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Nutrient release from decomposing *Eucalyptus* harvest residues following simulated management practices in multiple sites in Brazil

Gabriel W.D. Ferreira [a,*], Emanuelle M.B. Soares [a], Fernanda C.C. Oliveira [a], Ivo R. Silva [a], Jennifer A.J. Dungait [b], Ivan F. Souza [a], Leonardus Vergütz [a]

[a] Departamento de Solos, Universidade Federal de Viçosa, Av. PH Rolfs, s/n, Viçosa, MG CEP 36570-900, Brazil
[b] Sustainable Soil and Grassland Systems Department, Rothamsted Research, North Wyke, Okehampton, Devon EX20 SB, UK

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The potential export of nutrients by eucalypt plantations harvest raises concern about environmental and wood production sustainability. Keeping non-commercial components in the field can minimize it. However, little is known about changes in chemistry of decomposing eucalypt harvest residues. Simulated harvest residue management practices fully replicated across 11 Brazilian representative sites were undertaken to evaluate the dynamics of macronutrient release. We studied the influence of debarking in the field, the use of an external source of nitrogen and the placement of harvest residues (remained on the surface or incorporated into the soil). After the experiment set up, residues were sampled five times and contents of Ca, Mg, N, P, K and S were determined. We used the remaining mass and nutrient concentration to fit the single exponential decay model ($X = X_0e^{-kt}$) and calculate half-life ($hl = \ln(2)/k$) of each nutrient. At the end, we calculate element ratios to see differences in residue chemistry. The presence of bark and residue incorporation into soil enhanced decomposition and decreased nutrient half-life across all site. External N had little or no effect on nutrient dynamics. Site had significant effect on nutrient half-life, but only low correlations with climate or edaphic properties could be found. C:N, C:S and C:Ca ratios were much narrower at the end. On the other hand, N:P, N:K, Ca:S and Ca:Mg were wider. C:P varied among sites, but averaged almost the same as in the beginning. Ca was the nutrient that presented the greatest immobilization, particularly in the absence of bark, indicating a critical role of this element on decomposition under the conditions tested. Our results suggest that nutrient release is more controlled by management, chemical properties of the residues and specific decomposer community needs than climate or soil properties. Microbial community seems to change their carbon use efficiency and immobilize nutrients in limiting conditions.

1. Introduction

Eucalyptus plantations cover more than five million hectares in Brazil with expansion forecast (ABRAF, 2013). With an average productivity of 40 m^3 ha^{-1} yr^{-1}, eucalypt forest is the main source of wood production in the country, placing it among the world's largest pulp and sawn wood producers (Colodette et al., 2014). This high productivity was obtained through extensive research over the last 50 years, mainly in improvements of genetics and silviculture practices. Currently, some concerns have been raised about the sustainability of this high productivity in increasingly shorter rotations due to high nutrient export at harvesting, particularly because most of these forests are located in naturally poor soils.

A recent study has shown the depletion of soil Ca^{2+}, Mg^{2+} and K^+ under eucalypt plantations pointing toward the need of using a balanced nutrient budget that prevent soil nutrient exhaustion (Leite et al., 2010). This concern increases as fertilizer prices are likely to continue rising and the world reserves of nutrients, although still sufficient for a foreseeable future, are finite (Fixen and Johnston, 2012).

Sustainable management of fast-growing eucalypt plantations located on highly weathered soils relies on practices that maintain soil organic matter stocks (SOM). SOM is a key component of soil fertility in the tropics, retaining and supplying nutrients for plants, and is sustained mainly by litterfall and root turnover during rotations, and by harvest residues between rotations. Keeping harvest residues on field could have major impact on soil nutrient (Mendham et al., 2003) and SOM stocks (Epron et al., 2006) and sustain initial growth of eucalypt trees (Laclau et al., 2010a, 2010b; Versini et al., 2013).

* Corresponding author.
E-mail address: gabrielwdf@gmail.com (G.W.D. Ferreira).

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Average rotations in Brazilian commercial plantations yield around 30 t ha^{-1} of residues at harvesting (Gatto et al., 2010). Bark could account for more than a half of these and be a major source of nutrients for following rotations (Hernández et al., 2009; Laclau et al., 2000; Santana et al., 2008). To what extent residues will change soil properties depends on its decomposition rate. Both biotic and abiotic factors control on decomposition has been shown extensively in literature (Adair et al., 2008; Cusack et al., 2009; Gholz et al., 2000; Powers et al., 2009; Prescott, 2010; Silver and Miya, 2001), but little is known about the decomposition of more lignified woody residues (Bradford et al., 2014), particularly in eucalypt ecosystem. Climate is recognized as having a major control at regional scales, but it seems to fail if narrower ranges are evaluated (Bradford et al., 2014; Powers et al., 2009). Chemical changes during decomposition and its drivers also remain implicit, despite their critical role on carbon cycle (Grandy and Neff, 2008; Wickings et al., 2012). Furthermore, most of the studies addressed decomposition of different material separately, making any comparison difficult, as mixed materials should present different behavior and influence decomposer community, and hence highlight differences on decomposing materials (Blumfield et al., 2004; Hernández et al., 2009; Nzila et al., 2002; Vivanco and Austin, 2011; Wickings et al., 2012).

Increasing nitrogen addition to eucalypt forests aiming at higher productivity, or at least to balance soil N budget, has raised some questions about possible changes in litter dynamics and its mean residence time. Decomposition rate of plant materials is often addressed as a function of its nitrogen content and particularly C:N, N:P and lignin:N ratios. Eucalypt is known to efficiently cycle internal N and produce N-poor litter (Gama-Rodrigues and Barros, 2002; Laclau et al., 2010b). Therefore adding N could induce other changes than increasing productivity, but the influence of external N input on decomposition is largely debated and data are particularly scarce for tropical regions (Cusack et al., 2009; Hobbie, 2008; Moran et al., 2005). Moreover, the strong interaction of N with lignified compounds and tannins present in branches and bark residues requires more attention (Berg and Matzner, 1997; Knorr et al., 2005; Kraus et al., 2003).

Management practices that are common in planted forest might have effect on litter decomposition and nutrient release. Minimum cultivation is the common practice in most highly productive forests in Brazil. It's similar to the agricultural no-till system, but results in slight incorporation of residues into the first centimeters of topsoil in the planting row, that may lead to changes in decomposition, nutrient release and C sequestration through improving the contact of residues and soil particles (Lal, 2004; Lugato et al., 2006).

The appropriate management of litter could help match nutrient release rate with plants requirement. Several studies that evaluated litter decomposition and nutrient release showed that they do not always match, with expressive immobilization periods, usually controlled by limiting factors or specific decomposer community needs (Alvarez et al., 2008; Costa et al., 2005; Goya et al., 2008; Guo and Sims, 2002; Hernández et al., 2009; Ribeiro et al., 2002; Shammas et al., 2003). A better understanding of nutrient release behavior could guide management practices to take the best of decomposing litter. Based on this, we set up an experimental network across representative sites of eucalypt production aiming at understanding decomposition processes of harvest residues under different management practices.

In this study, macronutrient content of harvest residues was determined for several decomposition times and its release rate was estimated fitting data to a simple-exponential model. Half-life of each macronutrient was compared across sites and treatments. Treatments were applied based on three hypotheses: (i) increasing nitrogen availability would enhance decomposition and nutrient release; (ii) bark presence would reduce decomposition due to its chemical complexity; and (iii) incorporation of residues could accelerate decomposition and nutrient release.

2. Material and methods

2.1. Study sites

An experimental network was set up in representative sites for eucalypt production in Brazil (Abraf, 2013). The same experiment was installed across 11 sites in five states of Brazil, with different environmental and soil properties (Table 1). Total annual precipitation and mean annual temperature ranged from 960 to 1400 mm and 18 to 26 °C, respectively. Most of the soils are highly weathered, with low pH and low cation exchange capacity. Clay content ranged from 10% to 76%.

Experiments were carried out in commercial plantations and set up at the beginning of a new rotation, where eucalypt plantations had already been established for at least seven years in all sites except São Gabriel. At São Gabriel, experiment was set up at the beginning of the first rotation after conversion from grassland to eucalypt.

2.2. Field decomposition experiment

Harvest residues used in this study were collected in one unique area. They were obtained from a commercial *E. urograndis* hybrid stand harvested at two-year age. Trees were separated into leaves, branches, non-commercial stem, barks and roots. Residues were dried at 45 °C in a forced draft oven, chopped into smaller pieces varying from 4 to 8 cm (leaves were left uncut), transported to each site and dry stored until experiment establishment. Proportions of components used to represent harvest residue quantity and its composition were based on observations of harvested eucalypt commercial plantations with a mean annual increment of 50 m^3 ha^{-1} yr^{-1} (Table 2).

Our experimental unit (EU) were micro-plots (based on Blumfield et al., 2004) consisting of 15 × 15 cm (diameter and height) PVC tubes introduced 10 cm into soil between planting rows. Six lateral accesses (20 mm holes) in the tube wall were done to allow fauna and water movement. Residues were placed inside the EU, treatments applied and then the top part of the tubes was covered with a net of 1 × 1 cm mesh to avoid external material input. This type of experimental set up minimize some problems found in litterbag studies, such as destroyed and stolen bags, fauna exclusion, possible loss of tiny fragments and higher previous processing and fragmentation of litter (Bedford, 2004; Powers et al., 2009; Shorohova and Kapitsa, 2014).

Decomposition and nutrient release were studied under different forestry management practices fully replicated across sites. Management practices evaluated were maintaining bark (+B) on site or not (−B), use of an external source of N (+N) or not (−N), and the placement of the residues [on the surface (Sup) or incorporated (Inc) into the 5 cm topsoil] in a 2^3 factorial in randomized block design with four replications. For N fertilization, an equivalent dose of 200 kg ha^{-1} of N was applied as NH_4NO_3 diluted in deionized water at the experiment beginning in each experimental unit of +N treatments. This dose was expected to increase in 2.2-fold and 1.7-fold the initial N content for treatments without and with bark, respectively, if all the +N remained in the residues. However, we achieved an average of 17% and 53% of N-enrichment, without and with bark, respectively (Fig. 1).

Harvest residues were sampled five times during decomposition, *i.e.* 0, 3, 6, 12 and 36 months. At Mogi-Guaçu and São Gabriel sites, sampling occurred until 12 months. At each sampling time,