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Forest residue removal decreases soil quality and affects wood productivity even with high rates of fertilizer application

José Henrique Tertulino Rocha[a,b,*], José Leonardo de Moraes Gonçalves[a], Carolina Braga Brandani[c], Alexandre de Vicente Ferraz[d], Amanda Fernandes Franci[e], Eduardo Resende Girardi Marques[f], José Carlos Arthur Junior[g], Ayeska Hubner[a]

[a] Forest Science Department, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil
[b] Agriculture and Forest Engineering College, FAEF, Garça, SP, Brazil
[c] Soil and Water Science Program, Range Cattle Research and Education Center, University of Florida, United States
[d] Forestry Science and Research Institute, IPEF, Piracicaba, SP, Brazil
[e] Ramires Reflortec Company, Ribas do Rio Pardo, MS, Brazil
[f] Klabin Company, Telêmaco Borba, PR, Brazil
[g] Universidade Federal Rural do Rio de Janeiro, Seropédica, RJ, Brazil

A R T I C L E I N F O

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A B S T R A C T

Forest residues are frequently used as energy sources by Brazilian forest companies. The removal of such residues is known to reduce wood productivity, especially when fertilizer application rate is low. This study aimed to evaluate after two forest rotations the effects of forest residue management on wood productivity when fertilizer is applied at a high rate; and the effect of timber harvest intensity on soil organic matter and microbial activity. We assessed tree growth, soil microbial biomass and activity, and we fractionated soil organic matter (SOM) via its oxidation resistance. These assessments were performed after conducting a field trial comparing harvest residue management over two successive rotations in the same plots. We found no significant effect of treatments on wood productivity when the residues were removed for the first time; however, wood productivity reduced by 15% during the second rotation with residue removal even with high rates of fertilizer application. Further, 40% reduction in microbial biomass and soil respiration was noted with forest residue removal. At the reestablishment time, the SOM in the top soil (0–0.05 m layer) was 25% lower at the site where the forest residues were removed, and this difference increased to 50% at 300 days after the reestablishment. This reduction was found mainly in the SOM labile fraction.

1. Introduction

The use of forest residues (canopy, bark, and litter layer) as an energy source has become common, especially in subtropical countries (Achat et al., 2015). These residues can improve the contribution of renewable sources as world energy resources in the next 50 years (Chum et al., 2011). In Brazil, some forestry companies consider using forest residues, including stumps and roots, for energy production in cellulose industry. Their use is attractive since they do not cause direct or indirect land-use changes and are estimated to have low cost since they are by-products of existing operations (Daioglou et al., 2016). However, the removal of these residues from the sites can result in yield loss of the following forest rotation by about 20%, which might be even higher in wet tropical climate and low fertile soils (Achat et al., 2015; Nambiar and Harwood, 2014; Mendham et al., 2014; Huang et al., 2013; Kumaraswamy et al., 2014; Mendham et al., 2002; Laclau et al., 2010; Rocha et al., 2016a). This yield loss is mainly due to an increase in the nutrient outputs by harvesting. After the removal of forest residues, the nutrient outputs by harvest become 1.5 to 5 fold higher than that after stemwood harvest only (Achat et al., 2015; Laclau et al., 2010; Hernandez et al., 2009). If the maim role of forest residues on yield is nutritional, is the yield affected when the forest residues are removed but high rate of fertilizer are applied? Regardless of large number of studies about forest residues management, none addressed this question in a long term perspective.

Despite the adverse effects of forest residue removal on yield, low and inconsistent effects are found in soil nutrient availability assessed using conventional methods (Rocha et al., 2016b; Achat et al., 2015;

* Corresponding author at: Forest Science Department, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil.
E-mail address: rocha.jht@gmail.com (J.H.T. Rocha).

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Table 1
Physical and chemical attributes of the experimental site.

Depth	Sand	Silt	Clay[a]	pH[b]	CEC_7[c]	C[d]	N[e]	P[f]	Exchangeable Cations[f]			
									K	Ca	Mg	Al
cm	g kg^{-1}				mmol$_c$ kg^{-1}	g kg^{-1}		mg kg^{-1}	mmol$_c$ kg^{-1}			
0–10	802	22	175	3.8	14.8	9.61	1.44	4	0.25	4.28	2.81	7.50
10–20	811	12	176	3.9	13.7	10.05	1.67	3	0.27	2.80	2.17	8.43
20–30	790	34	176	3.9	8.6	6.77	1.53	1	0.20	1.32	1.00	6.09
30–40	777	23	200	3.9	8.9	5.33	1.29	1	0.15	0.88	0.81	7.03
40–60	747	14	239	3.9	9.4	5.42	1.14	1	0.15	0.99	0.72	7.50
60–100	712	12	276	3.9	7.9	5.04	0.99	1	0.15	0.66	0.54	6.56
100–150	712	11	277	4.0	3.7	3.44	1.04	1	0.08	0.71	0.54	2.34
150–200	704	20	276	4.2	3.9	0.87	1.04	1	0.05	0.55	0.54	2.81

[a] Pipette method.
[b] Determined in 0.01 mol L^{-1} $CaCl_2$ in soil/solution ratio of 1:2.5.
[c] Effective cation exchange capacity.
[d] Wet oxidation.
[e] Determined using the micro-Kjeldahl method after sulfuric acid digestion.
[f] Extracted with exchange ion resin (van Raij et al., 2001).

Nambiar and Harwood, 2014; Mendham et al., 2003; 2014; Laclau et al., 2010). Forest residue removal can reduce the amount and quality of soil organic matter (SOM; Achat et al., 2015; Nambiar and Harwood, 2014; Mathers et al., 2003). SOM plays an important role in soil chemical (cation exchange capacity, metal complexation, and nutrient availability), physical (soil structure and water holding capacity), and biological (microbial activity) properties, especially in highly weathered soils. Due these roles, the forest residue management can affect tree growth beyond nutrient supply, but it can be observed only in long term studies. Thus, forest residue removal needs to be considered without compromising soil fertility (Noormets et al., 2015).

Soil microorganisms are the most labile fraction of the SOM and account for around 1 to 4% of the total soil organic carbon (SOC; Jenkinson and Powlson, 1976). They are the transformation path for all organic material and are an important nutrient pool. Hence, they play an important role in nutrient cycling and energy flux into the soil (Jenkinson and Powlson, 1976). They are highly responsible for seasonal fluctuations and soil management changes (Gama-Rodrigues et al., 2005) and are considered a good indicator of soil management impacts (Balota et al., 1998).

Considering the role of SOM in highly weathered acidic soils and the impact of forest residue management on SOM, other effects of forest residue removal, in addition to nutrient outputs, might affect the productivity of the following forest rotation. Such effects might not be found in only one forest rotation with residue removal. However, this can be intensified in the successive forest rotations with residue removal (Mendham et al., 2014). This study aimed to evaluate after two forest rotations with residue removal the effect of forest residue management on wood productivity when high rates of fertilizer are applied, and the effect of timber harvest intensity on the SOM and microbial activity.

2. Material and methods

2.1. Study site

The study was performed at the Itatinga Forest Science Experimental Station of the University of São Paulo in Brazil (23°06′S lat and 48°36′W long and 857 m above sea level). The Köppen climate classification was humid subtropical Cfa, with a mean annual temperature of 19.4 °C [15.6 °C in the coldest month (July) and 22.3 °C in the hottest month (January)], and a mean annual rainfall of 1319 mm with 75% concentrated between October and March (Alvares et al., 2013). The mean annual precipitation during the first crop rotation (2004–2012) of this study was 1472 mm, and the mean annual temperature was 20.9 °C. During the second crop rotation (2012–2017) of the study, the mean annual precipitation was 1661 mm, and the mean annual temperature was 20.8 °C. Atypical climatic conditions were observed during the last years of the first crop rotation and the first two years of the second rotation. During 2012 and 2013, large precipitation (around 150 mm) was noted during winter when we expected a dry season. Conversely, a long dry season was noted in the summer of 2014, when we expected a rainy season.

The topography of the region was flat to undulating, and the soil was a very deep Ferralsol (IUSS Working Group WRB, 2015; red-yellow Latosol—Brazilian Classification System, and Oxisols—USDA Soil Taxonomy) that was developed on Cretaceous sandstone. The clay content ranged from 17% in the A_1 horizon to 25% in deeper soil layers. The mineralogy was dominated by quartz, kaolinite, and oxyhydroxides of Al and Fe with a low pH (approximately 4.6 in water) and small amounts of exchangeable cations (Table 1).

The original vegetation of the site was Cerrado *stricto sensu* (Ribeiro and Walter, 1998; Brazilian savannah). The site has been planted with eucalypt species since 1940. From 1940 to 1992, the site was cropped with *Eucalyptus saligna* and managed by coppicing with clear cutting each 7 or 8 years. In 1992, the plantation was harvested and replanted with *Eucalyptus grandis*, which was harvested (clear cutting) in 2004, when the study site was established.

2.2. Experimental design and treatments

The experimental area was established in 2004 (R1) and reinstalled in 2012 (R2) with three replicates of 9 treatments in a randomized block design. The plot sizes were 27 m × 18 m, with 81 trees per plot (9 lines with 9 plants each). The assessments were performed in an inner plot of 5 lines with 5 plants each (15 m × 10 m). Four treatments with different management levels of forest residue removal and fertilizer applications were assessed in this study (Table 2). The forest residues manipulated in this experiment include all organic residues remaining on the soil after wood harvesting of *E. grandis* plantations after 12-year growth: the leaves and branches less than 3 cm in diameter (canopy), bark, and litter layer. The following treatments were tested:

ReM + F — (Residues Maintained + Fertilization) Only stemwood was harvested; all forest residues (bark, canopy, and litter layer from the previous rotation) were maintained on the soil after clear-cutting; all nutrients were applied as fertilizer, and the soil was dressed with limestone;