledig, F.T. 1983. The influence of genotype and environment on dry matter distribution in plants. In: Huxley, P.A. (ed). *Plant research in Agroforestry*. ICRAF, Nairobi, pp. 427-454.
- Lee, K.H. and Jose, S., 2003. Soil respiration, fine root production, and microbial biomass in cottonwood and loblolly pine plantations along a nitrogen fertilisation gradient. *For. Ecol. Manage.* 185:263-273.
- Leitch, C.J., Flinn, D.W., van de Graaff, R.H.M., 1983. Erosion and nutrient loss resulting from Ash Wednesday (February 1983) wildfires: a case study. *Australian For.* 46(3):173-180.
- Leuning, R., Wang, Y.P and Cromer, R.N. 1991. Model simulations of spatial and daily totals of photosynthesis in *Eucalyptus grandis* canopies. *Oecologia* 88:494-503.

- LI-COR Inc. 1992. LAI-2000 Plant Canopy Analyser operating manual. Li-Cor Inc., Lincoln, N.C., USA. 183 pp.
- Likens, G.E., Bornman, F.H., Pierce, R.S., Eaton, J.S. and Johnson, N. 1977. Biogeochemistry of a forested ecosystem. Springer-verlag, New York.
- Linder, S. 1985. Potential and actual production in Australian forest stands. In: Landsberg, J.J., and Parsons, W. (eds). *Research for forest management*. CSIRO, Melbourne, pp. 11-35.
- Linder, S. 1987. Responses to water and nutrients in coniferous ecosystems. In: Schulze, E.D., and Zwolfer, H. (eds). *Potentials and limitations of ecosystem analysis. Ecological studies No. 61*. Springer-Verlag, Berlin, pp 180-202.
- Linder, S. and Rook, D.A., 1984. Effects of Mineral Nutrition on Carbon dioxide exchange and partitioning of carbon in trees. In Bowen, G.D. and Nambiar, E.K.S. (eds). *Nutrition of Plantation Forests*. Academic Press, London. pp 211-236.
- Linder, S., Benson, M.L., Myers, B.J., and Raison, R.J. 1987. Canopy dynamics and growth of *Pinus radiata*. I. Effects of irrigation and fertilization during a drought. *Can. J. For. Res.* 17:1157-1165.
- Little, K M. 1999. The influence of vegetation control on the growth of a *Eucalyptus grandis* x *camaldulensis* hybrid clone. PhD. Thesis, Univ. Of Natal. 136 pp.
- Little, K.M. and Rolando, C.A., 2002. Post-establishment vegetation control in a *Eucalyptus grandis* x *E. camaldulensis* stand. *Southern Afr. For. J.* 193:77-80.
- Little, K.M. and van Staden, J., 2003. Interspecific competition affects early growth of a *Eucalyptus grandis* x *E. camaldulensis* hybrid clone in Zululand, South Africa. *South Afr. J. Bot.* 69(4): 505-513.
- Little, K., Eccles, N., Oscroft, D., Viero, P. and Eastwood, T., 1996. Growth of eucalypts on slash managed and burned sites in Zululand. *ICFR Bulletin 3/96*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, 38pp.

- Little, K.M., Kritzing, J. and Maxfield, M., 1997. Some principles of vegetation management explained. *ICFR Bulletin 9/97*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Little, K. M., Smith, C. W. and Norris, C.H., 2000a. The influence of various methods of plantation residue management on replanted *Acacia mearnsii* growth. *Australian Forestry* 63(3):226-234.
- Little, K., Arnot, L., du Toit, B. and Maxfield, M., 2000b. The killing of *Eucalyptus grandis* multiple-stem cut-stumps in the Karkloof Project: putting recommendations into practice. *ICFR Bulletin 03/2000*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa., 6pp.
- Little, K.M., du Toit, B and Esprey, L.J., 2002. Competitive interactions between grasses and broadleaves and early *P. greggii* growth. In Frochet, H., Collet, C. and Balandier, P. (eds). *Popular summaries from the fourth international conference on forest vegetation management, Nancy, France, 17-21 June 2002*. Institut National de la Recherche Agronomique, 54 280, Champenoux, France. pp381-383.
- Louw, J.H., 1991. The relationship between site characteristics and *Pinus radiata* growth on the Tsitsikamma Plateau, South Africa. *S. Afr. For. J.* 158:37-45.
- Louw, J.H., 1995. Site classification and evaluation for commercial forestry in the Crocodile river catchment. Unpublished M.Sc. Thesis, University of Stellenbosch. 331pp.
- Louw, J.H., 1997. A site-growth study of *Eucalyptus grandis* in the Mpumalanga escarpment area. *S. Afr. For. J.* 180:1-14.
- Mackensen, J., Hölsher, D., Klinge, R. and Fölster, H., 1996. Nutrient transfer to the atmosphere by burning of forests in eastern Amazonia. *For. Ecol. Manage.* 86:121-128.
- Mäkelä, A. and Valentine, H. T., 2001. The ratio of NPP to GPP: evidence of change over the course of stand development. *Tree Physiol.* 21(14):1015-1030.

- Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E.; Ter-Mikaelian, M, Ågren, G.I., Oliver, C.D. and Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiol.* 20:289-298.
- McConway, K.J., Jones, M.C. and Taylor, P.C. 1999. Statistical modelling using GENSTAT®. Arnold, London, 502pp.
- Mendham, D.S., O'Connell, A.M., Grove, T.S., and Rance, S.J., 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. *For. Ecol. Manage.* 181:357-372.
- Miller, H.G., 1995. The influence of stand development on nutrient demand, growth, and allocation. *Plant and Soil* 168-169: 225-232.
- Misra, R.K., Turnbull, C.R.A., Cromer, R.N., Gibbons, A.K., and LaSala, A.V. 1998. Below- and above-ground growth of *Eucalyptus nitens* in a young plantation. I: Biomass. *For. Ecol. Manage.* 106:283-293.
- Monteith, J.L. 1965. Evaporation and Environment. In: Fogg, G.E (ed). *The state and movement of water in living organisms. Proceedings of the 19<sup>th</sup> Symposium of the Society of Experimental Biology.* Cambridge University Press, pp. 205-234.
- Morris, A. R., 1986. Soil Fertility and long term productivity of *Pinus patula* in Swaziland. Ph.D. Thesis, University of Reading, 388pp.
- Morris, A.R. and Smith, C.W., 2002. Growth and yield as an indication of sustainable forest management in industrial plantations. *Southern African J. For.* 195: 47-56.
- Musto, 1992. Impacts of plantation forestry on various soil types. In MacLennan, L. (ed). Institute for Commercial Forestry Research Annual Research Report 1992, pp 38-51.
- Nambiar, E.K.S. 1990. Interplay between nutrients, water, root growth and productivity in young plantations. *For. Ecol. Manage.* 30:213-232.
- Nambiar E.K.S, 1996. Sustained Productivity of forests is a continuing challenge to soil

science. *Soil Sci. Soc. Am. J.* 60:1692-1642.

Nambiar, E. K. S. 1999a. Pursuit of sustainable plantation forestry. *Southern Afr. For. J.* 184:45-62.

Nambiar, E.K.S., 1999b. Introduction. In: Nambiar, E.K.S., Cossalter, C. and Tiarks, A. (eds.) *Site Management and Productivity in Tropical Plantation Forests. Workshop Proceedings, 16-20 February 1998., Pietermaritzburg, South Africa.* Center for International Forestry Research, Bogor, Indonesia, pp 1-3.

Nambiar, E.K.S. and Brown, A.G., 1997. Towards sustained productivity of tropical plantations: science and practice. In: Nambiar, E.K.S. and Brown, A.G., (eds.) *Management of Soil, Nutrients and Water in Tropical Plantation Forests.* ACIAR Monograph No. 43, pp 527-557.

Neary, D.G., Klopatek, C.C., Debano, L.F. and Ffolliott, P.F., 1999. Fire effects on belowground sustainability: a review and synthesis. *For. Ecol. Manage.* 122:51-71.

Negi, J.D.S. and Sharma, S.C., 1985. Biomass and nutrient distribution in an age series of *Eucalyptus* hybrid plantation in Tamil Nadu. I. Distribution of organic matter. *Indian Forester* 111:1111-1122.

Nelson, D. W. and Sommers, L. E., 1996. Total carbon, organic carbon and organic matter. In: In Bartels, J. M., (Managing ed.). *Methods of soil analysis. Part 3. Chemical methods.* Soil Science Society of America Book series; No 5. Madison, Wisconsin, USA. pp 995-996.

Nicholson, G. 1984. Methods of soil, plant, and water analysis. FRI Bulletin No.70, Forest Research Institute, New Zealand Forest Service, Rotorua, New Zealand.

Nkosana, M. 2002. Some effects of early silvicultural management operations on root turnover in *Eucalyptus grandis* plantations. M.Sc. Thesis, Univ. of Witwatersrand, Johannesburg, South Africa.

Noble, A.D., 1992. Nutrition of Eucalypts on the Zululand sands. In MacLennan, L. (ed).

*ICFR Annual Research Report 1992*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, pp 56-72.

Noble, A.D., Donkin, M.J. and Smith, C.W., 1991. The importance of soil properties as indicators of site quality of *Eucalyptus grandis* on the Zululand coastal plain. In Schönau, A.P.G. (ed). *Intensive Forestry: The role of eucalypts. IUFRO Symposium Proceedings, 2-6 September 1991, Durban, South Africa*. Southern African Institute of Forestry, Pretoria, South Africa. Vol. 1, pp. 433-443.

Norris C W. 1995. Site preparation options for South African Forestry Soils. *ICFR Bulletin 6/95*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, 21 pp.

Nzila, J.D., Deleporte, P., Bouillet, J.P Laclau, J.P and Ranger, J., 2004. Effects of slash management on tree growth and Nutrient cycling in second-rotation *Eucalyptus* replanted sites in the Congo. In Nambiar, E.K.S., Ranger, J., Tiarks, A., and Toma, T. (eds). *Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003*. Center for International Forestry Research, Bogor, Indonesia. pp 15-30.

O'Connell, A.M., 1990. Microbial decomposition (respiration) of litter in eucalypt forests of south-western Australia: an empirical model based on laboratory incubation. *Soil Biol. Biochem.* 22(2):153-160.

O'Connell, A.M., and Rance, S.J., 1999. Predicting nitrogen supply in plantation eucalypt forests. *Soil Biol. Biochem* 31: 1943-1951.

O'Connell, A.M. and Sankaran, K.V., 1997. Organic matter accretion, decomposition and mineralisation. In: Nambiar, E.K.S. and Brown, A.G., (eds.) *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR Monograph No. 43, pp 443-480.

O'Connell, A.M., Grove, T.S., Mendham, D. and Rance, S.J., 2000. Effects of site management in eucalypt plantations in southwestern Australia. In: Nambiar, E.K.S., Tiarks, A., Cossalter, C, and Ranger, J., (eds.) *Site management and productivity in tropical plantation forests: a progress report. Workshop Proceedings, 7-11 December*

- 1999, Kerala, India. Center for International Forestry Research, Bogor, Indonesia, pp 61-71.
- O'Connell, A.M., Grove, T.S., Mendham, D., Corbeels, M., McMurtrie, R.F., Shammis, K. and Rance, S.J., 2004. Impacts of Inter-rotation site management on nutrient stores and fluxes and growth of Eucalypt plantations in southwestern Australia. In Nambiar, E.K.S., Ranger, J., Tiarks, A., and Toma, T. (eds). *Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003*. Center for International Forestry Research, Bogor, Indonesia. pp 77-91.
- Osório, J., Osório, M.L., Chaves, M.M., and Pereira, J.S. 1998. Water deficits are more important in delaying growth than in changing patterns of carbon allocation in *Eucalyptus globulus*. *Tree Physiol.* 18:363-373.
- Owen, D.L., and Van der Zel, D.W., 2000. Historical development of SA Forestry. In Owen, D.L. (ed.) *South African Forestry Handbook. 4th Ed.*, Southern African Institute of Forestry, V&R Printers, Pretoria. pp 3-8. ISBN 0-620-06439-0.
- Owens, L.B. and Watson, J.P. 1979. Rates of weathering and soil formation on granite in Rhodesia. *Soil Sci. Soc. Am. J.* 43:160-166.
- Paul, K.I., Polglase, P.J., O'Connell, A.M., Carlyle, J.C., Smethurst, P.J. and Khanna, P., 2002. Soil nitrogen availability predictor (SNAP): a simple model for predicting mineralisation of nitrogen in forest soils. *Australian J. Soil Res.* 40 (6):1011-1026.
- Pennefather, M. and Macgillivray, F., 1971. Fertilizing of *Eucalyptus grandis* (Saligna) on old wattle soils. *S. Afr. For. J.* 76:1-5.
- Poynton, R.J. 1979. Tree Planting in Southern Africa. Vol. 2. The Eucalypts. Department of Forestry, Republic of South Africa. pp 350-378.
- Raison, R.J., 1984. Potential adverse affects of forest operations on the fertility of soils supporting fast growing plantations. In: In Grey, D.C., Schönau, A.P.G. and Schutz, C.J. (eds). *Proc. IUFRO Symposium on site and productivity of fast-growing plantations. Pretoria and Pietermaritzburg, South Africa, 30 April -11 May 1984*.

Volume 1, pp. 457-471.

Raison, R.J., Connell, M.J. and Khanna, P.K., 1987. Methodology for studying fluxes of soil mineral-N in situ. *Soil Biol. Biochem* 19(5): 521-530.

Ranger, J and Turpault, M.P., 1999. Input-output nutrient budgets as a diagnostic tool for sustainable forest management. *For. Ecol. Manage.* 122:139-154.

Reuss, J.O. Cosby, B.J. and Wright, R.F., 1987. Chemical processes governing soil and water acidification. *Nature* 329:27-32.

Richards, B.N. and Charley, J.L. 1983. Mineral cycling processes and system stability in the eucalypt forest. *For. Ecol. Manage.* 7:31-47.

Rolando C A, Little K M and Norris C H. 2002. Initial results of the first rotation of a residue management trial in Zululand. *ICFR Bulletin 04/2002*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 19pp.

Romanyà, J. Khanna, P.K., and Raison, R.J. 1994. Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. *For. Ecol. Manage.* 65:89-103.

Ryan M.G., Hubbard, R.M., Pongracic, S., Raison, R.J. and McMurtrie, R.E., 1996. Foliage, fine-root, woody-tissue and stand respiration in *Pinus radiata* in relation to nitrogen status. *Tree Physiol.* 16:333-343.

Sands, P.J. and Landsberg, J.J., 2002. Parameterisation of 3-PGpjs for plantation grown *Eucalyptus globulus*. *For. Ecol. Manage.* 163:273-292.

Sands, P.J., Cromer, R.N., and Kirschbaum, M.U.F. 1992. A model of nutrient response in *Eucalyptus grandis* seedlings. *Aust. J. Plant Physiol.* 19:459-470.

Santantonio D. and Grace, J.C., 1987. Estimating fine-root production and turnover from biomass and decomposition data: a compartment-flow model. *Can. J. For. Res.* 17:900-908.

- Santantonio, D. and Santantonio, E., 1987. Effect of thinning on production and mortality of fine roots in a *Pinus radiata* plantation on a fertile site in New Zealand. *Can J. For. Res.* 17:919-928.
- Schafer, G.N., 1988a. A site growth model for *Pinus elliottii* in the Southern Cape. *S. Afr. For. J.* 146:12-17.
- Schafer, G.N., 1988b. A site growth model for *Pinus pinaster* in the Southern Cape. *S. Afr. For. J.* 146:18-22.
- Schönau, A.P.G. 1983. Fertilisation in South African Forestry. *S. Afr. For. J.* 125:1-19.
- Schönau, A.P.G. 1984. Silvicultural considerations for high productivity of *Eucalyptus grandis*. *For. Ecol. Manage.* 9:295-314.
- Schönau, A.P.G. 1989. Requirements for intensive silviculture. *South Afr. For. J.* 150:40-49.
- Schönau, A.P.G. 1991. Role of eucalypt plantations in timber supply and forest conservation in Sub-Saharan Africa. *S. Afr. For. J.* 156:56-60.
- Schönau, A.P.G. and Aldworth, W.J.K., 1991. Site evaluation in Black Wattle with special reference to soil factors. *S. Afr. For. J.* 156:35-43.
- Schönau, A.P.G. and Pennefather, M., 1975. A first account of profits at harvesting as a result of fertilizing *Eucalyptus grandis* at time of planting in southern Africa. *S. Afr. For. J.* 94:29-35.
- Schönau, A.P.G., Verloren van Themaat, R. and Boden, D.I., 1981. The importance of complete site preparation and fertilising in the establishment of *Eucalyptus grandis*. *S. Afr. For. J.* 116:1-10.
- Schulze, R. E., 1997. South African Atlas of Agrohydrology and -Climatology. Water

Research Commission, Pretoria, South Africa. Report TT82/96.

Schulze, R.E., Smithers, J.C., Lynch, S.D. and Lecler, N.L. 1995. Obtaining and interpreting output in ACRU. In: Smithers, J.C. and Schulze, R.E. ACRU agrohydrological modelling system: user manual, version 3.00, AM7-1 to AM 7-21. Water Research Commission, Pretoria, South Africa. Report TT70/95.

Schutz, C.J., 1990. Site Relationships for *Pinus Patula* in the eastern Transvaal Escarpment. Unpublished Ph.D. Thesis, University of Natal, Pietermaritzburg. 334pp.

Schutz, C.J, Bredenkamp, B.V. and Herbert, M.A., 1983. Stand density and litter depth of *Pinus patula*. *S. Afr. For. J.* 124:43-49.

Scholes, R.J. and Scholes, M.C., 1999. Nutrient imbalances following conversion of grasslands to plantation forests in South Africa. In Smaling, E.M.A., Oenema, O. and Fresco, L.O. (eds). *Nutrient Disequilibria in Agroecosystems*. CAB International. Chapter 9, pp 175-189.

Schumann, A. W., 1992. The impact of weeds and two legume crops on eucalyptus hybrid clone establishment. *S. Afr. For. J.* 160:43-48.

Scott. D.F. and Van Wyk, D.B., 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *J. Hydrol.*, 121:239-256.

Sherry, SP, 1953. The effect of different methods of brushwood disposal upon site conditions in wattle plantations. I. Experimental layout and apparatus designed for the measurement of run-off and soil-loss. In Wattle Research Institute Report for 1952-53 (sixth year), pp 33-41.

Sherry, SP, 1954. The effect of different methods of brushwood disposal upon site conditions in wattle plantations. II. A study of run-off and erosion during the first two years after clear-felling and regeneration. In Wattle Research Institute Report for 1953-54 (seventh year), pp 27-36.

Sherry, SP, 1961. The effect of different methods of brushwood disposal upon site

- conditions in wattle plantations. III. Run-off behaviour over a nine-year rotation. In Wattle Research Institute Report for 1960-61 (fourteenth year), pp 32-40.
- Sherry, SP, 1964. The effect of different methods of brushwood disposal upon site conditions in wattle plantations. IV. A study of run-off and erosion during the first two rainy seasons of the second crop cycle of the experiment. In Wattle Research Institute Report for 1963-64 (seventeenth year), pp 41-50.
- Simpson, D.E., 1991. Quantification of the effects of land use on runoff water quality in selected catchments in Natal: Final report to the Water Research Commission. *WRC Report 237/1/91*, Division of Water Technology, CSIR, South Africa. ISBN no. 1874858225.
- Smethurst, P.J. and Nambiar, E.K.S., 1990. Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. *Can. J. For. Res.* 20:1498-1507.
- Smethurst, P., Baillie, C., Cherry, M., Holz, G., 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. *For. Ecol. Manage.* 176:531-542.
- Smith, C.W., 1998. Site Damage and Long-term Site Productivity of Forest Plantations in South Africa: Impacts of Harvesting Operations and Suggested Management Strategies. *ICFR Bulletin 14/98*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 35 pp.
- Smith, C. W. 1999. Site damage and long-term site productivity of forest plantations in South Africa. *ICFR Handbook Series No. 1/99*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa, 44 pp.
- Smith, C.W., 2000. Harvesting impacts and long-term site productivity: the South African experience. In: Stokes, B and Lauhanen R. (eds). *Forest Operations and Environmental Protection, Forests and Society. Proceedings of IUFRO Group 3.11.00, International Union of Forest Research Organisations (IUFRO) XXI World Congress, 7 - 12 August 2000, Kuala Lumpur, Malaysia*. Finnish Forest Research Institute, Parkano, Finland. pp 14 – 22.

- Smith C.W., 2003. Does soil compaction on harvesting extraction roads affect long-term productivity of Eucalyptus plantations in Zululand? *Southern Afr. For. J.* 199:41-54.
- Smith, C.W. and du Toit, B., 2005. The effect of harvesting operations, slash management and fertilisation on the growth of a Eucalyptus clonal hybrid on a sandy soil. *Southern Afr. For. J.* 203:15-26.
- Smith, C.W., Johnston, M.A. and Lorentz, S., 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. *Geoderma* 78: 93 - 111
- Smith, C.W., Norris, C.H. and Esprey, L.J., 2000. The effect of land preparation at establishment on the productivity of fast growing hardwoods in the summer rainfall regions of South Africa. *ICFR Bulletin 06/2000*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 31 pp.
- Smith C.W., Johnston, M.A. and Lorentz, S. A. 2001a. The effect of soil compaction on the water retention characteristics of soils in forest plantations. *S. Afr. J. Plant Soil* 18: 87 – 97.
- Smith, C.W. Little, K.M. and Norris, C.H. 2001b. The effect of land preparation at re-establishment on the productivity of fast growing hardwoods in South Africa. *Australian For.* 64: 165 -174.
- Smith, C.W., Little, K.M, Rolando, C. and du Toit, B., 2005. The Plantation Forestry Sustainability Initiative: A framework for monitoring and measuring the sustainability of intensively managed southern African forest plantations. *ICFR bulletin 10/2005*. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.
- Smith, P., and Thomasson, A.J. 1974. Density and water release characteristics. In Soil survey laboratory methods, Tech. Monograph no.6. *Edited by Avery, B.W., and Bascomb, C.L.* Rothamstead Experimental Station, Harpendon, Herts, UK.
- Snowdon, P. and Waring, H.D., 1984. Long-term nature of growth responses obtained to fertiliser and weed control applied at planting and their consequences for forest management. In: Grey, D.C., Schönau, A.P.G., Schutz, C.J. and Van Laar, A. (eds.).

Proc. IUFRO Symposium on Site and Productivity of Fast Growing Plantations.  
Pretoria and Pietermaritzburg, South Africa, Volume 2, pp. 701-711.

Snowdon, P., 2002. Modeling Type 1 and Type 2 growth responses in plantations after application of fertiliser or other silvicultural treatments. *For. Ecol. Manage.* 163:229-244.

Soil classification working group, 1991. *Soil Classification: A taxonomic system for South Africa. Memoirs of the Natural Agricultural Resources of South Africa No. 15*, Department of Agricultural Development, Pretoria, South Africa.

Son, Y.H., 2001. Non-symbiotic nitrogen fixation in forest ecosystems. *Ecol. Res.* 16:183-196.

Squire, R. O., Flinn, D. W. & Farrell, P. W. 1979. Productivity of first and second rotation stands of radiata pine on sandy soils. I. Site factors affecting early growth. *Australian For.* 42, 226-235.

Squire, R.O., Farrell, P.W., Flinn, D.W. and Aeberli, B.C. (1985) Productivity of first and second rotation stands of radiata pine on sandy soils, II. Height and volume growth at five years. *Australian For.* 48: 127-137

Stape, J.L. 2002. Production ecology of clonal Eucalyptus plantations in northeastern Brazil. Ph.D. Dissertation, Colorado State University, Ft. Collins, U.S.A.

Stewart, H.T.L., Hopmans, P., Flinn, D.W. and Croatto, G., 1990. Harvesting effects on phosphorus availability in a mixed eucalypt ecosystem in southeastern Australia. *For. Ecol. Manage.* 36:149-162.

Stoneman, G.L., Crombie, D.S., Whitford, K., Hingston, F.J., Giles, R., Portlock, C.C., Galbraith, J.H., and Dimmock, G.M. 1996. Growth and water relations of *Eucalyptus marginata* (jarrah) stands in response to thinning and fertilization. *Tree Physiol.* 16:267-274.

Stubbings, J.A. and Schönau, A.P.G. 1980. Management of short rotation coppice crops of *Eucalyptus grandis*. *S. Afr. For. J.* 115: 38-46.

- Tandon, V.N., Pande, M.C. and Singh, R., 1988. Biomass estimation and distribution of nutrients in five different aged *Eucalyptus grandis* plantation ecosystems in Kerala state. *Indian Forester* 114:184-199.
- Tiarks, A., Nambiar, E.K.S. and Cossalter, C., 1998. Site Management and Productivity in Tropical Forest Plantations. *Occasional Paper no. 16*, Centre for International Forestry Research, Bogor, Indonesia. 11 pp.
- Toman, M.A. and Ashton, P.M.S., 1996. Sustainable forest ecosystems and management: A review article. *For. Sci.* 42: 366-377.
- Turnbull C.R.A., Beadle, C.L., Bird, T., and McLeod, D.E. 1988. Volume production in intensively managed eucalypt plantations. *Appita J.* 41: 447-450.
- Turner, J., 1986. Organic matter accumulation in a series of *Eucalyptus grandis* plantations. *For. Ecol. Manage.* 17:231-242.
- Turner, J. and Lambert, M. J., 1986. Effects of forest harvesting nutrient removals on soil nutrient reserves. *Oecologia* 70:140-148.
- UR2PI (Unite de reserche de Productivite des Plantations Industrielles), 2001. Unpublished hand-out for field trip during CIFOR workshop, Pointe-Noire, Republic of Congo, July 2001.
- Van Wyk, D.B. 1985. The effects of catchment management on sediment and nutrient exports in the Natal Drakensberg. In Schulze, R.E. (ed). Proceedings of the second South African National Hydrology Symposium, Pietermaritzburg, 16-18 September 1985.
- Van Wyk, D.B. 1986. The effects of catchment management on sediment and nutrient exports in the Natal Drakensberg. In: Schulze, R.E. (ed). Proceedings of the second South African National Hydrology Symposium, Pietermaritzburg, 16-18 September 1985. *Agricultural Catchments Research Unit , Report no. 22, Department of*

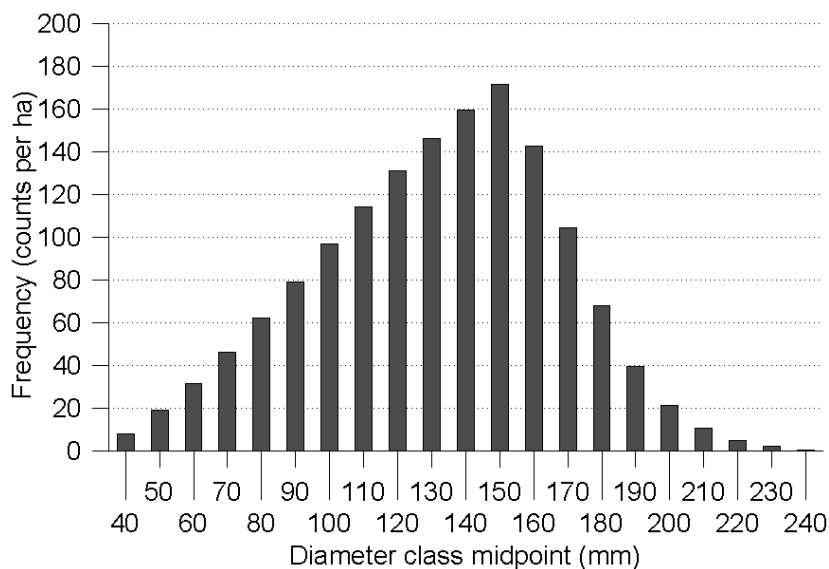
- Van Wyk, D.B., 1990. Atmospheric deposition at selected sites in the mountain catchments of South Africa. In: *Proceedings of the 1<sup>st</sup> IUAPPA regional Conference on Air pollution: Towards the 21<sup>st</sup> Century*. National Association for clean air, 24-26 October 1990, Pretoria, South Africa. Vol. 1, Paper no. 8.
- Viero, P.W.M., Chiswell, K.E.A., and Theron, J.M., 2002. The effect of a soil-amended hydrogel on the establishment of a *Eucalyptus grandis* clone on a sandy clay loam soil in Zululand during winter. *Southern Afr. For. J.* 193:65-75.
- Vogt, K., Asbjornsen, H., Ercelawn, A., Montagnini, F. and Valdés, M. 1997. Roots and mycorrhizas in plantation ecosystems. In: Nambiar, E.K.S. and Brown, A.G. (eds.) *Management of soil, nutrients and water in tropical plantation forests*, 247-296. ACIAR Monograph No. 43. ACIAR, Canberra, pp 247-296.
- Wallin, G., Linder, S., Lindroth, A., Råntfors, M., Flemberg, S. Grelle, A., 2001. Carbon dioxide exchange in Norway spruce at the shoot, tree and ecosystem scale. *Tree Phys.* 21:969-976.
- Waring, R. H. 1983. Estimating forest growth and efficiency in relation to canopy leaf area. *Adv. Ecol. Res.* 13:327-354.
- Waring, R.H. 2000. A process-based model analysis of environmental limitations on growth of Sitka spruce plantations in Great Britain. *Forestry* 73:65-79.
- Waring, R.H. and Schlesinger, W. H., 1985. *Forest Ecosystems. Concepts and Management*. Academic Press, London. 340pp.
- Waring, R.H., Landsberg, J.J. and Williams, M., 1998. Net primary production of forests: a constant fraction of gross primary production? *Tree Physiol.* 18:129-134.
- Wilkins A P. 1990. Influence of silvicultural treatment on growth and wood density of *Eucalyptus grandis* grown on a previous pasture site. *Australian For.* 53:168-172.

- Wilson, A.H., 2002. A new class of silica enriched, highly depleted komatiites in the southern Kaapvaal Craton, South Africa. *Precambrian Res.* 127:125-141.
- Wong, S.C. and Dunin, F.X., 1987. Photosynthesis and transpiration of trees in a eucalypt forest stand: CO<sub>2</sub>, light and humidity responses. *Australian J. Plant Physiol.* 14:619-632.
- Woods, P.V. and Raison, R.J., 1983. Decomposition of litter in sub-alpine forests of *Eucalyptus delegatensis*, *E. pauciflora* and *E. dives*. *Australian J. Ecol.* 8(3):287-299.
- Xu, D. Dell, B. Malajczuk, N and Gong, M., 2002. Effects of P fertilisation on productivity and nutrient accumulation in a *Eucalyptus grandis* x *E. urophylla* plantation in southern China. *For. Ecol. Manage.* 161:89-100.

## APPENDICES

### Appendix 1.

#### 1A: Diameter class distribution of the pre-harvest stand (Refer to Chapter 4)



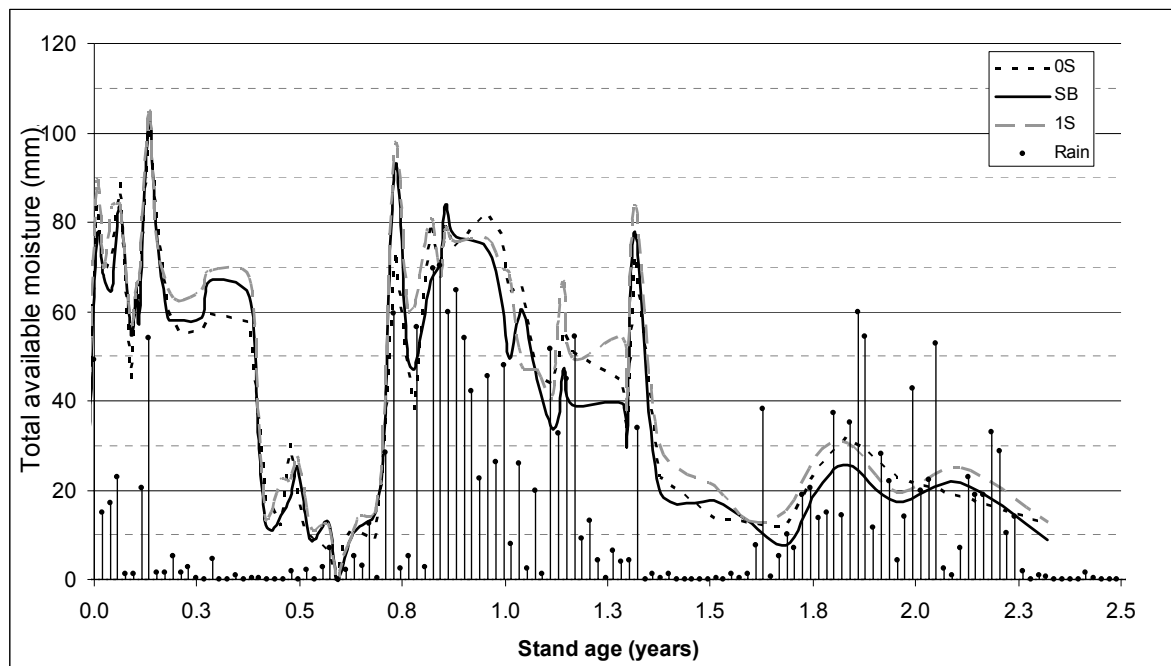
#### 1B: Sample trees selected for destructive harvesting

Tree #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Dbh (cm)	6.6	8.8	9.9	10.7	11.9	12.7	12.9	13.8	13.8	14.6	14.9	15.5	15.6	16.5	16.5	17.7	18.8	20.5
Height (m)	11.5	14.6	16.6	17.6	16.8	18.6	17.3	18.8	19.8	19.3	18.5	21.1	20.0	19.7	20.8	21.5	21.5	21.9

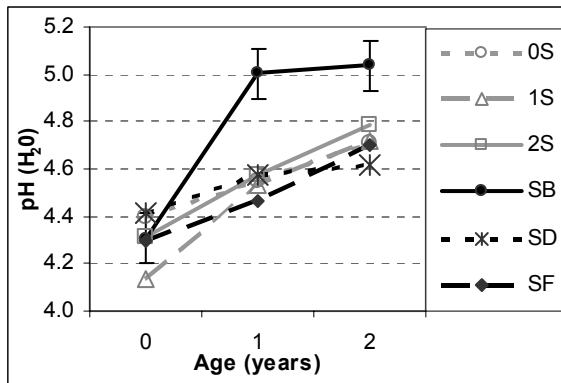
1C: Summary of curves fitted to describe the relationships between dbh and mass of individual tree components in the mature stand of *Eucalyptus grandis* at the Karkloof Project. A , B, C, R and M are constants and coefficients while d represents dbh over bark.

Variable	Curve fitted	% variance accounted for	A	B	C	M	R
$LN(\text{Foliage})$	$A+B \cdot R^d$	93.6	5.130	-9.600	*	*	0.9398
$LN(\text{Capsules})$	$M \cdot (LN(d)) + C$	86.5	*	*	-14.930	5.752	*
$LN(\text{Stem wood})$	$A+B \cdot R^{LN(d)} + C \cdot (LN(d))$	99.2	-1.303	-25 125	2.082	*	0.00777
$LN(\text{Bark})$	$A+B \cdot R^{LN(d)} + C \cdot (LN(d))$	98.8	-4.681	$-545 \times 10^5$	2.485	*	0.00017
Branches + stem tops	Estimated as woody parts minus stem wood	*	*	*	*	*	*
$LN(\text{Woody parts})$	$M \cdot (LN(d)) + C$	98.1	*	*	-2.297	2.5073	*

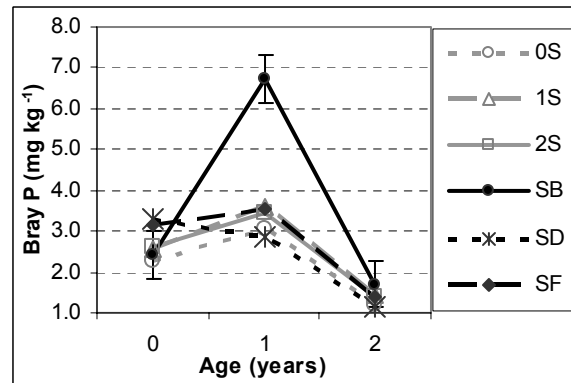
Appendix 2. Changes in total available moisture in the soil profile (as determined from neutron probe measurements at various depths) between the slowest growing (0S), fastest growing (SB) and control (1S) treatment for the period from planting until 2.4 years of age (Supplementary data for Chapter 5 - From du Toit and Dovey, 2004)



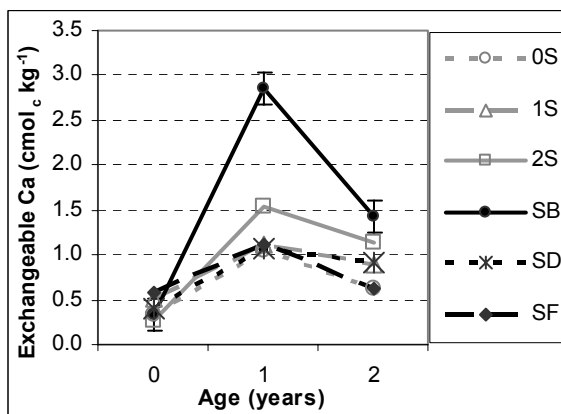
Appendix 3. Changes in topsoil (0-10 cm) properties over two years following implementation of site management treatments (from du Toit and Dovey, 2004).



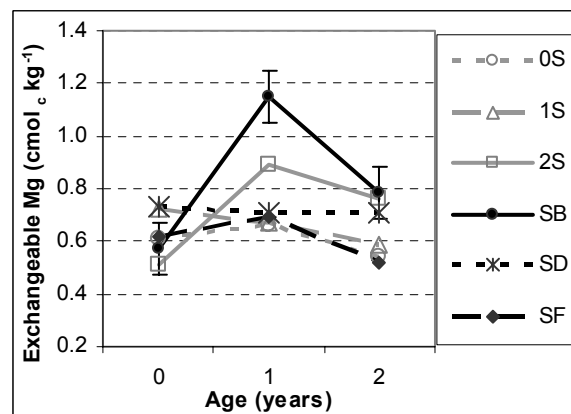
(a)



(b)



(c)



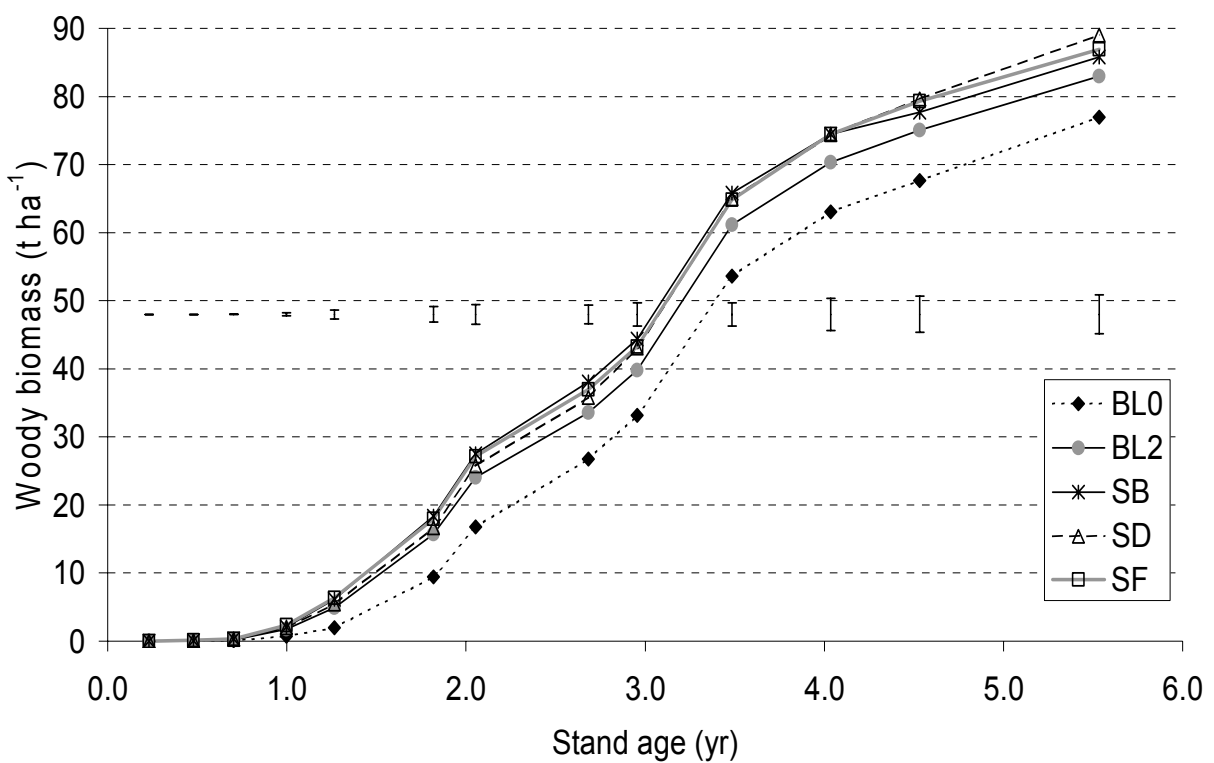
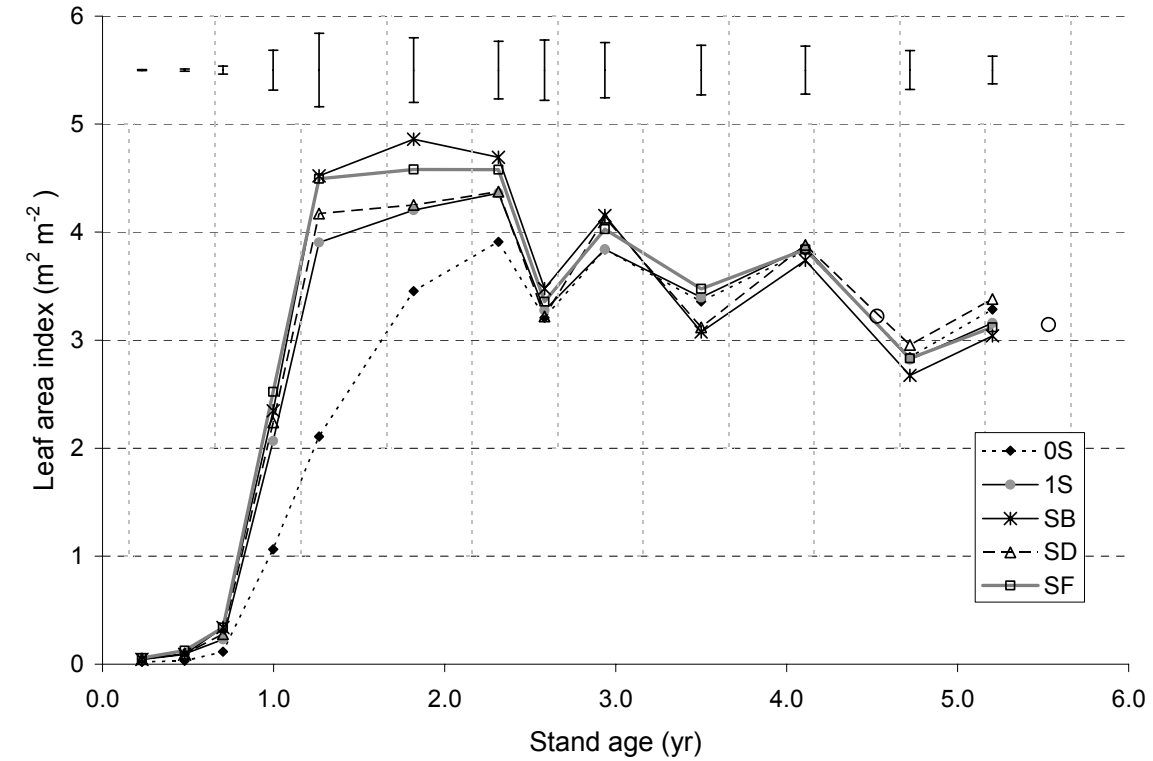
(d)

Changes in the topsoil nutrient fractions (a) pH in water, (b) Bray-2 Extractable P, (c) Exchangeable Ca, and (d) Exchangeable Mg.

Appendix 4. Foliar macronutrient concentrations from three monthly sampling events during the first year of growth. Values within a row followed by the same letter are not significantly different ( $p < 0.05$ ).

Event Number	Age (years)	Time of year (month)	Nutrients	Treatments (all values in percentages)				
				BL <sub>0</sub>	BL <sub>2</sub>	SB	SD	SF
1	0.25	May	N	3.47 <sup>a</sup>	3.63 <sup>a</sup>	3.24 <sup>a</sup>	4.02 <sup>a</sup>	4.02 <sup>a</sup>
			P	0.15 <sup>a</sup>	0.19 <sup>a</sup>	0.16 <sup>a</sup>	0.18 <sup>a</sup>	0.19 <sup>a</sup>
			K	0.91 <sup>a</sup>	1.18 <sup>a</sup>	0.92 <sup>a</sup>	1.20 <sup>a</sup>	0.92 <sup>a</sup>
			Ca	0.64 <sup>a</sup>	0.66 <sup>a</sup>	0.62 <sup>a</sup>	0.67 <sup>a</sup>	0.64 <sup>a</sup>
			Mg	0.33 <sup>a</sup>	0.29 <sup>a</sup>	0.33 <sup>a</sup>	0.31 <sup>a</sup>	0.31 <sup>a</sup>
2	0.50	Aug	N	2.91 <sup>a</sup>	3.24 <sup>a</sup>	2.90 <sup>a</sup>	2.92 <sup>a</sup>	3.20 <sup>a</sup>
			P	0.14 <sup>a</sup>	0.16 <sup>a</sup>	0.16 <sup>a</sup>	0.14 <sup>a</sup>	0.16 <sup>a</sup>
			K	0.62 <sup>a</sup>	0.70 <sup>a</sup>	0.66 <sup>a</sup>	0.62 <sup>a</sup>	0.72 <sup>a</sup>
			Ca	0.56 <sup>a</sup>	0.81 <sup>a</sup>	0.64 <sup>a</sup>	0.58 <sup>a</sup>	0.72 <sup>a</sup>
			Mg	0.28 <sup>a</sup>	0.31 <sup>a</sup>	0.36 <sup>a</sup>	0.26 <sup>a</sup>	0.28 <sup>a</sup>
3	0.75	Nov	N	2.69 <sup>a</sup>	3.37 <sup>b</sup>	2.55 <sup>a</sup>	3.21 <sup>b</sup>	3.28 <sup>b</sup>
			P	0.13 <sup>a</sup>	0.19 <sup>c</sup>	0.15 <sup>a</sup>	0.17 <sup>b</sup>	0.19 <sup>c</sup>
			K	0.60 <sup>a</sup>	0.82 <sup>b</sup>	0.68 <sup>a</sup>	0.85 <sup>b</sup>	0.86 <sup>b</sup>
			Ca	0.42 <sup>a</sup>	0.60 <sup>b</sup>	0.63 <sup>b</sup>	0.70 <sup>b</sup>	0.67 <sup>b</sup>
			Mg	0.28 <sup>a</sup>	0.31 <sup>a</sup>	0.32 <sup>a</sup>	0.28 <sup>a</sup>	0.26 <sup>a</sup>
4	1.00	Feb	N	2.86 <sup>a</sup>	3.04 <sup>ab</sup>	3.35 <sup>b</sup>	2.87 <sup>a</sup>	3.21 <sup>ab</sup>
			P	0.13 <sup>a</sup>	0.14 <sup>ab</sup>	0.17 <sup>c</sup>	0.14 <sup>ab</sup>	0.16 <sup>bc</sup>
			K	0.98 <sup>a</sup>	0.92 <sup>a</sup>	0.96 <sup>a</sup>	0.87 <sup>a</sup>	0.88 <sup>a</sup>
			Ca	0.82 <sup>a</sup>	1.02 <sup>ab</sup>	1.14 <sup>bc</sup>	1.35 <sup>cd</sup>	1.52 <sup>de</sup>
			Mg	0.24 <sup>a</sup>	0.28 <sup>a</sup>	0.29 <sup>a</sup>	0.25 <sup>a</sup>	0.33 <sup>a</sup>

Appendix 5. Development of leaf area index (top) and biomass (bottom) over time. The least significant difference ( $p < 0.05$ ) is shown as vertical bars per measurement event on each graph. (Open diamonds at 4.5 and 5.0 years: LAI determined through scaling up of destructively harvested trees to test optically determined LAI)



Appendix 6. Copies of three published papers and one submitted paper on which chapters 4 to 7 are based.