IN SITU MEASUREMENTS OF SOIL MINERAL-NITROGEN FLUXES IN HOOP PINE PLANTATIONS OF SUBTROPICAL AUSTRALIA

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ABSTRACT

The dynamics of nitrogen (N) mineralisation, plant uptake of nitrogen, and leaching in the 0–10 cm soil depth were studied in hoop pine (*Araucaria cunninghamii* Ait. ex D.Don) plantations aged 0, 3, 10, 14, and 62 years with *in situ* incubation cores. Although ammonium-nitrogen was the dominant form of mineral-nitrogen in the 0–10 cm soil depth, nitrification was also an important process in hoop pine plantation soils, indicating that there might be a potential for nitrogen losses through leaching and denitrification, particularly at recently clearfelled sites.

The results indicated that most net nitrogen mineralisation and plant uptake of nitrogen occurred during the growing season between October and May. The amount of nitrogen mineralised from soils during this period ranged between 25 and 53 kg N/ha, representing, on average, 2% of the total nitrogen pool in the 0–10 cm soil depth. Net nitrogen mineralisation was significantly correlated with the soil organic carbon (C), total nitrogen, carbon/nitrogen ratio, and plantation age.

Keywords: nitrogen mineralisation; nitrification; plant uptake; leaching; *Araucaria cunninghamii.*

INTRODUCTION

Hoop pine is a highly valued native tree species grown in plantations situated along the coastal highlands of subtropical and tropical eastern Australia. Just as in many other tree

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species, nitrogen deficiency has been recognised as one of the major factors limiting growth of hoop pine plantations, but little is known about the factors controlling mineral-nitrogen dynamics in soils which support these plantations. A better understanding of such factors would help identify periods throughout the rotation when the availability of soil mineral-nitrogen limits plantation growth. This could lead to the development of silvicultural practices to improve plantation production and reduce the potential for nitrogen to be lost from the forest system.

Currently there is no single reference method available for estimating rates of net nitrogen mineralisation under field conditions (Raison *et al.* 1987), although *in situ* incubation methods have been widely used in forest soils (Attiwill & Adams 1993). However, most studies of this type have been conducted in temperate forests. In general, few studies have assessed the *in situ* methodology in tropical and subtropical climates. Consequently, the suitability and reliability of these methods in hoop pine plantations situated in subtropical and tropical Australia is unknown. The objectives of the study reported here were to (1) estimate soil nitrogen fluxes for net mineralisation, stand uptake, and leaching potential over a chronosequence of hoop pine plantations; (2) investigate the relationship between the soil nitrogen fluxes and a number of environmental variables; and (3) evaluate the suitability of *in situ* incubations using undisturbed cores for estimating soil nitrogen fluxes in hoop pine plantations.

MATERIALS AND METHODS

Study Area

The experimental sites were in hoop pine plantations within the State Forests of Brooloo (26° 31′S, 152° 36′E) and Imbil (26° 28′S, 152° 37′E). These forests are in the coastal highlands of the upper Mary River catchment some 150 km north-west of Brisbane, Queensland, Australia. The plantations are at an altitude ranging between 100 and 300 m where the topography is broken with undulating to steep country. The climate is subtropical and can be influenced by both the tropical zone weather patterns (predominantly with a summer-dominant rainfall distribution) and the temperate zone patterns (predominantly winter rainfall) operating either singularly or simultaneously (Costantini *et al.* 1993). Consequently, there is a wide variation in annual rainfall between 495 and 1964 mm (mean 1188 mm). The average daily maximum and minimum temperatures for January (mid-summer) are 30.5°C and 19.4°C respectively (mean 25.0°C). Winters are typically mild with average daily mid-winter (July) maximum and minimum temperatures of 21.5°C and 6.9°C respectively (mean 14.2°C).

Experimental plots of approximately 0.2 ha were situated in five compartments with plantation ages 3,10, 14, 20, and 62 years (hereafter referred to as the 3-, 10-, 14-, 20-, and 62-yr plots). Some site characteristics are summarised in Table 1. Within each plot 10 trees were chosen randomly and the immediate area surrounding each tree was established as a micro-plot for *in situ* core incubation studies. During the 12-month period from October 1993 to September 1994 a study was conducted at the 10-, 14-, and 62-yr plots (hereafter referred to as the 1993/94 study). After this, a study was carried out at the 3-, 20-, and 62-yr plots between November 1994 and May 1995 (hereafter referred to as the 1994/95 study), the period generally regarded as the major annual growing season. Prior to the 1994/95 study,

TABLE 1–Site characteristics for hoop pine plantation plots where soil mineral-nitrogen fluxes were measured.

Parameter	Site (rotation)				
	3 yr (2R)	10 yr (1R)	14 yr (2R)	20 yr (1R)	62 yr (1R)
Soil type*	Red Podzolic	Krasnozem	Red Podzolic	Red Podzolic	Red Podzolic
Aspect (slope)	E (5°)	NE (10°)	SE (5°)	NE (5°)	NE (5°)
Site index†	25.9‡	N.D.	25.7	26.4	26.5
Stocking (stems/ha)	750	750	750	750	400
Soil chemical properties at—					
0–2.5 cm					
Total N (%)	0.39	0.48	0.41	0.40	0.44
Organic C (%)	5.3	6.3	6.1	5.6	7.1
2.5–10 cm					
Total N (%)	0.31	0.44	0.27	0.30	0.29
Organic C (%)	3.5	5.3	3.6	3.4	3.9
Total P (mg/kg)	423	521	339	703	775
Total K (mg/kg)	3201	4386	3409	9918	5646
pH (1:5 H_2O)	6.9	7.0	5.8	6.9	6.8

* Classification according to Stace *et al.* (1968).

† Site index (SI) is first estimated at plantation age of 10 years and is based on the predominant height (i.e., average height of tallest 50 trees/ha) of a 1% sample population projected to age 25 years using the Richard's function.

‡ SI of previous rotation.

one half of the 62-yr plot was clearfelled (hereafter this area will be referred to as the 0-yr plot) to investigate soil mineral-nitrogen fluxes during the initial site conversion phase to the second rotation. The site conversion phase included clearing the remaining understorey along with the majority of slash and litter into windrows with a dozer. These windrows were established away from the micro-plots of the previous study.

Rainfall was measured weekly, with total rainfall for the 1993/94 and 1994/95 studies 20–25% lower than the long-term average for the same periods. The seasonal variation in rainfall and soil moisture content in the study area for both study periods is presented in Fig. 1 and 2. Soil temperature was recorded by a thermograph at the 10- and 62-yr plots during the 1993/94 study and the 62- and 0-yr plots during the 1994/95 study.

In situ Core Incubation Methods

The *in situ* sequential "paired core" incubation method (after Adams & Attiwill 1986) was used to estimate net soil nitrogen and plant uptake of nitrogen with the exception of the 62- and 0-yr plots during the 1994/95 study (*see* later discussion). The cores were collected in PVC tubing (diam. 10 cm, length 15 cm) which had the bottom 10 cm perforated with 10 holes (diam. 1 cm) to allow equilibration (moisture and gaseous) with the outside soil. Sampling was limited to the upper 10 cm of the soil profile as the stony nature of the soils prevented the core tubes from being installed deeper in the profile. At the commencement of a sampling period, paired core tubes were positioned 1 m from the base of the tree in the centre of each micro-plot and pushed vertically to a soil depth of 10 cm. One core, termed "bulk", was immediately removed and the fresh soil subsequently analysed for the mineral-

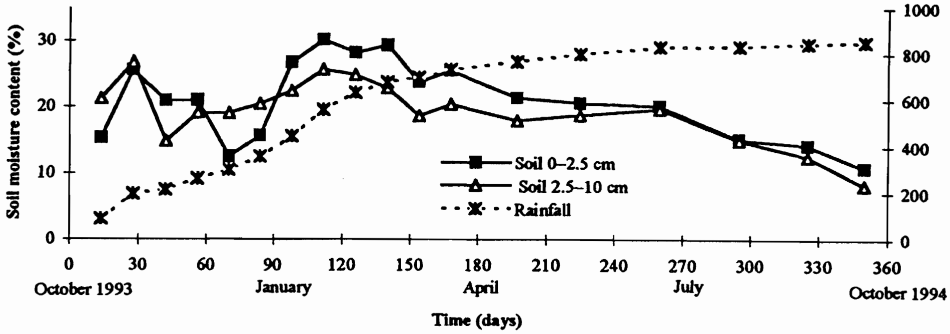

FIG. 1–Seasonal variations in rainfall and soil moisture (soil depth 0–10 cm) during the 1993/94 study. Data represent the mean of three plots.

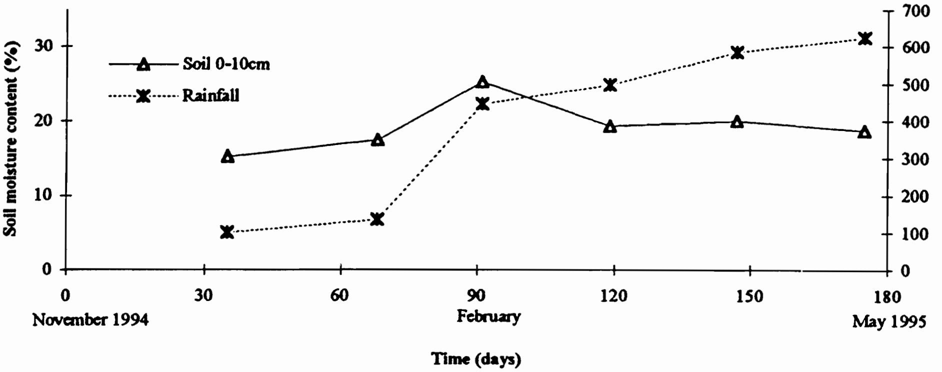

FIG. 2–Seasonal variations in rainfall and soil moisture (soil depth 0–10 cm) during the 1994/95 study. Data represent the mean of three plots.

nitrogen (ammonium-nitrogen and nitrate-nitrogen) concentration and moisture content. The remaining core, termed "confined", was capped and remained in the soil during the incubation period. The cap consisted of an inverted glass petri dish which was held in place by wire straps and wooden wedges (thickness 5 mm) which allowed air to circulate and prevented any appreciable build up of condensation. During the 1993/94 study, incubation periods were fortnightly over the typical growing season (October to May). This was extended to 4-week intervals during the cool dormancy period from June to September. During the 1994/95 study the incubation periods were 4-weekly intervals. At the end of the incubation period, the confined core was removed and the fresh soil subsequently analysed for mineral-nitrogen and soil moisture. Simultaneously, a further set of core tubes (for both bulk and confined cores) were pushed into the ground and the same protocol continued for the next incubation period.

During the 1993/94 study the fresh soil from each core was partitioned into two separate samples representing soil depths of 0–2.5 cm and 2.5–10 cm. Soil moisture was determined gravimetrically; mineral-nitrogen was extracted from soil samples with 2 *M* KCl by the method described by Keeney & Nelson (1982). Extracts were analysed for ammonium-nitrogen and nitrate-nitrogen by a flow injection analyser. For a given incubation period the net ammonification, net nitrification, net mineralisation, and plant uptake (for each micro-plot) were estimated from Equations 1, 2, 3, and 4:

$$\Delta NH_4\text{-}N = NH_4\text{-}N_C(t+1) - NH_4\text{-}N_B(t) \quad (1)$$

$$\Delta NO_3\text{-}N = NO_3\text{-}N_C(t+1) - NO_3\text{-}N_B(t) \quad (2)$$

$$\text{Net mineralisation} = \Delta NH_4\text{-}N + \Delta NO_3\text{-}N \quad (3)$$

$$\text{Plant uptake} = N_C(t+1) - N_B(t+1) \quad (4)$$

ΔNH_4-N is net ammonification, NH_4-$N_C(t+1)$ is the ammonium-nitrogen concentration in the confined core at the end of the incubation period, and NH_4-$N_B(t)$ the ammonium-nitrogen concentration in the bulk core at the start of the incubation period. ΔNO_3-N is net nitrification, NO_3-$N_C(t+1)$ is the nitrate-nitrogen concentration in the confined core at the end of the incubation period, and NO_3-$N_B(t)$ the nitrate-nitrogen concentration in the bulk core at the start of the incubation period. $N_C(t+1)$ is the mineral-nitrogen concentration in the confined core at the end of the incubation period and $N_B(t+1)$ the mineral-nitrogen concentration in bulk core at the end of the incubation. These equations assume that both leaching losses and atmospheric inputs of nitrogen were negligible (*see* later discussion).

During the 1994/95 study the sampling design and method were slightly modified with respect to the 62- and 0-yr plots. In a similar technique to that outlined by Raison *et al.* (1987), a third "open-top" core (perforated lower section) was also installed to assess nitrogen leaching potential. Net ammonification, net nitrification, and net mineralisation were calculated in micro-plots from the previous study, as outlined above in Equations 1–4. The difference between the mineral-nitrogen concentrations of the confined and open-top cores at the end of the incubation period was assumed to be due to leaching, or at least to represent leaching potential.

RESULTS

1993/94 *in situ* Incubation Study

Across all seasons ammonium-nitrogen was the dominant form of mineral-nitrogen at each plot. Nevertheless, substantial concentrations of nitrate-nitrogen were also present. Generally the ranges of mineral-nitrogen in the upper profile (0 to 2.5 cm depth) were from 20 to 80 mg/kg (3 to 12 kg/ha) for ammonium-nitrogen and 10 to 20 mg/kg (1.5 to 3 kg/ha) for nitrate-nitrogen, with the corresponding values of the lower profile (2.5 to 10 cm depth) ranging from 10 to 40 mg/kg (6 to 24 kg/ha) and 0 to 20 mg/kg (0 to 12 kg/ha) respectively. Frequent cycles of positive net mineralisation countered by negative net mineralisation (gross immobilisation) were evident throughout the year across all plots (Fig. 3, only one plot presented). Plant uptake was generally prominent during periods when net mineralisation was positive; however, there were instances where significant levels of plant uptake coincided with negative net mineralisation. The cumulative net mineralisation and plant uptake which occurred during the warm seasonal period between October and May represented 90 to 100% of the respective annual fluxes at each plot. The period coincided with the soil temperature being above 20°C.

Across all plots the annual net nitrogen mineralisation was equivalent to annual plant uptake (Table 2). As a proportion of the soil total nitrogen, the annual net nitrogen mineralisation in the upper profile (0–2.5 cm) at the 10-, 14-, and 62-yr plots was 3.1, 2.5,

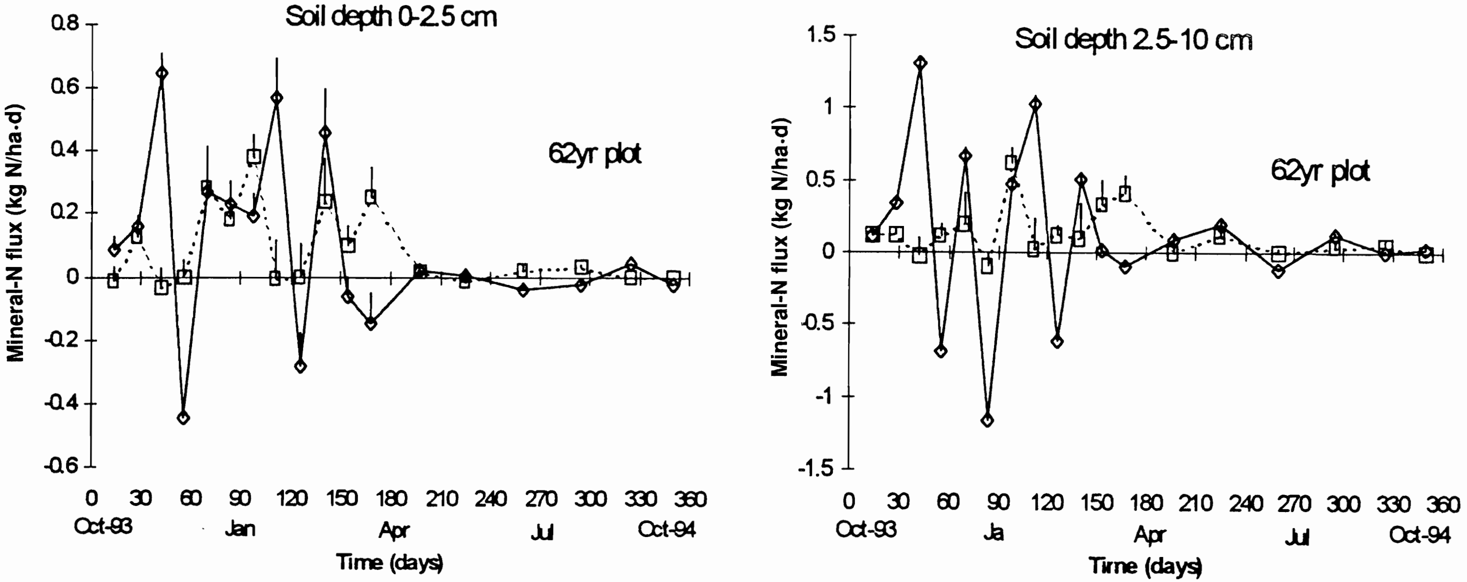

FIG. 3—Seasonal fluctuations of net mineralisation and plant uptake in the 62-year-old hoop pine plantation during the 1993/94 study. Data points represent the mean of 10 replicates: –◇– net mineralisation; –□– plant uptake. Bars represent standard error.

TABLE 2–Annual net nitrogen mineralisation and plant nitrogen uptake in hoop pine plantations aged 10, 14, and 62 years during 1993/94 (standard errors in parentheses).

Site: depth	Net nitrification (kg N/ha)	Net ammonification (kg N/ha)	Net mineralisation (kg N/ha)	Plant uptake (kg N/ha)
10-yr: 0–2.5 cm	7.9 (2.0)	8.5 (3.2)	16.4 (5.1)	16.4 (4.8)
10-yr: 2.5–10 cm	14.1 4.2)	10.1 (4.8)	24.2 (8.3)	24.7 (11.4)
Total	22.0 (6.2)	18.6 (8.0)	40.6 (13.4)	41.1 (16.2)
14-yr: 0–2.5 cm	2.7 (0.8)	9.7 (5.1)	12.4 (4.8)	12.8 (5.9)
14-yr: 2.5–10 cm	2.5 (1.0)	10.9 (2.8)	13.4 (3.4)	17.0 (6.2)
Total	5.2 (1.8)	20.6 (7.9)	25.8 (8.2)	29.8 (12.1)
62-yr: 0–2.5 cm	16.0 (3.3)	6.5 (2.8)	22.5 (6.8)	22.3 (7.4)
62-yr: 2.5–10 cm	15.5 4.5)	19.2 (6.0)	34.7 (9.1)	33.6 (12.3)
Total	31.5 (7.8)	25.7 (8.8)	57.2 (15.9)	55.9 (19.7)

and 3.7% respectively. In the lower profile (2.5–10 cm) this corresponded to 1.4, 1.4, and 2.9% respectively. The major difference between sites was the relatively low nitrification at the 14-yr plot.

1994/95 *in situ* Incubation Study

Throughout the study ammonium-nitrogen and nitrate-nitrogen concentrations in the soil at 0–10 cm ranged from 10 to 30 mg N/kg (6 to 18 kg/ha) and 5 to 20 mg N/kg (3 to 12 kg/ha) respectively at the 3-, 20-, and 62-yr plots. In contrast, at the 0-yr plot ammonium-nitrogen was relatively constant ranging between 20 and 25 mg N/kg (12 and 14 kg/ha), whereas nitrate-nitrogen ranged between 20 and 50 mg N/kg (12 and 30 kg/ha) until a series of intense rainfall events (216 mm of rainfall over a 72-hr period) during February 1995 presumably reduced this range to one similar to that of ammonium-nitrogen. As in the 1993/94 study, net nitrogen mineralisation fluctuated between positive and negative values (Fig. 4, only two plots presented), and plant uptake was generally comparable to net nitrogen mineralisation (Table 3). The nitrogen leaching potential estimated at the 62-yr and the 0-yr plots was 13.7 and 42.9 kg N/ha, indicating this pathway may be a potential loss mechanism from the soil nitrogen pool. Further to this, the evidence of potential nitrogen leaching suggests the paired-core incubation method may over-estimate plant nitrogen uptake as the methodology ignores leaching losses.

Comparison of 1993/94 and 1994/95 Studies

A comparison of the results of the two studies was difficult because of varying seasonal effects. Despite this, a number of broad trends were evident when comparing results on the basis that the major mineral-nitrogen turnover occurred between November and May (Table 4). For instance, the proportion of total nitrogen turnover through net nitrogen mineralisation (0 to 10 cm depth) ranged between 1.1 and 2.9% (mean 2.0%). There was a significant and positive linear relationship (R^2 0.69, $p<0.05$, n=5) between net nitrogen mineralisation and plantation age (0-yr plot data omitted). On average (excepting the 14-yr plot), the contribution by nitrification accounted for 60% of net nitrogen mineralisation, although it is recognised that this maybe overstated as *in situ* incubation techniques may enhance rates of nitrification.

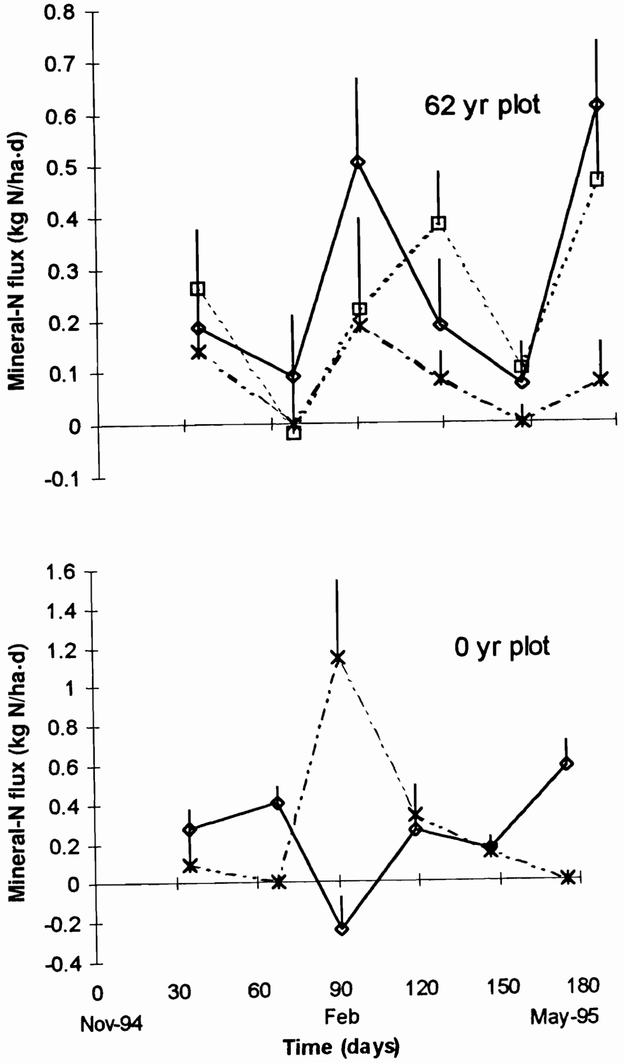

FIG. 4—Seasonal fluctuations of net nitrogen mineralisation, plant uptake, and nitrogen leaching potential during the 1994/95 study at the 62-year-old and 0-year-old hoop pine plantations. Data points represent the mean of five replicates: —◇— net mineralisation; —□—plant uptake; —✳— nitrogen leaching potential. Bars represent standard error.

TABLE 3—Summary of net nitrogen mineralisation, plant nitrogen uptake, and nitrogen leaching potential (kg N/ha) between November 1994 and May 1995 in hoop pine plantations aged 3, 20, 62, and 0 years (standard errors in parentheses).

Site	Net nitrification (kg N/ha)	Net ammonification (kg N/ha)	Net mineralisation (kg N/ha)	Plant uptake (kg N/ha)	Leaching potential (kg N/ha)
3-yr	18.1 (6.6)	7.2 (1.4)	25.3 (7.5)	24.9 (6.1)	
20-yr	16.8 (4.8)	14.1 (6.3)	30.9 (9.5)	19.0 (4.6)	
62-yr	29.3 (10.2)	16.2 (7.1)	45.5 (18.3)	40.2 (7.5)	13.7 (7.6)
0-yr	24.8 (18.6)	21.0 (14.6)	45.8 (26.9)		42.9 (12.2)

TABLE 4—Comparison of results (depth 0–10 cm) from the 1994/95 study and the corresponding period (November to May) during the 1993/94 study in hoop pine plantations (standard errors in parentheses).

Site	Net mineralisation (kg N/ha)		Uptake (kg N/ha)		Relative nitrification (%)	Total N turnover through net mineralisation (%)
3-yr	25.3	(7.5)	24.9	(6.1)	71.5	1.1
10-yr	41.4	(13.3)	36.0	(12.1)	58.9	1.9
14-yr	26.6	(8.5)	26.2	(11.2)	13.5	1.8
20-yr	30.9	(9.5)	19.0	(4.6)	54.4	1.7
62-yr (93/94)	53.0	(13.5)	49.1	(16.3)	53.8	2.9
62-yr (94/95)	45.5	(18.3)	40.2*	(7.5)	64.4	2.2
0-yr	45.8	(26.9)	–	–	54.2	2.3

Note: Relative nitrification was defined by Robertson (1982) as cumulative nitrification expressed as a percentage of cumulative net mineralisation.

* Adjusted for leaching estimated from open-top core.

DISCUSSION

The estimated nitrogen mineralisation fluxes are lower than those that have been reported for tropical forest soils. For instance, Rham (1970) reported a range of 135 to 170 kg N/ha annually for a humid tropical forest in Africa, which was similar to that reported by Maggs (1991) for rainforests in tropical North Queensland, whereas Vitousek & Denslow (1986) reported a high rate of 822 kg N/ha annually for a lowland tropical rainforest in Costa Rica. The range of annual net nitrogen mineralisation fluxes reported in an extensive review by Binkley & Hart (1989) indicates that results of this study are closer to those from many temperate forests.

During the 1993/94 study, nitrogen mineralisation in the upper profile (0–2.5 cm) was only slightly less than that of the lower profile (2.5–10 cm) despite the large differences in soil volume. This was probably due in part to soil temperature effects but, more importantly, to the higher levels and quality of carbon and nitrogen substrate often associated with the surface soil and the litter layer (Boone 1992). The abundance of nitrate-nitrogen was an important feature for plant nutrition as well as a nitrogen loss potential. The regular cycle of drying and re-wetting which occurred throughout both studies would have promoted nitrogen mineralisation, in particular nitrification (Attiwill & Adams 1993; Bauhus & Khanna 1994). Generally, the physico-chemical properties of soils at the study area would be close to optimal for nitrification, with soil temperatures ranging between 20 and 35°C, near neutral pH, good aeration, reliable ammonium-nitrogen supply, high total nitrogen, and low C/N ratio (Bauhus *et al.* 1993). Furthermore, the plot (14-yr) which had relatively low nitrification differed from the other plots in that soil pH was medium acid (5.8). The elevated levels of nitrate-nitrogen at the 0-yr plot (initially at least) were similar to trends reported in many studies at recently clearfelled sites (Matson *et al.* 1987). However, in contrast to many research findings (Attiwill & Adams 1993; Vitousek *et al.* 1992; Smethurst & Nambiar 1990), the elevated levels of nitrate-nitrogen persisted for less than 3 months after clearfelling (data not presented). The reasons for this are not entirely clear; however, it is thought the sudden absence of plant uptake and the disturbance caused by clearing may have been responsible for initial elevated nitrate-nitrogen. After the intense rainfall events in February nitrate-nitrogen was presumably leached (although denitrification may have also occurred); however, the elevated levels were not re-established because of the water-stress conditions which prevailed for the rest of the study.

A number of studies have indicated that the major constraint to autotrophic nitrification is the availability of ammonium-nitrogen as a precursor (Carlyle *et al.* 1990). Using an approach similar to that of Polglase *et al.* (1992), this theory was examined by regressing net nitrification for each incubation period with the total pool of available ammonium-nitrogen (i.e., ammonium-nitrogen present at commencement of incubation plus ammonium-nitrogen and nitrate-nitrogen mineralised during incubation). The regression slope represented the proportion of ammonium-nitrogen resulting in net nitrification. During the 1993/94 study there were highly significant relationships at all plots except the upper profile at the 14-yr plot (Table 5). These results reflected a strong dependence of nitrification on the supply of ammonium-nitrogen. In contrast, there were no significant relationships established for the 1994/95 study. A comparison of rainfall and soil moisture content between the studies (Fig. 1 and 2) suggests the availability of water in the 1994/95 study may have overshadowed the supply of ammonium-nitrogen as being the limiting factor in nitrification. Finally, it must be stressed that when interpreting these results some consideration must be given to the likelihood that *in situ* core methods promote the accumulation of ammonium-nitrogen (by preventing uptake) (Raison *et al.* 1987). Accordingly, these nitrification rates may not reflect the field situation entirely and are likely to some extent to be over-estimated.

A comparison of net nitrification, net ammonification, and net mineralisation fluxes for individual incubation periods with respect to the environmental variables of soil moisture content, rainfall, and mean temperature yielded poor linear correlations. This was expected as the individual fluxes represent the cumulative effect from the fluctuation and interaction of these variables throughout the incubation period, whereas the data used to represent the variables were derived from an instantaneous measurement taken at the end of an incubation period or, alternatively, the mean for the period. A number of researchers have also reported poor correlations for similar types of studies (Maggs 1991; Smethurst & Nambiar 1990; Vitousek & Denslow 1986). In contrast, nitrogen leaching potential at the 62- and 0-yr plots during 1994/95 was significantly correlated to rainfall ($r = 0.54$ and 0.91 respectively, $p < 0.05$). The leaching estimate at the 62- and 0-yr plots represented 30% and 94% respectively of net nitrogen mineralisation. However, one must be cautious in interpreting these results for a number of reasons. At the 62-yr plot the sampling depth was not below root depth, therefore it is not known whether leaching as truly defined had occurred. As discussed

TABLE 5—Relationship between nitrification and ammonium supply during 1993/94 study.

Site: depth	R^2	p level (n =18)	Slope (%)
10-yr: 0 to 2.5 cm	0.51	0.001	55.2
10-yr: 2.5 to 10 cm	0.71	0.001	77.1
14-yr: 0 to 2.5 cm	0.08	not significant	–
14-yr: 2.5 to 10 cm	0.39	0.006	36.7
62-yr: 0 to 2.5 cm	0.36	0.008	40.7
62-yr: 2.5 to 10 cm	0.73	0.001	52.1

previously, the *in situ* method may be also prone to over-estimate leaching through the possibility of artificially elevated rates of nitrification. In summary, these results indicate that there is a potential for substantial leaching losses of nitrogen from clearfelling and to a lesser degree from mature sites. However, further research employing a different methodology to that outlined above is required to better quantify nitrogen losses due to leaching. This research should also investigate the possibility that other loss mechanisms (i.e., denitrification and ammonia volatilisation) may also prevail.

The soil organic carbon (OC), total nitrogen, and C/N ratio have been widely recognised as important regulators of net nitrogen mineralisation (Adams & Attiwill 1983). Regression analysis between the seasonal net nitrogen mineralisation fluxes (November to May) and the soil properties yielded the coefficients of determination (R^2; $p<0.05$) of 0.73, 0.59, and 0.56 for organic carbon, total nitrogen, and C/N ratio respectively. The relationship between the net nitrogen mineralised and organic carbon proved to be the strongest for predicting net nitrogen mineralisation from a single variable (Fig. 5). Interestingly, the regression slope for the relationship with the C/N ratio was positive, which opposes the common belief that increasing C/N ratio favours immobilisation. However, this was probably due to the relatively narrow range observed (i.e., 12.0 to 14.9) where an increasing C/N ratio in this instance more likely reflected an increase in the supply of carbon substrate for nitrogen mineralisation.

In the past there has been no routine fertilising of hoop pine plantations and there has been little research into improving productivity with fertiliser. A useful guide for targeting the periods most likely to respond to nitrogen fertiliser is to compare the estimated annual nitrogen mineralisation fluxes to annual hoop pine plantation demands for nitrogen during a rotation. For instance, recent data (unpubl.) from biomass harvests have indicated that the annual demand for nitrogen by a hoop pine plantation aged younger than 4 years is below 25 kg N/ha. At around age 5 years until canopy closure (approx. 15 years) the demand for nitrogen is in excess of 50 kg N/ha. On the basis of the nitrogen mineralisation fluxes determined from this study, nitrogen may be limiting plantation growth during the period from age 5 years through to canopy closure. Recent fertiliser trials (unpubl. data) supported this in that they demonstrated substantial growth responses to nitrogen fertiliser applied at

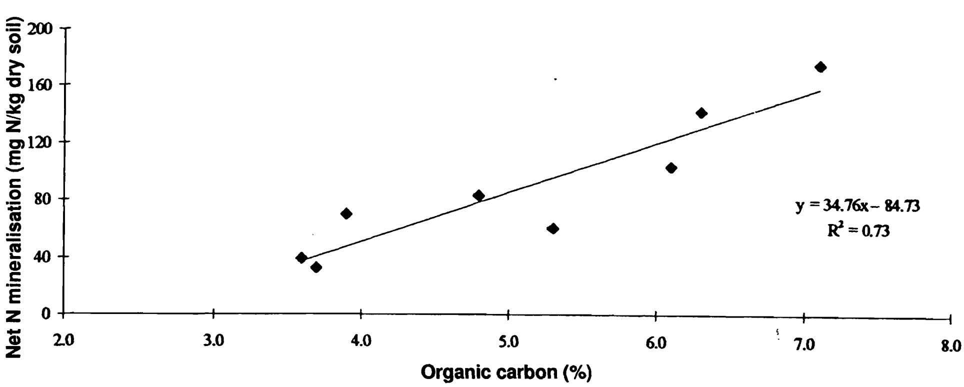

FIG. 5—Relationship between soil organic carbon and *in situ* net nitrogen mineralisation flux in the soil at 1–10 cm depth in hoop pine plantations during the period from November to May 1993/95.

plantation age 5, whereas, no growth responses were noted for nitrogen fertiliser applied at planting.

Some researchers (Campbell *et al.* 1988; Piccolo *et al.* 1994) have criticised the *in situ* core incubation method because the environmental conditions in the closed-top (confined) cores can vary considerably compared with those of open-top cores and ambient conditions. In both of the studies presented here, the *in situ* core tubes were perforated (as suggested by Adams *et al.* 1989) in an attempt to overcome this problem. To demonstrate the utility of this strategy, the mean soil moisture content of bulk cores was compared with the corresponding confined cores across all plots and sample periods during both studies. Statistical analysis using ANOVA revealed no significant differences between the means, with the exception of two sampling periods during the 1993/94 study in the upper profile of 14- and 62-yr plots. In both periods, rainfall had commenced after sampling had been initiated.

In general the major limitations of the method were that plant uptake was likely to be overestimated, and the soil profile below the 10 cm depth could not be investigated; this also limited any interpretation of leaching estimates. Despite these limitations, the level of variability measured by the standard error suggested this method was suitable for use in the upper 10 cm of hoop pine plantation soils. However, as this was the first study of this type in hoop pine plantations there is a need to confirm the reported nitrogen mineralisation fluxes by testing with other techniques.

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