NITROGEN BALANCE IN SOIL UNDER EUCALYPTUS PLANTATIONS[1]

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SUMARY

An understanding of the role of organic nitrogen (N) pools in the N supply of eucalyptus plantations is essential for the development of strategies that maximize the efficient use of N for this crop. This study aimed to evaluate the distribution of organic N pools in different compartments of the soil-plant system and their contributions to the N supply in eucalyptus plantations at different ages (1, 3, 5, and 13 years). Three models were used to estimate the contributions of organic pools: Model I considered N pools contained in the litterfall, N pools in the soil microbial biomass and available soil N (mineral N); Model II considered the N pools in the soil, potentially mineralizable N and the export of N through wood harvesting; and Model III (N balance) was defined as the difference between the initial soil N pool (0-10 cm) and the export of N, taking the application of N fertilizer into account. Model I showed that N pools could supply 27 - 70 % of the N demands of eucalyptus trees at different ages. Model II suggested that the soil N pool may be sufficient for 4 - 5 rotations of 5 years. According to the N balance, these N pools would be sufficient to meet the N demands of eucalyptus for more than 15 rotations of 5 years. The organic pools contribute with different levels of N and together are sufficient to meet the N demands of eucalyptus for several rotations.

Index terms: microbial biomass N, potentially mineralizable N, microbial cycling.

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RESUMO: *BALANÇO DE N EM SOLOS SOB PLANTAÇÕES DE EUCALIPTO*

O entendimento da participação de reservas orgânicas de N no suprimento de plantações de eucalipto é fundamental para o desenvolvimento de estratégias que maximizem a eficiência no uso de N por essa cultura. O objetivo deste trabalho foi avaliar a distribuição de reservas orgânicas de N em diferentes compartimentos no sistema solo-planta e a contribuição desses compartimentos no suprimento de N em plantações de eucalipto em diferentes idades de cultivo (1, 3, 5 e 13 anos). Para estimar a contribuição das reservas orgânicas, foram empregados três modelos: o modelo I considerou os estoques do N contido na serapilheira e na biomassa microbiana do solo e o N disponível no solo (N mineral); o modelo II considerou os estoques de N no solo, o N potencialmente mineralizável e a exportação de N na colheita da madeira; e o modelo III (balanço de N) foi definido pela diferença entre o estoque inicial de N no solo (0-10 cm) e a exportação de N, somada a uma aplicação de fertilizante nitrogenado. O modelo I mostrou que as reservas de N poderiam suprir de 27 a 70 % da demanda de N pelo eucalipto entre as idades. O modelo II mostrou que o estoque de N no solo pode ser suficiente para quatro a cinco rotações de cinco anos. Pelo balanço de N, o estoque de N seria suficiente para suprir a demanda desse nutriente pelo eucalipto por mais de 15 rotações de cinco anos. As reservas orgânicas contribuem para o fornecimento de N em diferentes magnitudes e, em conjunto, são suficientes para atender à demanda de N pelo eucalipto por várias rotações de cultivo.

Termos de indexação: N da biomassa microbiana, N potencialmente mineralizável, ciclagem microbiana.

INTRODUCTION

In Brazil, the high demand for forest products has led to a progressive increase in planted forests, which currently occupy an area of 6.5 million hectares. Among the species planted, eucalyptus is the most widely grown, occupying approximately 4.26 million hectares, an area corresponding to 66 % of the planted forest in the country (SBS, 2009).

Mineral fertilization promotes substantial productivity gains in most eucalyptus forests (Barros & Novais, 1990; Gonçalves et al., 1997; Barros et al., 2000), constituting a fundamental step for the establishment and development of trees as well as the maintenance of yields over subsequent rotations. However, in Brazil, the N fertilization of these plantations is usually based on generalized NPK formulations, regardless of the actual amount of N that should be applied. This situation arises partially from the inability to predict the actual N contribution of the soil (Pulito, 2009).

Gonçalves et al. (1996) recommended that the N fertilization of eucalyptus plantations be based on three classes of soil organic matter (SOM) content. However, although SOM is the primary source of soil N, this type of recommendation does not consider the bioavailability of this nutrient. Bioavailability is regulated not only by the SOM quantity and quality but also by climate and edaphic factors and by forest management (Cantarella & Raij, 1986).

In this context, the efficient management of N fertilization in planted forests, e.g., eucalyptus plantations, requires the quantification of the various N input and output flows in the soil-plant system, and nutrient cycling and harvest export must be taken into consideration to plan the management appropriately. Litterfall deposition and subsequent release of N, which is incorporated into the plant residues via mineralization, is a key process in N cycling and an important N source for trees (Gonçalves, 1995; Camargo et al., 1999; Alfaia, 2006).

In areas newly forested with eucalyptus, the mineralization of organic N pools can meet the demand of trees throughout the crop cycle (O'Connell & Rance, 1999; Gonçalves et al., 2001; Gonçalves et al., 2008; Barreto et al., 2010). In these areas, approximately 75 % of N is contained in the harvest residues (Santana et al., 2008). Therefore, plant responses to N fertilizers are often small or even negligible (Barros et al., 1990; Hebert & Schönau, 1989; Gonçalves et al., 1997).

The N-mineralization process is mediated by soil microbial biomass (MB), which controls N availability through the balance of immobilization-mineralization processes (Vargas & Scholles, 1998; Gama-Rodriguez et al., 2005). Thus, the MB is an active and potentially mineralizable compartment of soil N (Bonde et al., 1988; Gama-Rodrigues et al., 2005) and plays a key role in the availability of this element. Recent studies suggest that the cycling of N stored in the MB can supply eucalyptus with a considerable amount of N (Gama-Rodriguez et al., 2005; Barreto et al., 2008) since the cycling of this compartment is faster than of the other SOM fractions (Smith & Paul, 1990).

Estimates of the amount of inorganic N that can be released into the soil due to mineralization and the amount of mineral N that can be made available from MB through microbial cycling, along with estimates of the N quantities stored in the soil, in the litterfall and in the biomass of eucalyptus plantations, are essential to define the N balance in these ecosystems. Such estimates can improve the understanding of N dynamics and support the development of strategies to maximize the efficiency of N use by eucalyptus plantations.

This study was designed to assess the distribution of organic N pools in different compartments of the soil-plant system by three models and estimate the contributions of these compartments to the N supply of eucalyptus plantations at different ages (1, 3, 5 and 13 years).

MATERIAL AND METHODS

Study areas

The study was conducted in several commercial eucalyptus plantations located in Aracruz, in the coastal region of Espirito Santo (19° 50' S, 40º 03' W). The regional terrain is flat, the soil medium-textured, classified as dystrophic Yellow Argisolic (Embrapa, 2006), and the climate humid tropical (Aw), according to Köppen's classification, with an average annual temperature of 23°C and pluvial precipitation of 1,400 mm.

Eucalyptus plantations were selected based on age and crop rotation, covering an age sequence (1, 3, 5 and 13 years) using the reform system. The plant material (clone 1501, *"Urograndis"*), spacing (3 x 3 m) and soil class and texture were the same in all plantations. The history of tillage and fertilization used in the eucalyptus plantations, as well as the soil chemical properties, were described by Barreto et al. (2008).

Collection and analysis of plant biomass

Plant material was sampled in November 2003. At each plantation age, four plots (18 x 18 m, with 36 trees spaced 3 x 3 m) were established. On each plot, a tree with an average diameter at breast height (DBH = 4, 12, 15 and 20 cm in the plantations of 1, 3, 5 and 13 years, respectively) was selected, and litterfall was collected from a 3 x 3 m area around this tree. Subsequently, the selected trees were cut and harvested to quantify aboveground biomass (leaves, branches, bark, and wood).

The plant biomass (dry matter) of the tree components was determined based on biomass samples of leaves, branches, bark and wood (approximately 1 kg of each component) that were oven-dried to constant weight at 60 ºC (Embrapa, 1999). The dried samples were chopped and subjected to chemical analysis for the determination of N levels, using the Kjeldahl method as described by Bataglia et al. (1983).

Soil collection of soil and mineral N analysis

Soil samples were collected in November 2003. From the same plots used for collection of plant biomass, composite soil samples (composed of 20 single samples) were collected with a Dutch auger (0-10 cm). Undisturbed samples were also collected with volumetric rings for determination of soil density.

For mineral N extraction a 50 g soil sample was mixed with an equal amount of washed and sieved sand, and the mixture placed in percolation columns (PVC tubes, diameter 4 cm x height 30 cm). Glass wool plugs had been placed at the bottom of each percolator. Mineral N was extracted by percolating 100 mL of 0.01 mol L^{-1} $CaCl_2$ (extraction solution), applied in 20 mL fractions, through the samples in the percolation tubes.

Soil N mineral ($N\text{-}NH_4^+ + N\text{-}NO_3^-$) was determined using 20 mL of the percolate filtered through a fine paper filter to remove particulate matter. The $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ contents were evaluated by colorimetry in a continuous flow system (FIA) (Giné et al., 1980; Alves et al., 1993).

Microbial biomass and N mineralization

The data for microbial biomass N and N mineralization were obtained from Barreto et al. (2008) and Barreto et al. (2010), respectively, from data compiled from the same study areas as those analyzed in this study. Barreto et al. (2008) used the fumigation-extraction method to estimate soil microbial biomass N (Joergensen & Brookes, 1990). Barreto et al. (2010) adopted the laboratory aerobic incubation technique, proposed by Stanford & Smith (1972), to determine the soil N mineralization potential (N_o).

N pools in the soil

Nitrogen pools in the soils were calculated by the following expression:

$$N_S = (Nt * Ds * Th) \quad (1)$$

where N_S represents soil N pool (kg ha^{-1}); Nt, the total content of N in the soil (g kg^{-1}), from Barreto et al. (2008); Ds, soil density (kg dm^{-3}); and Th, the thickness of the analyzed layer (0-10 cm). The soils had densities of 1.27; 1.34; 1.41 and 1.44 kg dm^{-3} in the 1, 3, 5 and 13-year-old plantations, respectively.

Contribution of organic N pools

To estimate the contributions of organic pools to the N supply in eucalyptus plantations, three models (*Model I, Model II* and *N balance*) were used:

Model I

This model was applied to all plantations studied. N pools contained in the litterfall, N pools in the soil microbial biomass and mineral N in the 0-10 cm layer were considered. To calculate the contribution of N pools (NP%) present in these compartments to the N supply, it was necessary to estimate the microbial cycling, the N flow of the microbial biomass, N supply N from litterfall and N demand by eucalyptus trees at different ages. Thus, in this model, the prediction of the pools and their contributions were assessed by the following expressions (2 to 6):

$$MC = NMB/(N_{LF\ year} + 43\ \%\ \text{of}\ N_{abs}) \quad (2)$$

$$\text{Flow NMB} = NMB/CM \quad (3)$$

$$N_{supplied\ litterfall} = N_{LF\ accumulated} * 0.4 \quad (4)$$

$$NR = \text{NMB Flow N} + N_{supplied\ litterfall} + \text{Mineral N} \quad (5)$$

$$\%\ RN = RN * 100/ND \quad (6)$$

where MC is the microbial cycling in years; NMB is the N content of soil microbial biomass (kg ha^{-1}); $N_{LF\ year}$ represents N input in the soil through plant residues left on the surface, corresponding to the average increase of N in the accumulated litterfall of the plantations per year (20 kg ha^{-1} year^{-1}); N_{abs} is the amount of N absorbed by eucalyptus (N accumulated in the aboveground biomass of trees per year) (kg ha^{-1}); NMB Flow is the N flow of soil microbial biomass (kg ha^{-1} year^{-1}); $N_{supplied\ litterfall}$ is N supplied by litterfall (kg ha^{-1}), assuming a 40 % decomposition rate; $N_{LF cumulative}$ is the amount of N contained in the litterfall (kg ha^{-1}); NR is the N pool in the compartments analyzed by Model I (kg ha^{-1}); % NR is the NR contribution for the N demand by trees among the ages or up to the age assessed; and ND is the N demand of eucalyptus trees (kg ha^{-1}). The formula used (2) was proposed by Smith & Paul (1990).

The 40 % decomposition rate used for the calculation of $N_{supplied\ litterfall}$ represents the arithmetic average of the following different decomposition rates found in the literature for eucalyptus: Ferreira (1984), in *Eucalyptus grandis* in approximately 6-year-old plantations (50 %); Gama-Rodrigues & Barros (2002), in *Eucalyptus grandis/E. urophylla* in 16-year-old plantations (40 %); and Costa et al. (2005), in *Eucalyptus grandis* in 2, 5 and 8-year-old plantations (30 %). Several studies indicate that the decomposition rates of eucalyptus forests are typically below 50 % throughout the year under a number of different management practices and edaphoclimatic conditions (Adams & Attiwill, 1986; Louzada et al., 1997; Gama-Rodrigues & Barros, 2002; Costa et al., 2005).

The demand for N was estimated for 1 year and for age intervals, considering the amount of N absorbed by the crop and the N contained in the litterfall at each age, as proposed by Gama-Rodrigues (1997), according to the following expressions:

$$ND = N_{LF1} + N_{PB1} \quad (7)$$

$$ND_{1\text{-}3} = (N_{LF3} - N_{LF1}) + (N_{PB3} - N_{PB1}) \quad (8)$$

$$ND_{3\text{-}5} = (N_{LF5} - N_{LF3}) + (N_{PB5} - N_{PB3}) \quad (9)$$

$$ND_{5\text{-}13} = (N_{LF13} - N_{LF5}) + (N_{PB13} - N_{PB5}) \quad (10)$$

where ND is the N demand (ND_1 = ND up to 1 year of age, $ND_{1\text{-}3}$ = ND between the ages of 1 and 3 years, $ND_{3\text{-}5}$ = ND between 3 and 5 years, $ND_{5\text{-}13}$ = between 5 and 13 years); N_{LF1}, N_{LF3}, N_{LF5} and N_{LF13} are the amounts of N contained in the accumulated litterfall of the 1, 3, 5 and 13-year-old plantations, respectively; N_{PB1}, N_{PB3}, N_{PB5} and N_{PB13} are the amounts of N contained in the aboveground plant biomass of the 1, 3, 5 and 13-year-old plantations, respectively.

The participation of N Flow supplied by the soil microbial biomass in the flow of potentially mineralized N in the soil was calculated, considering an estimate of mineralized N per year (kg ha^{-1} year^{-1}), using the following equation:

$$\%\ \text{Flow NMB} = (\text{NMB Flow}*100)/N_o \quad (11)$$

Model II

This model considered the total N, the potentially mineralizable N (N_o) (0-10 cm depth) and the export of N due to wood harvesting. The model estimated the duration (in number of crop rotations) of the soil N pools. This model was applied only to plantations of 5 and 13 years of age, here considered as cutting age (crop rotation). For this purpose, N_o was considered an estimate of mineralized N per year. Moreover, it was assumed that the N values stored in the tree wood (Table 1) corresponded to the amount of N exported. In this model, the prediction of N supplied

Table 1. Above-ground biomass and N content from different compartments of eucalyptus in an age sequence

Component	Age (years)			
	1	3	5	13
	Above-ground biomass (Mg ha^{-1})			
Bark	0.4d[1]	8.0c	13.4b	24.8a
Leaves	2.5a	2.6a	2.1ab	1.84b
Branches	2.3b	3.2b	2.6b	8.9a
Wood	2.1d	38.5c	85.2b	252.8a
Litter [2]	1.6d	3.8c	15.3b	22.9a
Total	8.8	56.1	118.6	311.2
	N content (kg ha^{-1})			
Bark	1.6d	30.2c	55.1b	99.8a
Leaves	50.2b	66.0a	41.7c	35.5c
Branches	11.9b	15.8b	12.6b	44.3a
Wood	5.0d	67.5c	110.7b	309.7a
Litter [2]	20.3d	33.9c	102.0b	224.0a
Total	89.0	213.4	322.1	713.3

[1] Means followed by the same letter in a row do not differ by Duncan test at 5 %; [2] Data from Barreto et al. (2008).

by the mineralization process over a number of rotations (Nr) for the eucalyptus plantations was based on Gonçalves et al. (2000, 2001) and Barreto et al. (2010), according to the expressions (12) and (13):

$$Nr = Nt/(Q + N_{ex}) \quad (12)$$

$$Q = N_o * r \quad (13)$$

where Nr is the duration of the soil N pools in number of rotations; Nt is the total soil N pools in the 0-10 cm layer (kg ha^{-1}); Q is the amount of N mineralized per rotation (kg ha^{-1}); N_x is the amount of N exported by cutting (via debarked wood) at the end of each rotation (kg ha^{-1}); N_o is the potentially mineralizable N in the 0-10 cm layer (kg ha^{-1} year^{-1}); and *r* is the crop rotation in years.

N balance

The N balance (NB) was defined as the difference between the initial soil N pools (0-10 cm) (N_S) and the export of N (N_{ex}), with an application of N fertilizer (F = 40 kg ha^{-1}), with a 50 % use efficiency rate (Gonçalves et al., 2001) was also taken into account. From this result, the predicted duration of the NB pools in number of rotations (Nr_{BN}) was obtained through the relationship between NB and the N demand for the rotation considered (NDr). This model was also applied to plantations of 5 to 13 years of age only, using the expressions (14) and (15):

$$NB = (N_s - N_{ex}) + F \quad (14)$$

$$Nr_{NB} = NB/NDr \quad (15)$$

Statistical analysis

The data on the amount of plant biomass and N pools were analyzed using a completely randomized design with four replications. A 5 % F test was adopted. As a complement, the Duncan test was used to compare means at 5 % probability. A Pearson correlation (5 %) was established between the NMB data of Barreto et al. (2008), and the N_o data from Barreto et al. (2010).

RESULTS AND DISCUSSION

Plant biomass and N pool

The amounts of plant biomass and N content accumulated in the different components of the aboveground parts of eucalyptus trees from each plantation are presented in table 1. N accumulation in these trees reflected the pattern of plant biomass accumulation, highlighting the close relationship between N absorption and biomass production (Poggiani et al., 1983; Poggiani, 1985; Reis et al., 1987; Santana et al., 1999; Gonçalves et al., 2000).

There was a reduction in the N content per unit biomass with increasing age. Furthermore, there was a decrease in the N leaf content of three and more year-old trees (Table 1), demonstrating the intensification of biochemical cycling and increase in N use efficiency for eucalyptus production with increasing age. As the tree matures, an increasingly significant proportion of N demand is supplied by the biochemical cycle (Attiwill, 1980), and this is one of the main factors influencing the efficiency of nutrient use by eucalyptus as age increases (Reis & Barros, 1990; Ladeira, 1999).

One-year-old Eucalyptus

To achieve a total biomass production of 8.8 Mg ha^{-1} (aboveground parts + litterfall) up to 1 year of age, eucalyptus showed an N demand of 89 kg ha^{-1}. At this age, the leaves and accumulated litterfall were equivalent to 4 mg ha^{-1}, corresponding to more than 40 % of the total biomass (Table 1). These components contain 79 % of the N pools of the total biomass, representing the most important pathway of the biogeochemical cycle (Caldeira et al., 1999) and highlighting the important role of N return through litterfall deposition, decomposition and nutrient release for reabsorption by plant roots. The importance of this cycle has been demonstrated in forests growing on low fertility soils (Schumacher et al., 2003).

Three-year-old Eucalyptus

At this age, the eucalyptus plant biomass increased by 47 mg ha^{-1} compared to the one year old plantation, with an increase of N of 128 kg ha^{-1} (Table 1). Of the total aboveground biomass, 68 % is found in the wood (38.5 mg h^{-1}); however, 47 % of N pool is distributed in the leaves (31 %) and litterfall (16 %) (Table 1). The N content of the litterfall is equivalent to 51 % of the N content in the leaves, which indicates that 49 % of the N was retranslocated before senescence. In addition, the apparent decrease in the annual N demand up to this age suggests an increase in biochemical cycling and, consequently, N efficiency use by eucalyptus trees.

Five-year-old Eucalyptus

The leaves, branches, bark and litterfall components totaled to 33.4 mg ha^{-1}, corresponding to 28 % of the total biomass. These components, recycled via organic matter decomposition, contain 67 % of the N pool of the total biomass. This result is in agreement with findings of Gonçalves (1995), who showed that in *Eucalyptus grandis* plantations in the State of São Paulo, on average age between 5 and 6 years old, these components contained 69.5 % of the N of the aboveground biomass. Bark and litterfall contained nearly 50 % of the pools of this nutrient. This finding shows the importance of adopting a management system that involves the return of harvest residues to minimize decreases in soil organic matter and, in turn, of N content. Cutting eucalyptus after 5 years and removing the wood would cause result in an N export of approximately 111 kg ha^{-1} from the site, corresponding to 34 % of the N pools in the aboveground forest biomass.

Compared to the age of 3 years, 5-year-old eucalyptus trees needed only 106 kg ha^{-1} N (Table 1), demonstrating increased N use efficiency due to intensification of the internal cycling process (biochemistry). This result was corroborated by the N leaf contents of each plantation (Table 1), which decreased from the levels of the 3-year-old plantations.

Thirteen-year-old Eucalyptus

The total leaves, branches, bark and litterfall components was 58.4 mg ha^{-1}, 19 % of the total biomass. These components contained 56 % of the aboveground N pool, of which 45 % was contained in the bark and litterfall. At the age of 13 years, eucalyptus trees are is in a more advanced maturity stage, and much of the absorbed N is derived from the decomposition of forest residues accumulated on the soil (Poggiani, 1985). At this age, the plant biomass of the trees had increased by 193 mg ha^{-1} compared to the age of 5 years, requiring an additional 391.2 kg ha^{-1} N (Table 1).

Microbial biomass N *vs.* potentially mineralizable N

There was a significant positive correlation of the potentially mineralizable soil N (N_0) with the N content of the soil microbial biomass (NMB) at different ages ($r = 0.9547$, $p < 0.05$) (Table 2), which highlights the important role of the microbial component in the control of N availability through immobilization and mineralization processes (Vargas & Scholles, 1998).

It is possible that the differences of N content in N_0 and NMB among the different age groups were related to the growth stages of the plantations. The values of N_0 and NMB increased from the age of 1 to 3 years, then decreased until 5 years and increased again until 13 years (Table 2). In the first year of crop rotation, during crown formation, N demand is very high, and soil N pools consequently decrease (Silva, 1999; Gonçalves et al., 2000). Between 2 to 3 years of age, the increments of N and biomass decrease (Gonçalves et al., 1997), and the amount of mineralized soil N is usually high, especially when the harvest residues are left in the field (Smethurst & Nambiar, 1995), explaining the increase in potentially mineralizable N in plantations from 1 to 3 years of age (Table 2). Moreover, according to Miller (1995), when the canopy closes, approximately 2/3 of the nutritional demands of the plantation can be covered by nutrient redistribution (biogeochemical cycle), thereby decreasing the pressure on soil N pools. The decrease of N content in leaves of three and more year-old seedlings (Table 1) corroborates this information.

As the trees grow older, their N demand increases, and N mineralization becomes a limiting factor, as the entire amount of mineralized N is used by the system (Fölster & Khana, 1997). Thus, the reduction of potentially mineralizable N at the age of 5 years (Table 2) must be related with increased N demand, while the increase of N_0 after this age (Table 2) may be associated with larger increments of plant residues to the litterfall. These residues provided substantial increases in the amount of substrate for the activity of microorganisms, increasing the N mineralization potential of 13-year-old trees.

Proportions of 1.0; 1.1; 1.2 and 0.9 were obtained for plantations at the ages of 1, 3, 13 and 5 years,

Table 2. Nitrogen pools and microbial nitrogen turnover in the 0-10 cm layer and N demand for eucalyptus in an age sequence

Nitrogen pool	Age (years)			
	1	3	5	13
N_s (0-10 cm) (kg ha^{-1})$^{(1)}$	1890.2	2698.0	2538.0	2592.1
Soil mineral N (kg ha^{-1})	26.4	31.7	28.8	34.7
N_0 (0-10 cm) (kg ha^{-1} year^{-1}) $^{(2)}$	98.0	127.4	81.6	109.6
Nm (kg ha^{-1}) $^{(2)}$	74.7	93.8	68.3	81.9
NMB (0-10 cm) (kg ha^{-1}) $^{(1)}$	76.2	105.5	61.8	101.1
Microbial cycling (MC) (years)	1.5	2.4	1.7	2.9
Soil microbial biomass flux (kg ha^{-}1/years)	49.5	44.6	36.3	35.1
NMB contribution to the flow of mineral N (%)	50.6	35.0	44.4	32.0
N demand of eucalyptus trees (kg ha^{-1}) $^{(3)}$	89.0	127.8	105.5	391.2
Total N demand of eucalyptus trees (kg ha^{-1}) $^{(4)}$	89.0	216.8	322.3	713.3

Ns: N stock; No: Potentially mineralizable; N; Nm: mineralized N; NMB: N microbial biomass.

respectively, for the ratio of NMB contents by the amounts of mineralized N (Nm) (Table 2) (NMB:Nm ratio). The microbial biomass can function as a catalyst, a source and/or a drain of nutrients (Paul & Clark, 1989; Wardle, 1992). When acting as a drain, the amount of nutrients supplied via mineralization is less than that entering the system. As a source, the nutrient amount released is greater than that entering the system, and as a catalyst, the input and output amounts are equal (Gama-Rodrigues, 1999). Thus, based on the NMB:Nm ratio, the microbial biomass at the age of 1 year would be acting as a catalyst (NMB:Nm = 1), at the ages of 3 and 13 years as a drain (NMB:Nm > 1) and at the age of 5 years as a source (NMB:Nm < 1). These results demonstrate the dynamic role of MB in the potential supply of N throughout the growth cycle of the eucalyptus crop. Gama-Rodrigues et al. (1997) observed an inverse correlation of soil N microbial biomass with mineral N in a Red-Yellow Latosol under different forest covers, showing that in eucalyptus and pine plantations without N fertilization, the soil microbial biomass, in addition to being a catalyst, would also act as an N drain.

Microbial cycling

The values of microbial N cycling in soils under eucalyptus plantations ranged from 1.5 to 2.9 years, and the N flow supplied by the microbial biomass was between 35 and 50 kg ha^{-1} year^{-1} (Table 2). At different eucalyptus forest sites, Gama-Rodrigues (1997) observed microbial cycling from 0.54 to 1.36 years and N flows of microbial biomass from 40 to 98 kg ha^{-1} year^{-1}.

Contribution of N pools

Model I

One-year-old Eucalyptus

As the litterfall can provide 8 kg ha^{-1} N, N flow generated by the microbial biomass corresponds to 50 kg ha^{-1} year^{-1} in the 0-10 cm soil layer and the soil has a mineral N pool of 26 kg ha^{-1} (Table 2), eucalyptus at the age of 1 year would contain a total N pool of 84 kg ha^{-1}. These N pools would be sufficient to meet approximately 66 % of the N demand of eucalyptus from the age of 1 until 3 years (Table 2).

Based on the potentially mineralizable N in the soil at 1 year of age, the N flow supplied by the microbial biomass contributed with approximately 50 % of the flow of soil mineralized N (Table 2). This result is in agreement with that reported by Bonde et al. (1988), who observed that 55-89 % of mineralized N was derived from microbial biomass in soils cultivated with annual crops (cereals), which highlights the significant participation of this soil compartment in N supply.

Three-year-old Eucalyptus

At the age of 3 years, the litterfall and the soil can provide 14 to 32 kg ha^{-1} of mineral N, respectively, and the microbial biomass can provide an N flow of 45 kg ha^{-1} year^{-1}. Considering these compartments, the soil N pool would be sufficient to meet all N demands of eucalyptus from 3 up to 5 years, and the N flow supplied by the soil microbial biomass would be responsible for 70 % of the supply of this element for eucalyptus until the age of 5 years (Table 2).

The N flow generated by the microbial compartment represents 35 % of the flow of soil mineralized N, based on the potentially mineralizable N of the soil under the age of 3 years.

Five-year-old Eucalyptus

At the age of 5 years, the litterfall can provide 41 kg ha^{-1} N, the soil can provide 29 kg ha^{-1} of mineral N and the microbial biomass can provide an N flow of 36 kg N ha^{-1} year^{-1}. These compartments would be sufficient to meet approximately 27 % of the N demand of eucalyptus from 5 to 13 years of age (Table 2). The flow of microbial N accounted for 44 % of the flow of mineralized N in the soil, based on the potentially mineralizable N of the soil under the age of 5 years.

If a crop rotation of 5 years (cutting age) is assumed, the N requirement of eucalyptus trees for a yield of 103 mg ha^{-1} would be 322 kg ha^{-1} N, and the N export in the debarked wood would be 111 kg ha^{-1} rotation of N. Considering the N accumulated in the litterfall until this age (Table 1) and in the post-harvest residues left on the field, the amount of N released (decomposition rate 40 %) would correspond to 125 kg ha^{-1}. Considering that the microbial biomass also contributed with an N flow of 36 kg ha^{-1} and that the soil has a mineral N pool of 29 kg ha^{-1}, these N compartments should be sufficient to meet more than 50 % of the N demand of the following crop rotation (5 years).

Thirteen-year-old Eucalyptus

Considering the N flow of soil microbial biomass of 13-year-old trees (35 kg ha^{-1} year^{-1}) and the 90 kg ha^{-1} N released from the litterfall, the N supply made available by only these two compartments would be approximately 125 kg h^{-1} of N, representing 40 % of the amount of N export in debarked wood (Table 2). Based on the potentially mineralizable N of the soil under 13-year-old trees, the N flow supplied by the microbial biomass would contribute with 32 % of mineralized N in the soil.

Model II

Five-year-old Eucalyptus

Taking into consideration the initial soil N pools, the N demand of eucalyptus until the age of 5 years and the N export of 111 kg ha^{-1}/rotation (5 years), it was estimated that the N pools in the 0-10 cm soil layer would be sufficient for 4 to 5 eucalyptus rotations (Table 2).

Thirteen-year-old Eucalyptus

Assuming N export of 310 kg ha^{-1}/rotation, the N pools in the 0-10 cm soil layer were estimated to be sufficient for another 2 to 3 eucalyptus rotations (13 years).

N balance

Using the N balance based on 13 and 5 year-old-plantations, and leaving all forest residues on the soil, the harvest of debarked wood and the application of N fertilizer (40 kg ha^{-1} N, at 50 % use efficiency), it was estimated that the average soil (0-10 cm) N pool of 2,565 kg ha^{-1} was sufficient to meet the N demands of eucalyptus for more than 7 rotations of 13 years and over 15 rotations of 5 years.

The integrated analysis of different compartments of organic N pools appears to be an appropriate method to estimate N availability for the eucalyptus crop and can improve N fertilizer recommendations. Furthermore, the results indicate the relevant contributions of the microbial biomass to N supply because it is part of the potentially mineralizable soil N (Bonde et al., 1988; Gama-Rodrigues et al., 2005).

Future studies should analyze subsequent crop rotations, sampling larger volumes of soil (down to 1 m depth), to provide more detailed insights into the adequacy of the methodology used in this work; due to the high rates of N export (Barros et al., 1990; Poggiani, 1985; Reis et al., 1987; Gonçalves, 1995), there is a possibility of depletion of organic potentially mineralizable N. Research on this subject is still very scarce in other countries with forestry traditions, but particularly in Brazil (Serrano, 1997; Gonçalves et al., 2001; Pulito, 2009; Barreto et al., 2010).

CONCLUSIONS

1. The organic pools contribute to the N supply at different levels, and together they are sufficient to meet the N demands of eucalyptus for several crop rotations, especially in low fertility areas.

2. Among the organic pools, the microbial biomass flow can contribute with more than half of the potentially mineralizable soil N under eucalyptus cultivation.

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