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Research article

Fertilization using sewage sludge in unfertile tropical soils increased wood production in *Eucalyptus* plantations

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ABSTRACT

Fertilization of *Eucalyptus* plantations using sewage sludge on unfertile tropical soils represents an alternative to using mineral N and P fertilizers. A 44-month field experiment was conducted to study the effects of increasing application of sludge, and its interactions with mineral N and P fertilizers, on wood volume. Four rates of sludge (0, 8, 15 and 23 Mg ha^{-1}, dry base), N (0, 47, 95 and 142 kg ha^{-1}) and P (0, 28, 56 and 84 kg ha^{-1} of P_2O_5) were combined in a 4 × 4 × 4 factorial scheme in a totally randomized block design. Response surface and age-shift modeling was used to establish an initial recommendation for mineral fertilization of the *Eucalyptus* plantations treated with sludge and to analyze the implications of increased growth on the duration of the forest cycle in a tropical climate. The results showed that from 8 to 44 months after planting, the sludge application (with or without N and P) yielded a statistically larger wood volume ($P < 0.05$), compared to application of N and P fertilizers only. The response surface modeling showed the following outcomes: *i*) application of sludge based on N criterion reduced the need for N and P fertilizers by 100%; and *ii*) an increase in wood volume by 7% could be achieved, compared to NPK fertilizers only, if 2/3 of the recommended P was applied. The cultivation time to produce 150 m^3 ha^{-1} of wood volume was 45 months for the control and was reduced by two, three, four, or five months, respectively, through application of recommended P, sludge dose, sludge plus one third of P, and sludge plus two thirds of P. On the whole, sewage sludge could represent an excellent unconventional N and P fertilizer source for wood production on unfertile tropical soils.

1. Introduction

Planted forests are extremely important in the socio-economic and environmental context of many countries in tropical climate regions. The wood is used to manufacture pulp and paper, to produce charcoal, or for furniture; additionally, it can provide other ecosystem services such as sawmilling, panels, packaging, specialty chemicals, etc. (Carnus et al., 2012). From an environmental perspective, wood production can reduce greenhouse gas emissions by fixing CO_2 (Miehle et al., 2006; Ramlal et al., 2009) and generating biofuel (Gonzalez et al., 2011; Zhu and Pan, 2010).

Planting of *Eucalyptus* in Brazil has occurred on more than 5.1 million hectares, making Brazil the second-largest Eucalyptus-growing country in the world, second only to India (ABRAF, 2013;

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FAO, 2008). Areas planted with fast-growing *Eucalyptus grandis* Hill ex Maiden in tropical regions continue to expand (Forrester, 2013), due to the species' wide climatic suitability, use of new techniques, development of advanced genetic material, control of pests, diseases and weeds, soil preparation and fertilization (Flores et al., 2016). However, these tropical areas have an irregular moisture regime and dystrophic soils characterized by low fertility and high acidity (Abreu-Junior et al., 2003), which increases concern about the sustainability of the plantations. The success of commercial *Eucalyptus* plantations in these unfertile soils is highly dependent on the application of large amounts of mineral fertilizers (Forrester, 2013; Silva et al., 2013), with consequent high costs of production and environmental concerns.

An alternative to conventional fertilizers is to treat *Eucalyptus* plantation with sewage sludge at an agronomic dose, as a source of both nitrogen (N) and phosphorus (P). Forest use of sludge provides technical and economic feasibility for the management of this type of waste while increasing the environmental and economic sustainability of commercial *Eucalyptus* plantations in dystrophic soils (Abreu-Junior et al., 2005; Kimberley et al., 2004; Ramlal et al., 2009; Silva et al., 2008a, 2008b). For intensively managed *Eucalyptus* plantations in tropical soil, which present a pronounced increase in nutrient requirements for canopy establishment from 6 months after planting onwards (Laclau et al., 2010), sludge application at an agronomic dose can play a key role in N and P supply and result in high wood production (Campoe et al., 2013; Forrester, 2013; Gonçalves et al., 2004; Gspaltl et al., 2013).

The presence of inorganic and organic contaminants as well as pathogenic organisms limits sludge application to agricultural soils (Alvares et al., 2013; Alvarez et al., 2008; Fijalkowski et al., 2017; Kirchmann et al., 2017; Nafez et al., 2015; Smith, 2009). This residue must be used in soils with caution, avoiding harm to public health and pollution of the environment. Nevertheless, there is no hazard for humans or animals if few contaminants contained in the sludge are incorporated into the wood matrix, as wood products are not used for human or animal feed. Thus, the use of sludge to fertilize *Eucalyptus* plantations for pulp and paper is one of the most promising alternatives for its final disposal. The use of sewage sludge in Brazilian agriculture is regulated by Resolution 375 (CONAMA, 2006), which states that sludge should be applied according to the agronomic N requirement of each crop.

Nitrogen and P contained in the sludge, predominantly in organic form, can be better used by crops due to their slow release to the soil solution, compared to N and P contained in mineral fertilizer (Franco et al., 2010; Singh and Agrawal, 2008; Smith, 1996). However, the concentrations of N and P in sewage sludge are variable. Consequently, there are many uncertainties for farmers and wastewater treatment plant managers on the best fertility management of soils treated with sludge (Abreu-Junior et al., 2005; Franco et al., 2010), especially in tropical regions where soils are highly weathered and unfertile (Abreu-Junior et al., 2003).

One of the most promising benefits in using sewage sludge in *Eucalyptus* plantations is the enhancement of net primary production. Previous studies have reported early growth increase in pine tree plantations with the use of sludge (Kimberley et al., 2004; Wang et al., 2013). Further gain is expected by using sludge coupled with a complementary dose of mineral N and P fertilizers. This intensification of management (e.g., Smethurst, 2010) could reduce the duration of crop cycles and increase forest sustainability and economic returns, as the rotation length of plantations can be shortened. However, there is no information regarding the interactions between sludge and N and P rates to estimate the capacity of sludge to replace mineral N and P fertilizers in a planted forest. Therefore, it is not yet possible to formulate a recommendation for use of sewage sludge in *Eucalyptus* plantations.

We hypothesized that the application of sludge on *Eucalyptus* plantations can reduce both the use of mineral N and P fertilizers and the time of tree growth, while producing the same amount of wood. For this reason, a field experiment on a commercial *Eucalyptus* plantation area was conducted with the aim of monitoring the effects of sludge on planted forests. The main goal of the present study was to evaluate the effect of sludge doses and subsequent interactions with mineral N and P fertilizers on wood volume. The results were expected to establish initial recommendation for mineral fertilization of *Eucalyptus* plantations treated with sludge; and to aid in an analysis of the implications of increased growth on the duration of the forest cycle in a tropical climate.

2. Material and methods

2.1. Study area and sludge features

The experiment was set up in a commercial *Eucalyptus* field at the Suzano Pulp and Paper Company, located in the municipality of Angatuba, State of São Paulo, Brazil (Fig. 1). This area had not been previously treated with sludge. The local climate is moist tropical (Köppen's climate type Cwa), with relatively dry winters and hot and humid summers. The average temperature was 21.8 °C and the annual average total rainfall was 1297 mm in the period from December 2004 to August 2008, according to records of the local weather station (Alvares et al., 2013).

At the experimental area of 3.33 ha, the soil was classified as Typic Hapludox (Soil Survey Staff, 2014)/Rhodic Ferralsol (IUSS Working Group WRB, 2015). Before setting up the experiment, the soil A_p surface horizon (0–40 cm depth) was chemically (Table 1) and physically (12% clay, 4% silt, and 84% sand) characterized in accordance with official procedures contained in CONAMA (2006). Concentrations of potentially toxic elements were below reference values for soils of the São Paulo State, allowing for sludge applications in this area (CETESB, 2014).

The sludge was obtained from the Jundiaí waste treatment plant, in the municipality of Jundiaí, State of São Paulo, Brazil. The plant can treat a load equivalent to a population of 1.67 million inhabitants, reaching 90 ton of BOD day^{-1}. On the whole, the treatment plant generated 14,000 m^3 month^{-1} of sludge. The sludge was generated in a biological system of aerated ponds, with complete mixture, followed by sedimentation ponds for a period of approximately 12 months. The sludge was then further treated with polymers, centrifuged, and air dried for 120 days, with periodic mechanical turnover of the piles, to reduce the presence of pathogenic agents and to obtain material with up to 25% solids. The concentrations of potentially toxic elements (Table 2) were below the limits established by CONAMA (2006), making the sludge suitable for agricultural use (CONAMA, 2006).

2.2. Field preparation

The experiment ran from December 2004 until August 2008, for a total of 44 months. Before starting the experiment, in December 2004, lime (95% relative power of total neutralization) was applied at the rate of 1.8 Mg ha^{-1} over the whole experimental area. Such a dose was established in order to raise the base saturation to 45% of the cation exchange capacity.

The sewage sludge was applied in each row in a continuous band of 60 cm, just before planting, at doses of 0, 8, 15, and 23 Mg ha^{-1}, which are equivalent to 0, 50, 100, and 150% of the recommended N supply, based on the N criterion (CONAMA, 2006). The mineralization rate was 30% for the aerobic sludge. The doses of

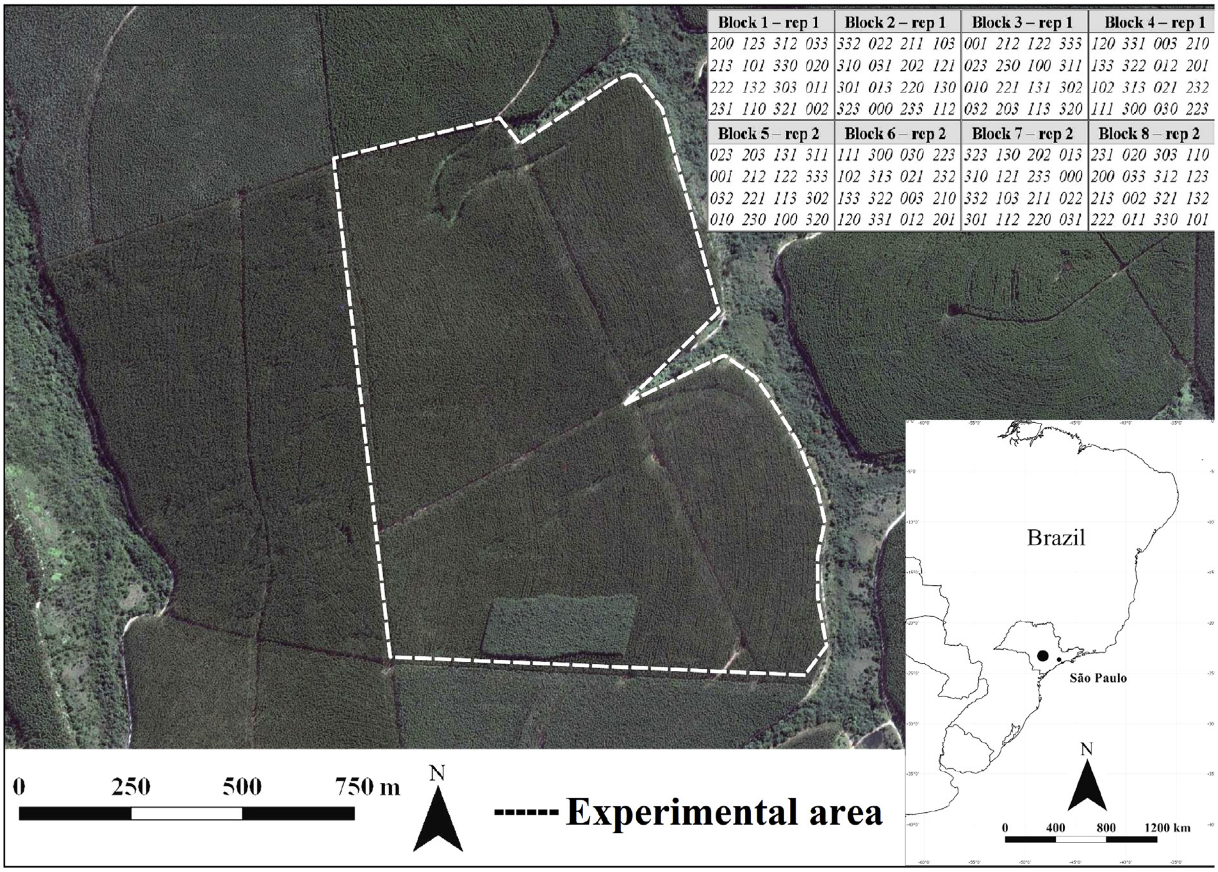

Fig. 1. Study area at the Suzano Pulp and Paper Company (Municipality of Angatuba, State of São Paulo, Brazil; 23°17′S and 48°15′W, 650 m asl).

Table 1
Chemical properties of soil (surface A_p horizon) in the experimental area before *Eucalyptus* planting (mean ± SE, $n = 3$).

	Unit	Layer depth		Quality values[a]	Prevention values[b]
		0–0.2 m	0.2–0.4 m		
pH-$CaCl_2$		3.60 ± 0.2	3.80 ± 0.1	–	–
Organic matter	g kg^{-1}	20.2 ± 1.9	15.5 ± 1.2	–	–
P_{resin}	mg kg^{-1}	6.50 ± 0.4	5.50 ± 0.2	–	–
K	$mmol_c$ kg^{-1}	0.25 ± 0.0	0.20 ± 0.0	–	–
Ca^{+2}	$mmol_c$ kg^{-1}	1.25 ± 0.2	1.00 ± 0.1	–	–
Mg^{+2}	$mmol_c$ kg^{-1}	1.00 ± 0.2	1.00 ± 0.2	–	–
H + Al	$mmol_c$ kg^{-1}	40.0 ± 0.5	30.2 ± 0.4	–	–
Sum of bases	$mmol_c$ kg^{-1}	2.50 ± 0.3	2.20 ± 0.3	–	–
Cation exchange capacity	$mmol_c$ kg^{-1}	42.5 ± 3.5	32.4 ± 3.0	–	–
Base saturation	%	5.70 ± 0.5	6.70 ± 0.4	–	–
Total recoverable metals					
As	mg kg^{-1}	2.23 ± 0.2	2.17 ± 0.2	3.5	15
Ba	mg kg^{-1}	3.52 ± 0.4	2.87 ± 0.3	75	120
Cd	mg kg^{-1}	0.009 ± 0.0	0.006 ± 0.0	<0.5	1.3
Cr	mg kg^{-1}	7.28 ± 0.6	6.51 ± 0.5	40	75
Cu	mg kg^{-1}	1.61 ± 0.2	1.59 ± 0.3	35	60
Hg	mg kg^{-1}	0.006 ± 0.0	0.003 ± 0.0	0.05	0.5
Mo	mg kg^{-1}	0.25 ± 0.0	0.23 ± 0.0	<4	5
Ni	mg kg^{-1}	0.72 ± 0.1	0.62 ± 0.2	13	30
Pb	mg kg^{-1}	2.76 ± 0.3	2.63 ± 0.4	17	72
Se	mg kg^{-1}	0.08 ± 0.0	0.03 ± 0.0	0.25	1.2
Zn	mg kg^{-1}	4.00 ± 0.5	3.50 ± 0.4	60	86

[a] Quality value for agricultural soils in the São Paulo State established by the Environmental Agency of the State of São Paulo (CETESB, 2014).
[b] Prevention value for agricultural soils in the São Paulo State established by the Environmental Agency of the State of São Paulo (CETESB, 2014).

mineral NPK fertilizers were defined based on technical recommendations of Suzano Company for commercial planting of *Eucalyptus* at the experimental site. Nitrogen, as urea (45% N), was applied at doses of 0, 47, 95 and 142 kg ha^{-1} of N, equivalent to 0, 33, 67 and 100% of the recommendation; 1/9 was applied upon planting and 8/9 later as side dressing (4, 10 and 23 months after planting). Phosphorus, as triple superphosphate (42% P_2O_5), was applied, at planting only, at doses of 0, 28, 56 and 84 kg $ha^{-1}$of P_2O_5, equivalent to 0, 33, 67 and 100% of the recommendation. Because the sewage sludge was poor in potassium (2.75 g kg^{-1}) (Table 2), this nutrient was applied at a rate of 188 kg ha^{-1} of K_2O (equivalent to 100% of the recommendation) in the form of potassium chloride (63% K_2O), on all the plots, in proportions of 1/7 applied upon planting and 6/7 applied later as side dressing (4, 10 and 23 months after planting). Crop management practices to control weeds and disease were performed in accordance with the Suzano Company for commercial production of *Eucalyptus*.

2.3. Experimental design and treatments

To study the effect of the sludge (0, 8, 15, and 23 Mg ha^{-1}, dry base), N (0, 47, 95, and 142 kg ha^{-1} of N), and P (0, 28, 56 and 84 kg ha^{-1} of P_2O_5) doses on the dependent variables by means of response surface modeling, a totally randomized block was realized. In particular, as seen on the top right of Fig. 1 the randomized block design used for the experiment is reported. The sequence of the three numbers represents (from left to right) the following combinations: *i*) the sewage sludge doses of 150 (*3*), 100 (*2*), 50 (*1*) and 0 (*0*)%; *ii*) the nitrogen doses of 100 (*3*), 66 (*2*), 33 (*1*) and 0 (*0*)%, and *iii*) the phosphorous doses of 100 (*3*), 66 (*2*), 33 (*1*) and 0 (*0*)%. This means that a 4 × 4 × 4 factorial scheme (4 doses of sludge x 4 doses of N x 4 doses of P), with confounding degrees of freedom, two replications distributed in eight blocks (16 treatments per block, Fig. 1), for a total of 64 treatments and 128 plots, was applied.

2.4. Wood volume measurement

The height (H) and the diameter at breast height (DBH) of the ten trees in the useful area of each plot were measured at 8, 11, 17, 23, 32, and 44 months after planting, to estimate wood volume per hectare. The volume of each tree was estimated using the following expression:

$$V = 1.7 \times 10^{-5} \text{ x } DBH^{\ 1.9117} \times H^{1.3065} \qquad (1)$$

where V is wood volume per tree (m^3), *DBH* is diameter at breast height (m), and H is height (m). This allometric equation was obtained in a previous field study with similar clone, soil, and weather conditions to the present study (Guedes, 2005). For each plot, the individual volume of ten trees was summed and the wood volume per hectare was estimated.

Table 2
Chemical composition of sewage sludge (mean ± SE, $n = 3$), on a dry weight basis, used in the experiment.

	Unit	Values	Limits[a]
pH-H_2O	–	6.2 ± 0.3	–
Moisture	%	79 ± 8	–
Total organic C	g kg^{-1}	340 ± 45	–
Total N	g kg^{-1}	33 ± 1	–
Total P	g kg^{-1}	8.1 ± 0.7	–
Total K	g kg^{-1}	1.00 ± 0.1	–
As	mg kg^{-1}	ND	41
Ba	mg kg^{-1}	273 ± 19	1300
Cd	mg kg^{-1}	11 ± 1	39
Cr	mg kg^{-1}	111 ± 14	1000
Cu	mg kg^{-1}	881 ± 183	1500
Hg	mg kg^{-1}	ND	17
Mo	mg kg^{-1}	ND	50
Ni	mg kg^{-1}	26 ± 2	420
Pb	mg kg^{-1}	85 ± 13	300
Se	mg kg^{-1}	ND	100
Zn	mg kg^{-1}	989 ± 133	2800

ND: not detected (concentrations < 0.1 mg kg^{-1}).
[a] Limits to sewage sludge agricultural use established by Resolution 375 (CONAMA, 2006).

2.5. Statistical analysis

The data on *Eucalyptus* wood volume produced at 8, 11, 17, 23, 32, and 44 months after planting were submitted to analysis of variance (ANOVA) by single and multiple regression, along with the following response surface modeling:

$$V = a + bS + cN + dP + eSN + fSP + gPN + hS^2 + iP^2 + jN^2 \qquad (2)$$

where V is wood volume (m^3 ha^{-1}), S is sludge dose (Mg ha^{-1}), N is N dose (kg ha^{-1}), and P is P_2O_5 dose (kg ha^{-1}), for each cultivation time.

To avoid under- or over-estimation of the calculated wood volume (South, 1995), we used the age-shift method of analysis, which compares treatments on the basis of *Eucalyptus* plant age at a fixed volume rather than *Eucalyptus* volume at a fixed cultivation time. The statistical analysis was performed in two steps. In the first step, we estimated the parameters of the Gomportz curve (Sit and Poulin-Costello, 1994) using the NLIN procedure, for a function that allowed estimation of the wood volume in each parcel of this study as a function of time varying from 8 up to 44 months after planting. The Gomportz curve proved statistically suitable ($P < 0.05$) for predicting the time required to obtain a fixed wood volume of 150 m^3 ha^{-1} in each of the plots of this experiment. This value was defined considering the average volume obtained at the time of 44 months by all the treatments without application of sludge (16 treatments, 4 × 4 combination of N and P doses). In the second step, a study was developed by the response surface RSREG procedure in order to model the effect of the sludge, N, and P doses on the time needed to obtain 150 m^3 ha^{-1} of wood volume. For this study, an expression was used as follows:

$$T = a + bS + cN + dP + eSN + fSP + gPN + hS^2 + iP^2 + jN^2 \qquad (3)$$

where T is time of tree growth (months), S is sludge dose (Mg ha^{-1}), N is N dose (kg ha^{-1}), and P is P_2O_5 dose (kg ha^{-1}). All statistical analyses were performed using the SAS system (SAS, 2008), with a significance level of 5%.

3. Results and discussion

3.1. Wood productivity

A very high potential for wood productivity in *Eucalyptus* plantations, growing in unfertile tropical soils treated with sewage sludge, was observed.

From 8 to 44 months after planting, the sludge application, with or without addition of mineral N and P, yielded wood volume ranging from 0.6 to 192 m^3 ha^{-1}, with a mean annual increment of 52 m^3 ha^{-1} $year^{-1}$ (Firme, 2009). These data were statistically superior ($p < 0.05$) to the volume ranging from 0.4 to 166 m^3 ha^{-1}, with an increment of 45 m^3 ha^{-1} $year^{-1}$, obtained among the treatments combining the 4 × 4 doses of mineral N and P fertilizers (Table 3).

On the whole, by 44 months, a wood volume of 163 and 166 m^3 ha^{-1} was reached (Table 3). This means that mean annual increments of 44 and 45 m^3 ha^{-1} $year^{-1}$, due to the application of recommended sludge dose and of mineral NPK fertilizer, were respectively obtained. Such a high productivity was realized in extremely unfertile soils, under minimum tillage and with the application of lime and NPK fertilizers at recommended doses. In comparison, in Brazil, the current mean annual increment is 40.7 m^3 ha^{-1} $year^{-1}$ (ABRAF, 2013).

Assessing wood volume recorded during the experiment (Table 3), the application of sludge at the recommended dose (based on the N criterion), statistically increased ($p < 0.05$) wood volume compared to the mineral NPK treatment until 17 months after planting (24 *vs* 23 m^3 ha^{-1}). During this time just 55% of the total of mineral N was applied, while it was completed at 23 months after planting. This explains the need for the recommended sludge dose to be complemented with N and P to yield a wood volume similar to the NPK treatment at 32 months after planting (Table 3). In the NPK fertilizer treatment, the complete application of N at 23 months after planting may have positively influenced the P uptake by the root system of *Eucalyptus* plant (Silva et al., 2013). The height of *Eucalyptus* plantations is increased with P fertilization when the N content in soil is suitable for this type of cultivation (Xu et al., 2002). Phosphorus uptake by the *Eucalyptus* plant is strongly influenced by an appropriate supply of N in the soil (Graciano et al., 2006). Consequently, the effect of P fertilization on plant growth may be minimal when N availability in soil is limiting, and *vice versa*.

3.2. Estimation of the minimum doses of fertilizer to yield a wood volume equivalent to the V_{NPK}

The response surface modeling allowed fitting equations (Table 4) based on linear and quadratic effects of doses of sludge, N, and P on *Eucalyptus* wood volume. The minimum and maximum average values at 8, 11, 17, 23, 32, and 44 months after planting indicate that the wood volume increased as a function of doses of treatments. The greatest volume increment was obtained with the sludge doses, followed by P doses, and then N doses.

The response surface equations (Table 4) can then be used to estimate the minimum dose of sludge, N and P fertilizers, to yield a wood volume similar to the treatment with mineral NPK fertilizers only (Table 5).

As shown in Table 3, the wood volume yielded using the sludge recommended dose was statistically higher ($p < 0.05$) than that using NPK fertilizers up to 17 months after planting. Thus, the response surface equations can be used to estimate doses of sludge, to obtain wood volume similar to the NPK treatment, below the recommended dose (<15 Mg ha^{-1}). However, the wood volume obtained using the sludge recommended dose was somewhat lower than that of the NPK treatment from 23 to 44 months after planting (Table 3). Therefore, the response surface equations were also used to estimate the lowest doses of P and N used to complement the sludge recommended dose in order to obtain a wood volume similar to that of the mineral NPK treatment. Hence, during the overall time of tree growth, the application of the sludge recommended dose boosted the yield of *Eucalyptus* wood volume when complemented with mineral P fertilizer in a dose varying from 17 to 48 kg ha^{-1} of P_2O_5, without the addition of mineral N fertilizer (Table 5).

Table 3
Wood volume of *Eucalyptus grandis* plantation yielded by the application of 15 Mg ha^{-1} of sewage sludge based on the N criterion ($V_{S100\%}$) and by the conventional application of mineral NPK fertilizer (V_{NPK}).

Time of tree growth	Wood volume of *Eucalyptus grandis* plantation	
	$Vs_{100\%}$	V_{NPK}
Months	m^3 ha^{-1}	
8	1	0.4
11	7	4
17	24	23
23	44	46
32	95	112
44	163	166

3.3. Recommendations for using sewage sludge together with mineral fertilizers

According to the results obtained and the response surface modeling for *Eucalyptus* wood yield, a first-approach recommendation is suggested for forest growers interested in using sewage sludge, based on the N criterion, to complement conventional mineral fertilizers (Table 6). This approach is valid for unfertile soils with a moderate concentration of available P (ranging from 6 to 8 mg dm^{-3}) and a low concentration of K (≤0.7 $mmol_c$ dm^{-3}). The estimated relative yield of 100% is equivalent to 166 m^3 ha^{-1} of wood volume for *Eucalyptus* plants grown for 44 months, with an increment of 45 m^3 ha^{-1} $year^{-1}$, under minimum tillage and application of lime and NPK fertilizers at recommend doses.

Since the sludge dose applied at the forest planting is increased up to the dose permitted by legislation (sludge recommended dose), the need for N and P nutrients decreased by up to 100% with the relative yield being nearly the same (Table 6). However, the recommended dose of sludge complemented with 28 or 56 kg ha^{-1} of P_2O_5, without the addition of N, provided a wood volume 4% or 7% statistically higher ($p < 0.05$) than that of the NPK treatment, respectively (Table 6). Such an increase in wood volume indicated that the management of sludge with P fertilizer improved the use efficiency of macro- and micro-nutrients by *Eucalyptus* plants. Notwithstanding, application of the recommended sludge dose alone resulted in a wood volume approximately 99% of that using mineral NPK fertilizers (Table 6), due to soil fertility improvement. The contents (surface A_p horizon) of total N, organic C, resin extractable P, K, Ca and Mg, and DTPA extractable and semi-total Cu, Fe, Mn and Zn in the soil increased as a function of sludge application dose, besides leaf litter, for up to 44 months of sludge application (Maldonado, 2009). Under these conditions, nutrient and water uptake and use by *Eucalyptus* plants are more efficient (Bouillet et al., 2002; Silva et al., 2013; Stape et al., 2006).

High forest wood production depends, in addition to water and nutrient availability, on the maintenance of the tree canopy's ability to intercept a high proportion of solar radiation (Forrester, 2013; Gonçalves et al., 2004). The increase in *Eucalyptus* wood production as a function of sludge dose was also related to leaf area index (LAI) and the amount of litter on the soil surface (Firme, 2009; Maldonado, 2009), as they are indicative parameters of forest production quality. We have observed that the higher the sludge dose, the higher the LAI, amount of litter and both N and P accumulation in shoots of the *Eucalyptus* plants (paper in process). When nutrient and water supplies are adequate for plant development, plants allocate carbon preferentially in leaves and stems instead of roots. In contrast, plants growing in unfertile soil have high dry matter allocated on roots instead of canopy (Campoe et al., 2013). The higher light, nutrient and water use efficiencies by *Eucalyptus* plants explain the higher wood production as a function of sludge dose.

Good silvicultural practices coupled with adequate input of nutrients are required for high growth and short rotation of tropical *Eucalyptus* plantations (Forrester, 2013; Laclau et al., 2010; Silva et al., 2013). Thus, the fertilization of planted forests with sludge can increase the economic return for producers, because this type of management reduces the amount of N and P needed to meet the nutritional requirements of *Eucalyptus* trees. Consequently, the rotation length can be reduced.

Table 4
Equations obtained by the response surface modeling study to fit the wood volume of *Eucalyptus grandis* plantation (V, $m^3\ ha^{-1}$) according to the doses of sewage sludge (S, Mg ha^{-1}), N (kg ha^{-1}), and P (P_2O_5, kg ha^{-1}), and their respective minimum (V_{min}) and maximum (V_{max}) average values at 8, 11, 17, 23, 32, and 44 months after planting ($n = 128$, for each time).

Time of tree growth	V_{min}	V_{max}	Equation	R^2 ($p < 0.01$)
Month	$m^3\ ha^{-1}$			
8	0.3	1.5	$V = 0.22 + 0.071S + 0.0045P + 0.0021N - 0.0018S^2 - 0.000033P^2 - 0.000012N^2$	0.96
11	3	9	$V = 2.60 + 0.36S + 0.009P + 0.013N - 0.0073S^2 - 0.000068N^2$	0.94
17	18	35	$V = 18.2 + 0.84S + 0.075P + 0.019N - 0.019S^2 - 0.00063P^2$	0.90
23	30	62	$V = 28.3 + 1.29S + 0.17P + 0.04N - 0.024S^2 - 0.001P^2$	0.90
32	76	129	$V = 71.9 + 2.29S + 0.41P + 0.096N - 0.051S^2 - 0.0029P^2$	0.88
44	136	195	$V = 135 + 2.697S + 0.35P + 0.094N - 0.066S^2 - 0.0022P^2$	0.86

Table 5
Minimum doses of fertilizer estimated to yield a wood volume equivalent to the V_{NPK}, at 8, 11, 17, 23, 32, and 44 months after planting.

Estimated input of fertilizer required to yield a wood volume equivalent to the VNPK		
S	P_2O_5	N
Mg ha^{-1}	kg ha^{-1}	
3	0	0
4	0	0
7	0	0
15	28	0
15	48	40
15	17	0

3.4. Estimating the time of tree growth by age-shift modeling

The study of response surface modeling also allows estimation of the time of tree growth (T, in months) to yield a wood volume equivalent to 150 $m^3\ ha^{-1}$, as a function of sludge (S, Mg ha^{-1}), N (kg ha^{-1}) and P (P_2O_5, kg ha^{-1}) doses using the following equation: $T = 44.9 - 0{,}26S - 0.05P + 0.005S^2 + 0.00002SP + 0.0004P^2$ ($R^2 = 0.57$, $p < 0.01$). The shorter time required to obtain 150 $m^3\ ha^{-1}$ of *Eucalyptus* wood volume was caused by the sludge doses and to a lesser extent by the P doses (*see below*). Mineral N doses had a significant effect on the time of tree growth; however, the N dose variable was neither adjusted into linear nor quadratic models.

The estimated time of tree growth to obtain 150 $m^3\ ha^{-1}$ of wood volume using the control and using the P recommended dose (84 kg ha^{-1} of P_2O_5) treatments were 45 and 43 months, respectively (Fig. 2). The application of the sludge recommended dose resulted in a shorter time of 42 months. Consequently, this recommendation permitted the *Eucalyptus* plantation to yield 150 $m^3\ ha^{-1}$ of wood volume three months earlier than the plantation using the control treatment (42 *vs* 45 months) and one month earlier than the plantation treated with the P recommended dose (42 *vs* 43 months).

The application of the sludge complemented with 28 kg ha^{-1} of P_2O_5 (Table 6, 1/3 of P recommended dose) provided a time of 41 months (Fig. 2), which would permit the plantation to yield 150 $m^3\ ha^{-1}$ of wood volume four and two months earlier, respectively, than those using the control (41 *vs* 45 months) and the P recommended dose treatments (41 *vs* 43 months).

The application of the sludge recommended dose complemented with 56 kg ha^{-1} of P_2O_5 (Table 6, 2/3 of P recommended dose) resulted in a shorter time of cultivation of 40 months (Fig. 2). This recommendation permitted the *Eucalyptus* plantation to yield 150 $m^3\ ha^{-1}$ of wood volume five months earlier than the plantation using the control treatment (40 *vs* 45 months) and three months earlier than the plantation treated with the P recommended dose (40 *vs* 43 months).

On the whole, there were consecutive gains of two, three, four, and five months in the cultivation time of the planted forest, respectively, with the application of P recommended dose (43 *vs* 45 months), sludge recommended dose (42 *vs* 45 months), sludge recommended dose plus one third P recommended dose (41 *vs* 45 months), and sludge dose plus two third P recommended dose (40 *vs* 45 months).

The likely profit obtained by the lower cost of fertilizers and shorter rotations can offset the costs of transportation and sludge application in *Eucalyptus* plantations as, for example, was found in pine (Wang et al., 2013) and poplar (Ramlal et al., 2009) plantations treated with sludge. Additionally, the reuse of sewage sludge could provide a low-cost alternative for its expensive and complex disposal and management (Guerrini et al., 2017) with, consequently, the possibility of turning currently bulky refuse material into a commodity (Capra et al., 2013).

The results indicate that the use of sewage sludge in commercial *Eucalyptus* plantations can provide new possibilities in management by combining sludge and mineral P fertilizer doses. Such management can increase wood production and reduce the rotation length of a planted forest, compared to conventional fertilization with mineral NPK fertilizers. Therefore, the wood producer will realize increased profits. In addition, the increase in plant biomass implies higher CO_2 sequestration, contributing to a

Table 6
Suggested recommendation for nitrogen and phosphate fertilizer applications for *Eucalyptus grandis* planting, as related to the sewage sludge doses, based on the N criterion.

Sewage sludge application[a]	N	P (P_2O_5)	K (K_2O)	Estimated relative productivity [b]
(%)	kg ha^{-1}			(%)
0	142	84	155	100
50	0	41	155	100
100	0	0	155	99
100	0	28	155	104
100	0	56	155	107

[a] The dose of 100% of sewage sludge is equivalent to the application of sludge at an agronomic dose, in Mg ha^{-1}, based on the N criterion (CONAMA, 2006).
[b] Relative yield of 100% is equivalent to a wood volume estimated at 166 $m^3\ ha^{-1}$ for eucalyptus grown for 44 months (with a mean annual increment of 45 $m^3\ ha^{-1}\ year^{-1}$), under minimum tillage and conventional application of lime and NPK fertilizers, at the recommended doses.

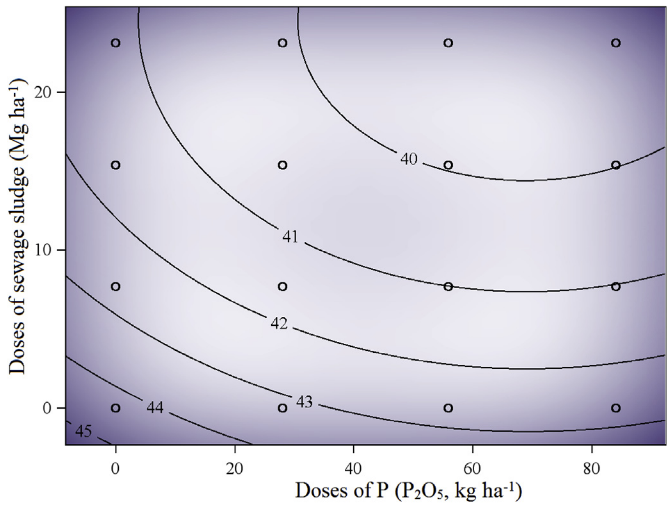

Fig. 2. Time of *Eucalyptus* tree growth (months) to yield 150 m^3 ha^{-1} of wood volume as related to dose of sewage sludge and P fertilizer.

reduction in adverse environmental impacts in terms of excessive greenhouse gas emissions (Miehle et al., 2006; Ramlal et al., 2009).

In spite of the benefits of using sewage sludge to increase the sustainability of planted forests, improving soil quality and plant ecophysiological features, there is still a concern regarding hazardous metal concentrations in soil-plant systems after applying sludge (Kirchmann et al., 2017; Nogueira et al., 2013; Smith, 2009). In the experimental area of the present study, some bioassays, e.g., *Lactuca sativa* L., *Daphnia magna* Straus, and *Pseudokirchneriella subcapitata* (Korshikov) F. Hindák, were used for a toxicity assessment of the soil after application of sludge. (Kirchmann et al., 2017; Nogueira et al., 2013; Smith, 2009). The ecotoxicity test results showed that the application of sludge in soil, by the N criterion, did not cause harmful impacts on the forest system compared to a soil-*Eucalyptus* system treated with mineral fertilizer (Brossi et al., 2007). However, long-term environmental consequences, mainly connected to the introduction of pathogens and heavy metals (Fijalkowski et al., 2017; Kirchmann et al., 2017; Nafez et al., 2015), must be taken into account in future investigations.

4. Conclusions

The wood volume of the *Eucalyptus* plantation increased with application of sewage sludge up to the dose based on the N criterion. The application of sludge based on N criterion reduced the need for N and P fertilizers by 100%; if two thirds of the P recommended dose was applied, wood volume increased by 7% compared to application of mineral NPK fertilizer only. Positive interactions between doses of sludge and mineral P fertilizer on the yield of wood volume were observed; on the whole, higher yield and shorter rotation were realized compared to application of mineral NPK fertilizers alone. In particular, the cultivation time to produce 150 m^3 ha^{-1} of wood volume is reduced by two, three, four or five months, respectively, through application of P recommended dose, sludge recommended dose, sludge dose plus one third of P recommended dose, and sludge dose plus two third of P dose, compared to the control.

The results of this study indicate that sewage sludge application, based on N criteria, provides adequate quantities of N and P. It is suggested that sludge is as efficient as conventional fertilizers in increasing wood production in *Eucalyptus* plantations. On the whole, sewage sludge could represent an excellent alternative for silvicultural management of *Eucalyptus* plantations in unfertile tropical soils.

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