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Response of *Eucalyptus grandis* in Colombia to mid-rotation fertilization is dependent on site and rate but not frequency of application

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ABSTRACT

A nutrient dose and application frequency study was installed in *Eucalyptus grandis* stands at six sites in the Colombian Andes to examine three hypotheses: (1) individual sites have different treatment responses (there is a significant site effect); (2) the relationship between volume growth response and applied nitrogen is not linear (there is an optimal amount of applied nitrogen beyond which growth improvements would be small); and (3) application frequency does not affect response if the cumulative dose applied is equivalent (there is no frequency effect). Nitrogen, phosphorus and boron were applied at a 1.0:0.1:0.005 ratio, where nitrogen rates ranged from 0 to 250 kg ha^{-1} and application frequency was 6, 12, 24 or 36 months. Fertilization began when trees were 11–24 months old and we examined volume growth response three years after study initiation when the maximum cumulative nitrogen application reached 720 kg ha^{-1}. There was a significant site effect: two sites were responsive and four were non-responsive to treatment. At the two responsive sites, the relationship between volume growth response and applied nitrogen was not linear. Three years after treatment initiation, the maximum absolute response was 142 m^3 ha^{-1} (91% increase) and 116 m^3 ha^{-1} (56% increase) for Sites 1 and 4, respectively. Sites 1 and 4 reached maximum volume response at cumulative nitrogen doses of 360 and 480 kg ha^{-1}, respectively. Tests that compared different nitrogen application rates and frequencies to achieve the same cumulative dose were not significantly different except for one test at Site 4 where the volume growth response to three applications of 180 kg nitrogen ha^{-1} was 58% greater than the response to six applications of 90 kg ha^{-1}.

1. Introduction

Plantation productivity can be predicted from the availability and use of site resources that are conditioned by environmental constraints (Stape et al., 2008). Good weed control and adequate fertilization increase water and nutrient availability. Consequently, these silvicultural treatments are needed for good survival and high initial growth rates of *Eucalyptus* plantations (Adams et al., 2003; Goncalves et al., 2004; Herbert, 1990; Prado and Toro, 1996; Schonau, 1983; Schonau and Herbert, 1989). In second rotation stands, the response to nutrients applied soon after establishment may be limited by adequate resource availability from mineralization of extant organic matter (the assart effect, (Kimmins, 1997; Tamm, 1964)) and relatively low nutrient demand by the seedlings (Goncalves et al., 2004; Nzila et al., 2004). However, after stand establishment, continued nutrient resource availability is necessary for rapid crown closure to achieve full site occupancy; nutrients play a role in stimulating leaf area development and decreasing the time to reach canopy closure (Cromer et al., 1993; Goncalves et al., 2013). For example, Cromer et al. (1993) found that fertilization during the first three years after planting increased the mean annual increment of *Eucalyptus grandis* by 28 m^3 ha^{-1} $year^{-1}$. While the observed gains in this study are impressive, the biological potential of the site-species

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combination may not have been achieved given other work in *Eucalyptus* where reported growth rates exceed 80 m^3 ha^{-1} $year^{-1}$ (Stape et al., 2004).

Fertilizer responses are variable in stands that have reached canopy closure. *Eucalyptus* plantations exhibit fertilizer growth responses at sites with inherent nutritional deficiencies (Bennett et al., 1997; Campion et al., 2006; Cromer et al., 1993; Herbert, 1983; Schonau, 1983; Schonau and Herbert, 1989). In one study where fertilizer was applied three times per year for the first six years, *E. grandis* volume decreased by 12 m^3 ha^{-1} in the first year; however, by age nine, productivity had doubled in the fertilized plots (Birk and Turner, 1992). Birk and Turner (1992) hypothesized that the lack of early response to fertilization was due to adequate soil fertility or that other species successfully competed for the added nutrients. However, fertilization in years 2 through 6 clearly had a large positive impact in this study. Similarly, sites where nutrient availability was reduced as a result of detrimental effects of past silvicultural treatments, including harvest intensity, would likely respond to fertilization applied after canopy closure (Judd, 1996; Turner and Lambert, 1996).

Conversely, other studies have shown no growth improvement to fertilization application after canopy closure on sites with high fertility levels or those prone to long water deficits (Dye, 1996; Little and Rolando, 2002; Miller, 1981; Myers et al., 1996). For example, a nutrition by irrigation study in three-year-old *E. grandis x urophylla* clones in a fertile region of Brazil showed no response to fertilization (Stape et al., 2008). A similar study examining clonal *Eucalyptus* growth potential across eight sites in Brazil did not show differences between fertilizer applied at planting and fertilizer applied three times annually for the first three years (Stape et al., 2010). In South Africa, four experiments with *E. grandis* had no response to fertilizer when fertilized with nitrogen, phosphorus, potassium, and lime eighteen months after planting (Schonau, 1983). Mechanisms to explain this lack of response to nutrient additions after canopy closure include high native site fertility (Stape et al., 2010), other resources (water) are primarily limiting (Campion et al., 2006), the nutrients that become available through mineralization or slash and litterfall decomposition are sufficient to meet plant demand (Goncalves et al., 2004; Nzila et al., 2004), and heartwood development, which can begin by age three in *E. grandis*, results in available nutrients from internal biochemical cycling (Da Silva et al., 2001). Another possibility is continued nutrient availability from early rotation applications that provide nutrients throughout the rotation (Smethurst et al., 2003).

Consequently, after canopy closure, fertilizer responses are dependent on a range of factors and this situation makes it difficult to determine which sites will be responsive. In addition, sites that do respond to fertilizer may not achieve the biological potential of the site because they could still be resource (nutrients or other resources) limited. For example, Smethurst et al. (2003) found that some sites that responded to fertilizer treatments at young ages also responded to additional fertilizer applied at later ages. In the literature, fertilizer application rates range from those applied to eliminate all nutrient limitation (many elements applied) (Stape et al., 2008) to those where a combination of relatively high rates of nitrogen and phosphorus were applied (1600 and 700 kg ha^{-1} for nitrogen and phosphorus, respectively) (Smethurst et al., 2003). No studies were found where the same total nutrient dose was achieved using different rates and frequencies of application.

There are 405,000 ha of planted forest in Colombia, of which approximately 19% are in *E. globulus* and *E. grandis* (FAO 2010, 2015). However, only about 60% of domestic demand is met from plantations, and there is pressure on the native forest such that the Colombian government is promoting the establishment of new plantations to reduce this pressure (Boyd, 1998; FAO, 2015). Another way to reduce the pressure on native forests is to increase the productivity of existing plantations with fertilization to help meet these demands. However, no information was found in the literature regarding mid-rotation fertilizer effects or productive potential for *E. grandis* plantations in Colombia. Given evidence for the assart effect in *E. grandis* stands (Goncalves et al., 2004; Nzila et al., 2004), our interest was in examining the response to nutrient applications after crown closure when the assart effect diminishes and stands may become nutrient limiting. These factors led us to investigate the response of *E. grandis* growing in the Colombian Andes to fertilization where both the rate and frequency of fertilization were varied. By altering the dose and frequency of application, we could determine if stands were responsive to fertilizer and, if they were responsive, at what point the response leveled off and no additional response was achieved. We examined these hypotheses: (1) individual sites have different treatment responses (there is a significant site effect); (2) the relationship between volume growth response and applied nitrogen is not linear (there is an optimal amount of applied nitrogen beyond which growth improvements would be small); and (3) application frequency does not affect response if the cumulative applied dose is equivalent (there is no frequency effect).

2. Methods

Six sites planted with *E. grandis* were selected to represent a range of soil-site conditions in the Colombian Andes (Table 1). The selected sites were representative of Quindio and of Valle, Lomajes and Meseta in the Cauca River Basin. The range in altitude was 1690–2127 m asl. Soils were loamy, well drained Andisols. Previous land use was pasture (Sites 1) or plantation (Sites 2–6); the plantation sites received fertilization at planting similar to that which was applied for the current rotation and is mentioned below. Information about prior fertilization of the pasture site was not available. Site index ranged from 22 to 28 m (base age 7 years). Site preparation for all sites was chemical preparation with glyphosate followed by tillage (30 × 30 × 30 cm) at each planting spot and residues were left in place to decompose. Each site was fertilized at planting with 12 g nitrogen, 13 g phosphorus, 8 g potassium and 10 g boron $plant^{-1}$, and received at least two weed control operations (mechanical and chemical (glyphosate)) during the first year of growth. Stand age at treatment initiation ranged from 11 to 24 months. Prior to treatment initiation, stocking across all sites ranged from 959 to 1280 trees ha^{-1}, diameter at breast height ranged from 3.3 to 9.5 cm, basal area ranged from 0.8 to 8.4 m^2 ha^{-1} and stem volume ranged from 12 to 67 m^3 ha^{-1} (Table 2).

2.1. Experimental design

We installed a randomized complete block design with three or four replications at each site. Sites were blocked on height, basal area and stocking prior to treatment initiation to ensure homogeneity. Plots within a block had less than 10% difference for these variables. Measurement plots varied in size from 0.021 to 0.039 ha (0.032 ha average) and were surrounded by a 15-m treated buffer such that the average treated plot size was 0.189 ha. Treatments were a combination of application frequency and nutrient (nitrogen, phosphorus and boron) dose (Table 3). Application frequency was every six, 12, 24 or 36 months. All nutrient applications mentioned in this document are elemental rates. Nitrogen was applied at 0, 60, 75, 90, 120, 150, 180, 240 or 250 kg nitrogen ha^{-1}. Phosphorus and boron were added with nitrogen at values of 0.1 and 0.005 times the nitrogen rate, respectively. The nitrogen:phosphorus ratio was selected based on the estimated 10:1