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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