Scientific
Research
Publishing

Decomposition of *Eucalyptus sp.* and *Pinus taeda* Harvest Residues under Controlled Temperature and Moisture Conditions

Gabriela Sánchez[1*], Amabelia del Pino[2], Jorge Hernández[2]

[1]Ministry of Livestock, Agriculture and Fisheries, Natural Resources Department, Montevideo, Uruguay
[2]Department of Soil and Water, Agronomy Faculty, University of the Republic, Montevideo, Uruguay
Email: *gasanchez@mgap.gub.uy or gabici1974@gmail.com, amabelia@fagro.edu.uy, jhernan@fagro.edu.uy

Abstract

Background: Following the harvest of *Eucalyptus grandis* Hill ex Maiden*, Eucalyptus globulus* Labill*, Eucalyptus dunnii* Maiden and *Pinus taeda* L. forests, an important proportion of the aerial biomass is left to decompose on the site. The decomposition process is known to alter the dynamics of nutrients in the soil, particularly N, which is essential for the growth of the next turn of the plantation. The decomposition of *E. grandis, E. globulus, E. dunnii* and *P. taeda* harvest residues (leaves/needles, twigs and bark) was studied, following individual incubation of each residue type for 6 months under controlled temperature and humidity. Net N mineralization was also determined. Chemical characteristics of the residues were tested to identify those that affect the rate of decomposition and N release. **Results:** The highest decomposition rates were found for *Eucalyptus* leaves and *P. taeda* needles, but the proportion of C respired by *P. taeda* needles was lower than that of *Eucalyptus* leaves. No differences among species were found in the amount of CO_2 produced during incubation of twigs. The lowest decomposition rates corresponded to *Eucalyptus* bark. Although C loss was related to many residue characteristics, the closest relationship was observed with their C:N ratio. Higher amounts of mineral N were produced by decomposition of *E. grandis* and *E. dunnii* leaves than *P. taeda* needles and *E. globulus* leaves. Bark decomposition produced N immobilization, irrespective of the species, and for twigs, this was also true, except for *P. taeda*. The net N mineralization by decomposition of *Eucalyptus* residues was highly correlated with their total N content and the C:N and lignin:N ratios. **Conclusion:** The total N content and the C:N ratio of residues can be used to satisfactorily assess the decomposition and net N mineralization potential of different residues types, avoiding the

need to conduct more complex determinations.

Keywords

Forestry Residues, N Immobilization, C:N Ratio, Lignin, Polyphenols

1. Background

A recent increase in Uruguay's forested area has led to a shift in land use from pastoral to forestation, *Eucalyptus* and *Pinus* being the prevalent genera. This vegetation change is likely to produce changes in soil organic matter and nutrient dynamics, given the differences in plant residue turnover (Shammas et al., 2003; Laclau et al., 2010). Following harvest, a large percentage of aerial biomass (leaves, bark and twigs) remaining on the site undergoes decomposition at an intensity that varies according to the intrinsic parameters (residue size, proportions of compounds with a higher and lower degradation resistance), the diversity of existing organisms in the particular soil, and climatic conditions such as temperature and moisture. The decomposition of harvest residues and the subsequent release of nutrients determine the growth conditions and the availability of nutrients for the next rotation (O'Connell et al., 2004; Kumaraswamy et al., 2014).

A field study conducted in a *E. globulus* Labill plantation in Uruguay showed leaves to be the most rapidly decomposing component, with biomass loss amounting to 70% after two years, while twigs (small and medium-sized) and bark had lower decomposition rates of 29% and 19% respectively (González et al., 2016). Also for *E. grandis* Hill ex Maiden and *E. dunnii* Maiden, the rapid decomposition of leaves (50% biomass loss after two years) was followed by that of twigs smaller than 1 cm in diameter (Hernández et al., 2009). In Brazil, Santos Costa et al. (2005) reported 30% biomass loss for *E. grandis* at the end of the decomposition period (382 days). Plantations of *E. dunnii* Maiden have shown low decomposition rates for leaf and bark residues fallen from trees, leading to the accumulation of C and therefore an increase in the amount of nutrients at the interface between soil and harvest residues (Louzada et al., 1997; Gama-Rodrigues & Barros, 2002). Although faster than other tree fractions, slow decomposition of *Eucalyptus* leaf residues has been reported by other authors, and has been described as characteristic of the genus (Barrera et al., 2004). Regarding to *Pinus taeda* L. harvest residues, unpublished studies conducted in Uruguay showed fast biomass losses for needles and small twigs, representing less than 10% of the original weight two years after harvest.

Typically in Uruguay, the site is planted immediately after harvest. Therefore the decomposition of the residues left by the former plantation influences the nutrient availability for the next turn. The identification of those characteristics of the different residue types that determine their decomposition process and

nutrient release could provide information for the implementation of the residue management and fertilizer application policies. The chemical characteristics of the residues: C and N contents, C:N ratio, and the proportion of soluble C and N compounds, readily available to microorganisms have been traditionally used as indicators of decomposition potential (Mary et al., 1996). The contents of decomposition resistant substances, such as lignin and soluble polyphenols have been also proposed with this aim (Mungai & Motavalli, 2006). The higher these contents, lignin:N and plyphenol:N ratios, the more resistant the materials are to decomposition —i.e., the lower the rate of their degradation. According to Berg & McClaugherty (2003) in forest-based ecosystems, the lignin content of residues has an influence on C and N mineralization, especially towards the end of decomposition. Fierer et al. (2001) reported that phenolic compounds negatively affect the decomposition rate and the release of N from forestry residues. In forest plantations of Uruguay, despite the differences found in decomposition rate according to residue type (Hernández et al., 2009), no information is available regarding the effect of the chemical composition of residues on their decomposition rate. Moreover, in the northern region *Pinus* and *Eucalyptus* are planted on low fertility soils, where the nutrient availability for the next turn, and the long term sustainability of this production system are important concerns.

Based on the assumption that different harvest residues have different decomposition rates according to genera and species, as well as within species, and that those differences are due to intrinsic characteristics of each residue type, our research aimed to: a) determine the decomposition patterns of different harvest residue types for *E. grandis*, *E. globulus*, *E. dunnii* and *P. taeda* under controlled temperature and moisture conditions, b) determine the chemical parameters of each residue type (N, C, lignin and polyphenol contents and ratios) that primarily affect decomposition rates, and c) estimate net N mineralization (amount of N released or immobilized) in the different stages of the decomposition process for the residue types.

2. Methods

2.1. Characterization of Harvest Residues

Different fractions of harvest residues: leaves, bark and twigs of *E. grandis, E. globulus and E. dunnii*, and needles and twigs of *P. taeda* were included in the study. The total and soluble C contents were determined at the start of incubation by oxidation with potassium dichromate, followed by colorimetric determination (Nelson & Sommers, 1996). The total and soluble N contents were determined by the Kjeldahl method. Lignin determinations were based on acidic hydrolysis, treating the material with concentrated sulphuric acid (1 h), followed by dilution to 3 % acid, boiling (4 h) and filtration before gravimetric determination of the remaining material (Schwanninger & Hinterstoisser, 2002). Colorimetric determinations of the soluble polyphenol content were made on aqueous extracts (100˚C, 1 h) of the different materials using the Fo-

lin-Ciocalteau method (Singleton & Rossi, 1965).

2.2. Incubation Experiment

The upper layer (0 - 20 cm) of a sandy soil, representative of the northern region of Uruguay (Thermic Humic Hapludult sandy loam, Soil Survey Staff, 2006) was used for the incubation. The soil was sieved to 5 mm, free of roots and gravel, and kept in moist conditions until later use. The total C and N contents of the soil were 8.0 and 0.7 mg·kg^{-1}, respectively, and pH$_{(H_2O)}$ was 4.2. For the incubation fresh harvest residues were collected from commercial farms.

The experiment consisted of 12 treatments: soil without residue (control) and soil with each of three types of residue (leaves, bark and twigs) from each of the *Eucalyptus* species *E. grandis*, *E. globulus* and *E. dunnii* and two types of residue (needles and twigs) from *P. taeda*. 25 g of soil were placed in individual beakers and residue pieces (1 cm-long) of each type of fresh residue were placed on the soil surface without mixing, simulating the post-harvest scenario. The added amount of each residue type was based on previous quantification studies (Hernández et al., 2009), placing the dry weight equivalents to 2.08, 4.64 and 3.52 g of leaves, bark and twigs, respectively, in each jar. These amounted to mass per area of 0.13, 0.29 and 0.22 g·cm^{-2} of leaves, bark and twigs, respectively. The dry weight equivalents to 2.08 g of needles and 3.52 g of twigs of *P. taeda* were also placed in jars. Deionized water in the amount required to reach the field water holding capacity of the soil was added. Gravimetric measurements were made fortnightly to determine the amount of water needed to maintain field capacity. The temperature was kept at 25°C throughout the six months (188 days) of the experiment. The experimental set included three replications of each of 12 treatments. The beakers with the soil and residues were placed in sealed 1-L jars also containing a vial with 5 mL of 0.25 M sodium hydroxide. The CO_2 production was determined weekly by titration of the remaining sodium hydroxide with 0.1 M hydrochloric acid (Anderson, 1982). Following each measurement the vial was filled with 0.25 M sodium hydroxide solution and placed in the jar. The amount of CO_2 respired was calculated by difference with the CO_2 determined in blank jars without soil, and was expressed as C-CO_2 mg·kg^{-1} of soil.

To assess the net N mineralization a similar procedure was conducted. The 12 treatments were incubated at the same moisture and temperature conditions as above. Because destructive sampling was used, a large number of replications were required (18 replications for each treatment). The soil with the different types of residue was placed in 0.5-L glass jars with screw-cap (slightly open to allow the ingress of oxygen), adding deionized water to reach the field water holding capacity. Three replications of each treatment were taken on days 15, 30, 60, 90, 120 and 188 for determinations of mineral N (nitrate and ammonium). Samples were extracted from each jar following 1-h stirring with 100 mL of 2 M potassium chloride. The nitrate content was determined according to the

Griess-Ilosvay reaction (Mulvaney, 1996) and ammonium determinations were based on the Berthelot method (Rhine et al., 1998). The nitrate and ammonium contents are expressed on a dry soil basis.

2.3. Calculation and Statistical Analysis

The correlations between the residue analyzed parameters (total C and N, soluble C and N, lignin and soluble polyphenol contents) were studied. Based on experimental results of mineral N in soil, the net mineralization of N (N released or immobilized) was calculated as the difference between the average value for each treatment and the control. ANOVA was conducted on the mineral N and respired C contents for each sampling, using a random plot design. The comparisons of residue means were made using Tukey test. Results were expressed as the average of three replications. In all analysis relationships were considered significant when $P < 0.05$.

The proportion (%) of remaining C for the different types of residue was adjusted to the following a double exponential decay model (Equation (1)).

$$w = w_r \mathrm{e}^{(-k_1 t)} + w_d \mathrm{e}^{(-k_2 t)} \tag{1}$$

where w_r is the pool of slowly mineralizing C; w_d the pool of fast mineralizing C; t time in days; and k_1 and k_2 daily decomposition constants.

The relationship between the decomposition percentage of residues at the end of incubation and the initial chemical characteristics of residues was examined using single variable regressions. Regression analysis was also conducted between the net mineralization of N at the end of incubation for each treatment and the initial total N, soluble N and C contents, the C:N, lignin:N and polyphenol:N ratios of the residues. Only *Eucalyptus* residues were used in this last analysis.

3. Results

3.1. Residue Composition

The total N and soluble C and N contents were highest in pine needles and in eucalyptus leaves, regardless of species, compared with the other residue types (Table 1). Although total and soluble C varied among residues the soluble C fraction represented a similar proportion of total C in leaves, bark and twigs of *Eucalyptus*, while *Pinus* residues showed lower values. The C:N ratio was lowest for *Eucalyptus* leaves and *Pinus* needles, followed by twigs of either genus, while *Eucalyptus* bark showed the highest values. The soluble polyphenol content was lower for *Pinus* residues than for any residue type of *Eucalyptus*. The lignin content was found to be higher in leaves than in twigs or bark within the *Eucalyptus* genus, the content in bark being relatively low regardless of species. In contrast, the lignin content of *Pinus* residues did not differ according to type. The lignin:N and polyphenol:N ratios were higher in bark and twigs than in leaves or needles. Table 2 shows correlation coefficients between the chemical characteristics of residues.

Table 1. Initial residue composition.

Residue type	Total C	Total N	C:N†	Soluble C	Soluble C: Total C	Soluble N	Soluble N: Total N	Lignin	Lignin: Total N††	Polyphenol	Polyphenol: Total N†††
	(mg·g⁻¹)			(mg·g⁻¹)	(%)	(mg·g⁻¹)	(%)	(mg·g⁻¹)		(mg·g⁻¹)	
P. taeda needles	508	10.8	47	129.4	25.5	0.7	6.6	314.1	29	94.3	9
P. taeda twigs	465	3.8	121	84.9	18.2	0.7	18.8	334.1	87	84.5	22
E. grandis leaves	436	16.9	26	138.9	31.8	1.1	6.5	330.1	20	245.4	15
E. grandis bark	411	3.2	130	69.3	16.9	0.4	14.1	213.1	67	142.5	45
E. grandis twigs	402	4.1	98	80.8	20.1	0.7	15.8	239.4	58	162.8	40
E. globulus leaves	508	10.3	49	153.2	30.2	0.8	7.7	381.3	37	210.6	20
E. globulus bark	389	2.3	167	61.3	15.7	0.3	11.6	205.2	88	100.2	43
E. globulus twigs	444	4.4	101	93.6	21.1	1.1	25.8	351.3	80	212.4	48
E. dunnii leaves	442	14.1	31	132.7	30.0	0.9	6.3	338.1	24	256.6	18
E. dunnii bark	446	2.7	162	78.6	17.6	0.2	7.7	229.0	97	198.6	72
E. dunnii twigs	410	4.5	90	84.8	20.7	0.6	12.9	269.6	59	194.2	43
Average	442	7.0	92.9	100.7	22.5	0.7	12.2	291.4	59	172.9	34
Standard Deviation	39.5	5.1	49.9	31.7	5.8	0.3	6.2	61.9	28	60.5	19
Coefficient of Variation (%)	8.9	72.8	53.7	31.5	26.0	43.4	51.0	21.2	47	35.0	55

† (C:N Ratio). †† (Lignin:Total N Ratio). ††† (Polyphenol:Total N Ratio).

Table 2. Pearson's correlation coefficient (r) between the chemical characteristics of residues of *E. grandis*, *E. globulus*, *E. dunnii* and *P. taeda.* Probability levels are indicated between parentheses.

	Soluble C	Total N	Soluble N	Lignin	Soluble polyphenols
Total C	0.72 (0.01)	0.44 (0.18)	0.31 (0.35)	0.77 (<0.01)	−0.02 (0.95)
Soluble C	-	0.90 (<0.01)	0.66 (0.03)	0.80 (<0.01)	0.49 (0.13)
Total N	-	-	0.67 (0.03)	0.60 (0.05)	0.53 (0.09)
Soluble N	-	-	-	0.75 (0.01)	0.49 (0.12)
Lignin	-	-	-	-	0.42 (0.20)

The soluble C content of residues correlated positively with total C and total N. The soluble N content was correlated with the total N and soluble C contents. The lignin content correlated positively with all other contents, except for polyphenols, which did not show significant correlation with any of the tested parameters.

3.2. Mineralization of C

At the start of incubation, *P. taeda* needles and *E. dunnii* leaves produced a significant smaller amount of CO_2 ($P < 0.05$) than *E. globulus* and *E. grandis* leaves (Figure 1). After day 119 a greater amount of CO_2 was produced by incubation of *E. globulus* leaves compared to the others, but this was not enough to
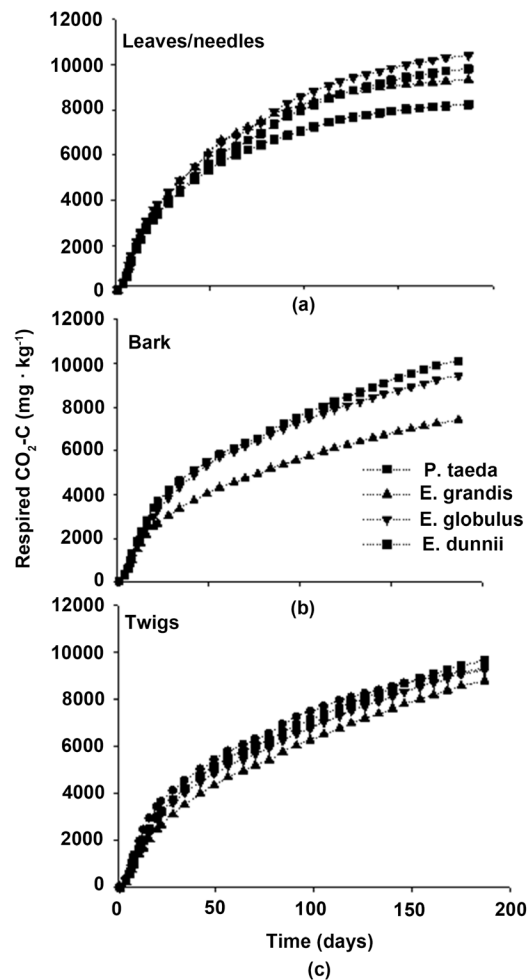
Figure 1. Mineralized C (C-CO$_2$) produced in soils with different residues (leaves, bark and twigs) from *P. taeda, E. grandis, E. globulus* and *E. dunnii.*

reverse the trend and the total amount generated by day 188 did not differ significantly from that generated by incubation of *E. dunnii* leaves ($P < 0.05$). From day 57 through the end of the incubation period, pine needles produced less CO$_2$ (8238 mg·kg^{-1} soil at end of incubation) than eucalyptus leaves (9322 mg·kg^{-1}, 9809 mg·kg^{-1} and 10410 mg·kg^{-1} for leaves of *E. grandis, E. dunnii* and *E. globulus*, respectively).

The total amount of CO$_2$ produced by decomposition of bark at incubation end was lower for *E. globulus* than for *E. grandis* and *E. dunnii* ($P < 0.05$), with no significant difference between the last two ($P < 0.05$). Significant differences were found at the start of incubation of twigs according to species, with *E. globulus* twigs producing the smallest amount of CO$_2$, but these differences tended to decrease and were not significant ($P < 0.05$) from incubation day 119.

The decomposition rate was also characterized as the proportion of the initial biomass C that remained in the residues. **Figure 2** shows the remaining C in the different residues as a percentage of initial C amounts. For each residue type
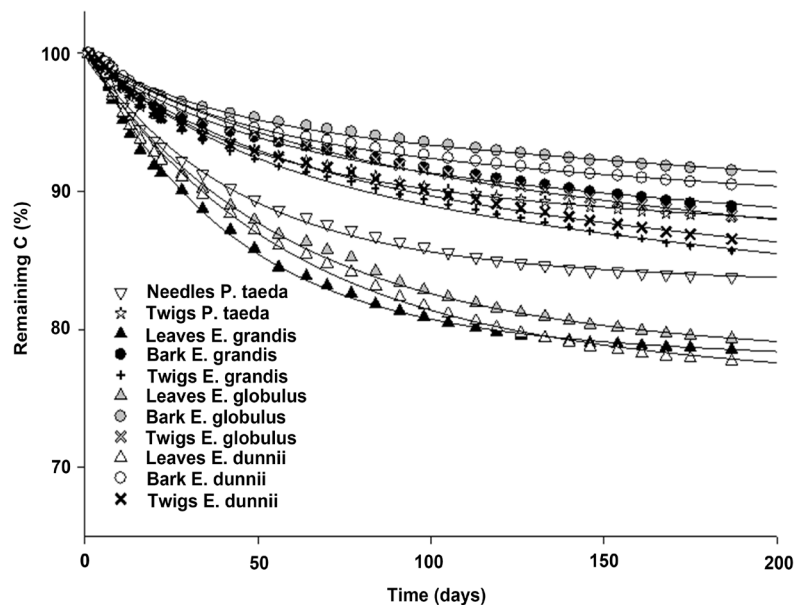
Figure 2. Remaining C in the different residue types as a percentage of initial C content for *P. taeda*, *E. grandis*, *E. globulus* and *E. dunnii*.

Eucalyptus residues were found to mineralize C at a higher rate than those of *Pinus*. The highest mineralization percentage at the end of incubation was found for *Eucalyptus* leaf residues (20%), followed by *P. taeda* needles (15%) and finally the woody residues (*ca.* 10%).

A large proportion of leaves was decomposed, especially in the initial stage, whereas bark had the lowest decomposition rate and twigs showed intermediate behaviour. Unlike leaves, woody residues showed a more steady decomposition pace, and no signs of reaching a plateau throughout the study.

The parameters of the decay model fitted for the proportion of mineralized C remaining in the different residue types was are presented in Table 3. *Eucalyptus* leaves showed lower w_r and higher w_d values than *Pinus* needles. The highest w_r and the lowest w_d were found for woody residues, which underwent decomposition in the smallest proportion.
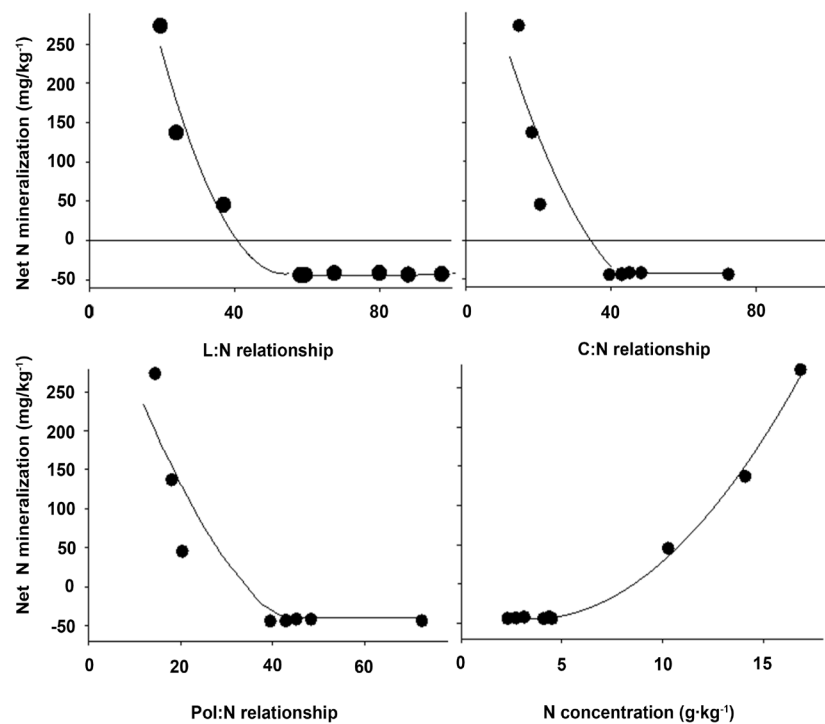
3.3. Relationship between the Chemical Characteristics of Residues and C Mineralization

The proportion of decomposed residue at the end of the incubation showed a negative linear relationship with the C:N and lignin:N ratios, and a positive linear relationship with the soluble C content of residues (Figure 3). The best fit ($R^2 = 0.74$) was found for the C:N ratio, followed by the lignin:N ratio, whereas the weakest relationship was found for the soluble C content. Using only eucalyptus residue for the regression analysis, the proportion of decomposing residue was found to correlate with the chemical characteristics of residues with R^2 values as high as 0.92 and 0.85 for C:N and lignin:N, respectively (data not shown).

Table 3. Parameters of the mineralization model fitted to decomposition data for *E. grandis, E. globulus, E. dunnii* and *P. taeda* residues.

Residue	[†] W_r	k_1	W_d	k_2	R^2
P. taeda needles	84.7	−0.0001	15.3	−0.0235	0.99
P. taeda twigs	90.4	−0.0001	9.5	−0.0228	0.99
E. grandis leaves	79.5	−0.0001	20.9	−0.0243	0.99
E. grandis bark	92.2	−0.0002	7.6	−0.0217	0.99
E. grandis twigs	90.2	−0.0003	9.6	−0.0210	0.99
E. globulus leaves	79.9	−0.0001	19.7	−0.0179	0.99
E. globulus bark	94.6	−0.0002	5.3	−0.0276	0.99
E. globulus twigs	91.7	−0.0002	9.0	−0.0159	0.99
E. dunnii leaves	78.8	−0.0001	21.2	−0.0181	0.99
E. dunnii bark	93.2	−0.0002	6.9	−0.0238	0.99
E. dunnii twigs	90.5	−0.0003	9.2	−0.0191	0.99

(†) w_r is the pool of slow mineralization C (%); w_d the pool of fast mineralization C (%); k_1 and k_2 are decomposition constants for t expressed as days.

Figure 3. Relationship between the chemical characteristics and decomposition percentage, C:N ratio, soluble C and lignin:N ratio for each residue type.

3.4. Mineralization and Immobilization of N during Decomposition of Harvest Residues

Figure 4 shows mineral N accumulated in soil incubated with the different residue types. Values in excess of that of the control treatment reflect net mineralization
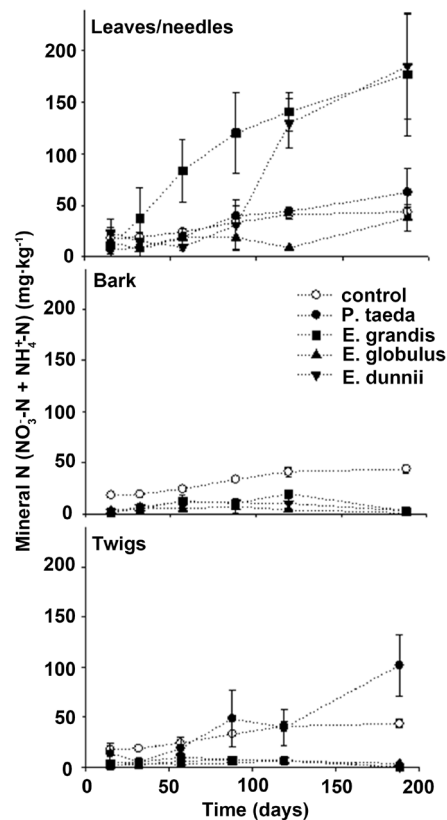
Figure 4. Mineral N (nitrate + ammonium) stored in soils by incubation with different types of *P. taeda*, *E. grandis*, *E. globulus* and *E. dunnii* residues, and the control treatment without residue.

of N, whereas those below show net immobilization. After 32 days' incubation, no statistically significant differences were found between residue types ($P < 0.05$). However, *E. grandis* leaves showed a clear tendency to release mineral N (18.4 mg·kg^{-1}) while the other residue types consistently led to net immobilization of N, with values below that of the control treatment. On day 57, *E. grandis* leaves had led to significant increases in the mineral N content of soil, compared with the other species and the control treatment, which did not differ among them. However, the soil with *E. dunnii* leaves increased N mineralization by the end of the period, when no significant differences were found between the soil mineral N after incubation of leaves of *E. grandis* and *E. dunnii* (176.9 mg·kg^{-1} and 185.5 mg·kg^{-1}, respectively). At lower values, *P. taeda* needles and *E. globulus* leaves led to mineral N contents which did not differ significantly at any sampling ($P < 0.05$), yet showed a consistent trend to net mineralization of N in soil with *P. taeda* needles and net immobilization of N after incubation of *E. globulus* leaves, by comparison with the control.

The content of mineral N in soil after incubation of *Eucalyptus* bark did not differ significantly between species ($P < 0.05$) at any time, but consistently reflected the net immobilization of mineral N, with values well below those of the control treatment.

No significant differences were found in mineral N content of soil with twigs at the start of incubation according to species ($P < 0.05$) or between any of the species and the control until 90 days' incubation. At the end of the incubation twigs of *P. taeda* led to net mineralization of N (48.6 mg·kg^{-1} compared with 33.4 mg·kg^{-1} of the control treatment), while Eucalyptus twigs did not show significantly different results ($P < 0.05$) at any time of incubation and consistently led to the immobilization of N.

3.5. Relationship between the Chemical Composition of Residues and N Mineralization or Immobilization

In this analysis only data obtained using residues of the Eucalyptus genus were included. A comparison of net mineralized N at the end of the incubation with the initial chemical composition of residues showed the good fit of a polynomial (quadratic-plateau) model (Figure 5). The C:N ratio, the lignin:N ratio, total N and the polyphenol:N ratio of residues at the start of incubation correlated highly with the net mineralization of N, the lowest fit corresponded to polyphenol:N. Increased C:N, lignin:N and polyphenol:N ratios were associated with the immobilization of N, whereas a higher total N content of the residues was associated with an increase in the net mineralization of N.

4. Discussion

4.1. Mineralization of C According to the Physical and Chemical Characteristics of Residues

Consistently with the data reported here, Zak et al. (1993) found that the amount of respired C depends on the tree species as well as on the type of residue. Unlike agricultural residues, the physical characteristics of forestry residues play an important role in decomposition processes. The decomposition of forestry residues is possibly limited by the incapacity of microorganisms to reach the substrate. This may mask the influence of the different chemical characteristics, especially in the case of woody residues.

The highest differences in C mineralization for the different types of residues were observed at the initial period when respiration rates of *Eucalyptus sp.* leaves, and in a lesser extent *Pinus* needles, more than double those of the woody fractions. Although differences are not great, the total C concentration was highest in leaves and needles, in line with data reported by Hernández et al. (2009) showing the highest C concentration in leaves and the lowest in bark of *E. dunnii*. But the total C concentration is unlikely to play any role in the susceptibility of the residues to decomposition, and is generally accepted that at the initial decomposition stages the respiration rates reflect the degradation of no structural C compounds, which integrate the soluble C fraction (Trinsoutrot et al., 2000; Girisha et al., 2003; Shammas et al., 2003). The comparison of the proportion of remaining C, shows that *E. globulus* leaves underwent decomposition to a lesser degree than leaves of *E. grandis* and *E. dunnii* and this could be
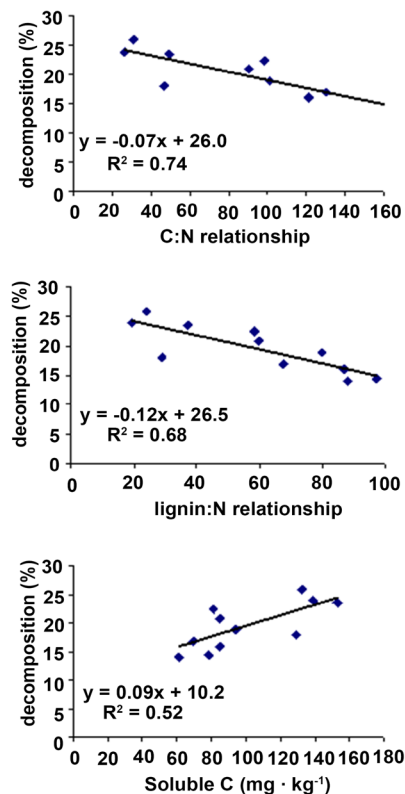
Figure 5. Relationship between the chemical characteristics (C:N ratio, lignin:N ratio, total N and polyphenol:N ratio) of residues and the amount of immobilized or mineralized N at the end of incubation.

related to the lower initial N content. A greater production of CO_2 found for *E. globulus* towards the end of the incubation period, compared in absolute terms with the other species, can be explained in terms of higher total and soluble C contents. Notably similar decomposition patterns were found for residues of *E. grandis* and *E. dunnii*. Earlier incubation studies using *E. grandis* residues under controlled conditions conducted in Brazil by Rezende et al. (2001) showed leaves to have a higher content of soluble organic C and a higher annual rate of decomposition (0.59 year half-life) than the other residues.

The high initial total and soluble C content of pine needles did not lead to a higher production of CO_2. The physical characteristics of needles are unfavourable for microbial attack, since their external waxy coating prevents the ingress of water, in particular at the start of the decomposition period (Woo et al., 2002), in addition to having a lower contact surface area. The positive effect of soluble substances on microbial activity is constrained by the availability of these substances to microorganisms, presumably restricted by the physical characteristics of needles and of *E. globulus* leaves (Canhoto & Graça, 1999). This would explain the apparent discrepancy between their high soluble C contents and lower decomposition rates, compared with leaves of *E. grandis* and *E. dunnii*.

A lower production of CO_2 by decomposition of *E. globulus* bark could be as-

cribed to physical characteristics (a thicker bark than for the other species of the genus) that are unfavourable for microbial attack (O'Connell et al., 2004). The exhaustion of soil N during the incubation of twigs and bark can decelerate the decomposition of these residues (Mary et al., 1996), explaining the lack of differences between species at the end of the decomposition period. Additionally the concentration of soluble C in woody residues was lower than in leaves of the different species, which also explains the low rate of mineralization.

The decomposition model used in this study provided a good fit in all cases (R^2: 0.99), showing that daily decomposition constants (k_1) in the case of W_r (pool of slowly mineralizing C) were greater for woody residues, where decomposition proceeded, though slowly, continuously throughout the period (Table 3). In contrast, the decomposition of leafy residues proceeded rapidly at an initial stage, when the pool of fast mineralizing C (W_d) was larger, and ceased towards the end of the period.

All the chemical characteristics studied had an influence on the decomposition of residues. The linear model showed a better fit for the C:N and lignin:N ratios than for the N, lignin, polyphenol and soluble C contents. In agreement with previous studies (Mary et al., 1996; Wagner & Wolf, 1999), we found a reduction in the proportion of decomposing matter with increasing C:N and lignin:N ratios. The lignin fraction—described as more resistant to degradation—increases in concentration over the decomposition process, while more soluble forms of C are released. However, our results do not confirm literature data reporting that increasing lignin and soluble polyphenol contents render these materials increasingly resistant to decomposition, reflected in a lower rate of decomposition (Lovett et al., 2004; Verkaik et al., 2006). Unlike those reports, in this work, *Eucalyptus* leaves, having the highest lignin and soluble polyphenol contents among the residues studied, showed the highest rate of decomposition. A high initial concentration of soluble polyphenols in eucalyptus leaves was reported earlier by Santos Costa, et al. (2005). Trinsoutrot et al. (2000) emphasize the need to include other than C:N ratios content in residue decomposition models, citing polyphenol content as one of the most influential factors in C and N transformations. In their work N was not a limiting factor, and therefore the decomposition rate was closely related to other biochemical properties, but the authors recognize that in N limited systems their effect would be lessened. According to the prevailing residue management in *Pinus* and *Eucalyptus* forests in Uruguay the harvest residues are likely to be decomposed on the soil surface, on the top of litter and other residue layers, which provide little contact with the soil. Therefore, without external N sources the decomposers' microbial population would develop in a slow pace, delaying the residue decomposition process.

4.2. Relationship between N Mineralization and Immobilization Behaviour and the Physical and Chemical Properties of Residues

A higher C:N ratio of *Pinus* needles and *E. globulus* leaves (47 and 49, respec-

tively), compared with leaves of *E. grandis* and *E. dunnii* (26 and 31, respectively), was consistent with the observed N mineralization behaviours of residues. It is generally accepted that the incorporation of residues with a C:N ratio of less than 20 results in net mineralization of N, whereas those with a C:N ratio greater than 20 lead to net immobilization (Wagner & Wolf, 1999). It is expected that the presence of soluble forms of organic N is an indication of N being readily available for microbial growth at the start of the decomposition period. In our experiment, however this parameter was not closely related to N release from the residues.

The chemical composition of twig and bark residues was such that the C:N ratio did not favour the release of N (Wagner & Wolf, 1999). No significant differences in the production of mineral N from bark of the different species were found in this study, presumably due to the similar initial chemical composition, with a notably low total N concentration in these fractions. *E. globulus* bark showed a clearer tendency to immobilize N than the other residues despite its lower decomposition rate. Nevertheless the N immobilization produced during decomposition of harvest residues can have a positive effect in terms of N economy, preventing mineralized N to be leached through the soil profile (Blumfield & Xu, 2003).

A greater amount of mineral N resulted from decomposition of *P. taeda* twigs, compared with twigs of *Eucalyptus*. This was unexpected, given the high C:N ratio of *P. taeda* twigs, and can be attributed to a lower content of soluble polyphenols of the former. The unfavourable effects of a high polyphenol content of residues on N mineralization were reported in previous work (Fierer et al., 2001). Residues rich in polyphenols have been reported to reduce the release of N (Palm et al., 2001) by the formation of complexes with N-containing ligands (Constantinides & Fownes, 1994).

According to previous studies (Constantinides & Fownes, 1994; Berg & McClaugherty, 2003), the lignin content of residues has an influence on decomposition and the amount of released N. In this study the lignin content of leaves was higher than that of woody residues; therefore no negative on N release was apparent. The lignin:N ratio of woody residues was less favourable for N mineralization and, like the C:N ratio, was associated with N immobilization. The lignin:N ratio was thus more important than the absolute lignin content, and confirms the importance of total N availability in this process.

The polynomial model used to describe the relationship between net N mineralization and the characteristics of eucalyptus residues allowed the good fit of all data. However, a quadratic-plateau model allowed a better fit of C:N ratio, lignin:N ratio and net N mineralization data. Using the latter model, the limit N content between mineralization and immobilization (7.9 g·kg⁻¹) was well below the value reported by other authors (*ca*. 17 g·kg⁻¹ reported by Frankenberger & Abdelmagid, 1985). It is worth noting that the net N mineralization values reported here were determined after 6 months of incubation. Of the residues studied, only leaves of *E. grandis* showed net N mineralization at an initial stage, and

its total N content was 16.9 g·kg^{-1}, a value consistent with reported data. An in situ decomposition study using five forestry species, Lovett et al. (2004) found a closer relationship between the C:N ratio and the amount of net N mineralization than between mineralized N and the concentrations of N, lignin, polyphenols and the respective ratios. However, in that study, a poor fit was found between the various content ratios and the amount of net N mineralization. This led these researchers to conclude that results cannot be predicted from the chemical composition of residues. However, the results reported here, in these N limited decomposition processes show that N content, or C:N ratio in the case of eucalyptus residues, can be used as predictors of the potential amount of net mineralization by decomposition of these residues, avoiding more complex analytical determinations required to determine the lignin:N or polyphenol:N ratios.

5. Conclusion

The decomposition patterns of eucalyptus residues were found to differ to a greater degree between different residue types of the same species than between the same residue in different species. The chemical composition of leaves clearly differed from that of the woody residue types (bark and twigs). These differences were reflected in distinct decomposition patterns found for leaves, showing a higher decomposition rate from the start of incubation, and a higher amount of mineral N released into soil. Overall, a lower rate of decomposition was found for residues of *E. globulus.*

The differences in decomposition rate cannot be ascribed to any of the individual chemical characteristics studied, but instead respond to their combined effects. The C:N and lignin:N ratios had a clear effect on the decomposition rate and the amount of net N mineralization. Leaves and needles, having the lowest C:N ratio and the highest content of soluble C, were the fastest-decomposing residue types. The total N content and the C:N ratio proved good indicators of the mineralization potential. The use of these parameters enables the preliminary assessment of expected changes in forested soil following harvest, avoiding the need to conduct complex tests entailed in the determination of the lignin:N and polyphenol:N ratios.

Acknowledgements

References

Anderson, J. P. E. (1982). Soil Respiration. In A. L. Page (Ed.), *Methods of Soil Analysis, Part 2,* (2nd Edition, pp. 837-887). Madison, WI: Soil Science Society of America.

Barrera, M. D., Frangi, J. L., Ferrando, J. J., & Goya, J. F. (2004). Descomposición del mantillo y liberación foliar neta de nutrientes de *Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizzarri en El Bolsón, Río Negro. *Ecología Austral, 14,* 99-112.

Berg, B., & McClaugherty, C. (2003). *Plant Litter: Decomposition, Humus Formation Carbon Sequestration* (p. 286). Germany: Springer. https://doi.org/10.1007/978-3-662-05349-2

Blumfield, T. J., & Xu, Z. H. (2003). Impact of Harvest Residues on Soil Mineral Nitrogen Dynamics Following Clearfall Harvesting of a Hoop Pine Plantation in Subtropical Australia. *Forest Ecology and Management, 179,* 55-67. https://doi.org/10.1016/S0378-1127(02)00485-1

Canhoto, C., & Graça, M. (1999). Leaf Barriers of Colonization and Shredders (*Tipula lateralis*) Consumption of Decomposing *Eucalyptus globulus*. *Microbial Ecology, 37,* 163-172. https://doi.org/10.1007/s002489900140

Constantinides, M., & Fownes, J. H. (1994). Nitrogen Mineralization from Leaves and Litter of Tropical Plants: Relationship to Nitrogen, Lignin and Soluble Polyphenol Concentrations. *Soil Biology and Biochemistry, 26,* 49-55. https://doi.org/10.1016/0038-0717(94)90194-5

Fierer, N., Schimel, J. P., Cates, R. G., & Zou, J. (2001). Influence of Balsam Poplar Tannin Fractions on Carbon and Nitrogen Dynamics in Alaskan Taiga Floodplain Soils. *Soil Biology and Biochemistry, 33,* 1827-1839. https://doi.org/10.1016/S0038-0717(01)00111-0

Frankenberger, W. T., & Abdelmagid, H. M. (1985). Kinetic Parameters of Nitrogen Mineralization Rates of Leguminous Crop Incorporated into Soil. *Plant and Soil, 87,* 257-271. https://doi.org/10.1007/BF02181865

Gama-Rodrigues, A. C., & Barros, N. F. (2002). Ciclagem de nutrientes em floresta natural e em plantios de eucalipto e de dandá no sudeste da Bahia, Brasil. *Revista Árvore, 26,* 193-207.

Girisha, G. K., Condron, L. M., Clinton, P. W., & Davis, M. R. (2003). Decomposition and Nutrient Dynamics of Green and Freshly Fallen Radiata Pine (*Pinus radiata*) Needles. *Forest Ecology and Management, 179,* 169-181. https://doi.org/10.1016/S0378-1127(02)00518-2

González, A., Hernández, J., & del Pino, A. (2016). Extracción y reciclaje de elementos nutritivos por cosecha de *Eucalyptus globulus* en Uruguay. *Bosque (Valdivia), 37,* 179-190. https://doi.org/10.4067/S0717-92002016000100017

Hernández, J., Del Pino, A., Salvo, L., & Arrarte, G. (2009). Nutrient Export and Harvest Residue Decomposition Patterns of a *Eucalyptus dunnii Maiden* Plantation in Temperate Climate of Uruguay. *Forest Ecology and Management, 258,* 92-99. https://doi.org/10.1016/j.foreco.2009.03.050

Kumaraswamy, S., Mendham, D. S., Grove, T. S., O'Connell, A. M., Sankaran, K. V., & Rance, S. J. (2014). Harvest Residue Effects on Soil Organic Matter, Nutrients and Microbial Biomass in Eucalypt Plantations in Kerala, India. *Forest Ecology and Management, 328,* 140-149. https://doi.org/10.1016/j.foreco.2014.05.021

Laclau, J. P., Levillain, J., Deleporte, P., de Dieu Nzila, J., Bouillet, J. P., Saint André, L., Versini, A., Mareschal, L., Nouvellon, Y., Thongo M'Bou, A., & Ranger, J. (2010). Organic Residue Mass at Planting Is an Excellent Predictor of Tree Growth in Eucalyptus Plantations Established on a Sandy Tropical Soil. *Forest Ecology and Management, 260,* 2148-2159. https://doi.org/10.1016/j.foreco.2010.09.007

Louzada, J. N. C., Schoereder, J. H., & De Marco Jr., P. (1997). Litter Decomposition in Semidecidous Forest and *Eucalyptus spp*. Crop in Brazil: A Comparison. *Forest Ecology and Management, 94,* 31-36. https://doi.org/10.1016/S0378-1127(96)03986-2

Lovett, G. M., Weathers, K. C., Arthur, M. A., & Schultz, J. C. (2004). Nitrogen Cycling in

a Northern Hardwood Forest: Do Species Matter? *Biogeochemistry, 67,* 289-308. https://doi.org/10.1023/B:BIOG.0000015786.65466.f5

Mary, B., Recous, S., Darwis, D., & Robin, D. (1996). Interactions between Decomposition of Plant Residues and Nitrogen Cycling in Soil. *Plant and Soil, 181,* 71-82. https://doi.org/10.1007/BF00011294

Mulvaney, R. L. (1996). Total Nitrogen, Nitrogen-Inorganic Forms. In D. L. Sparks (Ed.), *Methods of Soil Analysis. Part 3. Chemical Methods* (pp. 1123-1184). Madison, WI: Soil Science Society of America.

Mungai, N. W., & Motavalli, P. P. (2006). Litter Quality Effects on Soil Carbon and Nitrogen Dynamics in Temperate Alley Cropping Systems. *Applied Soil Ecology, 31,* 32-42. https://doi.org/10.1016/j.apsoil.2005.04.009

Nelson, D. W., & Sommers, L. E. (1996). Total Carbon, Organic Carbon, and Organic Matter. In D. L. Sparks (Ed.), *Methods of Soil Analysis. Part 3. Chemical Methods* (pp. 961-1010). Madison, WI: Soil Science Society of America.

O'Connell, A. M., Grove, T. S., Mendhan, D. S., Corbeels, M., McMurtrie, R. F., Shammas, K., & Rance, S. J. (2004). Impacts of Inter-Rotation Site Management on Nutrient Stores and Fluxes and Growth of Eucalypt Plantations in Southwestern Australia. In K. E. S. Nambiar, J. Ranger, A. Tiarks, & T. Toma (Eds.), *Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshop in Congo July 2001 and China February 2003* (pp. 77-91). Bogor: Center for International Forestry Research.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G., & Giller, K. E. (2001). Organic Inputs for Soil Fertility Management in Tropical Agroecosystems: Application of an Organic Resource Database. *Agriculture, Ecosystems and Environment, 83,* 27-42. https://doi.org/10.1016/S0167-8809(00)00267-X

Rezende, J. L. P., Garcia, Q. S., & Scotti, M. R. (2001). Laboratory Decomposition of *Dalbergia nigra All. ex Benth* and *Eucalyptus grandis W. Hill ex Maiden* Leaves in Forest and Eucalypt Plantation Soils. *Acta Botanica Brasilica, 15,* 305-312. https://doi.org/10.1590/S0102-33062001000300002

Rhine, E. D., Sims, G. H., Mulvaney, R. L., & Pratt, E. J. (1998). Improving the Berthelot Reaction for Determining Ammonium in Soil Extracts and Water. *Soil Science Society of America Journal, 62,* 473-480. https://doi.org/10.2136/sssaj1998.03615995006200020026x

Santos Costa, G., da Gama-Rodrigues, A. C., & de Melo Cunha, G. (2005). Decomposição e liberação de nutrientes da seraphilera foliar em povoamentos de *Eucalyptus grandis* no norte fluminense. *Revista Árvore, 29,* 563-570. https://doi.org/10.1590/S0100-67622005000400008

Schwanninger, M., & Hinterstoisser, B. (2002). Klason Lignin: Modifications to Improve the Precision of the Standardized Determination. *Holzforschung, 56,* 161-166. https://doi.org/10.1515/HF.2002.027

Shammas, K., O'Connell, A. M., Grove, T. S., McMurtrie, R., Damon, P., & Rance, S. J. (2003). Contribution of Decomposing Harvest Residues to Nutrient Cycling in a Second Rotation *Eucalyptus globulus* Plantation in South-Western Australia. *Biology and Fertility of Soils, 38,* 228-235. https://doi.org/10.1007/s00374-003-0654-x

Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of Total Phenolics with Phosphomolybdic-Phosphotungstic Acid Reagents. *Journal of Enology and Viticulture, 16,* 144-148.

Soil Survey Staff (2006). *Keys to Soil Taxonomy* (10th ed.). Washington DC: United States Department of Agriculture, Natural Resources Conservation Service.

Trinsoutrot, I., Recous, S., Bentz, B., Lineres, M., Cheneby, D., & Nicolardot, B. (2000). Biochemical Quality of Crop Residues and Carbon and Nitrogen Mineralization Kinetics under Nonlimiting Nitrogen Conditions. *Soil Science Society of America Journal, 64,* 918-926. https://doi.org/10.2136/sssaj2000.643918x

Verkaik, E., Jongkind, A. G., & Berendse, F. (2006). Short-Term and Long-Term Effects of Tannins on Nitrogen Mineralisation and Litter Decomposition in Kauri (*Agathis australis* (D. Don) Lindl.) Forests. *Plant and Soil, 287,* 337-345. https://doi.org/10.1007/s11104-006-9081-8

Wagner, G. H., & Wolf, D. C. (1999). Carbon Transformations and Soil Organic Matter Formation. In D. M. Sylvia, J. J. Fuhrmann, P. G. Hartel, & D. A. Zuberer (Eds.), *Principles and Applications of Soil Microbiology* (pp. 218-258). Upper Saddle River, NJ: Prentice Hall.

Woo, K. S., Fins, L., McDonald, G. I., Wenny, D. L., & Eramian, A. (2002). Effects of Nursery Environment on Needle Morphology of *Pinus monticola* Dougl. and Implications for Tree Improvement Programs. *New Forests, 24,* 113-129. https://doi.org/10.1023/A:1021230304530

Zak, D. R., Grigal, D. F., & Ohmann, L. F. (1993). Kinetics of Microbial Respiration and Nitrogen Mineralization in Great Lakes Forests. *Soil Science Society of America Journal, 57,* 1100-1106. https://doi.org/10.2136/sssaj1993.03615995005700040037x