Forest Ecology and Management 379 (2016) 1–10

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Forest residue maintenance increased the wood productivity of a *Eucalyptus* plantation over two short rotations

José Henrique Tertulino Rocha [a,*], José Leonardo de Moraes Gonçalves [a], José L. Gava [b], Tiago de Oliveira Godinho [c], Eduardo A.S.C. Melo [d], José Henrique Bazani [e], Ayeska Hubner [a], José C. Arthur Junior [f], Marcos P. Wichert [g]

[a] University of São Paulo, 'Luiz de Queiroz' College of Agriculture, Department of Forest Science, Piracicaba, Brazil
[b] Suzano Pulp and Paper S.A., Itapetininga, SP, Brazil
[c] Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural – Incaper, Venda Nova do Imigrante, Brazil
[d] Asia Pulp and Paper, Perawang, Indonesia
[e] 4tree Agroflorestal, Piracicaba, Brazil
[f] Universidade Federal Rural do Rio de Janeiro, Seropédica, Brazil
[g] Fibria, Jacareí, Brazil

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 26 July 2016
Accepted 27 July 2016
Available online 8 August 2016

Keywords:
Minimal tillage
Eucalyptus grandis
Nutrient cycling
Forest residue management

ABSTRACT

Forest residue (i.e., litter layer, slash and bark), when used as biomass for energy production, represents an important strategy for use as a renewable energy source in many countries. However, these residues can also have importance as sources of nutrients for trees and soil conservation. The objectives of the present study were to assess the effects of forest residue management on soil, wood production and nutrient accumulation dynamics during two crop rotations in a *Eucalyptus grandis* plantation. Thus, we set up an experimental site with different intensities of removal, burning and incorporation of forest residues (first crop rotation of study – R1). The stands of all treatments were harvested after eight years, and the trial was re-established with all forest residues maintained on the soil across all treatments (second crop rotation of study – R2). R2 was conducted for eight more years. The growth and nutritional status, biomass and nutrient accumulation of the trees were assessed. The forest residue burn increased the initial nutrient availability in the soil; however, this availability returned to initial levels in a short period of time. Wood productivity decreased by approximately 40% with the removal of all forest residues in R1. In R2, wood productivity after the removal or burning of forest residues was 6% lower than when all forest residues were maintained on the soil.

1. Introduction

In Brazil, *Eucalyptus* plantations are often established in areas that have low agricultural potential, as characterized by low soil fertility and low mineral reserves (e.g., Oxisols and Entisols Psamments) (Gonçalves et al., 2013). High productivity levels (39 m^3 ha^{-1} $year^{-1}$ of wood) were achieved under these conditions (IBÁ, 2015), reflecting favourable climatic conditions, genetic adaptation, appropriate management and fertilizer application as well as a high nutrient uptake capacity and usage (Barros et al., 2000; Laclau et al., 2010b, 2013).

Despite high *Eucalyptus* productivity, sustainability has become an increasingly important issue for planted forests in the medium and long-term, reflecting the low fertility of soil used for forest plantations. Organic matter largely influences the dynamics of the nutrients in these soils (Tiessen et al., 1994) and might reflect significant changes in the stock of soil nutrients for trees (Kumar and Goh, 2000). Thus, the maintenance of forest residues (i.e., litter layer, slash and bark) between rotations is essential to maintain or improve soil fertility and forest production sustainability (Huang et al., 2013; Kumaraswamy et al., 2014; Mendham et al., 2002; Tiessen et al., 1994; Achat et al., 2015). The effects of forest residue removal on wood productivity and soil fertility have been extensively studied (e.g., Huang et al., 2013; Kumaraswamy et al., 2014; Mendham et al., 2002, 2014); however, the potential site recovery after a previous rotation with residue removal is not known.

* Correspondig author at: USP, ESALQ, 11 Av. Padua Dias, Piracicaba, SP CEP 13418-900, Brazil.
E-mail address: rocha.jht@gmail.com (J.H.T. Rocha).

http://dx.doi.org/10.1016/j.foreco.2016.07.042
0378-1127/

Until the 1980s, in Brazil, forest residues were considered to be obstacles for the re-establishment of *Eucalyptus* plantations, motivating burn, removal or incorporation into soil. The concept that *Eucalyptus* plantations demand intensive soil preparation to achieve good yields was also considered to be a suitable management practice. Currently, most forestlands are established under a minimum or no tillage system (Gonçalves et al., 2013). However, with the restrictions on land use and elevation of fossil fuel prices, these residues were considered to be potential alternative power sources for the industrial sector. The benefits of residue maintenance on soil cannot to be neglected, despite their potential use as a renewable energy source (Achat et al., 2015). Thus, the sustainability of forest productivity will be ensured for future rotations.

The objectives of the present study were to: (i) assess the impact of contrasting inter-rotation management on stand productivity in low-fertility soil; (ii) explore the nature and extension of the maintenance or recovery of productivity from adverse impacts in response to conservative management during the second rotation; and (iii) discuss results with respect to biomass harvest for bioenergy and changes in soil properties.

2. Material and methods

2.1. Site description and treatments

This study was conducted in a commercial plantation at the municipality of Itatinga, São Paulo state (23°17′S and 48°28′O and 649 m above sea level). This region has a humid subtropical climate (Köppen climate classification Cfa) characterized by hot and humid summers with a mean annual temperature of 19.4 °C; 15.6 °C is the mean temperature in the coldest month (July) and 22.3 °C is the mean temperature in the hottest month (January). The historical mean (last 30 years) annual rainfall is 1300 mm, with 75% concentrated between October and March (Alvares et al., 2013). In the first crop rotation of the study (R1), between 1995 and 2003, the mean annual rainfall was 1600 mm and the mean annual temperature was 22.5 °C. In the second crop rotation of the study (R2), between 2004 and 2012, the mean annual rainfall was 1400 mm and the mean annual temperature was 22.0 °C.

The native vegetation of the site was the Cerrado *stricto sensu* (Brazilian savanna). This site has been planted with *Eucalyptus* species since 1974. The site was cropped with *Eucalyptus saligna* from 1974 to 1988 and with *Eucalyptus grandis* from 1988 to 1995. The local topography is flat, with deep Haplic Ferralsol, loamy, dystrophic (red-yellow Latosol) soil developed on cretaceous sandstone (Table 1). The mineralogy is dominated with quartz, kaolinite and oxyhydroxides.

The trial was a randomized complete block design with four replications. The measured plot comprised 49 plants distributed in 7 rows of 7 plants, with a double row buffer. Five treatments were assessed: (i) FRM - All forest residues were maintained on the soil, but only stemwood was harvested; (ii) LiM - only litter was maintained on the soil (all slash, stemwood and bark were removed); (iii) FRR - all forest residues (litter layer, slash and bark) were removed; (iv) FRI - all forest residues were incorporated into the soil at a depth of 0.2 m, with heavy harrow; and (v) FRB – all forest residues were burnt on the soil. The stands of all treatments were harvested after eight years, and the trial was re-established with all forest residues maintained across all treatments when the second rotation was planted.

2.2. Site management

In September of 1995, after the clear cutting of the previous *Eucalyptus grandis* plantation, the treatments were applied and the planting line was subsoiled at a depth of 0.4 m. The base fertilizer (15 kg ha^{-1} of N, 13 kg ha^{-1} of P and 12 kg ha^{-1} of K) was applied to all treatments. The seedlings of a monoprogeny (full-sib) of *Eucalyptus grandis* Hill Ex Maiden were planted, with a 3 m $\times$ 2 m spacing. Eight months after planting, topdressing fertilization (124 kg ha^{-1} of K) was applied in every treatment.

The experimental site was harvested in September of 2004, and all forest residues were maintained on the soil in all treatments. Two months after harvest, the same genetic material was planted in pits generated between the stumps at the same spacing as used in R1. Thus, it was possible to assess the residual effect of treatments applied in R1. The same fertilizer application as applied in R1 was used. The experimental site was maintained free of weeds through both crop rotations. Additional details about the set up and management of the trial are provided in Gonçalves et al. (2007, 2008).

2.3. Soil sampling and analysis

Soil samples were collected from 0 to 5, 5 to 10 and 10 to 20 cm layers. In R1, soil samples were collected at 1, 6 and 10 months and 2 and 6 years after treatment application, and in R2, soil samples were collected at 2, 4 and 7 years after planting (11, 13 and 16 years after treatment application in R1). Ten single samples were withdrawn to form a composite sample per plot, followed by sieving at 2 mm. The available P and exchangeable Ca, Mg and K were displaced using ion-exchange resins, and the pH was measured in a 0.01 mol L^{-1} $CaCl_2$ solution (van Raij et al., 2001). The soil organic carbon (SOC) was determined through wet oxidation (Walkley and Black, 1934), and the soil total N was determined using the micro-Kjeldahl method (Bremner, 1965).

Table 1
Soil physical and chemical attributes of the study site.

Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay[a] (g kg^{-1})	Bulk density (g cm^{-3})	pH[b]	C[c] (g kg^{-1})	N[d] (g kg^{-1})	P[e] (mg kg^{-1})	Cation exchange[e] (mmol$_c$ kg^{-1})			
									K	Ca	Mg	Al
0–10	770	30	200	1.25	3.5	15.2	1.8	6.0	0.4	1.7	1.5	14.5
10–20	770	30	200	1.25	3.6	10.5	1.0	4.5	0.3	1.4	1.2	11.5
20–30	760	20	220	1.30	3.7	9.3	0.9	3.0	0.3	0.9	0.6	12.0
30–50	760	20	220	1.30	3.8	4.6	0.5	3.0	0.2	0.5	0.3	11.0
50–100	740	20	240	1.31	3.8	1.5	0.2	2.0	0.2	0.5	0.3	11.2

[a] Pipette method (EMBRAPA, 2013).
[b] $CaCl_2$ 0.01 mol L^{-1}, soil to solution ratio 1:2.5.
[c] Wet oxidation.
[d] Sulfuric acid extraction.
[e] Ion exchange resin (van Raij et al., 2001).