TRANSFORMATIONS OF NITRATE ^{15}N UNDER DIFFERENT FOREST HARVEST RESIDUE REGIMES IN A HOOP PINE PLANTATION IN AUSTRALIA

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PU, G. X., SAFFIGNA, P. G. & XU, Z. H. 2005. Transformations of nitrate ^{15}N under different forest harvest residue regimes in a hoop pine plantation in Australia. A study was conducted to quantify the effects of harvest residue management on denitrification, leaching and immobilization of ^{15}N-labelled nitrate applied at 20 kg N ha^{-1} to 1-year-old hoop pine (Araucaria cunninghamii) in subtropical Australia. The experiment was undertaken in PVC microplots of 235 mm diameter and 300 mm long, driven into the soil (Lithosol) to a depth of 250 mm. Three replications were undertaken for each of the seven treatments: control without any residue, ground and unground foliage at 20 Mg dry matter (DM) ha^{-1}, ground foliage at 40 Mg DM ha^{-1}, ground and unground branches at 40 Mg DM ha^{-1}, and ground branches at 80 Mg DM ha^{-1}. In 15 days after simulated daily rainfall of 100, 50 and 25 mm respectively in the first three days, 6–26% of applied ^{15}N was lost via denitrification, 14–35% was immobilized and 32–53% was leached. The treatment incorporating foliage materials lost more ^{15}N (21–26%) via denitrification than other treatments. Measurement of ^{15}N gases ($^{15}N_2$+$^{15}N_2O$) showed higher ^{15}N gas emission on day 1, followed by low gas emissions thereafter. This study showed that significant amounts of mineral N could be lost through leaching and denitrification during plantation establishment.

Key words: Denitrification – leaching – immobilization – $^{15}N_2$ – $^{15}N_2O$ – water-soluble carbon

PU, G. X., SAFFIGNA, P. G. & XU, Z. H. 2005. Perubahan nitrat ^{15}N di bawah rejim sisa tuaian hutan yang berlainan di dalam ladang pain di Australia. Kajian ini dijalankan untuk menilai kesan pengurusan sisa tuaian terhadap denitrifikasi, larut lesap dan ketakmobilan nitrat berlabel ^{15}N (20 kg N ha^{-1}) pada pokok pain (Araucaria cunninghamii) berumur satu tahun yang tumbuh di kawasan subtropika Australia. Ujian dijalankan dalam mikroplot PVC berukuran 235 mm diameter dan 300 mm panjang. Mikroplot ini dipacu ke dalam tanah (Litosol) sehingga kedalaman 250 mm. Tiga ulangan dijalankan untuk kesemua tujuh perlakuan: kawalan tanpa sisa, dedaun yang dikisar dibubuh pada kadar 20 Mg jirim kering (DM) ha^{-1}, dedaun yang tidak dikisar dibubuh pada kadar 20 Mg DM ha^{-1}, dedaun di tanah dibubuh pada kadar 40 Mg DM ha^{-1}, dahan yang dikisar dibubuh pada kadar 40 Mg DM ha^{-1}, dahan yang tidak dikisar dibubuh pada kadar 40 Mg DM ha^{-1} dan dahan yang dikisar dibubuh pada kadar 80 Mg DM ha^{-1}. Ujikaji ini didedah kepada hujan tiruan harian sebanyak 100 mm, 50 mm dan 25 mm untuk tiga hari berturut-turut. Lima belas hari selepas itu didapati 6%–26% daripada ^{15}N yang dirawat hilang melalui denitrifikasi, 14%–35% ^{15}N menjadi tak mobil dan 32%–53% ^{15}N terlarut lesap. Perlakuan yang menerima dedaun kehilangan lebih ^{15}N (21%–26%) melalui denitrifikasi berbanding perlakuan lain. Kajian gas ^{15}N ($^{15}N_2 + ^{15}N_2O$) menunjukkan pelepasan gas ^{15}N yang lebih tinggi pada hari pertama kajian, diikuti oleh pelepasan gas yang rendah pada hari-hari seterusnya. Kajian

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ini menunjukkan bahawa jumlah bahan galian N yang bererti boleh hilang secara larut lesap dan denitrifikasi semasa penubuhan ladang.

Introduction

Both land management and climate can have a significant impact on the dynamics of terrestrial nitrogen (N) cycling processes such as denitrification, leaching and immobilization (Firestone 1982, Robertson & Tiedje 1988, Nadelhoffer et al. 1999). Considering the large number of denitrification studies in agricultural ecosystems (Firestone 1982, Bouwman 1998), few studies have been made in forest ecosystems, particularly in the tropics and subtropics (Carnol & Ineson 1999, Hall & Matson 1999, Priha & Smolander 1999).

Almost all of the new hoop pine (Araucaria cunninghamii) plantations in south-east Queensland, Australia are established on second-rotation sites. In subtropical Australia, hoop pine plantations have a much higher N requirement than plantations of Eucalyptus and Pinus species (Bubb et al. 1999, Prasolova et al. 2000). Therefore, minimizing N losses during harvesting and site preparation is likely to be an important management practice for the long-term sustainability of these plantations (Matson et al. 1987, Bubb et al. 1998a). Besides residue removal or burning, N losses from leaching or denitrification can occur in the inter-rotation period as a result of higher nitrification rates due to site disturbance caused by clear fell and site preparation (Robertson & Tiedje 1988, Hall & Matson 1999). Holt and Spain (1986) reported that soil organic C, total N, available P and exchangeable Ca, Mg and K in a mature hoop pine plantation were substantially lower than those in the adjoining rain forest area in tropical north Queensland, Australia due to harvesting removal and site preparation. Although all the new hoop pine plantations are now established on second-rotation sites, the effects of site management practices such as harvest residue management regimes on nutrient cycling and soil fertility status are poorly understood (Bubb et al. 1999). There is limited information on the impacts of harvest residues on N cycling processes such as denitrification, leaching and N immobilization of hoop pine plantations. Nitrogen losses via denitrification have been considered relatively unimportant in most forest ecosystems (Attiwill & Leeper 1987), but Palm et al. (1993) have reported that denitrification in tropical forest ecosystems, either disturbed or undisturbed, is higher than in temperate forest ecosystems. Several studies have shown a significant increase in N losses via denitrification in disturbed forest sites compared with undisturbed sites (Hulm & Killham 1988, Myrold 1988, Dutch & Ineson 1990). Verchot et al. (1997) have mentioned that nitrate loss in some forests is almost exclusively through denitrification.

Studies of Bubb et al. (1998a) and Prasolova et al. (2000) have shown that there is a significant amount of mineral N (80–120 kg N ha^{-1}) present during hoop pine plantation establishment . Of this amount, about 20–40 kg N ha^{-1} exist as nitrate-N due to active nitrification. The objective of this study was, therefore, to quantify the effects of harvest residue management regimes on denitrification, leaching and immobilization of ^{15}N-labelled nitrate applied at 20 kg N ha^{-1} to a 1-year-old, second rotation hoop pine plantation in south-east Queensland, Australia.

Materials and methods

Site and soil properties

The experimental site was located in a hoop pine plantation within the State Forest of Amamoor (26 ° 16' S, 152 ° 37' E), south-east Queensland, Australia, where a second-rotation plantation had been established for one year. The soil was classified as Lithosol according to the FAO Soil Classification System. The contents of sand, silt and clay were 63, 29 and 8% respectively for the 0–100 mm soil and 57, 33 and 10% for the 100–200 cm soil. For the 0–100 mm soil, pH (1:5 H_2O) was 6.4, total N 0.21%, organic C 3.2%, total K 1308 mg kg^{-1}, electrical conductivity 0.13 dS m^{-1}. The corresponding values were 6.2, 0.19%, 2.0%, 1259 mg kg^{-1} and 0.08 dS m-1 respectively for the 100–250 mm soil. The average temperature was 25 °C in summer and 14 °C in winter. The average annual rainfall was about 1200 mm (Bubb et al. 1998a) and more than half of rainfall occurred in summer (November–February) featured with heavy thunderstorms. During the period of this experiment (mid-summer 1997), an average daily evaporation rate of 7 mm was recorded and the maximum and minimum average temperatures were 32 and 23 °C respectively.

Experimental treatments and procedures

The experiment consisted of seven treatments and replicated three times using a randomized complete block design. They were (1) control, without any residues incorporated, (2) unground foliage materials (chopped to < 35 mm in length) applied at 20 Mg dry matter (DM) ha^{-1}, equivalent to the average rate of foliage materials remaining on the ground after harvesting of first-rotation hoop pine plantations in south-east Queensland (3) ground foliage materials (to pass a 2 mm sieve) at 20 Mg DM ha^{-1}, (4) ground foliage materials at 40 Mg DM ha^{-1}, (5) unground branch materials (chopped to a size of any dimensions < 35 mm) at 40 Mg DM ha^{-1} equivalent to the rate of branch materials remaining on the ground after harvesting, (6) ground branch materials at 40 Mg DM ha^{-1} and (7) ground branch materials (to pass a 2 mm sieve) at 80 Mg DM ha^{-1}. All residues were incorporated into the top 100 mm soil within the microplots. Total C and N were 410 and 10 g kg^{-1} (C/N ratio 41:1) respectively for foliage materials, and 478 and 4.3 g kg^{-1} (C/N ratio 111:1) for branch materials.

Soil was collected at two layers (0–100 and 100–250 mm) from 21 random positions using PVC tubes (235 mm diameter × 300 mm long). Soil samples were bulked and homogenized to give one composite sample for each depth respectively. Soil from 100–250 mm was repacked into each PVC core positioned at the original sampling places. Soil from 0–100 mm was mixed with oven-dried (60 °C) hoop pine residues according to treatments as described above. Soil plus residue was then repacked into each PVC tube. The procedure ensured that the top 250 mm soil in the PVC tube was mixed and replaced to simulate soil disturbance during the site preparation at the establishment of the hoop pine plantation.

Bromide (Br) was used as a companion tracer to monitor the potential path of nitrate movement in the soil profile (Smith & Davis 1974, Saffigna et al. 1977, Kessavalou et al. 1996, Turpin et al. 1999). The difference between the recovered Br and ^{15}N was assumed to be ^{15}N loss through denitrification. The percentage difference between applied and

recovered Br was regarded as the equivalent leaching losses of applied nitrate N.

Adequate water was added to the soil inside the PVC tubes until the soil reached field capacity (~42% w/w) in the top 250 mm soil. Water was also applied to the soil surrounding the PVC tubes at the same rate as inside the PVC tubes. The ^{15}N-labelled KNO_3 (98% ^{15}N excess) at 20 kg N ha^{-1} and bromide at 100 kg Br ha^{-1} as solutions were evenly applied to the soil surface within the PVC tubes. Application of 20 kg N ha^{-1} as ^{15}N-labelled nitrate would represent the lower end of 20–40 kg NO_3-N ha^{-1} present in the hoop pine soil during plantation establishment and would not be expected to interfere significantly with the soil mineral pools (about 100 kg N ha^{-1}) and fluxes (Bubb et al. 1998a). More water was added to simulate a rainfall event of 100 mm and the topsoil was saturated, which is common in summer in this area.

Evolved ^{15}N gases were collected daily by covering the microplots (Pu et al. 1999) for three hours each day, assuming the ^{15}N gas emission rate in the three-hour period was the average rate on that day. The gas was collected into a 10 ml venoject vial via a sampling port on the cover, after mixing all the air within the headspace of the microplot using a 10 ml syringe (Pu et al. 1999). The recovery of ^{15}N in gas form was regarded as the result of direct denitrification. After collecting gas samples on day 2 and day 3, more water, equivalent to 50 mm and 25 mm of rainfall respectively, was added to the soil surface. The amounts of added water were to simulate the common summer rainfall events of more than 100 mm in the experimental area. A natural rainfall event of 24 mm occurred on day 6. At the completion of the 15-day gas collection period, the soil inside the PVC microplot was removed and separated into the 0–100 and 100–250 mm layers. The PVC microplot was then driven into the soil two times to collect soil samples of 250–500 and 500–750 mm increments below the enclosed area. All soil samples were oven dried at 45 °C and finely ground to a powder (< 0.1 mm) for chemical analysis.

Chemical analysis

Water-soluble C analysis in soil

A modified Walkley-Black method (Batonda & Waring 1984) was used to measure water-soluble C. Twenty grams of moist soil collected at the end of the field study were shaken in 80 ml distilled water for one hour. The extracts were filtered through No. 42 Whatman filter paper and the filtrates were refiltered through 0.2 μm Sartorius cellulose filter paper to remove micro-organisms. A total of 15 ml of concentrated sulphuric acid were added to the mixture of 5 ml filtrate and 5 ml of 0.01 M K_2Cr_2O7. The solution was then titrated using 0.03 M $FeSO_4$ with 2% o-phenanthroline solution as an indicator.

^{15}N (N_2O+N_2) gas analysis

Gas samples collected were transferred to an arc vessel (Strong et al. 1991) and arced for a total of 250 s. The cooled arc vessel was connected to the inlet system of the mass spectrometer and the system evacuated to give a vacuum of less than 4 Pa. The arc vessel stopcock was then opened to allow the gas sample to expand through two cold traps immersed in liquid N. The gas sample was then introduced into the

mass spectrometer for ^{15}N abundance analysis. Recovery of ^{15}N in the gas sample was calculated using an equation described by Buresh and Austin (1988).

Soil total N and ^{15}N analysis

A variable amount of soil subsamples (depending on the soil total N content) was weighed into a tin capsule and introduced into a combined C/N analyser–mass spectrometer (Roborep CN (7001) / Tracermass System (9001) by an automatic sampler. ^{15}N-labelled $(NH_4)_2SO_4$ solution, prepared in the laboratory, and a series of $(^{15}NH_4)_2SO_4$ standard solutions of 0.38, 0.50, 1.00 and 2.00% ^{15}N excess, supplied by the International Atomic Energy Agency, were used for calibration of the mass spectrometer.

Soil mineral N and 15N analysis

Soil mineral N was extracted with 2 M KCl in a ratio of 1:4 (soil:solution). Mineral N was determined on a subsample of the extract by a flow injection analyser, using a method recommended by the Lachat Instruments (QuickChem Method 10-107-06-4-D). For ^{15}N analysis, a second subsample of the extract was acidified to pH 3 with 0.1 M H_2SO_4 and dried in an oven at 70–80 °C. The dried extract was analysed for ^{15}N enrichment using a mass spectrometer.

Soil Br analysis

A method described by Saffigna et al. (1977) was used to measure Br in soil. Soil was extracted using 0.0025 M K_2SO_4 solution in a ratio of 1:4 (soil:solution), and extract filtered using Whatman 42 filter paper. About 0.6 ml total ionic adjustment buffer solution (5 M $NaNO_3$) were added to 30 ml of extract. Bromide was measured using a Br electrode with a reference electrode. The electrode was calibrated using a series of standard solutions between 0 and 10 mg Br l^{-1}.

Other soil chemical analysis

Soil pH, organic C and total K were determined as reported by Xu et al. (1993).

Statistical analyses

The differences between treatment means were tested for statistical significance using the least significant difference procedure in Microsoft Excel (Windows 95).

Results and discussion

Water-soluble C

No significant difference in water-soluble C was found between treatments in the soil at 250–500 and 500–750 mm depths (Figure 1). However, there was a significant difference

($p < 0.05$) in water-soluble C between treatments for the top 250 mm soil, especially at the 0–100 mm depth. The insignificant difference in levels of water-soluble C in the soil of 250–500 and 500–750 mm depths for all treatments suggested that while Br and nitrate could be leached down to deeper layers of the soil profile by rainfall, the water-soluble C released from the incorporated residues did not move below the top 250 mm soil. This may be because the decomposition and release of water-soluble C were slower processes, compared with the leaching of Br and nitrate in the soil profile (Figures 2 and 3), or maybe water-soluble C was oxidized at the soil surface before it could be leached to deeper soil layers.

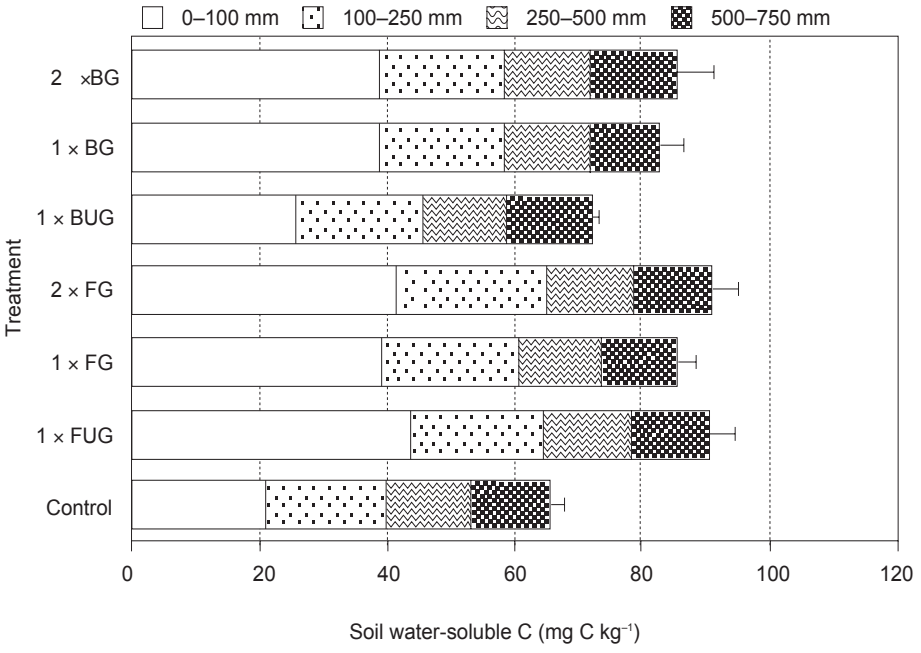

Figure 1 Water-soluble C in the top 750 mm soil profiles under different residue management regimes 15 days after watering. Control: no residues incorporated; 1×FUG: unground foliage at 20 Mg DM ha^{-1}; 1×FG: ground foliage at 20 Mg DM ha^{-1}; 2×FG: ground foliage at 40 Mg DM ha^{-1}; 1×BUG: unground branches at 40 Mg DM ha^{-1}; 1×BG: ground branches at 40 Mg DM ha^{-1}; 2×BG: ground branches at 80 Mg DM ha^{-1}.

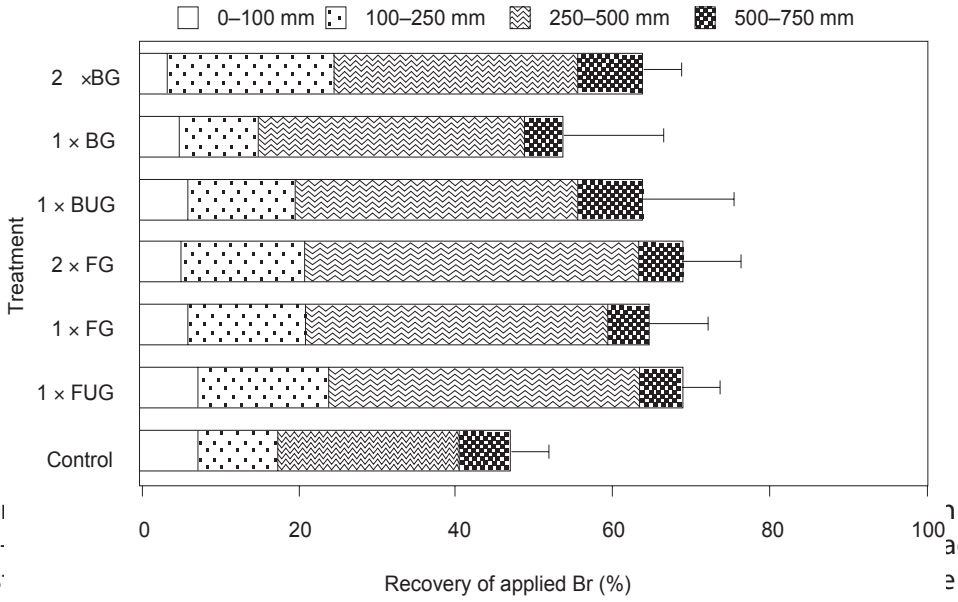

Figure 2. Recovery of applied bromide (Br) in the top 750 mm soil profiles under different residue management regimes 15 days after watering. Control: no residues incorporated; 1×FUG: unground foliage at 20 Mg DM ha^{-1}; 1×FG: ground foliage at 20 Mg DM ha^{-1}; 2×FG: ground foliage at 40 Mg DM ha^{-1}; 1×BUG: unground branches at 40 Mg DM ha^{-1}; 1×BG: ground branches at 40 Mg DM ha^{-1}; 2×BG: ground branches at 80 Mg DM ha^{-1}; all the residues were incorporated into the top 100 mm soil inside the microplots before ^{15}N labelled nitrate was added.

Ther…n to sub…ady exis… C, which may be stimulated by watering (Pu et al. 1999), is more likely to remain in the surface soil and available for the processes of denitrification (if the surface soil is wet enough) and immobilization.

Water-soluble C in the soil in microplots with unground foliage materials at 20 Mg DM ha^{-1} incorporated into the top 100 mm soil was much higher (43 mg C kg^{-1}) than that of unground branch materials (25 mg C kg^{-1}) at 40 Mg DM ha^{-1} even though the quantity of incorporated branch materials was twice that of the incorporated foliage treatment (Figure 1). This could be attributed to decomposition of foliage materials being faster than that of branch materials (Bubb et al. 1998b). Grinding residues increased water-soluble C in soil in microplots treated with branch materials, but this was not the case for the microplots treated with foliage.

^{15}N gas emissions

All microplots emitted ^{15}N labelled gases ($^{15}N_2 + {}^{15}N_2O$) from day 1 after the soil was watered and 0.2–4.5% of applied ^{15}N was lost on the first day (Figure 4).

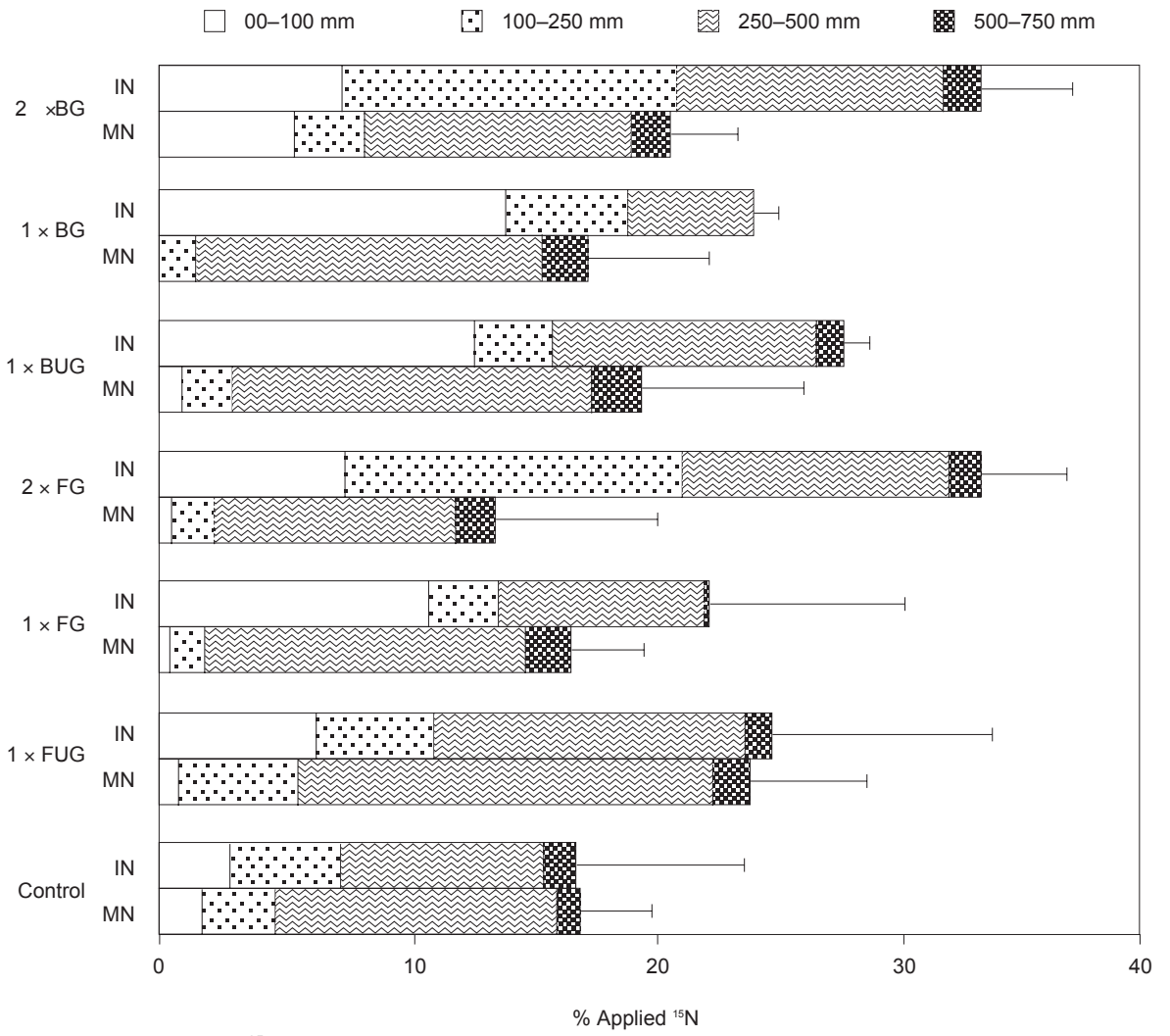

Figure 3 Distribution of mineral ^{15}N (MN) and immobilized ^{15}N (IN) in the top 750 mm soil profiles under different residue management regimes 15 days after watering. Control: no residues incorporated; 1×FUG: unground foliage at 20 Mg DM ha^{-1}; 1×FG: ground foliage at 20 Mg DM ha^{-1}; 2×FG: ground foliage at 40 Mg DM ha^{-1}; 1×BUG: unground branches at 40 Mg DM ha^{-1}; 1×BG: ground branches at 40 Mg DM ha^{-1}; 2×BG: ground branches at 80 Mg DM ha^{-1}.

Australia. The ^{15}N gas emission rates in those experiments generally had a three-phase pattern: an initial phase of low ^{15}N gas emission, a peak phase lasting a few days that accounted for most of ^{15}N gas losses

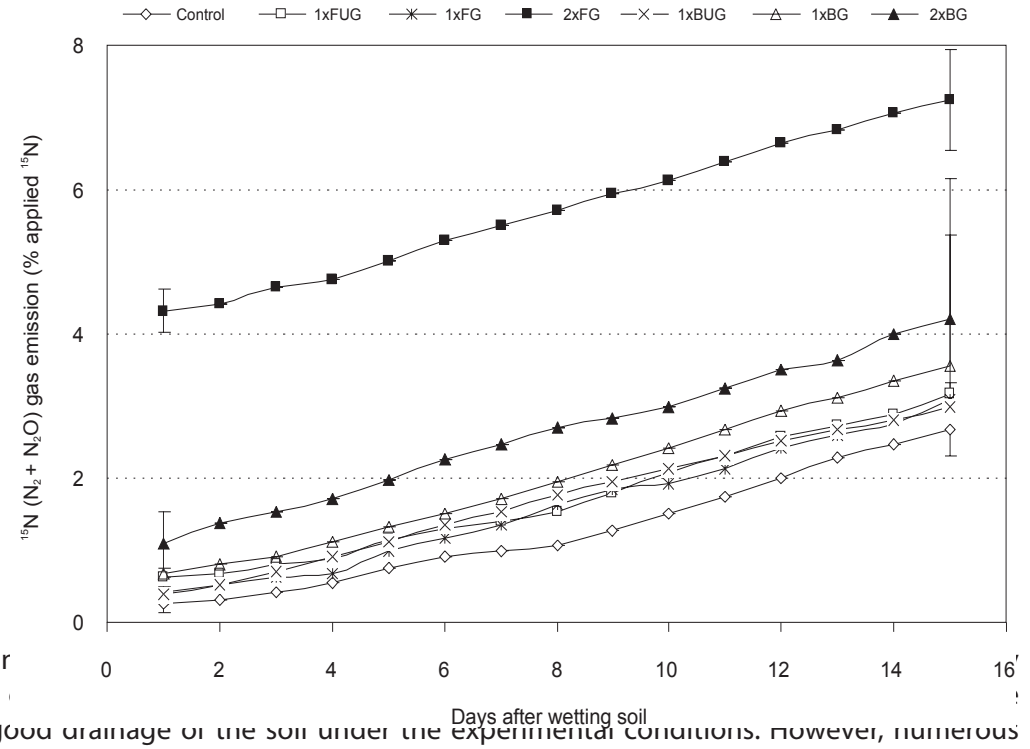

Figure 4 Accumulated daily ^{15}N gases (N_2+N_2O) emitted from microplots under different residue management treatments. Daily ^{15}N gas emission rates were calculated by multiplying a factor of 8 to the 3-hour value. Control: no residues incorporated; 1×FUG: unground foliage at 20 Mg DM ha^{-1}; 1×FG: ground foliage at 20 Mg DM ha^{-1}; 2×FG: ground foliage at 40 Mg DM ha^{-1}; 1×BUG: unground branches at 40 Mg DM ha^{-1}; 1×BG: ground branches at 40 Mg DM ha^{-1}; 2×BG: ground branches at 80 Mg DM ha^{-1}; all the residues were incorporated into the top 100 mm soil inside the microplots. Variations between replicates are presented as vertical line bars.

good drainage of the soil under the experimental conditions. However, numerous reports (Firestone 1982, Robertson & Tiedje 1988) have shown that anaerobic microsites are common under non-saturated conditions in the aggregates of fine-textured, well structured soils and under these conditions nitrification proceeds in the aerobic zone and appreciable denitrification occurs at the microsites.

The low and quite steady level of ^{15}N gas emission after day 1 from this experiment suggested that N loss via denitrification under field conditions occurred in soil microsites in which anaerobic conditions were maintained even over continued drying conditions from day 6 to day 15. Microplots with ground foliage materials at 40 Mg DM ha^{-1} showed the highest ^{15}N gas emission rate between zero and day 1, compared with those receiving other residue treatments. However, subsequent rates were similar. This initial higher rate could be attributed to the fact that the large quantity of foliage residues could immediately release available C for denitrifiers and also create anaerobic microsites in the soil by (1) accelerating microbial activity and depleting local oxygen supply as well as (2) retaining soil moisture. The presence of ample C substrate can cause rapid microbial O_2 consumption and therefore its depletion in soil microsites, thereby indirectly enhancing denitrification activity (Firestone 1982). Little difference in ^{15}N gas emission was found between control microplots and microplots treated with unground branch materials. This indicated that hoop pine branch materials might contain relatively low level of available C. The little available C would be rapidly used in moist soil by denitrifiers. When the residues were ground, more available C could be released quickly and available to denitrifiers.

N transformations

Recoveries of the applied ^{15}N and Br ranged from 33 to 59% and from 47 to 69% respectively in the top 750 mm of soil (Table 1). The difference between the recovered

Br and ^{15}N or denitrification loss ranged from 6 to 26%. The lower recovery of ^{15}N compared with Br was assumed as the ^{15}N loss via denitrification. However, this might be an underestimation as some of the ^{15}N might have already been denitrified before moving to deeper soil layers. The immobilized ^{15}N ranged from 16 to 34%, leaving 13 to 24% of the applied ^{15}N-NO_3 remaining in the top 750 mm of soil (Figure 3). The recoveries of both applied ^{15}N and Br from control microplots were significantly ($p < 0.05$) lower than those of the other treatments. It appears that the incorporation of residues into the top 100 mm of soil inside the respective microplots played an important role in reducing leaching and increasing the recoveries of the applied Br and ^{15}N in the soil profiles.

Surprisingly, denitrification loss was lowest (6%) for microplots with ground branch materials incorporated at 80 Mg DM ha^{-1} (Table 1). This result contradicted the finding that these microplots had the second highest denitrification loss, measured by ^{15}N gases evolved (Figure 4). Denitrification losses for all microplots treated with foliage materials were significantly higher than those of the control, suggesting that the added residues could promote denitrification loss. These results were consistent with many other studies (Xu et al. 1992, Avalakki et al. 1995a, Pu et al. 1999, 2001).

Incorporating branch materials into the soil did not show any increase in denitrification loss although there was generally a significant increase in water-soluble C (Figure 1). This suggests that while the foliage materials with lower C:N ratio (41:1) quickly released available C for soil denitrifiers, branch materials with high C:N ratio (111:1) were slower in releasing available C and might contribute little to the early stage of denitrification activity. This agrees with the findings that narrow C:N ratio encourages denitrification (Aulakh et al. 1991, 2000, Laverman et al. 2001). Grounded materials created much more surface areas in contact with soil and hence released more soluble extractable compound as indicated by the water-soluble carbon levels of the different regimes and hence increased denitrification activity.

About 31 to 53% of the applied Br could not be recovered from the 750 mm soil

Table 1 Recoveries of added ^{15}N and Br in the top 750 mm soil profiles 15 days after watering the soils and estimated ^{15}N losses via denitrification regimes in a 1-year-old hoop pine plantation

Residue management regime	^{15}N recovery	Br recovery	Denitrification loss
Control without any residue added	33.4 (10.0)	46.9 (5.1)	13.6 (5.8)
Unground foliage materials at 20 Mg DM ha^{-1}	48.6 (4.1)	69.4 (4.4)	20.8 (4.4)
Ground foliage materials at 20 Mg DM ha^{-1}	38.7 (2.2)	65.0 (7.7)	26.2 (6.8)
Ground foliage materials at 40 Mg DM ha^{-1}	48.6 (3.1)	69.3 (7.1)	20.7 (10.3)
Unground branch materials at 40 Mg DM ha^{-1}	48.2 (13.7)	63.6 (12.3)	15.4 (8.0)
Ground branch materials at 40 Mg DM ha^{-1}	41.7 (4.8)	54.2 (12.6)	12.5 (10.0)
Ground branch materials at 80 Mg DM ha^{-1}	58.5 (3.5)	64.2 (4.8)	5.8 (6.9)
LSD ($p < 0.05$)	11.2	12.0	10.1

profiles. More than half of the recovered Br was in the 250–500 mm soil depth and 5–10% of the applied Br recovered in the 500–750 mm soil depth (Figure 2). Distribution of Br in the soil profiles suggests that the unrecovered Br could have been lost due to either leaching of Br below the 750 mm soil profiles or the lateral movement of Br outside the microplot area below the 250 mm soil profiles, which were not sampled. It was estimated that about two thirds of the uncovered Br was due to lateral movement using data of the recovered Br from another field experiment (Pu et al. 2001). Xu et al. (1992, 1993) reported that significant amounts of fertilizer ^{15}N could move outside the microplots of 250 mm diameter and 320 mm long (driven into the 250 mm soil) below the top 250 mm soil in two to three months after ^{15}N application at 40 kg N ha^{-1} in a semi-arid environment of tropical Australia. Nevertheless, their studies have indicated that the downward movement of fertilizer ^{15}N in the soil profiles is much greater than the lateral movement below the 250 mm soil.

While useful information could be obtained using Br as a tracer to investigate the leaching and denitrification loss of applied ^{15}N, it should be noted that denitrification loss calculated by the difference between the recovered Br and ^{15}N-labelled nitrate could be underestimated. The leaching loss, determined by the difference between the applied and recovered Br, could be an overestimation. The possible underestimation of denitrification loss and overestimation of leaching loss may be attributed to the differences in the transformation behaviour between the applied ^{15}N-labelled nitrate and Br in the soil. Significant amounts of the applied ^{15}N-labelled nitrate could be immobilized and this part of applied ^{15}N would not be subjected to further leaching loss or denitrification. This is not the case for applied Br, which could be leached below the soil surface whenever there is vertical downward water movement in the soil profiles. Furthermore, the lateral movement of ^{15}N out of the microplots would underestimate denitrification and overestimate leaching loss. Therefore, we suggest that a circular plot of 1000 mm diameter should be established surrounding the 235 mm diameter microplot and the same rates of Br and ^{15}N-unlabelled (^{15}N natural abundance with about 99.6% ^{14}N) nitrate could be applied to the surrounding area as those applied to the area inside the microplot when a field microplot experiment would need to be conducted under the similar experimental conditions. This suggests improvement in the microplot installation has been confirmed in a denitrification study of Pu et al. (2001).

^{15}N recoveries as mineral N ranged from 13 to 24% and ^{15}N immobilized varied from 16 to 34 % (Figure 3). Total recovered mineral ^{15}N in the 0–100, 100–250 and 500–750 mm soil depths was less than in the 250–500 mm depth for all treatments, indicating that there was lateral movement of applied 15N. There was no significant difference in mineral ^{15}N recovery between treatments, except for the ground branch materials applied at 80 Mg DM ha^{-1}. Low recovery of the applied ^{15}N (Figure 3) and high level of water-soluble C (Figure 1) found in the top 250 mm soil suggested that the surface 250 mm soil was an active zone for denitrification and immobilization.

There was much more immobilized ^{15}N in the 0–100 and 100–250 mm soil depths. This suggested that while denitrification rate was low from day 2 as indicated by directly measuring ^{15}N gases, the process of immobilization was probably able to continue during the period of this study since immobilization would not require anaerobic conditions in the soil. The study by Pu et al. (1999) showed that ^{15}N immobilization is a

slower process than denitrification after water logging poorly drained soils. However, in fully aerobic soils, ^{15}N immobilization is a stronger competitor for the available soil nitrate than denitrification. All microplots treated with the hoop pine residues showed a higher rate of immobilized ^{15}N, compared with those of the control. This indicated that available C released from the residues (incorporated into the soil) after watering also promoted ^{15}N immobilization. The denitrification ^{15}N losses measured by the gas emission method were generally lower than those by the mass balance method, similar to the findings by Pu et al. (2001).

Conclusions

This study showed that after simulated heavy rainfall, substantial soil mineral N may be lost from the ecosystem through leaching (31–53%) and denitrification (6–26%). Incorporating foliage materials in the top 100 mm soil generally increased denitrification loss and promoted ^{15}N immobilization in the surface soil. Incorporating branch materials did not show any significant increase in the ^{15}N loss via denitrification, although ^{15}N immobilization was greater than that in control microplots. Water-soluble C released through the residue decomposition, which could be stimulated by watering, would be most likely to remain in the surface soil due to the slow residue decomposition process compared with the leaching process of Br and ^{15}N. The ^{15}N gas emissions indicated that for the well-drained soil, high rates of denitrification (~4% of applied ^{15}N/day) could only occur over a short period, but low rates of denitrification (~0.1% of applied ^{15}N/day) could continue for a longer period.

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References

Attiwill, P. M. & Leeper, G. W. 1987. Forest Soils and Nutrient Cycling. Melbourne University Press, Melbourne.

Aulakh, M. S., Doran, J. W., Waters, D. T., Mosier, A. R & Francis, D. D. 1991. Crop residue type and placement effects on denitrification and mineralisation. Soil Science Society of America Journal 55: 1020–1025.

Aulakh, M. S., Khera, T. S. & Doran, J. W. 2000. Mineralization and denitrification in upland, nearly saturated and flooded subtropical soil. II. Effect of organic manures varying in N content and C:N ratio. Biology and Fertility of Soils 31: 168–174.

Avalakki, U. K., Strong, W. M. & Saffigna, P. G. 1995a. Measurements of gaseous emissions from denitrification of applied nitrogen-15. II. Effects of temperature and added straw. Australian Journal of Soil Research 33: 89–99.

Avalakki, U. K., Strong, W. M. & Saffigna, P. G. 1995b. Measurements of gaseous emissions from denitrification of applied nitrogen-15. III. Field measurements. Australian Journal of Soil Research 33: 101–111.

Batonda, J. & Waring, S. A. 1984. Denitrification in relation to soil carbon for soils of the Darling Downs, Queensland. Pp. 231–239 in McGarity, J. W. et al. (Eds.) The Properties and Utilization of Cracking Clay Soils. University of New England Press, Armidale.

Bouwman, A. F. 1998. Nitrogen oxides and tropical agriculture. Nature 392: 866–867.

Bubb, K. A., Xu, Z. H., Simpson, J. A. & Saffigna, P. G. 1998a. In situ measurements of soil mineral nitrogen fluxes in hoop pine plantations of subtropical Australia. New Zealand Journal of Forest Research

28: 152–164.

Bubb, K. A., Xu, Z. H., Simpson, J. A. & Saffigna, P. G. 1998b. Some nutrient dynamics associated with litterfall and litter decomposition in hoop pine plantations of south-east Queensland, Australia. Forest Ecology and Management 110: 343–352.

Bubb, K. A., Xu, Z. H., Simpson, J. A. & Saffigna, P. G. 1999. Growth response to fertilisation and recovery of ^{15}N-labelled fertiliser by young hoop pine plantations of subtropical Australia. Nutrient Cycling in Agroecosystems 54: 81–92.

Buresh, R. J. & Austin, E. R. 1988. Direct measurement of dinitrogen and nitrous oxide in flooded rice fields. Soil Science Society of America Journal 52: 681–688.

Carnol, M. & Ineson, P. 1999. Environmental factors controlling NO_3^- leaching, N_2O emissions and numbers of NH_4^+ oxidisers in a coniferous forest soil. Soil Biology and Biochemistry 31: 979–990.

Dutch, J. & Ineson, P. 1990. Denitrification of an upland forest soil. Forestry 63: 363–377.

Firestone, M. K. 1982. Biological denitrification. Pp. 289–326 in Stevenson, F. J. (Ed.) Nitrogen in Agricultural Soils. Agronomy Monograph 22. ASA-CSSA-SSSA, Madison.

Hall, S. J. & Matson, P. A. 1999. Nitrogen oxide emissions after nitrogen additions in tropical forests. Nature 400: 152–155.

Holt, J. A. & Spain, A. V. 1986. Some biological and chemical changes in a north Queensland soil following replacement of forest with Araucaria cunninghamii (Conniferae: Araucariaceae). Journal of Applied Ecology 23: 227–237.

Hulm, S. C. & Killham, K. 1988. Gaseous nitrogen losses from soil under Sitka spruce following the application of fertilizer ^{15}N. Journal of Soil Science 93: 417-424.

Kessavalou, A., Doran, J. W., Powers, W. L., Qian, J. H. & Kettler, T. A. 1996. Bromide and nitrogen-15 tracers of nitrate leaching under irrigated corn in central Nebraska. Journal of Environmental Quality 25: 1008–1014.

Laverman, A. M., Zoomer, H. R. & Verhoef, H. A. 2001. The effect of oxygen, pH and organic carbon on soil-layer specific denitrifying capacity in acid coniferous forest. Soil Biology & Biochemistry 33: 683–687.

Matson, P. A., Vitousek, P. M., Ewell, J. J., Mazzarino, M. J. & Robertson, G. P. 1987. Nitrogen transformations following tropical forest felling and burning on a volcanic soil. Ecology 68: 491–502.

Myrold, D. D. 1988. Denitrification in rye grass and winter wheat cropping systems of western Oregon. Soil Science Society of America Journal 52: 412–416.

Nadelhoffer, K. J., Emmett, B. A., Gundersen, P., Kjonaas, O. J., Koopmans, C. J., Schleppi, P., Tietma, A. & Wright, R. F. 1999. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. Nature 398: 145–148.

Palm, C., Robertson, G. P. & Vitousek, P. M. 1993. Nitrogen availability. Pp. 158–163 in Anderson, J. M. & Ingram, J. S. L. (Eds.) Tropical Soil Biology & Fertility––A Handbook of Methods. CAB International, Wallingford.

Prasolova, N., Xu, Z. H., Saffigna, P. G. & Dieters, M. 2000. Spatial–temporal variability of soil moisture, nitrogen availability indices and other chemical properties in hoop pine (Araucaria cunninghamii) plantations of subtropical Australia. Forest Ecology and Management 136: 1–10.

Priha, O. & Smolander, A. 1999. Nitrogen transformations in soil under Pinus sylvestris, Picea abies and Betula pendula at two forest sites. Soil Biology and Biochemistry 31: 965–977.

Pu, G. X., Saffigna, P. G. & Strong, W. M. 1999. Potential for denitrification in cereal soils of northern Australia after legume or grass-legume pastures. Soil Biology and Biochemistry 31: 667–675.

Pu, G. X., Saffigna, P. G. & Xu, Z. H. 2001. Denitrification, leaching and immobilisation of ^{15}N-labelled nitrate in winter under windrowed harvest residues in hoop pine plantations of 1–3 years old in subtropical Australia. Forest Ecology and Management 152: 183–194.

Robertson, G. P. & Tiedje, J. M. 1988. Deforestation alters denitrification in a lowland tropical rain forest. Nature 336: 756–759.

Saffigna, P. G., Keeney, D. R. & Tanner, C. B. 1977. Lysimeter and field measurements of chloride and bromide leaching in an uncultivated loamy sand. Soil Science Society of America Journal 41: 478–482.

Smith, S. J. & Davis, R. J. 1974. Relative movement of bromide and nitrate through soils. Journal of Environmental Quality 3: 152–155.

Strong, W. M., Avalakki, U. K., Saffigna, P. G. & Walsh, J. J. 1991. Use of the arc method to measure fertiliser nitrogen loss. Pp. 297–306 in International Symposium on the Use of Stable Isotopes in Plant Nutrition, Soil Fertility & Environmental Studies. 1–5 October 1990. Vienna.

Turpin, J. E., Bridge, B. J., Orange, D. & Thompson, J. P. 1999. Water and bromide movement in a Vertisol under four fallow management systems. Australia Journal of Soil Research 37: 75–89.

Verchot, L. V., Franklin, E. C. & Gilliam, J. W. 1997. Nitrogen cycling in Piedmont vegetated zones. II. Subsurface nitrate removal. Journal of Environmental Quality 26: 337–347.

Xu, Z. H., Saffigna, P. G., Myers, R. J. K. & Chapman, A. L. 1992. Nitrogen fertilizer in leucaena alley cropping. I. Maize response to nitrogen fertilizer and fate of fertilizer-^{15}N. Fertilizer Reseach 33: 219–227.

Xu, Z. H., Saffigna, P. G., Myers, R. J. K. & Chapman, A. L. 1993. Nitrogen cycling in leucaena (Leucaena leucocephala) alley cropping in semi-arid tropics. I. Mineralization of nitrogen from leucaena residues. Plant and Soil 148: 63–72.