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Effect of pulp and paper mill sludge on the development of 17-year-old loblolly pine (*Pinus taeda* L.) trees in Southern Brazil

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A R T I C L E I N F O

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A B S T R A C T

Pinus taeda is a principal conifer tree species and has long been used in forest plantations in Southern Brazil. At the same time, experiments have been carried out in order to determine the wood productivity concerning the economic, social and sustainable forest management practices. In that sense, the organic fertilizers, such as the biosolid residues from pulp and paper industries, are one of the alternatives to achieve this sustainability. Nevertheless, few studies addressing this objective have been reported in Brazil. This study aimed to analyze the growth responses of loblolly pine trees treated with different doses of composted pulp-mill sludge and to propose a management guide based on a wood production simulation. A randomized block design with four replicates for every six treatments - control, 20, 40, 60, 80 and 100 $t\,ha^{-1}$ of composted pulp-mill sludge - were carried out in an experimental plantation located in Arapoti, Paraná state, Brazil. Ten 17 year-old-trees for each treatment were selected, the stem variables were analyzed and the stand wood productivity for the optimal dosage was simulated. The trees were significantly influenced by the application of the composted pulp-mill sludge, increasing up to 24, 37 and 127% in stem diameter, height and volume, respectively, and the rotation of the pine plantation control and treated stands was 33 and 21 years, respectively. The forest management applied for a 21-year harvesting cycle (thinning at 7 and 13 years) with 84 $t\,ha^{-1}$ of composted pulp-mill sludge resulted in a wood productivity of 11.9 $m^3\,ha^{-1}$ or 5.04 $Mg\,ha^{-1}$ per year. The results confirm the potential application of pulp-mill sludge as a fertilizer to improve the wood productivity of forest plantations established in poor-nutrient sites. Also, the forest management plans, using the guide proposed, could be replicated in loblolly pine and other tree species plantations according to the end use of wood.

1. Introduction

In Southern Brazil, Paraná and Santa Catarina states have 76.6% of the pine plantations and contribute with 22% of the commercial timber from national forest plantations (IBA, 2016). *Pinus taeda* is the most planted species (Vasques et al., 2007) due to its higher growth rates (35 $m^3\,ha^{-1}\,year^{-1}$; 18 year rotation) and economic importance represented by an internal return of 24% (Cubbage et al., 2007). Consequently, different studies to understand the effects of management practices on the development and productivity of *P. taeda* stands have been performed in this region (e.g. Bognola et al., 2010; IPEF, 2012; Cardoso et al., 2013; Kohler et al., 2015).

One of the management practices directly related to the wood productivity is fertilization (Will et al., 2002). This can be expensive due to the cost of inorganic fertilizers (Vance, 2000). Thus, the non-conventional fertilizers, such as mill residues, are an alternative to reduce the costs of this activity (Vance, 2000; Faria et al., 2015b; Ferraz et al., 2016).

Examples of these mill residues considered environmentally and economically important are the pulp and paper-mill biosolids that reach up to 48 tons of residues per 100 tons of cellulose (Bellote et al., 1998; Arruda et al., 2011). However, the high C:N ratio of pulp and paper-mill biosolids is a major limitation for their application in soils (Vance, 2000). Potential uses of pulp and paper-mill biosolids to improve the soil physical and chemical properties, especially the degraded soils, have been reported (Brockway, 1983; Bockheim et al., 1988; Bellote et al., 1998; Jackson et al., 2000; Faria et al., 2015a,b; Corbel et al., 2016), principally, after practices to reduce the C:N ratio, such as composting and pre-conditioning (Cabral et al., 1998).

Several studies have reported that pulp and paper-mill sludge (PMS)

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may benefit nutrient-limited forest plantations (Young et al., 1993; Henry et al., 1994; Feldkirchner et al., 2003). Furthermore, forest plantations are an attractive alternative for the paper companies for recycling pulp and paper-mill biosolids (Feldkirchner et al., 2003). This is supported by successful studies of forest companies in the United States demonstrating that fertilizer reduced costs and increased forest productivity (Vance, 2000). However, no consistent results for Brazil were found in the bibliography reporting the *P. taeda* tree growth responses to PMS application, including complete rotation and with a forestry management approach. Furthermore, it is necessary to contribute with examples of forest plantations under these residues that attend the national environmental regulations, such as the Brazilian Environmental National Council Resolution 481 (BRAZIL, 2017). On the other hand, there is information available on the growth response of *P. taeda* trees to nutrients incorporated in the soil with fertilizer treatments as an intensive forest management practice (Albaugh et al., 2004; Samuelson et al., 2004). Consequently, in this study, in addition to the references on PMS effects, other information about fertilization treatments in *P. taeda* plantations is discussed.

Thus, to contribute to decrease the mentioned gaps, we analyzed the development of *P. taeda* trees treated with doses of composted pulp-mill sludge as input for the soil chemical improvement, including the optimal dosage. In addition, a production simulation was performed to propose a management guide for *P. taeda* plantations using composted pulp-mill sludge.

2. Material and methods

2.1. Study area

The experimental area was located on the Matarazzo Farm, Jaguariaíva, Paraná state, Brazil (24°15′ S, 49°42′ W; 872 m a.s.l.; slope 3–8%) (Fig. 1A). The area is characterized by a subtropical moist mesothermic climate (Cfb under Köppen classification), with frequent and severe frost occurrence. The temperature is moderate, with an annual average of 18.1 °C. The average annual rainfall is 1323 mm, with a dry season between July and August (Fig. 1B). The soil is classified as dystrophic Red-Yellow Latosol, according to the Brazilian Soil Classification System (EMBRAPA, 2006). It has a medium texture with a clay content of less than 35% and a sand content of more than 15%, strongly drained and extremely acidic (pH < 4.3), poor in macronutrients for plants, low organic matter content (10.7–14 g dm^{-3}) and low cation exchange capacity (5–5.7 $cmol_c$ dm^{-3}) (Rodrigues et al., 2005).

Table 1
Chemical element concentration of composted pulp-mill sludge for each treatment.

CPMS		Treatment (t ha^{-1})					
Chemical element	Concentration (g kg^{-1})	Control	20	40	60	80	100
		(kg ha^{-1})					
N	2.1	0	42	84	126	168	210
P	7.4	0	148	296	444	592	740
K	0.9	0	18	36	54	72	90
Ca	4.8	0	96	192	288	384	480
Mg	1.3	0	26	52	78	104	130

The nutrient concentration refers to the composted pulp-mill sludge after two years of decomposition, 9:1 C:N ratio. Table constructed based on the information described in Rodrigues et al. (2005) for a previous study at the same experimental area and forest plantation.

2.2. Experiment design and treatments

An area of 3.5 ha of *Pinus taeda* planted at 3 × 2 m spacing was established in June 1996 in a complete randomized block design with six treatments and four replicates, for a total of 24 blocks (400 m^2; seven rows; 13 plants each). Five internal lines/block (12 trees/line/block and 60 trees/replicate) were selected to avoid the edge effect. Each treatment consisted of different doses of composted pulp-mill sludge (CPMS) as input for the chemical soil preparation (Table 1). The CPMS corresponds to the thermochemical process disposal, the paper cleaning machines, discarded fibers and impurities (due to size heterogeneity) unsuitable for the production of cellulose and paper. The CPMS was composted for 2 years in the open air to reduce the high C:N ratio (initial 150:1 and final 9:1) and distributed on the soil surface at the planting period and incorporated into the soil with a rotary spade.

After the establishment of *P. taeda* trees, a mortality index of 1.1% (19 trees) was registered and to reduce the competition the understory vegetation between the planting lines was cut in the 2nd year (July 1998). Then, a selective thinning of 53.4% of the stand density (940 smaller *P. taeda* trees) was conducted in the 9th year (June 2005), final

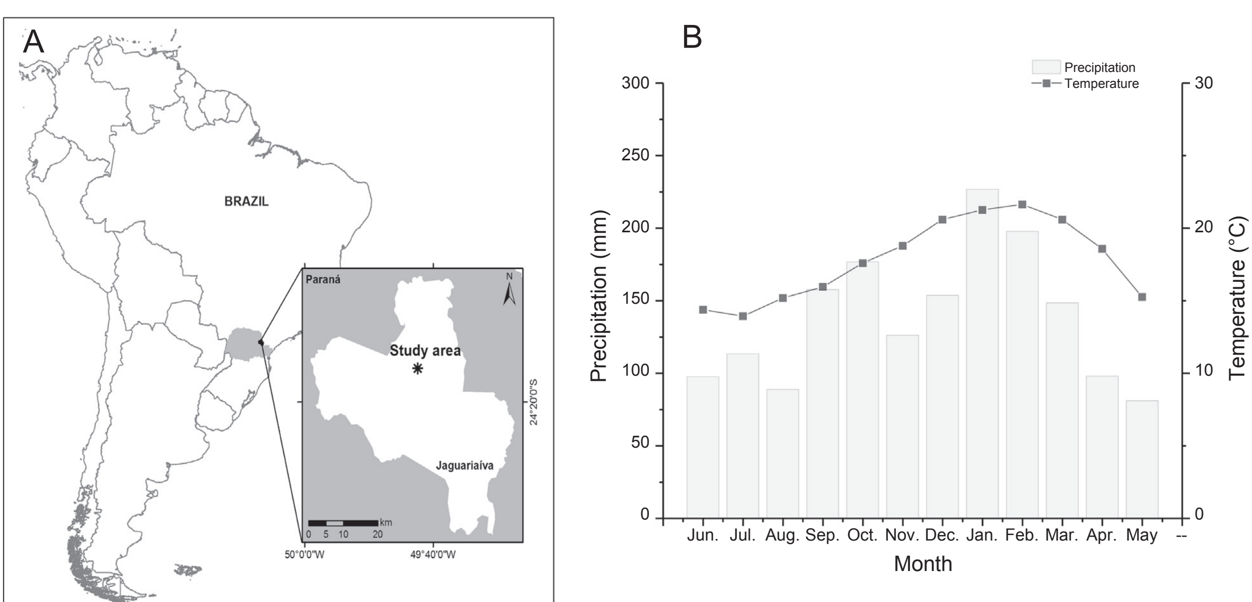

Fig. 1. Location (A) and climate variability (1996–2013) of the region (B) (KNMI, 2017).