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NITROGEN MINERALISATION IN A CLONAL *EUCALYPTUS* PLANTATION ON SANDY SOIL AFTER CLEARFELLING AND RESIDUE BURNING

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ABSTRACT

A study was designed to compare *in situ* soil N fluxes in a clonal *Eucalyptus* plantation (mean annual increment 21 m^3 ha^{-1} at 7 years) on sandy low-N soils. The study was established in an undisturbed eucalypt and clearfelled *eucalyptus* plantation. Clearfelled plots were subjected to residue burning (Burn) and residue retention (No-burn) prior to re-establishment. A sequential open and closed soil coring method was used to determine cumulative N-mineralisation, surface leaching and root uptake fluxes in the top 0 to 30 cm soil layer. Mineralisation and immobilisation in the undisturbed forest remained near zero over the study period, accumulating as net N immobilisation. Clearfelling increased net N mineralisation and nitrification, increasing mobile NO_3-N concentrations in the surface soil. Surface N leaching was increased and root uptake decreased after clearfelling. Surface N leaching was not altered by residue burning. Net N mineralisation in the burn plots was less than in the no-burn plots, reduced after burning by nearly 53% over the 20.1 month period. Atmospheric inputs strongly contributed to N inputs across all treatments.

Key words : Atmospheric deposition, Immobilisation, Nitrification, Plantation forest.

Introduction

Mineralisation of nitrogen (N) is crucial in forests soils where limited N availability has the potential to reduce tree growth rates during periods of high N demand (Binkley and Hart, 1989; Maithani *et al*., 1998; Smethurst *et al*., 2004). The supply of N through mineralisation is an important aspect in forest nutrient management and a good indicator of ecosystem health (Morris and Boerner, 1998; Reich *et al*., 1997). Potential N loss from plantation soils during periods of excess N mineralisation relative to uptake is of particular concern during the inter-rotational (fallow) period. Management of harvesting and post-harvest residues plays an important role in N losses during the inter-rotation period as soil temperature, soil moisture content; organic matter content and chemistry are affected by residue management (Gonçalves *et al*., 2007; Li and Herbert, 2004). Cessation of water and nutrient uptake combined with higher soil temperatures and soil moisture contents can result in increased losses through enhanced mineralisation, leaching and denitrification (Fisher and Binkley, 2000). Losses associated with burning (varying according to fire intensity) and resultant increases in soil NH_4-N release through heating and ash deposition and subsequent increased leaching can further compromise future N supply (Weston and Attiwill, 1996; Carlyle *et al*., 1998; Piatek and Allen, 1999). Given the increasing demand for forest biomass (Crickmay, 2005), the fate of N following clearfelling disturbance and residue management is key to N conservation and site recovery on N limited sites (Weston and Attiwill, 1996; Gomez-Rey *et al*., 2007). Studies investigating N mineralisation processes in South African plantation forestry are limited to predicting fertiliser requirements (Louw and Scholes, 2002) and do not describe changes after clearfelling and residue management.

Our study aimed to assess soil N fluxes during the inter-rotation period of a eucalypt stand on a site characterised as having small soil N pools and rapid turnover. The effect of clearfelling and two extremes of standard management practices (residue retention and residue burning) on in situ mineralisation and nitrification was determined. The method used also gave an indication of surface N leaching and root uptake. Nitrogen fluxes were expected to be substantially altered after clearfelling and again after residue burning compared to residue retention. This study describes soil mineral N fluxes and draws upon data in Dovey *et al*. (2011a,b) to describe the contributions of independantly measured soil moisture and atmospheric N inputs to soil mineral N fluxes.

Material and Methods

Study site and experimental design

The study was located on the Zululand coastal plains (northern KwaZulu-Natal, South Africa). The site, Dukuduku, was described in Dovey *et al*. (2011a) as

Net N mineralisation was reduced by 53% over 20.1 month period after residue burning compared to residue retention in clear felled *Eucalyptus* plantation.

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subtropical, characterised by fast-growing (site index 19.9 m at 5 years of age) clonal eucalypts on low N Albic Arenosols (Table 1) (FAO, 2006; Hartemink and Hutting, 2005; Fey, 2010). Low soil N supply has been confirmed through substantial tree growth responses to applications of N fertiliser at planting (du Toit and Oscroft, 2003).

The experiment was initiated in a seven-year-old clonal *Eucalyptus grandis x camaldulensis (G x C)* compartment (3 m x 3 m spacing). Clearfelling occurred in November 2008. Treatments were installed after clearfelling as a four replicate randomised complete block design with two replicates of un-felled trees forming a standing crop treatment. The standing crop areas were delineated as 138 x 276 m zones at the northern and southern end of the compartment with a surrounding buffer zone of 51 m which was clearfelled. Standing crop plots were delineated in central positions of the northern and southern areas, with additional buffer zones of 51m that were not felled. The central portion of the compartment was felled, and divided into 36 square experimental plots 42 x 42 m, each with an internal 15 x 15 m plot used for tree growth measurement. Residue burning (Burn), residue broadcast (No-burn) and standing crop treatments were installed. Burning occurred in March 2009 and site was planted in July 2009 and at a 3 x 2 m spacing to clonal *G x C*. Weed and coppice re-growth was controlled manually and with *glyphosphate* and Triclopyr. A full description of the experiment is given in Dovey *et al.* (2011a).

Sequential coring and analysis

A sequential coring method was used to assess *in situ* 0 - 30 cm N-mineralisation rates, including the net effects of surface N leaching, denitrification and atmospheric deposition (Adams *et al*., 1989; Adams and Attiwill, 1986; Raison *et al*., 1987). Fifteen PVC cores (5 cm internal diameter and 40 cm in length) were inserted into the soil, to depth of 30 cm, in each sample plot. Five cores were collected immediately to represent a time-zero undisturbed sample, while five closed (capped) and five open (uncapped) cores were left *in situ* for 28 to 35 days of incubation. The length of each incubation period depended upon accessibility to the study site. This sampling procedure occurred at the end of each incubation period where incubated cores were replaced with new cores and time-zero undisturbed samples were collected. All cores were inserted at randomly located positions in each plot. This duration was chosen as it was assumed to be an adequate period to allow small differences in physical conditions while enabling detection of N concentration changes (Jussy *et al*., 2004). Closed, open and time-zero cores were collected at the end of each incubation period and new cores were inserted to replace the extracted cores at the end of each period. Each core type was bulked as layers of 0 - 5 cm, 5 - 15 cm, and 15 - 30 cm and homogenised sub-sample was refrigerated at 5°C for next-day analyses. The remaining soil was used for determining gravimetric water content by oven drying at 105°C for 24 hrs. Samples were analysed for extractable NH_4-N using methods in Alves *et al*. (1993) and NO_3-N after Willis and Gentry (1987) after shaking 25 g soil with 50 ml 2 M KCl for 1 hour and filtering the extracts through 42 *u*m (Whatman No. 42) filter paper.

Mineral nitrogen (NH_4 and NO_3) fluxes were calculated for each incubation period as follows:

$$\Delta Closed = Closed_{(t+1)} - NI_t$$

$$\Delta Open = Open_{(t+1)} - \mathrm{NI}_t$$

$$\Delta NI = \mathrm{NI}_{(t+1)} - NI_t$$

Where Δ*Closed* is the N mineralisation in closed cores over each incubation period, NI_t is the non-incubated bulk soil core at *t* (time of core insertion). $Closed_{(t+1)}$ is the closed core sample taken after incubation at *t*+1. Δ*Open* is N fluxes in the open cores assumed to be mineralisation minus leaching plus deposition. Δ*NI* is N fluxes in the bulk soil assumed to be mineralisation minus leaching plus deposition minus root uptake. The difference between closed and open core N fluxes was used to estimate leaching and the difference between open cores and bulk soil N fluxes was used to estimate root uptake (Smethurst and Nambiar, 1989; Raison *et al*.

Table 1 : Basic soil physical and chemical properties of the top 100 *cm* (in 20 cm increments) at the start of the study (Dovey, 2012)

Depth (*cm*)	Bulk Density (*g cm^{-3}*)	Clay	Sand (%)	Silt	pH (KCl)	Organic carbon (Walkley-Black) (*g kg^{-1}*)	Total Kjedahl nitrogen (*g kg^{-1}*)	Exch. acidity (*cmol$_c$ kg^{-1}*)	Acid Saturation %
0-20	1.53	2.5	94.5	3.0	4.35	4.3	0.39	0.31	25
20-40	1.55	2.3	95.3	2.4	4.31	2.7	0.37	0.31	29
40-60	1.57	2.2	96.0	1.8	4.33	2.1	0.28	0.33	32
60-80	1.59	1.8	95.9	2.3	4.36	1.8	0.35	0.36	34
80-100	1.61	2.0	96.2	1.7	4.37	1.6	0.30	0.36	36

1987). A calculation of differences between core fluxes was therefore used to estimate leaching plus deposition (dissolved) and root uptake:

Net losses (Leaching minus deposition) = Δ*Open* – Δ*Closed*

Root uptake = ΔOpen - Δ*NI*.

Alternatively, as Raison *et al*., (1987) formulates it: $Closed_{(t+1)} – NI_{(t+1)}$ - (net losses)

Which is the same as $Closed_{(t+1)}$ - $NI_{(t+1)}$ - [Δ*O*pen - Δ Closed]

Residue and litter mineralisation (and leaching) was not recorded due to the size of the material and financial constraints. Litter was removed prior to core insertion. This study therefore only recorded the effect of residue management on mineral N within the first 30 cm of soil. Net N fluxes were calculated as the sum of NH_4-N and NO_3-N. Mean soil bulk density at each depth (using five samples per depth in each plot) was used with measured N concentrations to scale nutrient content to a per hectare basis.

Supporting measurements

Rainfall, air temperature and soil moisture data are reported in (Dovey *et al*., 2011a). Soil temperatures were measured in each plot using three replicates of copper constantan thermocouple probes at depths of 2.5 cm, 10 cm and 22.5 cm. These were placed within and between the tree rows to capture soil variability and logged at one minute intervals with a Campbell Scientific Cr10x logger. Net deposition of organic-N, ammonia and nitrates were monitored throughout the study period as bulk rainfall (outside the canopy) and throughfall plus stemflow (under the canopy) (Dovey *et al*., 2011b). These data were cumulated over each incubation period and correlated with the N fluxes at the end of each period. Assessments of biomass and N accumulation with growth, litterfall and residue decomposition were undertaken at regular intervals throughout the study period. Standing crop forest floor litter decomposition was corrected using weekly litterfall measurements. Aboveground tree biomass was estimated using destructively harvested trees from each treatment plot across the entire site. Standing crop litterfall was collected weekly using five litter traps randomly placed in each plot. Forest litter layer and residue biomass was collected at four weekly intervals using a metal ring (34 cm diameter) across five random points in each treatment plot. Dried subsamples from each tree component, litter, residue and ash were individually ground and homogenised then analysed for nutrient concentration (N, P, K, Ca, Mg, Na) using the methods described in Kalra and Maynard (1991) at the Cedara laboratories in South Africa.

Statistical analyses

Data was tested for normality using the Shapiro-Wilk test and homogeneity of variance using the Bartlett's test. ANOVA was used at the end of each incubation and final cumulative N measures, growth and biomass to test for treatment differences. Least significant difference ($LSD_{5\%}$) was used to show significance of treatment differences for each incubation period and each cumulative measure. Pearson correlation was used to test for correlation between N fluxes and soil measures. Statistical analysis was performed using GenStat 12th Edition (Payne *et al*., 2011).

Results

Changes in system N pools during the study period

The standing crop plots accrued a relatively small amount of biomass and of N into above-ground tree components and litterfall during the study period (Table 2). Clearfelling removed stem wood containing 118.1 kg ha^{-1} of N leaving 50.6 Mg ha^{-1} of residue and litter containing 303.5 kg ha^{-1} of N (Table 2). During three

Table 2: Nitrogen pool sizes and accretion over the inter-rotation for three treatments. Changes in pools given in parenthesis.

	Nitrogen (kg ha^{-1})		
Component	Standing crop	No-Burn	Burn
Post-Clearfelling Pools (October 2008)			
Forest floor/Residues	201.6	303.5	303.5
Pools after Burning (March 2009)			
Forest floor/Residues	203.8	232.3	111.1*
Accretion[1]	33.1	-	-
Pools at planting (August 2009)			
Forest floor/Residues	177.3	224.6	0.0
Accretion[1]	30.8	-	-
Pools at canopy closure of new crop (June 2010)			
Forest floor/Residues	169.9	176.0	
Accretion[1]	67.7	64.9	75.1

[1]includes litterfall; * ash after burning

month delay before burning 14.2 Mg ha^{-1} and 71.2 kg ha^{-1} of N was lost from the residues through decomposition. Burning reduced this to a 4.2 Mg ha^{-1} layer of ash and char inducing a loss of 121.2 kg ha^{-1} of N. A very small quantity of coarse char remained on the soil surface at a week after burning. Growth differences between the Burn and No-burn treatments were not significant at one year after planting. A large quantity of N (58 % of original) remained in the No-burn treatment residues at canopy closure.

Soil temperature and moisture

Standing crop and No-Burn soil temperatures were similar throughout the study. Soil temperature increased after burning by 10.0 ^{o}C in the Burn compared to the No-Burn treatment. The albedo effect diminished after the ash moved into the soil with rainfall two weeks after burning, decreasing the difference to 3.0 ^{o}C. These differences remained significant up to four months after planting (p < 0.001). Soil moisture content increased after clearfelling and the No-Burn plots were slightly wetter than the Burn plots (Dovey *et al*., 2011a). All treatment soil moisture levels were similar by canopy closure.

Net mineralisation

Net N mineralisation occurred in all treatments between clearfelling and planting; statistically similar in the no-burn and Burn treatments and significantly lower than the standing crop treatment on one occasion (Table 3, Fig. 1). Statistically similar net N immobilisation occurred in the Burn and standing crop treatments between planting and canopy closure, while net N mineralisation occurred in the No-burn treatment. Cumulative net N mineralisation between clearfelling and canopy closure was significantly different across all treatments (Table 3, Fig. 1). Largest net N mineralisation occurred in the No-burn followed by the Burn, and net immobilisation occurred in the standing crop. The nine months between clearfelling and planting was dominated by NH_4-N immobilisation (Fig. 1A) and nitrification (Fig. 1B). Treatment differences were significant for each period at p < 0.001 for nitrification.

No-Burn treatment immobilisation of NH_4-N was significantly larger than in the Burn treatment, which was significantly larger than the standing crop treatment (p < 0.001). Immobilisation of NH_4-N did not change significantly with depth between felling and planting (p >

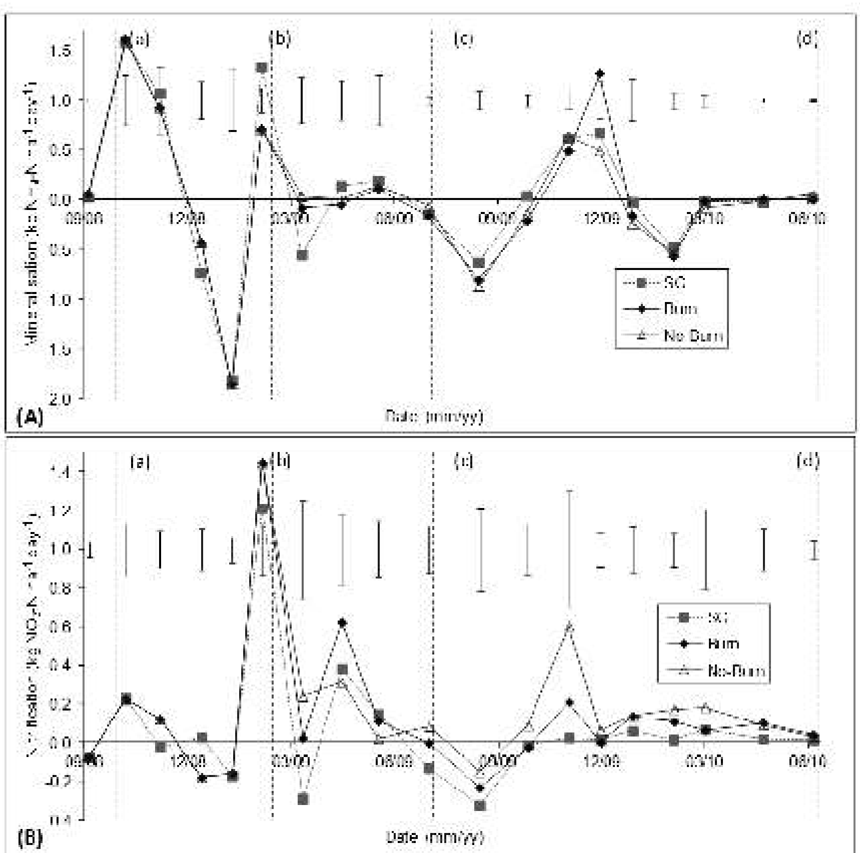

Fig. 1 : Mineral N fluxes in the 0 - 30 cm soil layer after in situ incubation of closed cores. (A) mineralisation to NH_4-N (B) and nitrification to NO_3-N. Treatments are standing crop (SC), residue retention (No-Burn) and burned residue (Burn). Dashed lines are (a) clearfelling; (b) residue burning; (c) planting and (d) canopy closure. I-bars are $LSD_{5\%}$ between treatments.

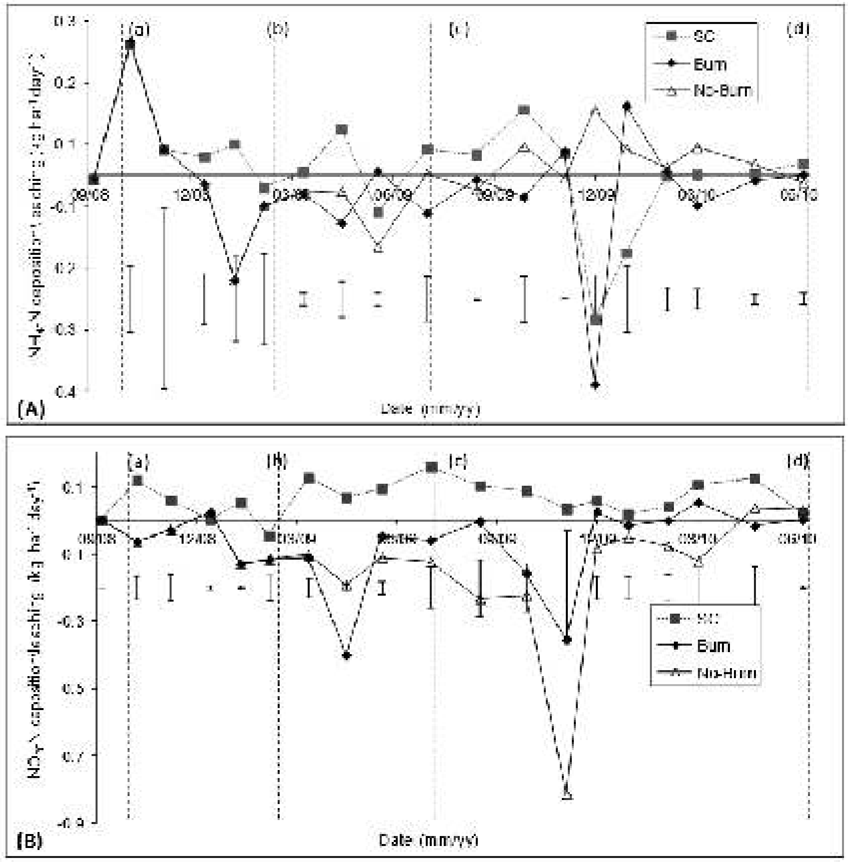

Fig. 2 : Mineral N [(A) NH_4-N and (B) NO_3-N] added to the 0 - 30 cm soil layer through atmospheric deposition (positive values) or lost through leaching (negative values). Treatments are standing crop (SC), residue retention (No-Burn) and burned residue (Burn). Dashed lines are (a) clearfelling; (b) residue burning; (c) planting and (d) canopy closure. I-bars are $LSD_{5\%}$ between treatments.

0.08) and planting and canopy closure (p = 0.232). Nitrification however tended to be greater at the surface than at depth between felling and planting (p < 0.001) and planting and canopy closure (p < 0.001), (Table 4). Overall nitrification was 2.7 fold greater at 0 to 5 cm than 5 to 15 cm depths and 7.0 fold greater at 5 to 15 cm than

Table 3: Net nitrogen fluxes in-field cores over the inter-rotation. Mineralisation, nitrification and deposition gains are positive; immobilisation, loss and uptake are negative.

		Cumulative (kg ha^{-1})				Annualised (kg ha^{-1} year^{-1})		
		No-Burn	Burn	SC	p	No-Burn	Burn	SC
Clearfelling to planting (9 months)	Net Mineralisation	38.1^{a}	28.8^{a}	6.0^{b}	0.011	50.6	38.2	8.0
	Deposition minus leaching	-28.8^{a}	-31.9^{a}	24.5^{b}	<.001	-38.2	-42.3	32.5
	Net deposition	15.3	15.3	19.2		20.3	20.3	25.5
	Uptake	11.1^{a}	6.1^{a}	63.1^{b}	<.001	14.7	8.1	83.8
	N accretion			63.9*				
Planting to Canopy (11 months)	Net Mineralisation	7.7^{a}	-4.3^{b}	-11.6^{b}	0.02	8.4	-4.7	-12.6
	Deposition minus leaching	-48.5^{a}	-26.6^{b}	21.3^{c}	<.001	-52.7	-28.9	23.1
	Net deposition	9.5	9.5	15.0		10.3	10.3	16.3
	Uptake	32.6^{a}	42.7^{a}	56.2^{b}	<.001	35.4	46.4	61.1
	N accretion	64.9	75.1	67.6*				
Clearfelling to Canopy (20.1 months)	Net Mineralisation	45.7^{a}	24.5^{b}	-5.7^{c}	0.004	27.3	14.6	-3.4
	Deposition minus leaching	-77.2^{a}	-58.6^{a}	45.8^{b}	<.001	-46.1	-35	27.4
	Net deposition	24.7	24.7	34.2		14.8	14.8	20.4
	Uptake	43.7^{a}	48.8^{a}	119.3^{b}	<.001	26.1	29.2	71.3
	N accretion	64.9	75.1	131.5*				
	Residue/litter mass loss	118.7	62.4	148.4*				

a, b, c superscripts denote significant differences (LSD5%). * includes litterfall.

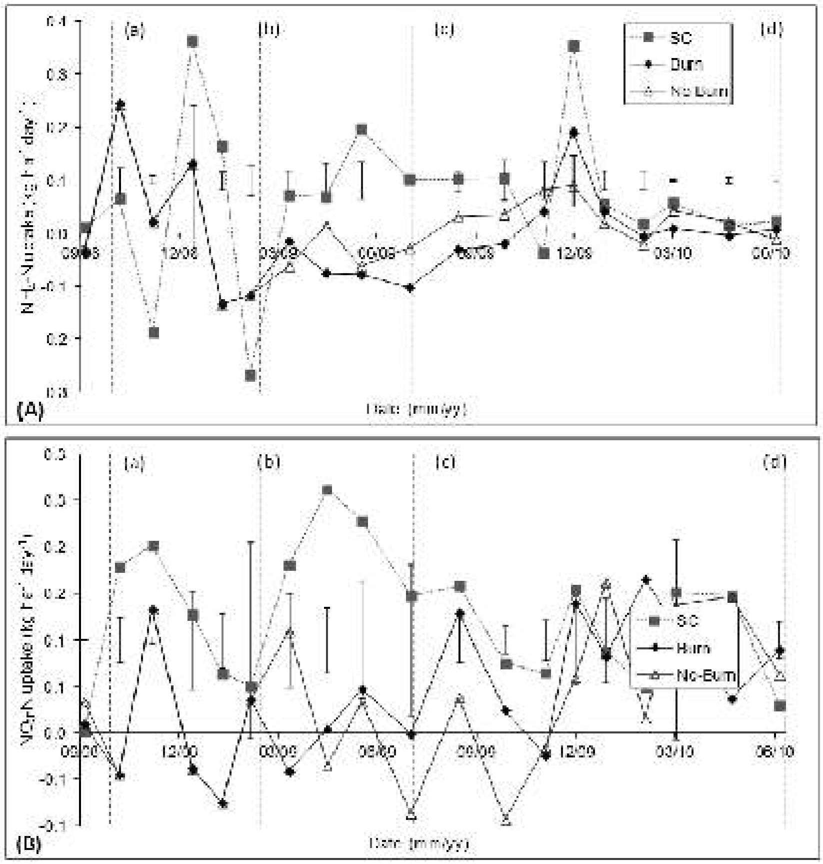

Fig. 3 : Changes in mineral N [(A) NH_4-N and (B) NO_3-N] in the 0 - 30 cm soil layer through root uptake and residue/litter additions. Treatments are standing crop (SC), residue retention (No-Burn) and burned residue (Burn). Dashed lines are (a) clearfelling; (b) residue burning; (c) planting and (d) canopy closure. I-bars are $LSD_{5\%}$ between treatments.

15 to 30 cm depths (p < 0.001), (Table 4). Addition of N (organic and mineral) through atmospheric inputs followed similar trends to mineralisation and core measured atmospheric inputs. Organic-N added with throughfall was positively correlated with the nitrification rate (R = 0.633; p < 0.01). Throughfall NH_4-N deposition was however, negatively correlated with nitrification rate (R = -0.502; p < 0.01).

Deposition and surface leaching

A net N gain occurred in the standing crop treatment throughout the study through atmospheric deposition (Table 3, Fig. 2) with a slightly higher deposition rate during the first nine months of the study. Although this occurred in the felled treatments, it was significantly outweighed by leaching losses. An overall net N loss occurred in the No-Burn and Burn treatments. These were statistically similar for the first period (felling to planting) and larger in the No-Burn during the second period (planting to canopy closure). Differences between the felled treatments were not significant over the entire period (felling to canopy closure). Differences between treatments in Table 3 were attributed to treatments differences in NO_3-N during the first, second and full period p < 0.001in each case Figure 2B. Deposition of NH_4-N (Fig. 2A) was not significantly different between treatments during any period (p = 0.24, 0.06, 0.09, respectively). Leaching of NO_3-N (Fig. 2B) decreased significantly with depth for all periods (p = 0.01, 0.04, 0.01, respectively), whereas NH_4-N (Fig. 2A) was only significant with depth during the first period (p = 0.00, 0.21, 0.11, respectively). This significant difference occurred as a greater leaching at 15 cm than at 30 cm depth (Table 4). A total of 4.1 kg ha^{-1} yr^{-1} of NH_4-N and 41.8 kg ha^{-1} yr^{-1} NO_3-N was gained with rainfall in the standing crop during the clearfelling to canopy closure period. A total of 3.6 and 19.1 kg ha^{-1} yr^{-1} of NH_4-N and 73.6 and 39.6 kg ha^{-1} yr^{-1} NO_3-N was leached during the clearfelling to canopy closure period in the No-burn and Burn treatments respectively. Less N was recorded as throughfall above ground during each period than was recorded by open core calculations.

Root uptake

A large quantity of N was lost from the soil surface of the standing crop with root uptake (Table 3, Fig. 3) across both periods. Root uptake was significantly larger in the standing crop treatment than in the felled treatments throughout the study. Calculated root uptake was small prior to planting, with no significant differences between felled treatments. Post planting root uptake was larger, but differences were not significant between felled treatments. Root uptake prior to planting occurred as a loss of NO_3-N in the felled treatments, occurring primarily from 0 to 5 cm depth (Table 4). A small gain in NH_4-N occurred in the felled treatments at the 0 to 5 cm soil depth during this period (Table 4). Root uptake prior to planting was attributed to weed and old stump coppice re-growth. Root uptake of NO_3-N and NH_4-N was largest in the standing crop treatment, but not significant different between felled treatments (Table 4). More NO_3-N was taken up than NH_4-N throughout the entire study period. Uptake in all plots did not change with depth prior to planting ($p = 0.25$), but decreased with depth after planting ($p < 0.001$). These differences occurred through significant differences in NO_3-N across each period, $p < 0.001$ in each case. Although differences in NH_4-N did occur, these were as a smaller uptake from the 0 to 5 cm depth than from the other two depths ($p < 0.001$ for each period). Root uptake amounted to 42.8 kg ha^{-1} yr^{-1} of NH_4-N and 76.5 kg ha^{-1} yr^{-1} NO_3-N in the standing crop treatment for the entire study period. A total of 8.6 and 4.6 kg ha^{-1} yr^{-1} of NH_4-N and 35.2 and 44.1 kg ha^{-1} yr^{-1} NO_3-N was leached during the clearfelling to canopy closure period in the No-Burn and Burn treatments respectively. Aboveground N accumulation (accretion) was larger than 0 to 30 cm root uptake calculated using core methods (Table 3). However, standing crop aboveground N accumulation (including litterfall) was of a similar order of magnitude to core calculated uptake. Loss of N from the litter and residues was large. This loss could not be directly related to soil core fluxes as fine root growth occurred near the surface (visual observation) in direct contact with the humus layer component of the residues and litter layer.

Discussion

Denitrification was likely to have been zero or negligible at our study site due to the well drained nature of the soil (sandy texture) and the water contents measured over the course of the trial (Dovey *et al*., 2011a) remaining at or well below field capacity (Færge and Magid, 2004; Groffman, 1995). Net mineral N content in incubated cores was therefore affected by a combination of some or all of the following processes: microbially-mediated N mineralisation and nitrification fluxes, N addition with rainfall/throughfall, litter decomposition and N leaching.

Standing crop N fluxes

Net N mineralisation (Table 3) remained relatively stable in the standing crop throughout the study period alternating between N release and N immobilisation (or consumption). The relatively stable soil temperatures and consistently low soil moisture contents between rainfall events gave little opportunity for rapid mineralisation to occur. This shows that the standing crop was sub-optimally supplied with both water and soil-derived N. A large proportion of above-ground tree N accretion was most likely supplied from large throughfall inputs (Dovey *et al*., 2011b), litter decomposition and deeper soil N. More N entered and left the soil than was utilised and immobilised (Table 3).

Felled crop N fluxes

Changes in N-fluxes in the felled treatments became more apparent at around three months after clearfelling, coinciding with the time that rainfall induced soil moisture contents began to diverge.

Differences in soil moisture and drainage fluxes between felled and standing crop plots gradually diminished with growth and increasing water demand of the new crop (Dovey *et al*., 2011a).

Soil temperature differences were reduced through shading of the soil by the residues in the No-Burn and the open canopy architecture of the standing crop treatment. These results are consistent with N mineralisation relying on a stable and wet soil moisture regime. Higher levels of net N mineralisation in the No-burn treatments were likely related to the larger amounts of organic substrate on the soil surface and more stable soil surface temperature and moisture regimes. Nitrogen mineralisation continued, but decreased in the No-burn plots after planting. Immobilisation of N occurred in the Burn treatment after planting. The low N mineralisation rates under rapidly drying soils in the standing crop and the increased N mineralisation rates with soil moisture recharge after clearfelling show the reliance of N mineralising soil micro-organisms on a stable and wet soil moisture regime. Net mineralisation rates may peak again in the No-Burn treatments later in the rotation as substrate provision (large levels of residue remaining on the No-Burn as opposed to the Burn treatment), soil moisture retention and temperature stabilisation continue enhance net N mineralisation. This was found to occur in a similar study on sands (Nzila *et al*., 2002).

This continued N supply will satisfy a larger proportion of tree growth N demand later in the rotation, given the reduced N supply in the Burn treatment. Net mineralisation rates can continue in the No-Burn treatments later in the rotation as substrate provision (large levels of residue remaining on the No-Burn as opposed to the Burn treatment), soil moisture retention and temperature stabilisation continue to enhance net N mineralisation. Immobilisation of N (Table 3) in the burnt plots after burning indicates a soil depletion of organic substrates required for N mineralisation. However, given that early growth was similar at 2.5 years, factors other than N were growth initially limiting at this site. The effect of reduced soil N availability on tree growth may also depend on other site factors (moisture, temperature, soil texture and topology) and tree species selection that alter growth rates. Growth rate and species specific nutrient demand may influence tree growth responses to N availability (Millner and Kemp, 2012a, b). The effects of windrow residue burning and mechanical site management practices carried out on sandy soils were shown to have no significant effect on 20 year tree survival and growth in the colder, dryer sub-boreal *Pinus contorta* forests in Canada (Boateng *et al*., 2012). Similarly growth and survival of two *Eucalyptus* species (native and exotic) grown on cold, dry climate on sandy soils Tasmania were unaffected by site management which included residue burning and mulching (Close *et al*., 2010). Treatment effects on cumulative net mineralisation (Table 3) were similar to those in a comparable study in Brazil (Gonçalves *et al*., 2007), where higher rates of N mineralisation occurred after minimal disturbance (residue retention) than after residue burning. Similar quantities of N were mineralised in the Brazil study compared to our study, 58 kg ha^{-1} in the minimum disturbance treatment and 28 kg ha^{-1} in the burned treatment over a 21 month period (Table 3). Mean monthly net mineralisation rates (Table 3) were also within a similar order of magnitude to studies in Congo reported in Nzila *et al*. (2002) under similar crop, climate and soil conditions to our study. Growth rate was reduced under lower N availability in the Tropical Brazil and Congo study sites above. The effect of site management and soil N availability is of greater consequence to tree growth on the fast-growth tropical and sub-tropical sites, given the increased nutrient demand through rapid growth. Soil texture can also play a major role in soil N mineralisation. The sandy soils in our study suffer from reduced water retention and an increased leaching potential. Slower draining soils with a greater water holding capacity will enable a more favourable environment for N mineralisation and retention. Silt and clay content, total organic matter and the fraction of organic matter associated with sand fraction are also correlated with N mineralisation (Scott Bechtold and Naiman, 2006; Matus *et al*., 2007).

Consequence of atmospheric N inputs

This study suggests a large amount of atmospheric N input to the site which may have increased both the rate and quantity of nitrification and mineralisation. Intrinsic site differences such as atmospheric N inputs overriding treatment effects has been observed in a number of studies (Carlyle *et al*., 1998; Månsson and Falkengren-Grerup, 2003). Atmospheric deposition affects the rate and quantity of N released from N mineralisation through changes in C:N ratios, soil pH and litter quality (Månsson and Falkengren-Grerup, 2003; Rao *et al*., 2009). This was demonstrated using N fertilisation in a number of studies (Aarnio and Martikainen, 1992; Prescott *et al*., 1995; Fox, 2004). Large N additions however, reduced organic matter quality and mineralisation rates in one study through base cation stripping after increased nitrification (Fox, 2004). The addition of organic and inorganic compounds from the decomposing residues and from atmospheric deposition in particular, may have altered the basal mineralisation rates by changing the quantity and quality of mineralisable soil organic compounds. This may also be a constraint in some N mineralisation models that assume a basal mineralisation rate that is altered by water and temperature regimes alone (Paul *et al*., 2002). Such models do not allow N to become immobilised in the soil and do not account for the effects of N additions from above the soil surface either. Although literature does not report on the interaction between atmospherically derived organic-N and N-mineralisation, it is suggested in our study to have contributed to N-fluxes. A lack of large differences between the treatment extremes during the period under study may also indicate net N mineralisation to be largely dependent on intrinsic site factors rather than upon soil and site management differences. Intrinsic site differences overriding treatment effects has been observed in a number of similar studies, reviewed in Carlyle *et al*. (1998). The role that the quantity and form of atmospheric N inputs plays in N mineralisation processes needs further investigation as this may drive the ability of a site to immobilise and conserve N during the inter-rotation.

Our study shows relatively balanced N fluxes in the undisturbed standing crop where release and consumption of N occurs at low levels, increasing during high soil moisture conditions.

Nitrogen gained with rainfall under the canopy (throughfall) appeared to be rapidly mineralised,

Table 4: Cumulative fluxes in-field cores at three soil depths over the inter-rotation (kg ha^{-1}). Least significant differences (LSD5%) are given across treatments and depths.

Flux	Treatment	Depth	Clearfelling to planting			Planting to canopy closure			Clearfelling to canopy closure		
			NO_3-N	NH_4-N	Net-N	NO_3-N	NH_4-N	Net-N	NO_3-N	NH_4-N	Net-N
Mineralisation and Nitrification	No-Burn	5	23.8	-3.5	20.3	34.2	-6.6	27.6	58.0	-10.1	47.9
		15	13.6	-0.3	13.3	12.5	-9.7	2.8	26.0	-9.9	16.1
		30	16.6	-12.1	4.5	-5.2	-17.6	-22.7	11.4	-29.6	-18.2
	Burn	5	28.4	1.3	29.6	13.0	-9.8	3.2	41.3	-8.5	32.9
		15	19.3	-5.4	13.9	3.6	-4.9	-1.4	22.8	-10.3	12.5
		30	8.4	-23.2	-14.8	-3.8	-2.3	-6.1	4.6	-25.5	-20.9
	Standing crop	5	16.9	-14.2	2.7	4.6	-0.1	4.5	21.5	-14.3	7.2
		15	8.9	2.9	11.7	-4.2	-1.8	-6.0	4.7	1.1	5.8
		30	3.2	-11.7	-8.5	-8.3	-1.8	-10.2	-5.1	-13.5	-18.6
		LSD5%	1.5	1.2	2.0	0.6	1.5	1.6	1.4	2.5	2.8
Deposition minus leaching	No-Burn	5	-11.5	-0.1	-11.5	-29.5	-1.4	-30.9	-40.9	-1.4	-42.4
		15	-4.6	-12.0	-16.6	-16.3	5.1	-11.2	-20.8	-6.9	-27.7
		30	-2.3	1.6	-0.7	-9.6	3.2	-6.4	-11.9	4.7	-7.2
	Burn	5	-5.5	-5.8	-11.3	-10.5	1.0	-9.5	-16.0	-4.8	-20.8
		15	-10.4	-8.1	-18.6	-3.8	-0.4	-4.2	-14.2	-8.6	-22.7
		30	-4.8	2.8	-2.0	-4.5	-8.5	-13.0	-9.4	-5.7	-15.0
	Standing crop	5	4.9	-2.0	2.9	13.1	-0.4	12.7	18.0	-2.3	15.7
		15	3.8	2.2	5.9	5.1	1.2	6.3	8.9	3.4	12.3
		30	10.1	5.6	15.7	4.9	-2.6	2.3	15.0	3.0	18.0
		LSD5%	1.3	0.9	1.6	0.9	1.7	2.2	1.7	2.3	2.8
Root Uptake	No-Burn	5	8.2	-0.6	7.7	11.6	-0.4	11.2	19.9	-0.9	18.9
		15	3.3	-2.7	0.6	5.8	8.3	14.1	9.1	5.7	14.8
		30	5.7	-3.0	2.8	0.5	6.8	7.3	6.2	3.8	10.0
	Burn	5	13.3	-3.1	10.1	13.3	0.3	13.6	26.5	-2.9	23.7
		15	3.2	-3.0	0.1	8.1	6.7	14.8	11.3	3.7	15.0
		30	1.2	-5.3	-4.1	5.3	9.0	14.3	6.4	3.8	10.2
	Standing crop	5	19.3	-11.9	7.4	20.6	4.7	25.3	39.9	-7.2	32.7
		15	9.8	19.6	29.3	6.8	8.7	15.4	16.5	28.2	44.8
		30	13.6	12.7	26.4	6.4	9.0	15.4	20.1	21.8	41.8
		LSD5%	1.0	0.9	1.5	0.7	1.1	1.4	1.2	1.7	1.9

nitrified and possibly removed with tree uptake. Site disturbance through clearfelling increased the rate of N release through mineralisation processes through more favourable soil moisture and temperature regimes and the provision of additional substrate. Increased soil moisture and NO_3-N concentration in the soil of the felled plots induced an increase in NO_3-N leaching, displacing N from upper to lower soil layers. Burning of residues in this low-N system reduced soil net N mineralisation by nearly 53% over the 20 month period. The first six months of tree growth was improved on the burnt plots, which suggest that factors other than N supply were more limiting to growth during this period. However, the loss of N through burning followed by reduced mineralisation will reduce future N availability to the current crop and negatively impact on soil N pools and fluxes in the long-term (O'Connell, 2004; Smaill *et al.*, 2010). Lower soil nutrient levels may necessitate selection and planting of tree species adapted to lower soil nutrient contents (Millner and Kemp, 2012b). The positive N mineralisation after residue retention will enable a more sustained supply of N to the new crop throughout the rotation. Conservation of the residues and the subsequent slower release of N in the No-Burn treatment is a more sustainable practice on this site than residue burning.

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पूर्ण पातन और अवशेष जलाने के उपरान्त बलुई मृदा में एक क्लोनीय यूकेलिप्टस रोपण में नाइट्रोजन खनिजीकरण

एस.बी. दोवे और बी. डियू. टोइट

सारांश

बलुई निम्न–नाइट्रोजन मृदाओं में एक क्लीनीय यूकेलिप्टस रोपण (7 साल में औसत सालाना वृद्धि 21 m^3ha^{-1}) में स्वस्थाने मृदा नाइट्रोजन प्रवाहों की तुलना करने के लिए यह अध्ययन अभिकल्पित किया गया। अध्ययन को अविक्षुब्ध यूकेलिप्टस और पूर्ण पातित यूकेलिप्टस रोपण में स्थापित किया गया। पूर्ण पातित भूखण्डों में अवशेष जलाने (जला) और पुनर स्थापना से पहले अवशेष धारण (बिना जला) का कार्य किया गया। ऊपरी0 स े3 0स े.मी.म ृदाप रतम ें स ंचयीन ाइट्रोजनख ानिजीकरण,स तहि वक्षालनअ ौरज ड़उ द्ग्रहणप्रवाहोंक ा िनर्धारणक रनेक े ि लिएए क आनुक्रमिक खुली एवं बन्द मृदा कोरिंग विधि का उपयोग किया गया। अविक्षुब्ध वन में खनिजीकरण और स्थिरीकरण कुल नाइट्रोजन स्थिरीकरण के रूप में संचयन करके अध्ययन अवधि में लगभग शून्य रहा। पूर्ण पातन ने सतह मृदा में गतिशील NO_3-N सान्द्रताएं बढ़ाकर कुल नाइट्रोजन खनिजीकरण और नाइट्रीकरण को बढ़ाया। पूर्ण पातन के उपरान्त सतह नाइट्रोजन विक्षालन बढ़ा और जड़ उद्ग्रहण घटा। सतह नाइट्रोजन विक्षालन अवशेष जलाने से बदला नहीं। जले भूखण्डों में कुल नाइट्रोजन खनिजीकरण गैर जले भूखण्डों से कम था, जो 20.1 माह की अवधि में लगभग 53 प्रतिशत तक जलने के बाद घटा। वातावरणीय निवेशों ने सभी उपचारों में नाइट्रोजन निवेशों में काफी सहयोग दिया।

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