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Original Article

Silviculture

Initial Growth of *Pinus taeda* by Fertilization Response at Planting

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ABSTRACT

The objective of this study was to evaluate how the fertilizer composition, type and application method contribute to the initial growth of *Pinus taeda* applied at planting. Seedlings from an open-pollinated seed orchard of *Pinus taeda* were planted on a Humic Dystrudepts soil containing 15 treatments of fertilizer application at planting. Basal diameter (immediately above ground – about 5 cm) and total height were measured on all live plants after six, 12 and 42 months. The basal diameter at six and 12 months ranged from 0.49 to 0.63 cm and 1.64 to 2.15 cm, respectively. The height at six and 12 months ranged from 0.49 to 0.64 m and 0.77 to 1.01 m, respectively, indicating that fertilizing improved this characteristics in ~30%. Fertilizer composition, type and application method contributed to the first year of growth of *Pinus taeda*. Nevertheless, fertilization response disappeared after 42 months.

Keywords: loblolly pine, NPK, fertilizer, orthogonal contrast, forestry.

1. INTRODUCTION

Sustainability is a moving target in forest management. Mineral fertilization must balance productivity with low costs of production and fertilizer doses should be appropriate and correctly applied (Silva et al., 2013).

To improve upon sustainable management of short-rotation plantations, especially when nutrient deficiencies are common, fertilization plans based on better knowledge on tree physiology, forest nutrition and growth characteristics are required (Alvarado, 2015).

Forest productivity is driven by the water availability and nutrient resources; then, fertilization is a tool that forest managers can use to manipulate resource availability and resources to individual trees within a stand. Fertilization increases resource availability by the direct application of limiting nutrients and influences quality and plants development in the field (Albaugh et al., 2012, 2017; Grossnickle, 2012). In addition, fertilization can compensate for decreased water availability by increasing the efficiency of stem volume production per unit of leaf area for *Pinus taeda* stands (Maggard et al., 2017). Fertilization regimes have been developed to enable foresters to match nutrient supply with the stand demand. Depending on the soil type, various types and amounts of fertilizer may be added (Fox et al., 2004), regarding several applications of nutrients in optimum nutrition regimes, which may further accelerate tree growth (Sullivan & Sullivan, 2017). Pine stand fertilization has been an operational practice in the United States since the late 1960s (Everett & Palm-Leis, 2009), and it is a common practice worldwide to mid-rotation responses to fertilization after the first or second thinning (Fox et al., 2007; Carlson et al., 2008; Campoe et al., 2010; Alzate et al., 2016; Zhao et al., 2016; Albaugh et al., 2017).

Fox et al. (2007) concluded that financial return after fertilization depends on the growth response, the cost of the fertilizer treatment, and the stumpage value of the timber produced. The internal rate of return from mid-rotation fertilization of a loblolly pine plantation with N and P would be approximately 16%.

Despite of being a common practice in forest plantations, fertilization in pine stands in Brazil is not normally performed, mainly because it is believed that pine trees are not able to respond to mineral fertilizations. However, by the reduction of the production period, successive plantations, and the absence of periodic fertilization, the production sustainability of pine stands may be compromised. As the pine tree plantation in Brazil is very representative, around 1.6 million hectares in 2016 (IBA, 2017), it is necessary to research how to sustain the soil fertility to maintain or even increase the pine stands productivity. The objective of this study was to evaluate how the fertilizer composition, type and application method contribute to initial growth of *Pinus taeda* applied at planting.

2. MATERIAL AND METHODS

2.1. Study area and experimental design

The study was established in Rio Negrinho, Santa Catarina state, Brazil (26°40' S and 49°98' W). The area is located at Primeiro Planalto Catarinense, Koppen's climate classification Cfb, Humid Subtropical zone with temperate summer (Alvares et al., 2013). Annual average precipitation is 1,700 mm, average annual temperature is 18 °C, average minimum and maximum temperature are 13 °C and 23 °C, respectively, with an average of 10 frost days annually (EPAGRI, 2009).

Seedlings from an open-pollinated seed orchards of *Pinus taeda* were planted on a Humic Dystrudepts soil (Souza et al., 2017), previously used under grazing by cattle. The seedlings were selected by keeping the same morphological and biometrics characteristics. Soil was prepared by a subsoiler to reduce soil compaction before planting by hand on a 2.5 m × 2.5 m spacing. The chemical analysis of the soil before implementation of the experiment is described in Table 1.

A randomized complete block design was installed with eight replications containing 20 plants each plot, where 15 treatments of fertilizer application were evaluated according to Table 2. They were applied as a base fertilization in a single dose during planting. The dosages were selected according to the type (brand) recommendations.

The "mixed to soil" application method was considered by the standard form of fertilizer application, where the fertilizer was blended to the soil by a hoe after the opening of the planting hole. On the other hand, "in contact to the roots", the fertilizer was applied after the opening of the planting hole and was not mixed to soil,

Table 1. Chemical and physical soil analysis before planting.

Depth	pH	P	K	Ca	Mg	Al	H+Al	CEC	Clay	Silt	Sand
(cm)	SMP	mg dm^{-3}		Cmol$_c$ dm^{-3}					g Kg^{-1}		
0-20	4.2	3.5	31	0.7	0.4	11.8	28.1	29.3	552	393	55
20-40	4.2	2.4	51	0.7	0.4	10.5	28.1	29.3	585	360	55

pH in $CaCl_2$ was determined in a 1:2.5 (v:v) soil:solution ratio; K and P were extracted with MEHLICH-1 and determined by flame photometry and spectrometry, respectively; Ca, Mg and Al were extracted with KCl 1 mol L^{-1} and determined by spectrometry; H+Al was estimated by the pH SMP method; CEC = cation exchange capacity – was estimated by the sums of exchangeable cations; Clay and Silt fractions were obtained by repeated gravitational sedimentation in water; Sand fraction was recovered as the sediment left.

Table 2. Treatments applied by the dose, composition type and application method at planting.

Treatment	Dose	Composition	Type	Application
T1	Control			
T2	50 g/plant	NPK 0-42-0	A	Mixed to soil
T3	100 g/plant	NPK 0-42-0	A	
T4	150 g/plant	NPK 0-42-0	A	
T5	150 g/plant	NPK 8-20-10	B	
T6	150 g/plant	NPK 8-20-10	B	
T7	100 g/plant	NPK 0-32-0	C	
T8	12 g/plant	NPK 0-23-14 + Mg, S, B	D	In contact to the roots
T9	18 g/plant	NPK 0-23-14 + Mg, S, B	D	
T10	12 g/plant	N - 44%	E	
T11	21 g/plant	NPK 20-10-5 + Mg, Ca + Micro	F	
T12	42 g/plant	NPK 20-10-5 + Mg, Ca + Micro	F	
T13	8 g/plant	NPK 16-7-15 + Mg, S, Fe	G	
T14	10 g/plant	NPK 16-7-15 + Mg, S, Fe	G	
T15	12 g/plant	NPK 16-7-15 + Mg, S, Fe	G	

where the seedling was put in contact to the fertilizer by its substrate, and the hole was filled with soil.

An operational vegetation control treatment was frequently applied to plots to reduce competing vegetation, allow better access to the plants for measurements and prevent differential development of competing vegetation across the treatments.

2.2. Measurements and statistical analysis

Basal diameter (immediately above ground – about 5 cm) and total height were measured on all live plants after six, 12 and 42 months. Surviving was measured by counting the number of live plants per plot after 42 months. Individual tree volume was estimated by the solid volume of a cone, according to Vallet et al. (2006).

Statistical analysis was performed separately for each parameter. Differences between treatments were tested using ANOVA. Normality and homogeneity of variances tests were examined by Lilliefors and Cochran tests, respectively. Post-hoc means comparisons were carried out using Tukey test. The level of significance of statistical tests throughout this study is 0.05. All of the statistical analyses were performed using IBM SPSS 19 software package.

Aiming better answers on the influence of the used characteristics in the treatments, comparisons between the means of type and application method were also obtained by orthogonal contrasts, according to Table 3.

3. RESULTS AND DISCUSSION

3.1. First year of growth

The evaluation at six and 12 months is important to understand the fertilization effects during the initial growth phase, during which cultural tending is unpredictable. Results showed significant differences between the treatments, evidencing the importance of fertilization for the initial growth of *Pinus taeda* (Table 4). Fertilizing at planting has little effect on site fertility, but promotes the development of a vigorous root system, which allows for continually improved growth (Alvarado, 2015).

The basal diameter at six and 12 months ranged from 0.49 to 0.63 cm and 1.64 to 2.15 cm, respectively, indicating that fertilizing improved this characteristic in ~30%. The height at six and 12 months ranged from 0.49 to 0.64 m and 0.77 to 1.01 m, respectively, also equivalent to ~30% of enhanced growth.

At the two evaluation occasions, the treatments T8 and T9 presented averages of diameter and height statistically superior to most of them, at the same time that the control treatment and T10 presented the lowest means.

Several studies have demonstrated the importance of fertilization for the increase of productivity in pine plantations, most of them are fertilization by phosphorus and nitrogen (Hunter et al., 1986; Tiarks & Haywood, 1986; Vose & Allen, 1988; Fife & Nambiar, 1997; Dedecek et al., 2008; Albaugh et al., 2017).

In a N and P fertilization study developed by Hunter et al. (1986) in New Zealand, the largest responses occurred in stands that had received fertilizer at an early age and were in soils poor in N availability such as sandy soils. In addition, Vose & Allen (1988) reported, for an N deficient site, the highest volume

Table 3. Description of orthogonal contrasts used, comparing application method and fertilizer type.

Contrast	Mean comparison	Comparison
Y1	***6*** (T8 + … + T15) – ***8*** (T2 + … + T7)	In contact to the roots vs. Mixed to soil
Y2	T2 + … + T7 – ***6*** T1	Mixed to soil vs. Control
Y3	T8 + … + T15 – ***8*** T1	In contact to the roots vs. Control
Y4	T2 + T3 + T4 – ***3*** T1	Type A vs. Control
Y5	T5 + T6 – ***2*** T1	Type B vs. Control
Y6	T7 – T1	Type C vs. Control
Y7	T8 + T9 – ***2*** T1	Type D vs. Control
Y8	T10 – T1	Type E vs. Control
Y9	T11 + T12 – ***2*** T1	Type F vs. Control
Y10	T13 + T14 + T15 – ***3*** T1	Type G vs. Control

Table 4. Diameter and height averages at six and 12 months after fertilizer application at planting of *Pinus taeda*.

Treatment	Diameter (cm) six months	Diameter (cm) 12 months	Height (m) six months	Height (m) 12 months
T1	0.49 d	1.67 c	0.48 d	0.80 c
T2	0.54 c	1.78 b	0.52 b	0.89 b
T3	0.57 b	1.85 b	0.52 b	0.87 b
T4	0.56 b	1.86 b	0.51 b	0.94 b
T5	0.49 d	1.64 c	0.49 c	0.86 b
T6	0.50 d	1.67 c	0.49 c	0.84 b
T7	0.52 c	1.89 b	0.49 c	0.93 a
T8	0.62 a	2.02 a	0.53 a	0.95 a
T9	0.63 a	2.15 a	0.54 a	1.01 a
T10	0.50 d	1.51 c	0.48 d	0.77 c
T11	0.61 a	1.88 b	0.53 a	0.91 b
T12	0.58 b	1.88 b	0.53 a	0.90 b
T13	0.57 b	1.88 b	0.52 b	0.88 b
T14	0.58 b	1.85 b	0.52 b	0.87 b
T15	0.57 b	1.87 b	0.51 b	0.87 b

Averages followed by the same letter in the same column did not differ significantly at 5% probability by Tukey test.

production for the highest application of N fertilizer (336 kg ha^{-1}).

Tiarks & Haywood (1986) observed an increase of *Pinus taeda* volume at age 5 years to 26 m^3/ha, compared to 12 m^3/ha without the treatments, when they evaluated a complete fertilizer (112 kg of nitrogen, 49 kg of phosphorus, and 93 kg of potassium per hectare) applied at planting, and control of herbaceous for the first 4 years. The fertilizer contained nitrogen, phosphorus, and potassium, but analysis of pine foliage indicates that phosphorus was the element causing the pine response to the fertilizer (Tiarks & Haywood, 1986).

Fife & Nambiar (1997) indicated that the amount of translocated foliar N within the tree increased with increasing rate of N application and contributed to the growth response of trees for five years after nitrogen fertilizer application.

To evaluate the influence of the site on the growth of *Pinus taeda*, Dedecek et al. (2008) selected eight different sites of at 22 years old stands, in Telêmaco Borba, southern Brazil. The authors concluded that the most productive sites presented higher levels of K and P, higher pH, higher base saturation and lower saturation by Al. They also stated that the water content available in the soil was the variable that best correlated with the growth of *Pinus taeda*.

Two levels of fertilization (none and 224 and 28 kg ha^{-1} of elemental nitrogen and phosphorus, respectively) were applied on trees between 10 and 15 years old in an experiment elaborated by Albaugh et al. (2017). The authors concluded that at six years after treatment, fertilizer significantly increased the diameter, stand basal area and stand volume increments.

The best fertilizer responses to treatments T8 and T9 is probably due to the best availability of nutrients because they are closer to the roots. For a better understanding, treatments were compared by using orthogonal contrasts (Table 5).

Contrasts Y1 and Y3 (comparison between "in contact to the roots" and "mixed to the soil" or "control", respectively) were significant for the diameter and height at six months, evidencing the importance of easy availability of the elements to the plant utilization. In addition, through the evaluation of contrast Y2 (comparison between "mixed to the soil" and "control"), it is seen that there were no significantly differences to diameter and height at six and 12 months, fact that could prove that the elements closer to the roots would facilitate their plant absorption during the initial growth phase.

The mobility and availability of nutrients to the plants could limit the productivity and yield of forest stands (Vadeboncoeur, 2010). Phosphorus in the soil is known as less mobile and bioavailable than other macronutrients (Hinsinger et al., 2011), and requires using effective soil management systems and fertilization practices to increase its efficiency and bioavailability (Barrow & Debnath, 2014).

On the other hand, nitrogen in the soil is more mobile than other macronutrients. In addition, nitrogen can result in toxicity symptoms when the

Table 5. Difference between the means of comparison of the assessed orthogonal contrasts diameter (cm) and height (m) at six and 12 months.

Contrast	Diameter six months	Diameter 12 months	Height six months	Height 12 months
Y1	0.45 **	0.80 ns	0.14 *	0.08 ns
Y2	0.21 ns	0.69 ns	0.11 ns	0.49 ns
Y3	0.73 **	1.68 ns	0.35 **	0.72 *
Y4	0.18 *	0.49 ns	0.12 **	0.28 ns
Y5	0.01 ns	-0.02 ns	0.03 ns	0.08 ns
Y6	0.03 ns	0.22 ns	0.02 ns	0.13 *
Y7	0.26 **	0.83 **	0.12 **	0.35 **
Y8	0.01 ns	-0.16 ns	0.00 ns	-0.03 ns
Y9	0.21 **	0.42 ns	0.11 **	0.20 ns
Y10	0.24 **	0.59 ns	0.13 **	0.21 ns

ns = not significant by t-test ($p > 0.05$); *significant by t-test ($p < 0.05$); **significant by t-test ($p < 0.01$).

dosage is higher than the one recommended (Britto & Kronzucker, 2002). Plants at treatment T10, which presented the lowest means of diameter and height at six and 12 months, could have experienced some toxicity as the fertilizer was put in contact to the roots (Table 4). In addition, most of the applied N might have been taken up by the trees or leached below the rooting zone within one year after application (Fife & Nambiar, 1997).

Contrast Y7 (comparison between "Type D, NPK 0-23-14 + Mg, S, B" and "control") showed significant results for all comparisons, indicating to be efficient to the diameter and height to the first year of growth. Contrasts Y4 (comparison between "Type A, NPK 0-42-0" and "control"), Y9 (comparison between "Type F, NPK 20-10-5 + Mg, Ca + Micro" and "control") and Y10 (comparison between "Type G, NPK 16-7-15 + Mg, S, Fe" and "control") were statistically significant only to the diameter and height to the first six months.

3.2. Forty-two months of growth

There were no significant differences between treatments for diameter ($p = 0.982$), height ($p = 0.991$), individual volume ($p = 0.978$) and survival (0.107) after 42 months of *Pinus taeda* growth (Figure 1).

Plant diameter and height oscillated from 3.26 cm (T9) to 3.43 cm (T3), and 4.6 m (T9) to 4.91 m (T13), respectively. Plant individual volume and survival ranged from 1,935 cm^3 (T9) to 2,271 cm^3 (T13), and 95.6% (T5) to 97.5% (T3), respectively. The volume per ha estimated by individual volumes, spacing (2.5 m × 2.5 m) and survivals ranged from 2.99 m^3/ha (T9) to 3.5 m^3/ha (T13).

Current fertilization regimes focus on maintaining N and P supply, although significant growth increases in the future are likely to occur from this more sophisticated management of nutrient availability (Fox et al., 2004). Yet, results have reported the efficiency of fertilizer application for pine tree stands, although most of them evaluated the influence of fertilizer application after thinning (Carlson et al., 2008; Alzate et al., 2016; Albaugh et al., 2017).

Data from 43 installations of a nitrogen and phosphorus mid-rotation fertilizer trial series established in the southeastern United States were analyzed by Carlson et al. (2008), which investigated how the diameter distribution of *Pinus taeda* L. stands changes. The results indicated that both the absolute growth response and the relative growth response of individual trees were greater among the largest trees.

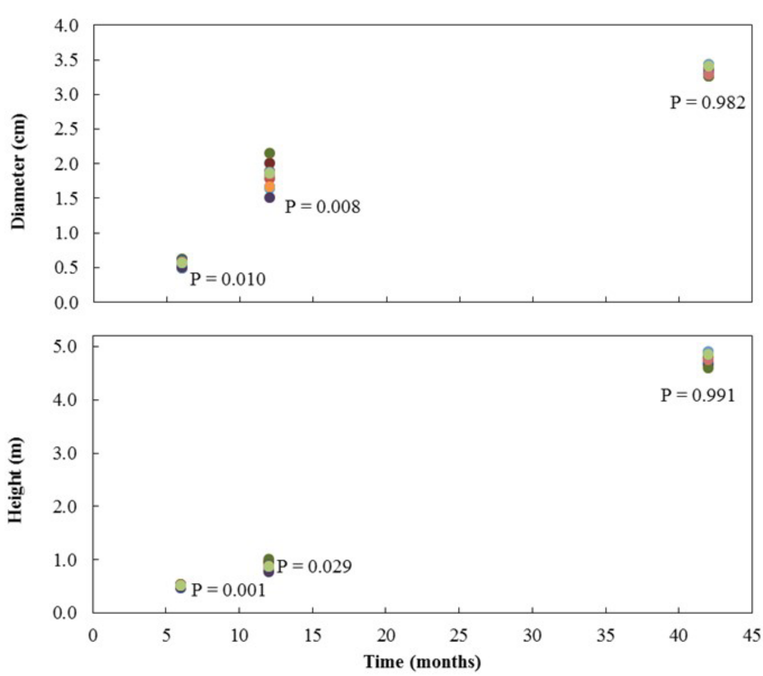

Figure 1. Diameter and height of *Pinus taeda* at six, 12 and 42 months after fertilizer application at planting.

Alzate et al. (2016) assessed the effects of nitrogen (150 and 300 kg N ha^{-1}) and phosphorus (0, 20 and 40 kg P ha^{-1}) in three mid-rotation *Pinus radiata* plantations after thinning at three contrasting sites. The authors found that nitrogen and phosphorus were limiting at both granitic and sandy sites, and high fertilization doses would ameliorate nutrient resource limitations and yield a cost-effective increment in stand volume.

Albaugh et al. (2017) installed a thinning and fertilization study in a 12-16 years old mid-rotation *Pinus taeda* L. stands in southeastern United States. The authors found that 224 and 28 kg ha^{-1} of elemental nitrogen and phosphorus, respectively, increased diameter and stand basal area increments.

It was observed that fertilization at planting positively and significantly affected *Pinus taeda* growth during the first 12 months after planting. However, this enhancing effect disappeared at 42 months. Operational recommendations in this regard should consider whether the higher diameter and height growth during the first 12 months contribute, for example, to reducing tending costs. This would be an argument for recommending fertilization for *Pinus taeda* plantations in southern Brazil.

On the other hand, it is necessary to look further in the production period. Since fertilization showed no significant effect at 42 months of age, for maintaining the highest growth levels observed during the first 12 months, it might be necessary to keep performing fertilization periodically, before or after thinning, as widely described in the United States. Repeated fertilization regimes were recommended to enhance growth of pine plantations in the southeastern United States (Bartkowiak et al., 2015). According to Alvarado (2015), the frequency of pine fertilization depends on the natural fertility of the soils and silvicultural practices, recommending fertilization at 0, 7, and 12 years when soil fertility is high; and at 0, 1, 3, 5, 7, and 12 years when natural soil fertility is low. As the fertility of the evaluated soil was already considered sufficient (Table 1), the plants response to fertilizers was not consistent. It is worth considering a fertilizer recommendation trial in sites of low fertility, where possibly the effect could be longer lasting and consequently efficient.

Substantial volume increase was found in young ponderosa pine plantations in northern California, USA, by Wei et al. (2014), although these trees were fertilized four times, reinforcing the need of repeated fertilizations.

4. CONCLUSIONS

Fertilizer composition, type and application method contributed to the first year of growth of *Pinus taeda* when fertilizer was applied at planting and in contact to the roots, resulting in growth rates ~30% higher than the control. Nevertheless, this enhanced growth level as a result of fertilization disappeared after 42 months.

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