Nutritional sustainability of *Eucalyptus* plantations: A case study at Karkloof, South Africa

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SYNOPSIS

The nutritional sustainability of a short-rotation *Eucalyptus grandis* plantation system was evaluated in a trial located at Karkloof, KwaZulu-Natal, South Africa, by determining nutrient pools and 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 was estimated from chemical extractions. 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 overseas. The readily available soil pools are moderately large (100 to 800 kg ha^{-1}) 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^{-1}). This indicates that the system is well buffered against nutrient 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 system (95% of total N inputs, 92% of total Ca and Mg and 82% of total K inputs). 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 most elements in the absence of firewood collection or slash burning and changed to losses of between ca. 5 to 10 kg ha^{-1} a^{-1} 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 for all regimes tested still indicated a stable 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.

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 optimize the incoming radiation, carbon dioxide concentration or temperature. 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 paper.

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.

MATERIALS AND METHODS

Site and terrain

The Karkloof experiment is located in the Midlands of the province of KwaZulu-Natal (KZN), South Africa. The site lies at an altitude of 1260 m above sea level on gently undulating terrain where the rainfall is approximately 950 mm a^{-1}. The soil is classed as a ferralsol (FAO system): it has a humus-rich, clayey A horizon (0 to 0.2 m depth) overlying a yellow-brown clayey B1 horizon (0.2 to 0.4 m); and finally a red clayey B2 horizon which grades into weathered shale at approximately 0.7 to 1.0 m depth. The weathered shale layer is colonised by roots, to a limited degree, and exceeds at least 5 m in depth (own observations from pit profile and road cuttings). The experimental design is a randomised complete block with eight site and slash management treatments (implemented at time of re-establishment) across four replications. Selected data sets from the standing crop, soil and forest floor before harvesting, as well as the slash burnt treatment were used for this paper. More detail on the experimental location, experiment design and site factors are given in du Toit *et al*. (2000).

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 du Toit *et al*., (2000). (2) Soil samples were taken at three depths (0 - 0.2, 0.2 - 0.6 and 0.6 - 1.0 m) which correspond closely 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 the best approximation of what is available to plants (**Table 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 paper.

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. 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 was obtained from Cathedral Peak research catchment near the town of Winterton (van Wyk, 1990), approximately 100 km northwest of the study site.

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 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 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).

RESULTS AND DISCUSSION

Nutrient pools in system components

The biomass components of the system (foliage, branches, stem and roots) have been described previously by du Toit *et al*. (2000) and only a brief summary is given here: Both the above-ground biomass of the standing crop (123.3 t ha^{-1}) 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^{-1}), (b) the root plus stump biomass contributes approximately 30% of the total biomass (du Toit *et al*., 2000), which has been attributed to

TABLE 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 [1]	N in particulate organic matter [4]	Kjeldahl [8]
P	Bray 2 method [2]	Forest accessible P [5]	XRF [9]
K	Exchangeable [3]	Nitric acid extraction [6]	XRF
Ca	Exchangeable	Mehlich extractant [7]	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_4F & 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_2SO_4 (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).

repeated coppicing, and (c) the mass of the forest floor in the Karkloof study site is considerable (70 t ha^{-1}), which is thought to be chiefly attributable to the cold and dry winters which would slow down the rate of decomposition (du Toit *et al.*, 2000).

The soil nutrient pool constitutes a large reservoir of nutrients but only a fraction can be considered potentially plant available. **Table 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 mμg g^{1} for horizons A, B1 and B2, respectively. The small negative values obtained for the B_2 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^{-1}, which constitutes approximately 1% of the total N contained in these horizons. 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 basically plays no nutritional role at all. 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 (Attiwill and Leeper, 1979). The N contained in lighter frations 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 Brazillian 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 2**) is fairly large by most southern African standards, due to the high organic matter content in all horizons, specifically the topsoil (du Toit *et al.*, 2000). Neither the available nor the total pools of P are large (Table 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 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 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

TABLE 2. Nutrients contained in various components of the Karkloof system. The terms "available", "potential", and total refer to different nutrient pools in the soil as defined in Table 1.

System component	Nutrient pools (all values in kg ha^{-1})				
	N	P	K	Ca	Mg
Biomass (a)	514	44	278	470	128
Forest floor (b)	749	19	67	404	85
Readily available soil nutrients (c)	105	21	401	663	678
Potentially available soil nutrients (d)	782	83	2 466	862	1 130
Total soil nutrients (e)	16 290	4 710	326 350	2 920	50 150
System potential (a+b+d)	2045	146	2 811	1 736	1 343
System total (a+b+e)	17 553	4 773	326 695	3 794	50 363

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.

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 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 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

TABLE 3. Approximate nutrient input-output budget for the Karkloof system

Process	Site and description	Nutrient flux (kg ha^{-1} $year^{-1}$) N	P	K	Ca	Mg	Reference
Weathering	Mean of 2 granitic catchments, Zimbabwe	0.0	– 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 *E. grandis*, Karkloof, SA	13.3	1.7	8.7	8.3	2.4	Du Toit et al. (2000) and unpublished data.
Other biomass removals	Firewood collection (75% of branch mass), Karkloof, SA	5.4	0.4	6.1	7.7	2.6	Du Toit et al. (2000) and unpublished data.
Slash burning	Medium intensity fire, Karkloof, SA	11.2	0.8	3.6	0.5	0.9	Du Toit et al. (2000) and unpublished data.

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 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 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 4) are relatively minor. **Table 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.

Firewood collection removes sizeable quantities of N, K and Ca (**Table 3**). The net result for option Y is small losses of N and moderate losses of K and Mg (**Table 4**). Slash burning impacts most heavily on the N budget (**Table 3**). This results in moderate (N) and small losses (K and Mg) when option Z is implemented.

The net loss of N in option Z could be replaced by fertilization without incurring excessive costs. The net loss in P is roughly 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 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 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 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.

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 $PSI_{(stem\ wood)}$ = (Nutrients in stem wood) / (nutrients in soil). They point out that the soil nutrient pool estimates should

TABLE 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^{-1} a^{-1})				
	N	P	K	Ca	Mg
Planted crop + double coppice, no burning (X)	1.6	0.3	- 1.0	6.2	- 5.0
Planted crop + double coppice & firewood collection after clear felling (Y)	- 3.8	- 0.1	- 7.1	- 1.5	- 7.6
Planted crop + double coppice, slash burnt (Z)	- 9.7	- 0.5	- 4.6	5.7	- 5.9

* 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.

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 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, an 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(INS),as shown here:

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

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 2) will yield an index of short-term nutritional sustainability [denoted $p(INS)_{RA}$] , while an index of long-term nutritional sustainability [denoted $p(INS)_{POT}$] will be obtained by using the potentially available system pool described in **Table 2**.

In cases where a net nutrient flux is positive, i.e. the system is gaining in that element, the p(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(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(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 $p(INS)_{RA}$ 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 $p(INS)_{POT}$ 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 $p(INS)_{POT}$ value of 2 is therefore proposed as a norm for evaluating long-term nutritional sustainability. Both $p(INS)_{RA}$ and $p(INS)_{POT}$ 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) will need to be adjusted to ensure sustained productivity. 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**): The Congolese site is located on sandy soils on an extremely infertile coastal plain (Bouillet *et al.*, 1999) while the Brazillian site is representative of a large body of medium-textured forest soils on the Brazillian Cerrado with moderately low fertility (Gonçalves *et al.* 1999).

The PSI values listed in the top half of **Table 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**. 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 K and Mg in the subsoil at Karkloof.

The middle section of **Table 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 1.4 to 2.7 These data show that the net losses under current management constitute fairly small fractions of the readily available nutri-

TABLE 5. Plantation stability indices and indices of nutritional sustainability for the Karkloof case study and selected sites in a CIFOR[1] 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 2.

Plantation Stability Indices (Fölster & Khanna, 1997)	N	P	K	Ca	Mg
$PSI_{(stem\ wood)}$ Karkloof System[A]	n.d.	0.58	0.15	0.09	0.03
$PSI_{(stem\ wood)}$ Itatinga, Brazil[B]	n.d.	0.69	0.88	0.24	0.21
$PSI_{(stem\ wood)}$ Kondi, Congo[C]	n.d.	n.d.	0.83	0.49	0.4
Proposed short term Indices of nutritional sustainability : $p(INS)_{RA}$	N	P	K	Ca	Mg
$P(INS)_{RA}$ Karkloof, SA[A]	1.44	2.31	1.75	2.65	1.95
$P(INS)_{RA}$ Kondi, Congo[D]	n.d	n.d.	Gain[E]	Gain[E]	2.88
Proposed long term Index of nutritional sustainability : $p(INS)_{POT}$	N	P	K	Ca	Mg
$P(INS)_{POT}$ Karkloof, SA[A]	2.72	3.16	2.60	3.06	2.25

n.d = not determined
A = Karkloof system under management regime Y (refer Table 4);
B = Calculated from Gonçalves *et al*.(1999);
C = Calculated from Bouillet *et al*. (1999): management roughly similar to regime Y (Table 4)
D = Calculated from Laclau (2001) and Bouillet *et al*. (1999);
E = Net budget showed nutrient gain (system stable), pINS thus not calculated.

[1] 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 (Center for International Forestry Research, Bogor, Indonesia)

ent 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**; Laclau, 2001). This system is particularly unstable for the element N, which has a net loss of 23.7 kg ha^{-1} a^{-1} (Laclau, 2001) and a small readily available soil N pool, judging by *in situ* N-mineralisation 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 is largely offset by fertilization and atmospheric inputs (**Table 3**) while, on the other hand, net Mg losses are much greater than harvesting exports, mainly due to leaching (Table 3).

Evaluation of the long-term sustainability of a system can be done by inspecting $P(INS)_{POT}$ values (**Table 5**, bottom). The $p(INS)_{POT}$ values for the Karkloof system using management scenario Y (refer **Table 4**), varies between 2.3 (Mg) and 3.1 (P & 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 4**), the $p(INS)_{POT}$ values for N and P are most strongly affected: The $p(INS)_{RA}$ values for N and P decrease to levels of 1.0 and 1.6, respectively, while the $p(INS)_{POT}$ indices for N and P drop to 2.3 and 2.5. However, all indices remain above the proposed critical values, despite the increased losses due to slash burning, underscoring the resilience of the Karkloof system.

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.

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 is 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 that 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 resilient, even with increased nutrient losses due to slash burning.

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