XXXV Congresso Brasileiro de Ciência do Solo
CENTRO DE CONVENÇÕES - NATAL / RN
O SOLO E SUAS MÚLTIPLAS FUNÇÕES
02 a 07 DE AGOSTO DE 2015

Mineral Fertilizers and Sewage Sludge to Increase Wood Production in *Eucalyptus* Plantations in Tropical Soil[1].

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ABSTRACT: Effects of sludge and N and P fertilizer application on the *Eucalyptus* wood volume yielded up to 44 months after planting, and the time needed for the wood production of 150 m^3 ha^{-1} were evaluated. Rates of sludge (0, 8, 15 and 23 Mg ha^{-1}, dry base), N (0, 47, 95, and 142 kg ha^{-1}) and P_2O_5 (0, 28, 56 and 84 kg ha^{-1}) were combined in a 4 x 4 x 4 factorial scheme, in a randomized block design, with two replications. From 8 to 44 months after planting, the sludge application, with or without N and P, yielded wood volume ranging from 0.6 to 192 m^3 ha^{-1}, which was larger than the volume ranging from 0.4 to 166 m^3 ha^{-1} obtained with the application of N and P fertilizers. The response surface study was the basis for a recommendation of N and P fertilizer doses for *Eucalyptus* treated with sludge. The application of sludge on the N criterion reduces the need of N and P fertilizers by 100%, and, if two third of recommended P were applied, increases wood volume by 7% in comparison with the volume yielded by application of NPK fertilizer. The cultivation time to produce 150 m^3 ha^{-1} of wood volume was 45 months for control, and reduced by two, three, four, or five months, respectively, through application of recommended P, sludge recommended dose, sludge plus one third of P, and sludge plus two third of P.

Keywords: Eucalypt, Nitrogen, Phosphorous.

INTRODUCTION

The fertilization with sewage sludge of fast-growing *Eucalyptus* plantations is an alternative to mineral N and P fertilizers because of the higher technical and economic feasibility for the management of this type of waste, and of the sustainability of commercial plantations in infertile tropical soils. The proper nutrient management enhances light, nutrient and water use efficiencies by *Eucalyptus*, and, therefore, increases plant growth and may reduce the cultivation time. Studies on the need for complemental doses of mineral N and P fertilizers to be applied in plantations treated with sludge are still scarce. Planted forests are extremely important in the social, economic, and environmental performance of many countries in the tropical climate regions. The application of sludge can improve soil biological, chemical, and physical properties, and, therefore, increases soil fertility (Abreu-Junior et al., 2005) and the quality of the forest ecosystem (Arriagada et al., 2009). Thus, this treatment improves, or at least maintains, the sustainability of the planted forests (Silva et al., 2008a, 2008b). 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, as compared to N and P contained in mineral fertilizer. However, the concentrations of N and P in sewage sludge are variable. (Abreu-Junior et al., 2005; Franco et al., 2010). There is no information about the capacity of sludge to replace mineral N and P fertilizers on planted forest. Therefore, it is not yet possible to formulate a recommendation for use of sewage sludge to fertilize *Eucalyptus* plantations. 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 cycle and increase forest sustainability and economic returns, as the rotation length of plantations can be shortened.

The objective of this study was to evaluate the effects of doses of sludge and their interactions with doses of N and P fertilizers on the volume of wood, to establish al recommendation for mineral fertilization of *Eucalyptus* plantations, and to analyze implications of any increase in growth on the duration of forest cycle

MATERIAL AND METHODS

The experiment was set up in a commercial *Eucalyptus* field located in the municipality of Angatuba, State of São Paulo, Brazil. This area had not been previously treated with sludge. the soil was classified as Typic Hapludox/Rhodic Ferralsol.

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Before setting up the experiment, the soil was chemically and physically. Concentrations of potentially toxic elements were below the reference values for soils of the São Paulo State (CETESB, 2014), allowing sludge applications in this area.

The sludge was obtained from the Jundiaí Waste Treatment Station, SP. It was generated in a biological system of aerated ponds, with complete mixture, followed by sedimentation ponds for a period of about 12 months. The sludge was characterized conforming to the recommendation of Resolution 375 (CONAMA, 2006). The concentration of potentially toxic elements are below the limits established in Resolution 375, making the sludge suitable for agricultural use.

The sludge was applied, in December 2004, just before planting, at the doses of 0, 8, 15, and 23 Mg ha^{-1}, equivalent to 0, 50, 100, and 150% of the of the recommended N supply, based on the N criterion (CONAMA, 2006). The doses of mineral NPK fertilizers were defined based on technical recommendations of Suzano Company for commercial planting of *Eucalyptus* at the experimental site. Nitrogen, as urea, was applied at the doses of 0, 47, 95 and 142 kg ha^{-1} of N, equivalent to 0, 33, 67 e 100% of the recommendation, in proportions of 1/9 applied upon planting and 8/9 later as side dressing (4, 10 and 23 months after planting). Phosphorus, as triple superphosphate, was applied, at planting only, at the doses of 0, 28, 56 and 84 kg ha^{-1} of P_2O_5, equivalent to 0, 33, 67 and 100% of the recommendation. Potassium was applied at 188 kg ha^{-1} of K_2O, as KCl, on all the plots. The crop management practices to control weed and disease were performed in accordance with Suzano Company for commercial production of *Eucalyptus*. The experimental design was in a randomized block, in a 4x4x4 factorial scheme, with two replications.

The height (H) and the diameter at breast height (DBH) were measured at 8, 11, 17, 23, 32, and 44 months after planting, to estimate the wood volume per hectare ($V = 1.7x10^{-5} \times DBH^{1.9117} \times H^{1.3065}$). For each plot, the individual volume of ten trees was summed and the wood volume per hectare was estimated. The data were submitted to multiple regression for response surface modeling: $V = a + bS + cN + dP + eSN + fSP + gPN + hS^2 + iP^2 + jN^2$, 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 analyze the effect of the sludge, N, and P doses on the dependent variables by means of response surface modeling.

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 (Kimberley et al., 2004) was studied. The Gomportz curve proved suitable for predicting the time required to obtain a fixed wood volume of 150 m^3 ha^{-1} in each treatment. This value was defined considering the average volume obtained at the time of 44 months by all the treatments without application of sludge. In the second step, a study was developed by 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. All statistical analyses were performed using the SAS system, with a significance level of 10%.

RESULTADOS E DISCUSSÃO

Our results (**Table** 1) are indicative of very high potential of wood productivity for tropical *Eucalyptus* plantations, with mean annual increment of 44 and 45 m^3 ha^{-1} $year^{-1}$, or of 308 and 315 m^3 ha^{-1} for 7 year rotation, due to the application of sludge recommended dose and of mineral NPK fertilizer, respectively, for soils with moderate concentration of P and low concentration of K, and under minimum tillage and application of lime and NPK fertilizers at recommend doses. In Brazil, the current mean annual increment is 40.7 m^3 ha^{-1} $year^{-1}$. However, Stape et al. (2006) had estimate 62 m^3 ha^{-1} $year^{-1}$ as the potential productivity for *Eucalyptus* plantations.

The increase in *Eucalyptus* wood volume with the sludge application was due to the nutrient supply and organic matter added to the forestry plantation. Previous studies have shown that the use of sludge as fertilizer can improve chemical, physical and biological soil properties, and, therefore, its fertility and ability to boost plant growth (Abreu-Junior et al., 2005; Arrigada et al., 2009; Franco et al., 2010; Kimberley et al., 2004). The losses by N by leaching and/or volatilization and by P adsorption are greater than in slow-release conditions, which may compromise the absorption efficiency of these nutrients by the roots of plants (Silva et al., 2008a, 2008b). This explains the equivalent effect of sludge application on wood volume compared to the conventional application of mineral NPK fertilizer, indicating that the use of this waste in planted *Eucalyptus* forests promotes the entry of N and P in the soil-plant system (**Table 1**). Similar finding was also reported by Silva et al. (2008a, 2008b).

The application of sludge at the recommended dose, based on the N criterion, had greater wood volume than the mineral NPK treatment until 17 months after planting, since just 55% of the total of

mineral N was applied at this time. The N fertilization was completed at 23 months after planting, which explains the need of the recommended sludge dose be complemented with N and P to yield a wood volume similar to the NPK treatment at 23 and at 44 months after planting (**Table 1**). The complete application of N at 23 months after planting may have positively influenced the P uptake by the root system of *Eucalyptus* plant, mainly in the NPK fertilizer treatment. The height of *Eucalyptus* plantations is increased with the P fertilization when the N content in soil is suitable for this type of cultivation. Phosphorus uptake by *Eucalyptus* plant is strongly influenced by appropriate supply of N in soil (Graciano et al., 2006). Consequently, the effect of P fertilization on plant growth may be minimal when N availability in soil is the limiting, and vice versa.

Increases in wood volume at the sludge recommended dose complemented with 28 or 56 kg ha^{-1} of P_2O_5, without N addition (**Table 2**), indicates that the management of the sludge with P fertilizer provides better physical, chemical and biological conditions of the soil. Under these conditions, nutrient and water uptake and use by *Eucalyptus* plants are more efficient (Stape et al., 2006). Notwithstanding, the effect of the sludge recommended dose solely on the wood volume was 99% of that of the mineral NPK treatment. The efficiency of sludge management was likely due to the degradation of organic matter by improving the soil biota quality. The variety, number and activity of microorganisms found in forest soils are much higher than those in soils with annual crops (Arriagada et al., 2009), which might enhance the turnover of organic matter and nutrients.

A high production of wood by forest depends, besides water and nutrient availability, on the maintenance of the tree leaves canopy intercepting a high proportion of solar radiation (Gspaltl et al., 2013). When nutrient and water supplies are adequate for plant development, plants allocate carbon preferentially in leaves and stems instead of roots. On the contrast, plants growing in unfertile soil have high dry matter allocated on roots instead of canopy (Gspaltl et al., 2013). The higher light, nutrient and water use efficiencies by *Eucalyptus* plants explain the higher wood production as function of sludge doses.

Good silvicultural practices coupled with adequate inputs of nutrients are required for high growth and short rotations of tropical *Eucalyptus* plantations (Smethurst, 2010; Stape et al., 2006). Consequently, the rotation length can be reduced. The estimated time needed for the *Eucalyptus* plant to yield 150 m^3 ha^{-1} of wood volume, which was 45 months for the control treatment, decreased with doses of sludge and of mineral P fertilizer (**Figure 1**). 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, sludge recommended dose, sludge recommended dose plus one third P recommended dose, and sludge dose plus two third P recommended dose. The likely profit obtained by the lower cost of fertilizers and short rotations can offset the costs of transportation and sludge application in *Eucalyptus* plantations as, for example, it was found in pine plantation treated with sludge (Kimberley et al., 2004).

CONCLUSIONS

The application of sludge at dose base on the N criterion reduces the need of N and P fertilizers by 100%, and, if two third of P recommended dose were applied, increases wood volume by 7% as compared to application of mineral NPK fertilizer only. 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, as compared to control. The sewage sludge is an excellent alternative for silvicultural management of the *Eucalyptus* plantation in tropical soils.

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Table 1. Wood volume of *Eucalyptus grandis* plantation yielded by the application of 15 Mg ha^{-1} of sludge based on the N criterion ($V_{S100\%}$) and by the conventional application of mineral NPK fertilizer (V_{NPK}), and the lower dose of sludge (S) with the lower doses of N and P_2O_5.

Time	$Vs_{100\%}$	V_{NPK}	Input required to yield a wood volume equivalent to the V_{NPK}		
			S	P_2O_5	N
Months	— m^3 ha^{-1} —		Mg ha^{-1}	----- kg ha^{-1} -----	
8	1	0.4	3	0	0
11	7	4	4	0	0
17	24	23	7	0	0
23	44	46	15	28	0
32	95	112	15	48	40
44	163	166	15	17	0

Table 2. 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 agronomic dose, in Mg ha^{-1}, based on the N criterion (CONAMA, 2006).

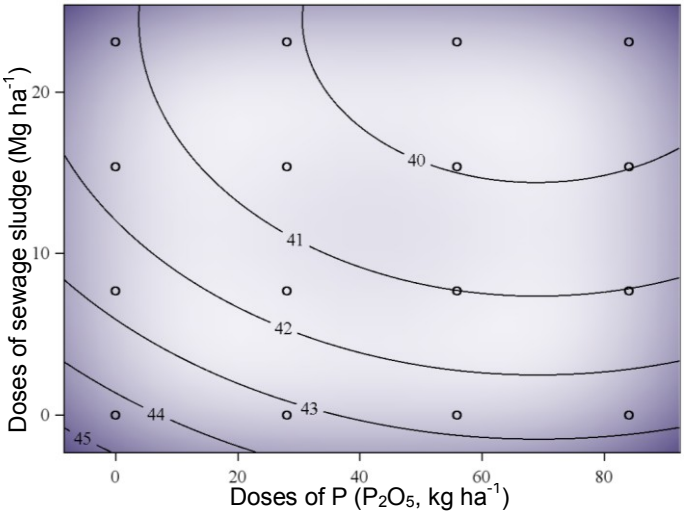

Figure 1. Time of *Eucalyptus* tree growth (months) to yield 150 m^3 ha^{-1} of wood volume as related to doses of sewage sludge and P fertilizer.