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Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa

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SYNOPSIS

The Karkloof Project is a case study of the effects of intensive site management operations during the inter-rotational period, on (a) the nutrient capital of the system, and (b) the availability of growth resources (nutrients and water) in a commercial *Eucalyptus grandis* stand in South Africa. This paper specifically focuses on the nutrient contents in various pools of the system, namely the soil, the forest floor, and the above- and below-ground biomass. 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 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 N, P, K, Ca and 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 in perpetuity. The comparatively large percentage loss of P is small in actual quantity (*ca*. 20 kg ha^{-1} 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 ecological sustainability. Strategies to ensure sustainable supplies of these nutrients are discussed.

Keywords: Intensive silviculture, *Eucalyptus grandis*, harvesting, slash burning, fertilization

INTRODUCTION

Site management operations carried out during the inter-rotational period in forest plantations (harvesting, slash management and other silvicultural operations) 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, 1999). 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.*, 2001), fertilization (Herbert and Schönau, 1989 & 1990; Herbert, 1996), management of competing vegetation and harvesting residue (Little,1999; Little *et al.*, 1996; Little *et al.*, 2000) and harvesting operations impacts (Smith, 2000).

Despite this large body of evidence regarding growth responses to early, intensive silviculture in southern African plantations (Schönau, 1988), 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. The Karkloof Project has been initiated to study the impacts of site management operations in the inter-rotational period on the availability of growth resources and the productivity of the new tree crop. The Project forms part of an international series of trials entitled "Site management and productivity in tropical forest plantations" (Tiarks *et al.*, 1998). This paper reports on only one aspect of the Karkloof Project trial, namely the initial changes in the nutrient capital of the various nutrient pools of the system, brought about by six inter-rotational site management operations.

MATERIALS AND METHODS

The Karkloof Project experiment is located in the Midlands of the KwaZulu-Natal (KZN) province, South Africa (29º 24' S and 30º 12' E). The site lies on gently undulating terrain at 1260 m above sea level and the soil is classified as a Kranskop (Soil Classification Working Group, 1991). The soil has a humus-rich, clayey A horizon (zero to 0.2 m depth) overlying a yellow-brown clayey B1 horizon (0.2 to 0.4 m), and a red clayey B2 horizon which grades into weathered shale at approximately 0.9 m depth. The highly weathered soils are porous and well drained. The mean annual precipitation is 950 mm, with a summer maximum. The mean annual temperature is 15.2 ºC and occasional frost can be expected between May and August. Detailed monthly climatic data for the site have been published by du Toit *et al.* (2000). The natural vegetation on the site was *Themeda* grassland until the site was afforested during 1964 with *Eucalyptus grandis*. Four crops have been harvested since 1964: One from the planted seedlings and three subsequent coppice crops (du Toit *et al.* 2000). 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. 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. Future plot locations were then demarcated on the experimental site 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 m^2 of which the inner 286 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).

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).

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 done 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 saprolite 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^3 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). 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: 995-6). Total N was determined by the Kjeldahl method (Bremner, 1996: 1103-8). 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 NH_4F 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.

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. Six treatments were imposed prior to establishment of the new crop while the replicated plots of the remaining two treatments were earmarked for future use. Treatments 1, 2 and 3 were aimed at creating a wide range in nutrient pool sizes: Harvesting residue plus forest floor (collectively referred to as slash) was removed with fire rakes (treatment 1) and transferred to treatment 2 (double slash load), or conserved in place (treatment 3). Treatments 4, 5 and 6 were used to simulate site management operations and these treatments were all superimposed onto plots that initially had a regular slash load (similar to treatment 3). In treatment 4, the slash load was burnt in a medium intensity fire. In treatment 5, slash was conserved and trees were fertilized at establishment with 17 kg N + 33 kg P ha^{-1} (using mono-ammonium phosphate enriched with 0.75% Zn). Fertilizer was localized in two spot applications, approximately 0.15 m away from, and situated on opposite sides of each newly planted seedling. In treatment 6, the topsoil and slash layers were disturbed and mixed during timber extraction using a 3-wheeled loader. The operation crushed most of the branched material and caused a mixing of the slash and the superficial soil layers to a maximum depth of approximately 50 mm. The aerial extent of slash and soil mixing was not specifically measured, but is estimated at approximately 30 to 50% of the total surface area of the plot. Treatments 7 and 8 were earmarked for future use and their slash was not manipulated during the inter-rotational period (i.e. the same as treatment 3).

In treatments 1, 2, 3 and 4, two sets of three slash samples each were collected per plot by cutting out squares of 0.071 m^2 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 4, 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 burnt 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.

RESULTS

Basic soil properties are listed in **Table 1**. The mass of each of the nutrient pools and the macronutrient capital contained therein are presented in **Table 2**. The nutrient capital in components other than the soil and root pools has been altered considerably

TABLE 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^{-3})	pH in KCI	pH in H_2O	C	N	C:N	P	Exchangeable cations				Sum of Bases	Extr. acidity	ECEC
				(g kg^{-1})			(mg kg^{-1})	Ca	Mg	K	Na			
								(cmol$_c$ kg^{-1})						
0-20	**0.9** (0.02)	**3.94** (0.03)	**4.33** (0.03)	**66.5** (1.3)	**3.2** (0.1)	**21.3** (0.6)	**2.75** (0.20)	**0.43** (0.04)	**0.64** (0.04)	**0.16** (0.01)	**0.23** (<0.01)	**1.46** (0.09)	**3.25** (0.09)	**4.71** (0.10)
20-40	**1.21** (0.02)	**4.23** (0.03)	**4.87** (0.04)	**42.3** (1.3)	**1.8** (0.1)	**23.7** (0.6)	**0.94** (0.09)	**0.33** (0.04)	**0.56** (0.03)	**0.11** (0.01)	**0.21** (0.01)	**1.20** (0.07)	**1.48** (0.21)	**2.68** (0.23)
40-60	**1.35** (0.04)	**4.40** (0.03)	**5.13** (0.03)	**23.5** (1.0)	**1.2** (<0.1)	**20.4** (0.8)	**0.34** (0.07)	**0.31** (0.03)	**0.55** (0.03)	**0.09** (0.01)	**0.21** (0.01)	**1.16** (0.05)	**0.81** (0.12)	**1.97** (0.12)

TABLE 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^{-1}					
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 10^3	124*	5	120	167	151
B1 Horizon (0.2-0.4 m)	2420 x 10^3	87*	2	104	159	165
B2 Horizon (0.4-0.9 m)	6750 x 10^3	162*	3	241	416	455
Totals						
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 10^3	373*	10	466	742	771
Total all components	11399 x 10^3	1964	84	874	1768	1030

* Note: 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).

through the implementation of treatments. Nutrient capital after treatment implementation is listed in **Table 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 3**).

DISCUSSION

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 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 (unpublished data) 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 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 (O'Connell *et al.*, 2000; Adams and Attiwill, 1986). A topsoil C:N ratio of 21 suggests a modest rate of N mineralisation 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

TABLE 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 different letters are significantly different ($p<0.05$).

Treatment/operation	**Mass**	**N**	**P**	**K**	**Ca**	**Mg**
	All values in kg ha^{-1}					
Slash loads						
Double slash	153 200^{a}	1378^{a}	67^{a}	275^{a}	1413^{a}	286^{a}
Standard error (double slash)	(7 038)	(150)	(5)	(26)	(152)	(15)
Regular slash	116 527^{b}	1044^{b}	53^{a}	193^{b}	823^{b}	201^{b}
Standard error (regular slash)	(7 262)	(46)	(3)	(13)	(42)	(6)
Burnt slash	31 415^{c}	604^{c}	27^{b}	96^{c}	747^{b}	151^{c}
Standard error (burnt slash)	(2 935)	(51)	(2)	(7)	(80)	(16)
Management removals						
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
Management additions						
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.

organic N pool contained in the soil is in excess of 16 t ha^{-1} (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 pool in soils are made available to plants per annum. I have chosen to estimate the short-term available N as 2% of the total soil N for the purposes of this study. 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^{-1} 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^{-1} (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 N pool.

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^{-1}, while that of other short rotation systems ranged from approximately 52 to 196 t ha^{-1}. 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^{-1}) (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^{-1} in the Karkloof study, with wood mass in the published studies ranging from approximately 30 to 147 t ha^{-1}. 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 that 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^{-1}, respectively, which sums to 84.7 t ha^{-1} (**Table 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^{-1}, 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).

Nutrient capital in the forest floor

The mass of the forest floor in the Karkloof study site amounts to 69.6 t ha^{-1}. The forest floor loading in tropical systems rarely exceed 20 t ha^{-1}, while upper ranges listed for temperate systems sometimes exceed 100 t ha^{-1} (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. The forest floor contains large quantities of N, P and Ca relative to system totals in **Table 2** (where total system nutrients are defined as nutrients in biomass plus forest floor plus readily available nutrients in the soil). N, P, K, Ca and Mg in the forest floor constitute 53, 33, 12, 30 and 12 percent of system totals, respectively. This data illustrates 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).

Nutrient capital and site management effects

Nutrient pools and litter mass in double, regular and burnt slash (**Table 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 burnt 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 3**). The slash removed 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 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. 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 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 kg ha^{-1} (38 to 61%) have been recorded in eucalypt stands managed for sawtimber (du Buisson, 2003). Morris (1986) recorded a loss of 1183 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 kg N ha^{-1} (**Table 3**), which is larger than the harvesting losses per rotation. The combined losses of N through harvesting and slash burning (*ca.* 250 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 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 (du Toit and Scholes, 2002) showing that the net N loss in a “plant + 2” regime including slash burning is moderately small (in the order of 10 kg ha^{-1} a^{-1}).

Approximately 26 kg P ha^{-1} was lost through burning in this study, which constitutes 49% of the P pool in slash (**Table 3**). Harwood and Jackson (1975) recorded a loss of 10 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 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 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 kg P ha^{-1}) would apply to planted crops but not to coppice crops. An average of 11 kg P ha^{-1} per cycle in a "plant + 2" regime would mitigate the estimated loss of 21 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 2 shows that a relatively large soil pool exists for K (466 kg ha^{-1}) and that a total of 258 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 kg ha^{-1} (**Table 3**), which is less than the quantity estimated for K in the non-utilized biomass (**Table 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 kg ha^{-1} (i.e. 38% of the K pool initially present in the slash - **Table 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 kg ha^{-1} K was lost through burning. The average loss in the order of 100 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 kg ha^{-1} (**Table 2**) while that of the conventional (single) slash load totals 823 kg ha^{-1} (**Table 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 kg Ca ha^{-1} was lost through slash burning, compared to 100 kg ha^{-1} in the study of Harwood and Jackson (1975). It is clear from **Table 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^{-1} per rotation. Removal of the bark (109 kg Ca ha^{-1}) 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 3**). Applications of Ca in the form of lime ($CaCO_3$) 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^{-1} 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^{-1} out of a value of 1030 kg ha^{-1} for the system (**Table 2**). In contrast to the high levels of Ca, the Mg pool in the slash following conventional harvesting contains only 201 kg ha^{-1} (**Table 3**). The Mg lost through burning amounted to 50 kg ha^{-1}, compared to a figure of 37 kg ha^{-1} reported by Harwood and Jackson (1975). In the local "plant + 2" system, wood harvesting and slash burning remove 19 and 17 kg Mg ha^{-1} 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.

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. N 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. though 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.

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APPENDIX 1. 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(Foliage)	$A+B*R^d$	93.6	5.130	-9.600	–	–	0.9398
LN(Capsules)	M*(*LN*(d))+C	86.5	–	–	-14.930	5.752	–
LN(Stem wood)	$A+B*R^{(LN(d))} + C*(LN(d))$	99.2	-1.303	-25 125	2.082	–	0.00777
LN(Bark)	$A+B*R^{(LN(d))} + C*(LN(d))$	98.8	-4.681	-545×10^5	2.485	–	0.00017
Branches + stem tops	Estimated as woody parts minus stem wood	–	–	–	–	–	–
LN (Woody parts)	M*(*LN*(d))+C	98.1	–	–	-2.297	2.5073	–