Ann. For. Sci. 64 (2007) 699–706
© INRA, EDP Sciences, 2007
DOI: 10.1051/forest:2007050

Available online at:
www.afs-journal.org

Original article

Lysimetric study of eucalypt residue management effects on N leaching and mineralization

María X. Gómez-Rey*, Ernesto Vasconcelos, Manuel Madeira

Departamento de Ciências do Ambiente, Instituto Superior de Agronomia, Tapada de Ajuda, 1349-017 Lisboa, Portugal

(Received 13 September 2006; accepted 2 February 2007)

Abstract – The effects of woody residues from *Eucalyptus globulus* Labill. plantations on N losses were assessed through a lysimetric experiment. Treatments were: (NW) forest floor litter and non-woody residues (leaves, bark, twigs) incorporated into the soil; (IP) as NW plus woody residues (branches) cut in 20-cm long pieces and incorporated into the soil; (IC) as IP, but with branches chopped into chips; (SP) non-woody and woody residues (pieces) placed on the soil surface; (SC) as SP plus branches chopped into chips; and (CT) absence of organic residues. Leaching of N-NO_3^- and N-NH_4^+ was followed during a six-year period and N mineralization was evaluated at the end of the experiment. Non-woody residues enhanced N leaching as compared with the control. Conversely, woody residues decreased N losses. Although differences between treatments were not significant at the end of the experiment, incorporation and fragmentation of woody residues resulted in the more favourable management option regarding the reduction of N leaching observed at short-term. As high amounts of residues were used, the effect observed on decrease N leaching could be higher than that existing in Portuguese eucalypt plantations.

harvest residues / N mineralization / *Eucalyptus globulus* / N leaching / residue quality

Résumé – Étude lysimétrique des effets de la gestion des rémanents d'exploitation sur la lixiviation et la minéralisation d'azote. Les effets des restitutions de matière ligneuse de plantations d' *Eucalyptus globulus* Labill. sur la lixiviation d'azote ont été mesurés au travers d'une expérience de lysimétrie. Ont été comparés les traitements : (NW) litière au sol et restitutions non ligneuses (feuilles, rameaux, écorce) incorporés au sol ; (IP) comme NW plus restitutions ligneuses (branches) coupés en morceaux de 20 cm de longueur et incorporés au sol ; (IC) comme IP, mais les branches étant coupés en copeaux ; (SP) restitutions non ligneuses et ligneuses placées à la surface du sol ; (SC) comme SP mais branches coupées en copeaux ; (CT) absence de restitutions organiques. La lixiviation de N-NO_3^- et N-NH_4^+ a été suivie pendant 6 années, et la minéralisation d'azote a été mesurée à la fin de l'expérience. L'apport de restitutions non ligneuses augmente la lixiviation par rapport au témoin (CT) ; inversement les restitutions ligneuses on diminué les pertes d'azote. Bien que les différences inter traitement ne soient pas significatives à la fin de l'expérience, l'incorporation et la fragmentation de résidus ligneux paraissent une option plus favorable vis à vis de la réduction de la lixiviation de nitrate. Comme nous avons pratiqué des apports très élevés vis à vis de la situation courante des forêts d'eucalyptus au Portugal, la réduction des pertes par l'incorporation de résidu ligneux a pu être artificiellement augmentée.

restitutions ligneuses / minéralisation de N / *Eucalyptus globulus* / lixiviation de N / qualité des restitutions

1. INTRODUCTION

In Portugal, eucalyptus plantations, covering an area of 7×10^5 ha, generally are exploited intensively as coppiced stands and are grown on soils that are low in organic matter and nutrients, largely due to their use in agriculture. At the end of the rotation period, the amount of N in harvest residues and forest floor litter layer can reach 700 kg ha^{-1} [20]. Frequent harvesting of short rotations (10–12 years) and removal of these residues involves high rates of removal of nutrients from the site. As sustaining productivity of eucalypt plantations will be largely dependent on the fertility enhancement from silvicultural practices, there are concerns about maintaining nutrient availability under those plantations. Retention of organic residues as the result of tree harvest is crucial for managing site fertility in forest plantations [35], mainly when occupy soils with low reserves of nutrients [12]. Large amounts of harvest residues, especially woody residues (branches) with high C/N ratio, may have a high potential for N immobilization during decomposition, after harvesting, and to release immobilized N at a later stage of decomposition [6, 35], affecting N availability to trees the following rotation. Moreover, N dynamics may also be altered through woody residues fragmentation, which increase contact between residues and soil [8].

Two experimental trials were installed in Portugal to assess the effects of organic residues (harvest residues and forest floor litter) management on tree nutrition status and growth, N in soil solutions and soil fertility [9, 19]. In contrast to results reported by Powers et al. [30], Nzila et al., [25], Turner and Gessel [37], and Proe and Dutch [31], which showed that organic residues can have positive effects on tree growth, Portuguese trials showed that the removal of those residues, as compared with its maintenance on the soil surface or its incorporation into the soil, did not affect either tree nutrition and productivity, or mineral N availability [21]. Meanwhile, decomposition studies showed that eucalyptus residues with high

---

* Corresponding author: mxgomez@isa.utl.pt

C/N ratio (e.g. branches), either on the soil surface or incorporated into the soil, decomposed slower than other residues, and retained or immobilized N [4, 22], suggesting that woody residues can influence N leaching and availability, as reported by Carlyle et al. [8] and Barber and Van Lear [6].

Consequently, to assess the effect of absence or presence (including fragmentation and placement) of woody residues from eucalyptus plantations on N availability and leaching, a study was developed in controlled conditions (lysimetric experiment), in the absence of nutrient uptake. Nitrogen leaching dynamics was examined for a six-year period to understand whether woody residues of different size (pieces or chips) and placement (soil surface or soil incorporation) contribute to reduce N losses, in the short-term, and to improve the N retention in the system, in the long-term. Moreover, aerobic incubations were carried out at the end of the experiment to assess the potential of woody residues to release immobilized N.

2. MATERIALS AND METHODS

2.1. Lysimeter description

The study was carried out in a lysimetric station located in the Instituto Superior de Agronomia, Lisboa (lat. 38° 42' N; long. 9° 11' W; 60 m a.s.l.). The area has a Mediterranean climate, tempered by an oceanic influence. The 30-year-mean (1951–1980) rainfall is 730 mm, and approximately 75% occurs between November and April [18]. The mean annual temperature is 16.4 °C. During the study period, at the meteorological station of Lisboa/Tapada da Ajuda, located adjacent to the experimental site, the mean annual rainfall was 780 mm. There were two very rainy periods: from October until December 1997, and from November 2000 until to March 2001. The rainiest year (1057 mm) occurred in 1997, while rainfall was lower than the mean (459 mm) in 1998. Mean annual temperature was 16.8 °C, ranging from a monthly mean of 9.6 °C in January to 23.4 °C in August.

The lysimetric station consisted in 30 lysimeters constructed in PVC (29.5 cm inner diameter, 50 cm long, 0.068 m^2 soil area). A double plastic mesh (2 mm), a gravel layer (2–5 mm and 5–10 mm diameter) washed with deionised water, a double layer of filtering material and, finally, a washed sand layer, were put, in this order, on the bottom of each lysimeter. At the top of these layers were subsequently placed 25 kg (dry weight) of sieved homogenised mineral soil (30 cm depth) that, according to treatments, was mixed or beneath organic residues. In the lysimeters base, a hole was connected, through a plastic tube, to a plastic bottle for collection of leaching solution; these bottles were in the dark to avoid biological growth in the sample.

2.2. Experimental materials

The mineral soil (Ah horizon) and the organic residues (forest floor litter and harvest residues) to be used in the lysimeters were collected, at harvesting time (March, 1997), from a 12-year-old *E. globulus* plantation located at 70 km east of Lisboa (39° 15' N, 8° 59' W; 119 m a.s.l.). The plantation density was about 1000 tree ha^{-1} and its productivity (commercial timber with bark) was 20 m^{-3} ha^{-1} y^{-1}.

The soil was classified as Dystric Cambisol [15] and developed over miocenic sandstones. The soil was sieved (< 5 mm) and stored at room temperature until being introduced in the lysimeters. Five subsamples were used for analysis and five were used for measuring the moisture content. Characteristics of the mineral substrate, as determined by methods described below, are shown in the Table I.

Harvest residues were separated into leaves, bark, twigs (diameter < 5 mm) and branches (diameter 20–30 mm), and were dried (45 °C). Twigs and branches were cut into sections of 12 and 20 cm long, respectively. Half of the branches were then chopped into chips, resulting in an increase of its surface of approximately 90 times. The bark was also divided into sections with an area of about 12 cm^2. The leaves were green at the time of collection and were not fragmented. Nutrient contents of forest floor litter and of harvest residues components were determined from three subsamples of bulked material (Tab. II) and five subsamples used to determine moisture content. Despite low soil nutrient status, leaf N and P contents were high, because they were not senescent and therefore not affected by the translocation process.

2.3. Treatments

Six treatments, simulating different residue management, were installed in the lysimetric station with a randomized block design and five replicates. The treatments were: (NW) forest floor litter (500 g, dry weight) and non-woody residues (300 g of leaves, 88 g of bark, 100 g of twigs) both incorporated into the soil; (IP) as NW, and with woody residues (1000 g of branches) cut into 20 cm long pieces and incorporated into the soil; (IC) as IP, but with the branches chopped into chips; (SP) forest floor litter and non-woody and woody residues (20 cm long pieces) placed on the soil surface; (SC) as SP, but with branches chopped into chips; and (CT) absence of organic residues (control lysimeter). The amounts of forest floor litter, leaves, bark, twigs and branches corresponded to 73.2, 43.9, 12.9, 14.6 and 146.3 t ha^{-1}, respectively. The quantity of nutrients in the mass of residues is indicated in the Table III. N, P, K, Ca and Mg applied were: 7.43, 0.5, 2.41, 8.83 and 1.25 g, respectively, in each lysimeter of treatment NW; in treatments IP, IC, SP and SC the amounts were 8.62, 0.62, 3.38, 13.96 and 2.05 g, respectively.

The proportion of dry weight of leaves and bark (26%) and the twigs and branches (74%) in relation to the total weight of the harvesting residue was similar to that observed at the end of the first rotation of such plantations [9]. The experiment began in April 1997 and finished six years later, in April 2003.

2.4. Sampling

Leachate volume was measured and collected for analysing according to the occurrence of rainfall. At the end of the experimental period (May 2003) the lysimeters were destructively sampled and the potential mineralizing and nitrifying capacities of the upper mineral soil layer were assessed. The mineral substrate was divided into three depths (0–5, 5–10 and 10–20 cm), and the field-moist soil was sieved (< 5 mm) and stored at 4 °C until processing within three days after collection.

Table I. Particle size (SA, sand; ST, silt; CL, clay), pH value and contents of organic C, total N, exchangeable bases, extractable Al, effective cationic exchange capacity (ECEC) and extractable P and K of the mineral substrate (< 2 mm, 105 °C dry weight) used in the lysimeters.

Particle size					pH	Exchangeable bases						Extractable	
SA	ST	CL	C	N	H_2O	Ca^{2+}	Mg^{2+}	Na^+	K^+	Al^{3+}	ECEC	P	K
(g kg^{-1})						(cmol$_c$ kg^{-1})						(mg kg^{-1})	
907.4 ± 13.9	72.4 ± 4.4	20.2 ± 3.1	11.9 ± 0.7	0.52 ± 0.00	4.90 ± 0.81	0.44 ± 0.03	0.15 ± 0.01	0.11 ± 0.01	0.06 ± 0.00	0.56 ± 0.03	1.32 ± 0.03	2.0 ± 0.6	23.9 ± 0.6

Values are means ($n = 5$) ± standard deviation (S.D.).

Table II. Nutrient contents (mg g^{-1} ash-free dry mass) from forest floor litter (FFL) and harvest residues (LV, leaves; BK, bark; TW, twigs; BR, branches) used in the lysimeters.

Material	N	P	K	Ca	Mg	Mn	C/N	C/P
FFL	6.71 ± 0.05	0.32 ± 0.02	0.57 ± 0.06	7.77 ± 0.06	0.90 ± 0.00	0.50 ± 0.00	75	1563
LV	12.06 ± 0.11	0.92 ± 0.04	5.43 ± 0.15	7.73 ± 0.21	1.63 ± 0.06	0.27 ± 0.06	41	543
BK	1.29 ± 0.10	0.18 ± 0.01	2.27 ± 0.06	15.10 ± 0.17	1.90 ± 0.00	0.10 ± 0.00	388	2776
TW	3.38 ± 0.40	0.38 ± 0.20	2.87 ± 0.76	12.93 ± 3.95	1.40 ± 0.26	0.27 ± 0.21	148	1315
BR	1.19 ± 0.17	0.12 ± 0.02	0.97 ± 0.06	5.13 ± 0.84	0.80 ± 0.00	0.10 ± 0.00	420	4167

Values are means ($n = 3$) ± S.D.

Table III. Amounts of nutrients (g) supplied to each lysimeter through forest floor litter (FFL) and harvest residues (LV, leaves; BK, bark; TW, twigs; BR, branches).

Material	N	P	K	Ca	Mg
FFL	3.36	0.16	0.29	3.89	0.45
LV	3.62	0.28	1.63	2.32	0.49
BK	0.11	0.02	0.20	1.33	0.17
TW	0.34	0.04	0.29	1.29	0.14
BR	1.19	0.12	0.97	5.13	0.80

2.5. Laboratory procedures

Organic samples were ground in a laboratory mill to a particle size < 1 mm for chemical analysis. The mineral elements (Ca, Mg, K and P) were determined after ashing (6 h at 450 °C) and taken up in HCl. Total N was determined using Kjeldhal digestion (Digestion System 40, Kjeltec Auto 1030 Analyzer). The C amount was calculated assuming an average C content of 50% of ash-free mass [3]. The soil physical and chemical properties were determined on the fine earth fraction (< 2 mm) of air-dried samples. Particle size analysis was performed by the methodology described by Póvoas and Barral [29]. Soil pH was determined potentiometrically in distilled water (soil:water ratio 1:2.5). The organic C content was determined by wet oxidation following the method described by De Leenheer and Van Hove [13]. Extractable P and K were extracted using the Egner-Riehm method [14]. The exchangeable base cations were extracted by 1 M NH_4OAc, adjusted at pH 7.0, and the extractable Al was determined after extraction with 1M KCl. The Ca, Mg, Na, K and Al of all extracts were measured by atomic absorption spectroscopy, and P by colorimetry [24]. Total N was determined as above.

A subsample of leachates was taken (60 mL), filtered through a 0.45 μm membrane and stored at –15 °C until chemical analysis. Concentrations of N-NO_3^- and N-NH_4^+ were determined by a segmented flow autoanalyzer (Skalar, SAN^{plus} System, Breda), using the hydrazinium reduction and the modified Berthelot method, respectively [17].

Net N mineralization potential was evaluated for all the treatments, except SC, through laboratory incubations. About 2 kg of a composite soil sample (0–20 cm) from each lysimeter was incubated under aerobic conditions (without leaching) in polythene bags, in the dark, at 20 °C during six months. Each week, the bags were opened for aeration over 15 minutes and the loss of water was corrected by addition of distilled water. The N-NO_3^- and N-NH_4^+ present before and after 2, 4, 6, 8, 10, 12, 16, 20 and 24 weeks of incubation were extracted by shaking 10 g of soil (soil:solution ratio 1:5) for 1 h in 2N KCl. Soil moisture was measured by drying a subsample at 105 °C. Extracts were then stored at –15 °C.

For IP, SP and CT treatments, N mineralization potential was assessed through leaching tubes following the method described by Standford and Smith [36]. A soil sample (40 g, 0–20 cm depth layer) from each lysimeter was mixed with sand (1:1 ratio) and placed in a leaching tube as described by Campbell et al. [7]. Mineral N initially present was removed by leaching with 100 mL 0.01 M $CaCl_2$, followed by 25 mL of the N-minus nutrient solution, and vacuum (60 cm H_2O) was applied to remove excess solution. The tubes were incubated at 35 °C and the leaching process was repeated after 2, 4, 6, 8, 10, 12, 16, 20 and 24 weeks of incubation. The leachates were filtered and analyzed for mineral N.

2.6. Calculations and statistical analysis

Net N mineralization was calculated as the quantity of accumulated N-NO_3^- and N-NH_4^+ produced during aerobic incubation (without leaching) subtracted from the inorganic N levels at the beginning of the incubation. The N mineralization potential (*No*) was estimated using the first-order exponential equation proposed by Stanford and Smith [34], $Nm = No[1\text{-}\exp(\text{-}kt)]$, where *Nm* is the cumulative N mineralized in time *t*, and *No* and *K* are the N-mineralization potential and rate constant values. Nitrogen contents were corrected for moisture and mineralized N was calculated (mg N kg^{-1} soil). The treatment effects on cumulative net N mineralization and quantity of N leached were tested by analysis of variance (ANOVA). Differences between treatments were tested using the Tukey multiple range test.

Table IV. Cumulative volume of leachates (mm), cumulative N-NO_3^-, N-NH_4^+ and N-(NO_3^-+NH_4^+) losses (mg/lysimeter), and NO_3/NH_4 ratio over the experimental period.

Treatments	Volume	N-NO_3^-	N-NH_4^+	N-(NO_3^-+NH_4^+)	NO_3/NH_4
NW	3219.1 ± 128.1 ac	1407.5 ± 251.4 a	161.7 ± 23.8 a	1569.2 ± 233.5 a	9.0 ± 3.1 a
IP	3119.4 ± 40.4 a	352.5 ± 189.7 b	113.9 ± 7.6 a	466.5 ± 192.4 b	3.1 ± 1.6 b
IC	3245.5 ± 58.9 ac	638.4 ± 213.8 bc	104.6 ± 4.0 a	743.0 ± 211.7 bc	6.1 ± 2.2 ab
SP	3800.1 ± 179.6 b	638.2 ± 52.1 bc	327.7 ± 76.6 b	966.0 ± 47.6 bc	2.1 ± 0.6 b
SC	3456.9 ± 85.3 c	482.0 ± 284.9 bc	259.7 ± 48.3 b	741.7 ± 255.8 bc	2.0 ± 1.5 b
CT	3034.2 ± 85.1 a	1000.6 ± 318.5 ac	93.6 ± 27.8 a	1094.2 ± 334.5 ac	10.9 ± 3.1 a

Values are means (n = 5) ± S.D. Different letters in the same column denote significant differences ($P < 0.05$) between treatments by the Tukey multiple range test.

3. RESULTS

3.1. Volume leachate and N leaching

Lysimeter drainage volume was found to have a similar trend to that of rainfall, with paralleled amounts (data not shown) in all years. Cumulative rainfall during the experimental period was 4883.2 mm, 62% of which was drained from the control lysimeters. The amount of leachate in the control (treatment CT, 3034.2 mm) was significantly smaller than that measured in lysimeters with organic residues on the soil surface (treatments SP and SC), which originated the greatest volume of leachate (3800.1 mm in SP, 3456.6 mm in SC, Tab. IV). Treatments with residues incorporated into the soil (treatments IP, IC and NW) gave intermediate values (respectively, 3119.4, 3245.5 and 3219.1 mm).

The highest amount of N-NO_3^- leaching over the experimental period (Tab. IV) was observed in lysimeters with non-woody residues incorporated into the soil (treatment NW, 1407.5 mg). This value was about 1.4 times higher than that measured in the control (CT, 1000.6 mg). These amounts were measured mostly during the autumn months of the first three years, when approximately 80% of the total N-NO_3^- was leached (Fig. 1). Nitrate losses in the other treatments ranged from 352.5 (treatment IP) to 638.4 mg (treatment IC), and were significantly lower than in the NW treatment. Values observed in the control only significantly differed from those of IP treatment.

The treatments SP and SC, with organic residues on the soil surface, showed a N-NO_3^- leaching significantly higher than in the other treatments during the early phase (first sampling date, May 1997) of the experiment (156.5 and 209.0 mg, SP and SC treatments, respectively, vs. 3.2 mg in control), but subsequent losses were minimal for the remainder. In the treatment IC (incorporated non-woody residues+chips), negligible amounts of N-NO_3^- were lost during the first two and half years, while a significant loss (383.1 mg) occurred in the autumn of the third year (Fig. 1). As a contrast, treatment IP did not avoid N-NO_3^- loss in the early months. Although, over the experimental six years, the value in IC almost doubled (638.4 mg) that of IP treatment (352.5 mg), the differences were, however, not statistically significant.

Leaching of N-NH_4^+ was lower than that observed for N-NO_3^- (Tab. IV). Amounts of N-NH_4^+ were significantly higher in treatments with residues (both woody and non-woody) on the soil surface (SP, 327.7 mg; SC, 259.7 mg) than in the control (93.6 mg). However, differences were not significant between the latter and the other treatments (104.6–161.7 mg). Differences among treatments mostly occurred during the first rainy months (Fig. 1). Afterwards, losses showed small

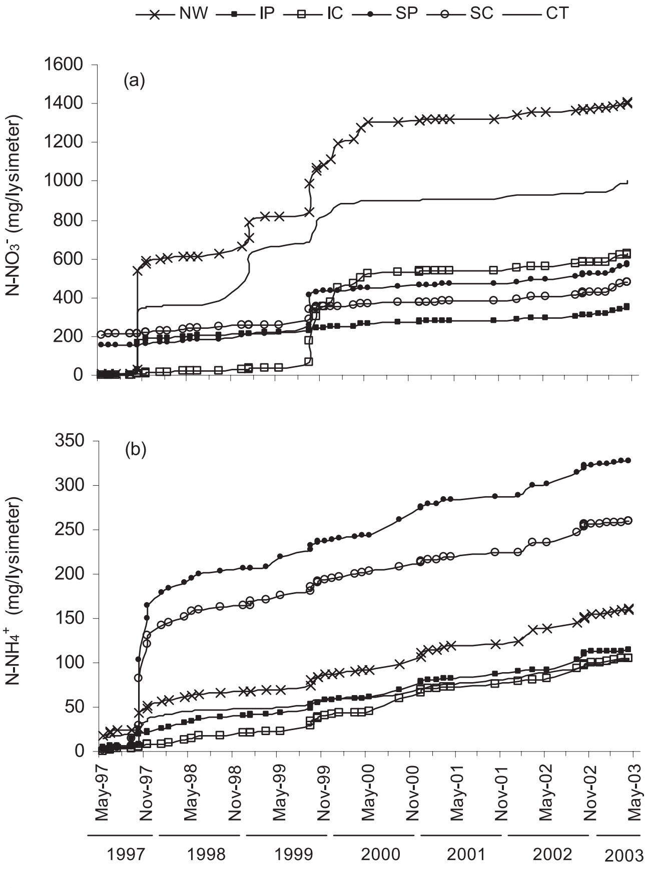

Figure 1. Cumulative losses (mg/lysimeter) of N-NO_3^- (a) and N-NH_4^+ (b) from the lysimeters over the experiment period (n = 5). NW – non-woody residues incorporated into the soil; IP – as NW, and with woody residues cut into 20 cm long pieces and incorporated into the soil; IC – as IP, plus the branches chopped into chips; SP – non-woody and woody residues (20 cm long pieces) placed on the soil surface; SC – as SP, plus branches chopped into chips; CT – absence of organic residues.

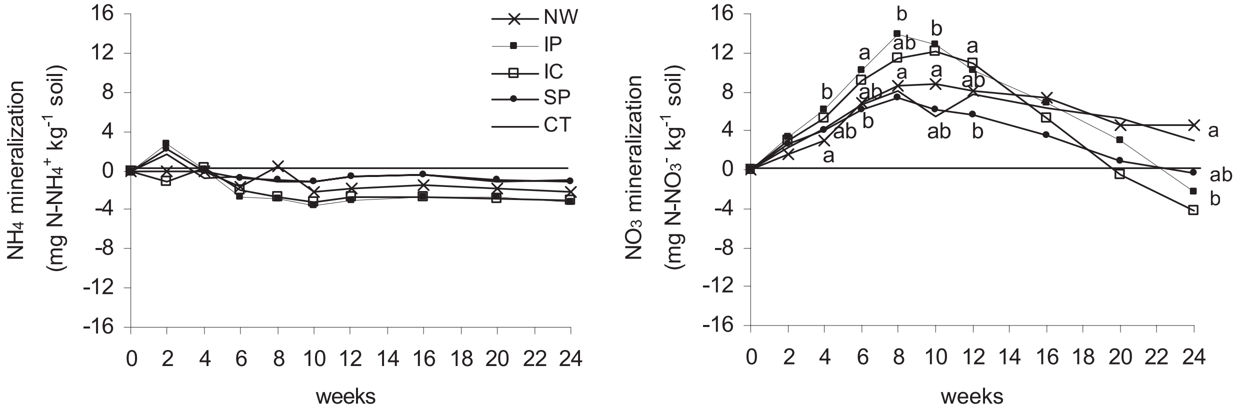

Figure 2. Net amonification (a) and net nitrification (b) rates in the soil of lysimeters (0–20 cm depth). Different letters denote significant differences ($P < 0.05$) between treatments by the Tukey multiple range test.

differences among treatments, between 68.0 mg (CT) and 163.0 mg (SP).

At the end of the experiment, the highest amount of N leached was also observed in the treatment without woody residues (NW), with losses about 1.5 times higher (1569.2 mg) than the control lysimeter (1094.2 mg) (Tab. IV). In these treatments, N was mainly leached as N-NO_3^- (NO_3/NH_4 ratio 9.0 and 10.9 in NW and CT, respectively). The presence of woody residues tended to decrease the amount of mineral N leached, which was generally lower than that observed in the control. The only effective treatment in reducing N losses was IP, with branches incorporated into the soil and cut into pieces, which statistically reduced to a half (466.5 mg) the N leaching observed in the control (1094.2 mg). Most of the treatments with woody residues significantly reduced the NO_3/NH_4 ratio (Tab. IV).

3.2. Nitrogen mineralization

The initial mineral N (N-NO_3^- + N-NH_4^+) concentrations ranged from 4.8 to 8.7 mg kg^{-1} and were greater in treatments with incorporated woody residues (in IP 8.0 mg kg^{-1} and 8.7 mg kg^{-1} in IC treatments) than in the control (4.8 mg kg^{-1}), but there were no significant differences among treatments. Mineral N was predominantly present as nitrate (53–71%), as averaged N-NO_3^- and N-NH_4^+ concentrations were 4.1 and 2.7 mg kg^{-1}, respectively. The treatment SP, with non woody and woody residues (pieces) placed on the soil surface, showed N-NH_4^+ concentration similar to control (1.8 and 1.8 mg kg^{-1}, respectively), which were statistically lower than incorporation placement (IP, 3.8 mg kg^{-1}).

The treatments approximately showed the same temporal pattern of net amonification during 24 weeks of aerobic incubation under non-leaching conditions (Fig. 2). Net amonification was not observed after the second week, and by 24 weeks, the rates ranged from –0.9 to –3.2 mg N-NH_4^+ kg^{-1} soil. The lowest values were found in the treatments with residues incorporated (–3.2 and –3.0 mg N-NH_4^+ kg^{-1} soil in the IP and IC treatments, respectively), which were significantly lower than in the control (–0.9 mg N-NH_4^+ kg^{-1} soil).

All treatments showed net nitrification (Fig. 2). The highest rates of net nitrification were reached after 8–10 weeks of aerobic incubation. At week 8, the treatment with branches incorporated and cut into pieces showed the highest net nitrification rates (IP, 14.0 mg N-NO_3^- kg^{-1} soil), whereas lower values were observed in the treatments without woody residues incorporated (NW, SP and CT). During the following weeks, net nitrification exhibited different trends among the treatments. The treatments without woody residues always showed positive nitrification rates (4.5 in NW and 3.0 mg N-NO_3^- kg^{-1} soil in CT), whereas in the treatments with woody residues the nitrification declined until reaching negative values (from –0.4 to –4.2 mg N-NO_3^- kg^{-1} soil) after 24 weeks of incubation.

Net N mineralization rates (N-NO_3^- + N-NH_4^+), after 8 weeks of incubation, ranged from 6.7 to 11.1 mg N kg^{-1} soil, which corresponded to about 1.5% of the total N. Residue incorporation into the soil tended to increase N mineralization although differences were not statistically significant. The presence of residues, especially when incorporated, produced net immobilization at the end of incubation (–5.4 and –7.1 mg N kg^{-1} soil in IP and IC treatments, respectively), whereas lysimeter without woody residues continued to present net mineralization (2.4 and 2.0 mg N kg^{-1} soil in NW and control, respectively).

Cumulative net N mineralized during incubation period under leaching conditions (Fig. 3) showed the highest values in treatment IP (6.0 mg kg^{-1} soil), which were significantly greater than in the control (4.0 mg kg^{-1} soil). The percentage of soil total N mineralized in leaching tubes was less than 1% (0.7–0.9%). Cumulative net N mineralized followed typical first-order exponential equation (r^2 = 0.98–0.99). The N mineralization potential (*No*) obtained by the exponential model was significantly higher in soil with residues (6.5 and 6.4 mg kg^{-1} soil in IP and SP treatments) than in the control (4.5 mg kg^{-1} soil). The *K* values were similar among treatments (0.07–0.08 $week^{-1}$).

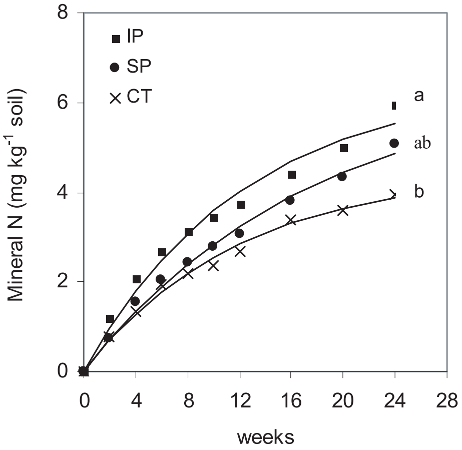

Figure 3. Cumulative N mineralized in IP, SP and CT treatments (0–20 cm depth) produced during 24 weeks in leaching tubes. Curves represent best fits of the equation $Nm = No[1\text{-exp}(\text{-}kt)]$. Different letters denote significant differences ($P < 0.05$) between treatments by the Tukey multiple range test.

4. DISCUSSION

The methodology used in this study to assess the effects of residue management on N leaching presents several limitations. In the lysimeters, the soil and water transfers are disturbed, the amounts of residues used are two to three times greater than at the harvest of the first rotation of eucalypts plantations [19], and the environmental conditions are modified (e.g., soil water content, absence of root exudates and root uptake). Although experimental conditions have a limited value in assessing the complexity of field situations, they allow gaining insight into the capability of harvest residues to decrease N leaching.

The amount of N leached from the soil in the absence of harvest residues (control) reached 26.6 kg ha^{-1} y^{-1}, which was much higher than the mean annual input from the atmosphere (4.0 kg ha^{-1} y^{-1}) reported by Cortez [11] in a nearby area. Such amount was also higher than that usually applied as fertiliser (10–15 kg ha^{-1}) at planting in Portuguese eucalyptus plantations [19]. Incorporation of non-woody residues (leaves, bark and twigs) and forest floor litter enhanced N leaching, mostly as N-NO_3^-, by 11.6 kg ha^{-1} y^{-1}, accounting for 6.4%, during the experimental period, of the amount of N supplied to lysimeters through those residues. This may be explained by the high N content (12.06 mg g^{-1}) and a low C/N ratio (41) of green leaves, the main component of the non-woody residues and responsible for 42% of N supplied to lysimeters. These leaves may have decomposed quickly and may have released and leached N at a high rate during the early phase of the experiment. This is in a good agreement with results reported by Azevedo et al. [5] for decomposition of similar leaves in the field, which lost about 40% of their initial N content during the first 180 days of incubation, and by Mendham et al. [23] for N release from eucalypt green leaf residues incubated in the laboratory. Then, N leaching from green leaves of eucalyptus, should be greater than from senescent leaves (with a higher C/N), as suggested by data reported by Ribeiro et al. [33] and Xu [38], in the field, and by Aggangan et al. [2] in laboratory studies.

In contrast to leaves, woody residues (branches) incorporated into the soil with the non-woody residues and the forest floor litter reduced N leaching between 15.2 and 8.5 kg ha^{-1} y^{-1}, when cut into pieces and into chips, respectively. This pattern suggests that branches may have a slow decomposition and have promoted the retention or immobilization of N, which may be ascribed to their very low N content (1.19 mg g^{-1}) and high C/N ratio (420). This is in agreement with results reported by other authors [4, 19, 22, 26, 34] who showed that eucalypt branches decompose slower than the other harvest residues and can act as a sink for N over 2–3 years. Similar trend is also reported by Carlyle et al. [8] for radiata pine branches, in a lysimeter experiment, and by Barber and Van Lear [6] for loblolly pine branches decomposing in the field.

The amount of N leaching after three years (52.1–194.0 kg ha^{-1}) was close to that measured at the end of the experimental period (68.1–229.1 kg ha^{-1}), and therefore leaching during the second half of the study was low (16.0–35.1 kg ha^{-1}) and not significantly different between treatments. This means that the effect of residue management on N availability and leaching mostly occurred during the first three years of experiment, when tree N uptake is low (about 36 kg N ha^{-1} y^{-1}) [4]. A clear effect of branches fragmentation was observed during this period in treatments where they were incorporated into the soil. In fact, branches chopped into chips induced negligible losses of N-NO_3^- (10.0 kg ha^{-1}) during the first two and half years, while in lysimeters with branches in pieces a significant loss of N-NO_3^- (27.9 kg ha^{-1}) was measured at the beginning of the experiment. Such a difference is corroborated by the observations of Carlyle et al. [8] who demonstrated that the reduction of size of woody debris of radiata pine branches is an important factor to decrease N losses from the soil at short-term, given the increment of branch specific surface, which leads to a better accessibility to microbial attack [10]. However, the effect of branch fragmentation was not noticeable three years after the beginning of our experiment, which is in agreement with N release from decomposing branches in the field two years after incubation [4].

Maintenance of harvest residues on the soil surface is being considered as an alternative management practice in Portugal. Our results showed that, after three years, this residue placement did not increase significantly the amount of mineral N losses through leaching. However, differences were observed during the early phase of the experiment (both for N-NO_3^- and N-NH_4^+). Independently of branch fragmentation, residues placed on the soil surface showed large initial losses of N-NO_3^- (about 30 kg ha^{-1}) only one week after their application into the lysimeters. Such placement also originated higher leaching of N-NH_4^+ (8.0 and 6.3 kg ha^{-1} y^{-1} for branches in pieces and chips, respectively) than that observed for residues incorporated into the soil (2.8 and 2.5 kg ha^{-1} y^{-1} for branches in pieces and chips, respectively), which is in agreement with the trend reported by Raimundo et al. [32] for leaf fall of *Castanea* *sativa* decomposing in lysimeters. The less effect of branch placement on the soil surface in reducing N leaching during the early phase of our experiment agrees with results observed by Azevedo [4] during the first year after harvesting, in the site in which the present experimental soil was taken. In addition, we emphasize that the amounts of N leached during such period were slightly higher (59 and 34 kg N ha^{-1} for surface and incorporation placement, respectively) than those observed in the field (47 and 25 kg N ha^{-1}, respectively [4]).

At the end of the experiment, only N-NO_3^- was measured through incubation under aerobic conditions, which is opposite to the trend commonly observed for soil taken from eucalyptus plantations in Portugal [4, 21], Australia [1, 28] or Brazil [16], where N-NH_4^+ has been found to be largely predominant, or in plantations in Congo [25], where nitrification and amonification were of the same order of magnitude. This suggests that the effect of eucalyptus harvest residues alone on the mineral N dynamics is substantially different from that observed in the respective plantations or the conditions in lysimeters could be clearly different from those of the field. Although the highest net N mineralization rates at week 8, under aerobic conditions, were measured in the soil with incorporated woody residues, such rates were nil or negative at week 24, whereas they were positive in soil without woody residues. This suggests that the presence of woody residues in the soil affects the dynamics of N availability, as reported by Gonçalves et al. [16] and O'Connell et al. [27] in eucalyptus plantations. However, it should be emphasized that such treatment differences could have low importance under natural conditions in Portugal, as similar treatments applied in the field did not affect significantly tree growth and nutrition status in eucalyptus plantations as reported by Magalhães [22] and Madeira et al. [21].

The effect of harvest residue management options strongly differ with time. At short-term, retention of woody harvest residues contributes to reduce N leaching, which may decrease N losses during the first two/three years of a rotation when tree N uptake is small and tree root system does not fully explore soil volume. In the long-term, retention of woody harvest residues is beneficial for maintaining site N fertility, since it improves the total N balance of the system.

5. CONCLUSIONS

The results of the present study show that, at short-term, under the environmental conditions of Portugal, the incorporation of non-woody residues mixed with woody residues, especially when chopped into chips, is the more adequate option for N management in eucalyptus plantations. This management option may delay N losses by reducing leaching during the early stages of plantations and it might allow a greater synchrony between N supply by residues and N demand of new plants. Despite the effect of woody harvest residues in reducing N leaching following harvesting, at long-term (two/three years after their management), these residues do not show significant effect on N availability to trees.

Acknowledgements: Laboratory staff of the Departamento de Ciências do Ambiente (Instituto Superior de Agronomia) is acknowledged for their technical assistance and Paulo Marques and Luis Hilario for their help in sampling. Authors want to thank the comments of Prof. Ana Carla Madeira during the preparation of the manuscript.

REFERENCES

[1] Adams M.A., Attiwill P.M., Nutrient balance in forests of Northern Tasmania. 2. Alteration of nutrient availability and soil water chemistry as a result of logging, slash-burning and fertilizer application, For. Ecol. Manage. 44 (1991) 115–131.

[2] Aggangan R.T., O'Connell A.M., McGrath J.F., Dell B., The effects of *Eucalyptus globulus* Labill. leaf litter on C and N mineralization in soils from pasture and native soils, Soil Biol. Biochem. 31 (1999) 1481–1487.

[3] Allen S.E., Grimshaw H.M., Perkinson J.A., Quanby C., Chemical analysis of ecological materials, Blackwell Scientific Publications, Oxford, UK, 1989.

[4] Azevedo A.P., Estudo da dinâmica do azoto e do carbono em plantações florestais intensivas, Doctoral Thesis, Universidade Técnica de Lisboa, Lisboa, 2000.

[5] Azevedo A., Madeira M., Hilário L., Marques P., Fertilidade dos solos afectados por práticas de silvicultura intensiva. 1. Efeito da gestão dos resíduos de abate e da sua composição química nas dinâmicas do C e do N, Revista de Ciências Agrárias 27 (2004) 329–346.

[6] Barber B.L., Van Lear D.H., Weight loss and nutrient dynamics in decomposing woody loblolly pine logging slash, Soil Sci. Soc. Am. J. 48 (1984) 906–910.

[7] Campbell C.A., Ellert B.H., Jame Y.W., Nitrogen mineralization potential in soils, in: Carter M.R. (Ed.), Soil sampling and methods of analysis, Lewis Publ., Boca Raton, Florida, 1993, pp. 341–349.

[8] Carlyle J.C., Bligh M.W., Nambiar E.K.S., Woody residue management to reduce nitrogen and phosphorus leaching from sandy soil after clear-felling *Pinus radiata* plantations, Can. J. For. Res. 28 (1998) 1222–1232.

[9] CEC (Contract AIR3-CT92-0492), Organic matter management in eucalyptus forestry to enhance soil structure, stability and nutrition, Final Report to Commission of European Communities, Lisboa, 1996.

[10] Corbeels M., O'Connell A.M., Grove T.S., Mendham D.S., Rance S.J., Nitrogen release from eucalypt leaves and legume residues as influenced by their biochemical quality and degree of contact with soil, Plant Soil 250 (2003) 15–28.

[11] Cortez N.R.S, Compartimentos e ciclos de nutrientes em plantações de *Eucalyptus globulus* Labill. ssp. *globulus* e *Pinus pinaster* Aiton, Doctoral Thesis, Universidade Técnica de Lisboa, Lisboa, 1996.

[12] Dambrine E., Vega A., Taboada T., Rodríguez L., Fernández C., Macias F., Gras J.M., Bilans d'éléments minéraux dans des petits bassins versants forestiers de Galice, Ann. For. Sci. 57 (2000) 23–38.

[13] De Leenheer L., Van Hove J., Détermination de la teneur en carbone organique des sols. Étude critique des méthodes titrimétriques, Pédologie 8 (1958) 39–77.

[14] Egnér H., Riehm H., Domingo WR., Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoff-zustandes der Böden. II Chemische Extraktionmethod zur Phosphor-und Kaliumbestimmung, Kungl. Lantbr. Högsk. Ann. 26 (1960) 199.

[15] FAO-UNESCO, Soil Map of the World (revised legend), FAO, Rome, 1988.

[16] Gonçalves J.L.M, Serrano M.I.P., Mendes K.C.F., Gava J.L., Effects of site management in a *Eucalyptus grandis* plantation in the humid

tropic: São Paulo, Brazil, in: Nambiar E.K.S., Tiarks A., Cossalter C., Ranger J. (Eds.), Proceedings of the CIFOR Workshop on Site Management and Productivity in Tropical Plantation Forests, Kerala, India, 1999, pp. 3–9.

[17] Houba V.J.G., Novozamsky I., Tenminghoff E., Soil analysis Procedures, Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, The Netherlands, 1994.

[18] INMG, Normas climatológicas da região de "Ribatejo e Oeste" correspondentes a 1951–1980. O Clima de Portugal. Fasciculo XLIX, vol. 2–2^a Região, Instituto Nacional de Metereologia e Geofísica, Lisboa, 1991.

[19] Jones H.E., Madeira M., Herraez L., Dighton J., Fabião A., González-Rio F., Fernandez Marcos M., Gomez C., Tomé M., Feith H., Magalhães M C., Howson G., The effect of organic matter management of the productivity of *Eucalyptus globulus* stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment, For. Ecol. Manage. 122 (1999) 73–86.

[20] Madeira M., Changes in soil properties under eucalyptus plantations, in: Pereira J.S., Landsberg J.J. (Eds.), Biomass production by Fast-Growing Trees, Kluwer Academic Publishers, 1989, pp. 81–99.

[21] Madeira M., Magalhães M.C., Azevedo A., Fabião A., Araújo M.C., Pina J.P., Efeito da gestão dos resíduos de abate nas características do solo e no crescimento de uma plantação de *Eucalyptus globulus* em talhadia, Revista de Ciências Agrárias 27 (2004) 414–431.

[22] Magalhães M.C.S., Efeitos de Técnicas de Preparação do Solo e Gestão dos Resíduos Orgânicos em Características Físico-Químicas do Solo de Plantações Florestais, Doctoral Thesis, Universidade Técnica de Lisboa, Lisboa, 2000.

[23] Mendham D.S., Kumaraswamy S., Balasundaran M., Sankaran K.V., Corbeels M., Grove T.S., O'Connell A.M., Rance S.J., Legume cover cropping effects on early growth and soil nitrogen supply in eucalypt plantations in south-western India, Biol. Fertil. Soils 39 (2004) 375–382.

[24] Murphy J., Riley J.P., A modified single solution method for determination of phosphate in natural waters, Anal. Chim. Acta 27 (1962) 31–36.

[25] Nzila J.D., Bouillet J.P., Laclau J.P., Ranger J., The effects of slash management on nutrient cycling and tree growth in *Eucalyptus* plantations in the Congo. For. Ecol. Manage. 171 (2002) 209–221.

[26] O'Connell A.M., Decomposition of slash residues in thinned regrowth eucalypt forest in Western Australia, J. Appl. Ecol. 34 (1997) 111–122.

[27] O'Connell A.M., Grove T.S., Mendham D.S., Rance S.J., Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* in south western Australia, Soil Biol. Biochem. 36 (2004) 39–48.

[28] Polglase P.J., Attiwill P.M., Adams M.A., Nitrogen and phosphorus cycling in relation to stand age of *Eucalyptus regnans* F. Muell, Plant Soil 142 (1992) 167–176.

[29] Póvoas I., Barral M.F., Métodos de Análises de Solos, Comunicações do IICT, Instituto de Investigação Científica Tropical, Série de Ciências Agrárias, 10, Lisboa, 1992.

[30] Powers R.F., Alban D.H., Miller D.H., Tiarks A.E., Wells C.G., Avers P.E., Cline R.G., Loftus Jr. N.S., Fitzgerald R.O., Sustaining productivity in North America forests: problems and prospects, in: Gessel S.P., Lacater D.S., Weetman G.F., Powers R.F. (Eds.), Sustained Productivity of Forest Soils, Proceedings of 7th North American For. Soils Conf., Vancouver, Canada, 1990, pp. 49–79.

[31] Proe M.F., Dutch J., Impact of whole tree harvesting on second-rotation growth of Sitka spruce: the first ten years, For. Ecol. Manage. 66 (1994) 39–54.

[32] Raimundo F., Madeira M., Coutinho J., Martins A., Simulação lisimétrica da gestão de folhada de *Castanea sativa*. Efeito na lixiviação de nutrientes e nas características químicas do solo, Revista de Ciências Agrárias 25 (2002) 157–172.

[33] Ribeiro C., Madeira C., Araújo M.C., Decomposition and nutrient release from leaf litter of *Eucalyptus globulus* grown under different water and nutrient regimes, For. Ecol. Manage. 171 (2002) 31–41.

[34] Shammas K., O'Connell A.M., Grove T.S., McMurtrie R., Damon P., Rance S.J., Contribution of decomposing harvest residues to nutrient cycling in a second rotation *Eucalyptus globulus* plantation in south-western Australia, Biol. Fertil. Soils 38 (2003) 228–235.

[35] Smethurst P.J., Nambiar E.K.S., Changes in soil carbon and nitrogen during the establishment of a second crop of Pinus radiata, For. Ecol. Manage. 73 (1995) 145–155.

[36] Standford G., Smith S.J., Nitrogen mineralization potentials of soils, Soil Sci. Soc. Am. Proc. 36 (1972) 465–472.

[37] Turner J., Gessel S.P., Forest productivity in the southern hemisphere with particular emphasis on managed forests, in: Gessel S.P., Lacater D.S., Weetman G.F., Powers R.F. (Eds.), Sustained Productivity of Forest Soils, Proceedings of 7th North American For. Soils Conf., Vancouver, Canada, 1990, pp 23–39.

[38] Xu X., Nutrient dynamics in decomposing needles of *Pinus luchuensis* after typhoon disturbance in a subtropical environment, Ann. For. Sci. 63 (2006) 707–713.