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 to 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 m³ ha⁻¹ (91% increase) and 116 m³ 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.

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 $28 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. While the observed gains in this study are impressive, the biological potential of the site-species combination may not have been achieved given other work in *Eucalyptus* where reported growth rates exceed $80 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (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 $12 \text{ m}^3 \text{ ha}^{-1}$ 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; FAO 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).

Methods

Six sites planted with *Eucalyptus 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 to 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 x 30 x 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 m² ha⁻¹ and stem volume ranged from 12 to 67 m³ ha⁻¹ (Table 2).

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. The nitrogen:phosphorus ratio was selected based on the estimated 10:1 nitrogen:phosphorus ratio found in many plants (Knecht and Göransson 2004; Linder 1995). Boron was added because boron is known to be limiting in these soils (Shorrocks 1997) and boron deficiencies have been induced by macronutrient fertilizer applications (Stone 1990). There is a narrow range between adequate and toxic levels of boron (Dell and Malajczuk 1994; Stone 1990); consequently, we added boron at 0.005 times the nitrogen rate to insure that sufficient boron would be available and that potentially toxic levels would not be generated with high nitrogen doses applied in some treatments. Subsequent references to treatment indicate only applied nitrogen for brevity in presentation; however, as noted here, nitrogen, phosphorus and boron were applied. The nutrients were added as urea, diammonium phosphate and borax. Urea applications may be susceptible to urea volatilization (Zerpa and Fox 2011). An additional benefit of adding boron is that it acts to reduce urea volatilization (Whitehurst and Whitehurst 2004). Furthermore, the fertilizer applications were completed under conditions that reduce the risk of volatilization (low temperature and humidity with the expectation of heavy rainfall within 24-48 hours after application).

The application frequencies and nutrient doses were selected to span a range of nutrient applications such that the same total dose at a given time would be achieved from different combinations

of nutrient dose and application frequency. For example, applying 120 kg nitrogen ha⁻¹ every six months for three years resulted in a cumulative dose of 720 kg nitrogen ha⁻¹. This same cumulative dose was also achieved with the annual application of 240 kg nitrogen ha⁻¹ over three years. Different doses and application frequencies were used at each site; however, the control (no nutrients added), 120 kg nitrogen ha⁻¹ applied every year and 240 kg nitrogen ha⁻¹ applied every two years were implemented at all sites (Table 3).

Foliage samples were collected from five dominant or co-dominant trees in each plot prior to treatment initiation at all sites and every six months thereafter for Sites 1, 2, 3, and 4. Available resources did not permit foliage sampling and nutrient analysis after treatment initiation at Sites 5 and 6. Foliage was collected in the upper one-third of the live crown and foliar samples were dried at 65 °C to a constant weight. Samples were composited by plot and analyzed using a CHN analyzer (CE Instruments NC2100 elemental analyzer) for nitrogen (CE Instruments, 1997) and a nitric acid digest and ICP (Varian Liberty II ICP-AES) analysis was used for the other elements (Huang and Schulte 1985). Duplicate samples and standard samples from the laboratory and the United States National Bureau of Standards were included with all analytic runs to ensure data quality. Soil pH was measured in water. Soil was analyzed using the Semimicro-Kjeldhal method for nitrogen (Hitchcock and Belden 1933), the Walkley-Black method for organic matter (Walkley 1947), the Bray II method for phosphorus (Bray and Kurtz 1945), extracted with ammonium acetate and analyzed using an atomic absorption spectrophotometer for potassium, calcium and magnesium, and extracted following the Yuan method and analyzed using an atomic absorption spectrophotometer for aluminum (Yuan and Fiskell 1959).

Diameter at breast height (1.3 m) and tree height were measured prior to treatment initiation and every six months thereafter. Individual tree volume was calculated from diameter at breast height using a proprietary function developed by Smurfit Cartón de Colombia. Individual tree volume and basal area were summed by plot and scaled to a hectare basis. The treatment response at a given time period was calculated as the mean of the treatment growth minus the control growth for all blocks at a site. The relative treatment response was the treatment response divided by the control growth.

Statistical Analyses

PROC MIXED (SAS Institute, 2002) was used to examine the treatment effects three years after treatment initiation for diameter, height, basal area, volume and survival. Survival data were arc sine transformed for statistical analysis. Site effects were examined, where fixed effects were site, treatment and their interaction, and random effects were block within site. Within site treatment effects used treatment as the fixed effect and block as the random effect. Tukey-Kramer means tests were used to determine the treatment differences for the three year growth data at each site. Linear and quadratic effects were tested to determine whether fertilizer rate affected response. Contrasts tested treatments at each site that resulted in the same cumulative rate achieved from different frequencies. Foliar nutrient concentrations were examined by site and element using repeated measures analysis with PROC MIXED. Block was treated as a random variable. Tukey-Kramer means test were used to determine differences in treatment means for a given measurement date. If more than three dates for a site-element combination had significant differences between treatment means, the data for that element, site and set of treatments were graphed. All statistical tests were evaluated with alpha equal to 0.05.

Results

Initial foliar nitrogen concentrations ranged from 1.73 to 2.34 % (Table 4). Control treatment foliar nutrient concentrations varied significantly through time (significant time since treatment initiation effect) for all sites and all elements except for phosphorus at Site 1 (Tables 4 and 5). Treatment effects and treatment by time effects were significant for nitrogen and phosphorus at Site 4 such that the control treatment was lower than all treatments, and significant means comparisons were observed at 18, 30 and 36 months since treatment initiation (Table 5 and Figure 1A and 1B). Treatment effects and treatment by time effects were significant for boron at Site 3 such that the control treatment was lower than all treatments and significant means comparisons were observed at 24, 30 and 36 months since treatment initiation (Table 5 and Figure 1C). Other significant treatment means were observed at Site 1 for calcium at 12 months where the 224 treatment was less than the control, Site 2 for magnesium at 36 months where the control treatment was greater than the 124, 224 and 506 treatments, and Site 4 for sulfur (at 18 months the control was less than the 509 treatment), zinc (at 12 months the control was less than the 224 treatment), and copper (at 36 months, treatment 118 was less than the 218 and 506 treatments).

Three years after treatment initiation, site effects were significant (at least $p < 0.002$) for all growth measurements (diameter, height, basal area, volume and survival); consequently, the studies were examined individually.

Three years after treatment initiation, Sites 1 and 4 exhibited significant treatment effects for diameter, height, basal area and volume growth (Tables 6a and 6b). Means comparisons for Sites 1 and 4 indicated that the control was typically less than most or all of the other treatments. Absolute responses for the other four sites (2, 3, 5, and 6) were both positive and negative (greater than or less than the control); however, these effects were not statistically significant and means comparisons indicated that none of the means were significantly different for any variable measured. Treatments 124 (240 kg nitrogen ha^{-1} applied every year) and 118 (180 kg nitrogen ha^{-1} applied every year) had the greatest absolute responses at Sites 1 and 4, respectively. At Site 1, treatment 124 increased diameter (3.6 cm, 30%), height (4.7 m, 29%), basal area (9.3 $\text{m}^2 \text{ha}^{-1}$, 60%) and volume (142 $\text{m}^3 \text{ha}^{-1}$, 91%). At Site 4, treatment 118 increased diameter (2.1 cm, 14%), height (3.3 m, 15%), basal area (7.9 $\text{m}^2 \text{ha}^{-1}$, 38%) and volume (116 $\text{m}^3 \text{ha}^{-1}$, 100%). Survival was not influenced by treatment at any site (Tables 6a and 6b) and averaged 97% across all sites and treatments.

Three years after treatment initiation, significant linear and quadratic effects were observed at Sites 1 and 4, indicating that response was affected by rate (Table 7 and Figure 2). At Site 1, linear effects were found for diameter, height, basal area and volume responses, and quadratic effects were found for diameter and basal area. At Site 4, linear and quadratic effects were found for diameter, height, basal area and volume responses. None of the other sites (2, 3, 5, and 6) had significant linear or quadratic rate effects on growth response. At Sites 1 and 4, volume response continued to increase until a dose of 480 and 360 kg nitrogen ha^{-1} , respectively, was applied (Figure 2). Survival was not influenced by rate at any of the sites.

Three years after treatment initiation, only one of the eleven tests comparing application frequency to achieve the same cumulative dose was significant (Table 8 and Figure 3). The significant test was at Site 4 where a cumulative dose of 540 kg nitrogen ha^{-1} (achieved in three applications of 180 kg nitrogen ha^{-1}) increased volume growth response by 38 $\text{m}^3 \text{ha}^{-1}$, whereas the same dose achieved with six applications of 90 kg nitrogen ha^{-1} increased volume growth response by 24 $\text{m}^3 \text{ha}^{-1}$.

Discussion

We accepted our first hypothesis because site was a significant factor in the analyses. Sites 1 and 4 were responsive to treatment but none of the other sites were. Both of the responsive sites had relatively low pre-treatment foliar nitrogen concentrations (1.90% and 1.81% nitrogen for Sites 1 and 4, respectively) (Table 4).

We accepted our second hypothesis at Site 4 but not at Site 1. At Site 4, there was a significant quadratic effect for volume growth (Table 7) and there was a significant quadratic effect for diameter, height and basal area growth. When the applied nitrogen dose exceeded 480 kg ha⁻¹, no additional growth response was observed (Figure 2). At Site 1, there were significant quadratic responses for diameter and basal area but not for height or volume. However, had we selected a less strict significance level (0.10 instead of 0.05), volume and height would have shown significant quadratic effects and no additional volume growth would be expected above a nitrogen dose of 360 kg ha⁻¹. A linear response function implies that response continues to increase regardless of the amount of resource applied, i.e., in contrast to a quadratic response, the treatment level where no additional response occurs has not been applied in the case where a linear response is observed. For example, Whitesell *et al.* (1992) report data where biomass production continued to increase linearly as nitrogen was applied from 0 to 450 kg ha⁻¹. Consequently, we do not know the maximum response possible for their species-site combination. Our study was designed to apply sufficient nutrients (up to 720 kg ha⁻¹ of applied nitrogen) such that the response would no longer be linear because an asymptote would be reached, resulting in a significant quadratic effect. The sites with a significant quadratic effect followed Liebig's Law of the Minimum where some factor (e.g., water, other nutrients, space) other than that being applied became limiting.

We accepted our third hypothesis at Sites 1, 2, 3, 5 and 6 but not at Site 4 for all treatment comparisons. For example, at Site 1, a cumulative dose of 360 kg nitrogen ha⁻¹ was achieved in three applications of 120 kg nitrogen ha⁻¹ or six applications of 60 kg nitrogen ha⁻¹. In addition, a cumulative dose of 720 kg nitrogen ha⁻¹ was achieved in three applications of 240 kg nitrogen ha⁻¹ or six applications of 120 kg nitrogen ha⁻¹. In both of these cases, there was no difference between the effect of three large doses and six smaller doses of nitrogen on the three-year volume response (Table 8 and Figure 3). At Site 4, one comparison followed this pattern; however, when 540 kg nitrogen ha⁻¹ was applied as three

and six doses of 180 and 90 kg nitrogen ha⁻¹, respectively, there was a significant difference in the three-year volume response for these treatments. The three dose application yielded a response of 38 m³ ha⁻¹ yr⁻¹, i.e., 58% greater than the volume response when the dose was applied in six doses. It is unlikely that the low dose (90 kg ha⁻¹ per application) did not allow the trees to overcome their limitation or that volatilization was a factor in reducing the effective dose given that we applied a lower dose (60 kg ha⁻¹ per application) in the 506 treatment that responded to treatment and grew as well as the 112 and 218 treatments in the other comparison at this site. We selected uniform sites with little competing vegetation, maintained good vegetation control throughout the study, selected plots that were uniform with regards to tree size and stocking prior to treatment, and used large buffers between plots that would exclude cross contamination of treatments. Care was taken when applying fertilizers throughout the study to ensure that the proper dose was applied and to apply the fertilizer under conditions that would minimize volatilization. Survival at the end of the study was 100% in both of these treatments (i.e., the three and six dose applications at Site 4). These conditions make it difficult to determine why this comparison indicated a significant difference. One possibility is the selected plots were similar at the time of installation but other site factors, such as effective rooting depth, differed across the site such that later in the rotation, this factor adversely affected the response differentially across the site.

Considerable work has been completed in measuring *Eucalyptus* foliar nutrient concentrations; one review compiled data from over 500 references (Judd *et al.*, 1996). Interestingly, while most data from our study were within the reported ranges for *E. grandis* in that review, the magnesium concentrations measured at Sites 1, 2 and 3 fell below the range, and boron concentrations were above (Sites 1, 2, 3, 4, and 6) and below (Sites 1 and 3) the reported range (Table 4). Few references make recommendations regarding optimum nutrient concentrations for *E. grandis* plantations (Herbert 1996; Schonau 1983), whereas a greater emphasis has been placed on identifying optimum nutrient ratios (Judd *et al.*, 1996). At the same time, few critical concentrations (i.e., the concentration associated with 90% of maximum productivity) have been determined, in part because of the difficulty in measuring and then verifying these values in the field (Dell 1996). Initially, all sites in this study were below the most conservative optimum values for phosphorus (0.15%) and magnesium (0.30%). Additionally, all sites except Site 4 were below the optimum value for boron, Site 4 was below the optimum for nitrogen (2.0%),

potassium (0.70%) and calcium (1.0%), and Site 6 was below the optimum for nitrogen. Recommendations for the optimum nitrogen:phosphorus ratio range from 13 to 18 (Herbert 1996; Judd *et al.*, 1996; Schonau 1983). Averaged over all measurement periods, Sites 1, 2 and 4 had nitrogen:phosphorus ratios within this range; however, individual measurement periods were as high as 23. Sites 3, 5 and 6 had nitrogen:phosphorus ratios greater than this range.

The production rates reported here are in the range of *Eucalyptus* growth rates documented in the literature. The volume growth in our study ranged from 50 to 108 m³ ha⁻¹ yr⁻¹ or 23 to 49 Mg ha⁻¹ yr⁻¹ using the wood density data (~2.2 m³ Mg⁻¹) from Smethurst *et al.* (2003) for conversion. Reported growth rates in Australia are in the same range, i.e., 10 to 30 Mg ha⁻¹ yr⁻¹ for *E. nitens* (Smethurst *et al.*, 2003) and 274 Mg ha⁻¹ at age nine (~30 Mg ha⁻¹ yr⁻¹) for *E. grandis* (Birk and Turner 1992). Other reports include 28-42 Mg ha⁻¹ yr⁻¹ for *E. grandis* x *urophylla* clones in Brazil (Stape *et al.*, 2008) and 22-35 Mg ha⁻¹ yr⁻¹ for *E. grandis* in South Africa (Campion *et al.*, 2005). The studies in Brazil and South Africa included an irrigation component and both sites experienced positive volume growth responses to irrigation to produce the high end of the reported ranges. Our sites had similar or better productivity likely due, at least in part, to relatively high ambient rainfall where four sites (1, 2, 4 and 6) received an average of more than 2000 mm annual precipitation. Site 5 had the lowest productivity (22-27 Mg ha⁻¹ yr⁻¹) and lowest average rainfall (1165 mm yr⁻¹, i.e., less than half that observed at Sites 2 and 6). In this situation, the primary limiting factor at Site 5 may have been water availability rather than nutrient limitations, which may explain the lack of treatment response at this site. Sites 2, 3 and 6, which were also not responsive to treatment, may have been close to their maximum potential productivity given that control growth at these sites was more than 79 m³ ha⁻¹ yr⁻¹. The treatments may have improved growth but not enough such that a significant improvement could be detected. However, maximum growth rates at Sites 1 and 4 were 99 and 108 m³ ha⁻¹ yr⁻¹, respectively, and both reached an asymptote (significant quadratic response), indicating they had reached maximum productivity given their other resources (nutrients, light, water).

All sites had at least one nutrient concentration below optimum, but only two sites had a positive growth response to treatment, which indicated that other factors were limiting (e.g., Site 5), stands were already close to their productive potential (e.g., Sites 2, 3, and 6), not all nutrient limitations were

addressed with treatment, or the treatments induced other problems that limited growth. Calcium and magnesium were not added although they were considered below optimum for Sites 4 and 1, respectively. These were the responsive sites; apparently sub-optimal nutrient concentrations may support very good overall growth. For Sites 1, 2, 3, and 4 where nutrient concentration data were available throughout the study, there was no indication that other elements were adversely affected by treatment. Potassium was reduced through time at Sites 1 and 2 but never dropped below the optimum and never dropped as low as the potassium at Site 4 where the highest growth rates were achieved. Other elements fluctuated slightly over time but the absolute value did not change much.

Several conditions observed in this study provide a cautionary note in using foliar nutrient concentrations as the sole guide for determining nutrient limitations: Foliar nutrient concentrations may decrease when nutrients are added, e.g., foliar nitrogen concentrations decreased when nitrogen was added at Site 1. Foliar nutrient concentrations may not change when nutrients identified as limiting are added, e.g., phosphorus at Site 1. Foliar nutrient concentrations could be well below optimal levels and still support high growth rates, e.g., potassium at Site 4. Significant fluctuations in the control plot nutrient concentrations were observed over time, e.g., Site 4 nitrogen, Site 3 potassium. These situations make it difficult to interpret foliar nutrient concentration data with confidence and use them as a management tool. However, the nitrogen limitation at Site 4 was identified by examining the foliar nitrogen concentrations and even though there was fluctuation over time in the control, the treated plots tracked the control but at a higher level (Figure 1A and 1B). Another option to improve utility of the foliar nutrient concentration data is to compare them directly to the growth response data; however, this has met with mixed success; in some studies, foliar nutrient concentrations explained over 70% of the variation in growth while in other studies, foliar nutrient concentrations were not significant explanatory variables (Judd *et al.*, 1996). Other work found the amount of foliage, estimated as leaf area index, to be a useful tool for predicting growth and potential response to nutrients in *Eucalyptus* (Campion *et al.*, 2005; Cannell 1989; Landsberg and Sands 2011; Smethurst *et al.*, 2003; Stape *et al.*, 2008).

Our study examined not only whether a site was responsive to nutrient addition but also the nutrient addition needed to maximize productivity. Juvenile *E. grandis* stands can respond to nutrient additions and these additions can be quite large before the response stops increasing. The two

349 responsive sites required 360 and 480 kg nitrogen ha⁻¹ to reach a point where no additional volume
350 response was produced with additional nitrogen. As previously mentioned, growth at this point was quite
351 high; however, it may not have been the maximum productivity possible because another resource may
352 have been limiting at that time. In all but one test, application frequency did not affect response if the
353 cumulative applied dose was equivalent. This information gives confidence that a given dose applied
354 using a range of frequencies will yield the same response and allows managers more flexibility in
355 planning their nutrient applications. Foliar nutrient concentrations are helpful in identifying sites that may
356 respond to fertilization applied at juvenile stages; however, they need to be used with caution.

Figure titles

Figure 1. Foliar nitrogen (A), phosphorus (B) and boron (C) concentrations from Sites 4, 4 and 3, respectively. Asterisks indicate measurement dates when the control treatment was significantly less than at least one of the fertilizer treatments. Treatment codes correspond to treatments listed in Table 3.

Figure 2. Three-year volume response versus cumulative applied nitrogen dose at six *Eucalyptus grandis* sites in Colombia where nitrogen, phosphorus and boron were applied at different rates and frequencies.

Figure 3. Three-year volume response at six *Eucalyptus grandis* sites in Colombia where a given nitrogen dose was applied at different rates and frequencies of application. X axis labels represent the site-cumulative dose, where site is nominal (1-6) and dose is in kg elemental nitrogen ha⁻¹ applied in 1, 2, 3 or 6 applications.

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Table 1. Site location and soil and geologic characteristics for the six sites in Colombia where *Eucalyptus grandis* was fertilized at different doses and frequencies.

Variable	Site					
	1	2	3	4	5	6
County	Cauca-Cajibío	Valle-Darien	Valle-Darien	Cauca-Meseta	Valle-Cumbre	Cauca-Salinas
Nearest town	Popayan	Pereira	Darien	Popayan	Cumbre	Salinas
Latitude (decimal degrees)	2.6	4.7	4.05	2.5	3.67	2.43
Longitude (decimal degrees)	-76.62	-75.67	-76.43	-73.62	-76.52	-76.55
Installation Year	2000	2000	2000	2003	2004	2004
Age (months)	22	21	24	17	11	14
Previous Land use	Pasture	E. grandis Plantation	E. grandis Plantation	P. oocarpa plantation	P. maximinoi plantation	E. grandis Plantation
Elevation (masl)	1774	1690	1900	1730	1738	2127
Precipitation (mm yr ⁻¹)	2310	2664	1602	2169	1165	2591
Mean annual temperature (°C)	19.3	18.3	19.9	19.3	19.9	19.3
Soil Series	Pubenza	Santa Rosa	La Cristalina	Pubenza	Carbonero	Salinas
Parent material	Volcanic ash	Volcanic ash	Volcanic ash	Volcanic ash	Volcanic ash	Volcanic ash
Soil taxonomy	Hapludands	Acrudoxic hapludands	Andic Dystrudepts	Acrudoxic Hydric Melanudands	Acrodoxic hydric hapludands	Acrudoxic Melanudands
Surface texture	Loam	Clay loam	Silty clay loam	Silty loam	Silty loam	Silty loam
Drainage	Well drained	Well drained	Well drained	Well drained	Moderately well drained	Well drained
A horizon depth (cm)	24	15	13	40	25	35
Bulk density (g cm ⁻³)	0.49	0.69	0.56	0.51	0.51	0.71
pH	5.4	4.8	5.3	4.7	4.8	5.3
Organic matter (%)	0.58	9.2	18.2	25.6	18	0.46
Nitrogen (%)	15.9	0.4	0.63	0.8	0.63	11.8
Phosphorus (mg kg ⁻¹)	3	3	2	0.5	1	5
Potassium (mg kg ⁻¹)	0.07	0.16	0.17	0.09	0.12	0.34
Calcium (mg kg ⁻¹)	0	0.3	0.1	0.1	2.4	2.3
Magnesium (mg kg ⁻¹)	0.1	0.1	0.2	0.1	0.6	0.5
Aluminum (mg kg ⁻¹)	0.3	0.7	1.6	1.7	0.9	0.4
Number of blocks	3	3	3	4	4	4

Table 2. Initial stand conditions (prior to fertilization) showing mean and standard error (SE) at the six sites in Colombia where *Eucalyptus grandis* was fertilized with different frequencies and doses of nutrients.

Site	Diameter at		Height		Basal area		Volume		Stocking	
	breast height		mean	SE	mean	SE	mean	SE	mean	SE
	mean	SE								
	cm		m		m ² ha ⁻¹		m ³ ha ⁻¹		trees ha ⁻¹	
1	6.9	0.07	7.0	0.12	5.3	0.12	43.9	0.8	1280	6
2	5.2	0.05	5.6	0.03	2.9	0.10	27.6	0.9	1147	28
3	9.5	0.04	10.9	0.06	8.4	0.05	66.6	0.5	1129	8
4	5.7	0.04	6.5	0.03	2.9	0.03	27.4	0.2	1119	9
5	3.3	0.02	3.4	0.02	0.8	0.01	12.5	0.1	959	4
6	5.1	0.05	5.0	0.03	2.2	0.04	22.3	0.2	1027	4

Table 3. Treatments applied at each of the six sites in Colombia where *Eucalyptus grandis* was fertilized. Phosphorus and boron were added at the same time as nitrogen at 0.1 and 0.005 times the nitrogen rate, respectively. An 'x' indicates that treatment was applied.

Treatment code	Dose of elemental N applied each time (kg N ha ⁻¹)	Frequency of application (years)	Cumulative N dose 3 years after initiation (kg N ha ⁻¹)	Study					
				1	2	3	4	5	6
0	0	0	0	x	x	x	x	x	x
506	60	0.5	360	x	x	x	x		
509	90	0.5	540				x		
512	120	0.5	720	x	x	x			
106	60	1	180	x	x	x			
107	75	1	225					x	x
109	90	1	270				x	x	x
112	120	1	360	x	x	x	x	x	x
115	150	1	450					x	x
118	180	1	540				x	x	x
124	240	1	720	x	x	x			
212	120	2	240				x	x	x
218	180	2	360				x	x	x
224	240	2	480	x	x	x	x	x	x
225	250	2	500						x
324	240	3	240						x

Table 4. Foliar nutrient concentrations for the control treatment (no fertilizer additions) prior to study initiation and every six months thereafter at the six sites in Colombia where fertilizer was applied in *Eucalyptus grandis* stands. No samples were collected at Sites 5 and 6 after the initial measurement due to limited resources available for sampling. NA indicates data is not available.

Site	Months since treatment initiation	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	B (ppm)	Zn (ppm)	Mn (ppm)	Cu (ppm)
1	0	2.02	0.11	1.01	1.11	0.15	0.19	10	20	437	8
	6	1.75	0.10	0.90	0.88	0.14	0.15	7	17	360	7
	12	1.55	0.11	0.92	1.12	0.15	0.17	13	18	488	7
	18	1.60	0.11	0.84	0.94	0.16	0.16	14	19	503	6
	24	1.47	0.11	0.88	1.03	0.17	0.12	17	14	422	7
	30	1.91	0.11	0.84	0.77	0.22	0.16	68	14	316	7
	36	1.83	0.11	0.91	0.80	0.23	0.15	53	14	319	8
2	0	2.26	0.13	1.13	1.03	0.17	0.19	21	27	842	10
	6	1.83	0.08	0.84	1.33	0.14	0.16	20	22	872	6
	12	1.67	0.10	0.84	1.31	0.17	0.18	27	17	1138	7
	18	1.71	0.09	0.90	1.40	0.19	0.16	31	17	1100	6
	24	1.66	0.10	0.83	1.04	0.21	0.15	31	14	941	6
	30	1.80	0.12	0.92	0.93	0.24	0.17	33	18	830	7
	36	1.90	0.14	0.78	0.88	0.31	0.19	26	19	688	8
3	0	2.15	0.10	0.74	1.33	0.16	0.19	13	20	1527	7
	6	2.12	0.10	0.74	1.14	0.13	0.19	17	17	1365	5
	12	2.13	0.11	0.80	1.21	0.16	0.18	21	21	1504	6
	18	2.45	0.13	0.79	0.96	0.16	NA	NA	NA	NA	NA
	24	2.19	0.11	0.77	0.84	0.13	0.16	19	17	1330	7
	30	2.35	0.11	0.75	0.99	0.15	0.21	29	15	1667	6
	36	2.18	0.13	0.82	0.85	0.20	0.21	19	20	1353	7
4	0	1.73	0.09	0.49	0.72	0.23	0.15	35	12	688	7
	6	1.77	0.08	0.47	0.71	0.22	0.14	51	12	696	7
	12	1.50	0.08	0.57	0.70	0.25	0.13	44	11	525	5
	18	1.19	0.07	0.54	0.60	0.23	0.13	29	10	444	5
	24	1.58	0.10	0.56	0.62	0.29	0.15	23	12	516	5
	30	1.35	0.09	0.59	0.51	0.22	0.13	35	14	471	6
	36	1.77	0.11	0.66	0.60	0.29	0.18	32	15	498	6
5	0	2.34	0.11	0.98	1.37	0.17	0.20	23	21	415	8
6	0	1.95	0.08	0.78	1.59	0.14	0.17	31	15	914	8

Table 5. Statistical tests (p values) for treatment, time since treatment initiation and interaction effects on foliar nutrient concentrations for four of the six sites where fertilizer was applied at different rates and frequencies in Colombia. Tests were not completed on Sites 5 and 6 because foliar collections were only completed prior to treatment initiation at those sites. Values in bold are less than 0.05.

Site	Effect	N	P	K	Ca	Mg	S	B	Zn	Mn	Cu
1	Treatment	0.010	0.584	0.002	0.011	0.236	0.080	0.817	0.837	0.408	0.238
1	Time since treatment initiation (TSTI)	0.000	0.072	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
1	Treatment x TSTI	0.404	0.584	0.341	0.318	0.997	0.289	0.174	0.880	0.134	0.463
2	Treatment	0.271	0.122	0.009	0.185	0.000	0.662	0.359	0.076	0.123	0.082
2	Time since treatment initiation (TSTI)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	Treatment x TSTI	0.628	0.016	0.084	0.474	0.113	0.783	0.369	0.999	0.082	0.550
3	Treatment	0.234	0.797	0.076	0.249	0.105	0.110	0.000	0.963	0.959	0.473
3	Time since treatment initiation (TSTI)	0.002	0.000	0.012	0.000	0.000	0.000	0.000	0.000	0.003	0.000
3	Treatment x TSTI	0.806	0.498	0.917	0.600	0.808	0.982	0.004	0.772	0.884	0.741
4	Treatment	0.000	0.000	0.168	0.806	0.086	0.011	0.000	0.140	0.950	0.922
4	Time since treatment initiation (TSTI)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	Treatment x TSTI	0.000	0.000	0.368	0.820	0.155	0.625	0.197	0.063	0.477	0.079

Table 6a. Three year survival and growth measurements (treatment mean) and response and percent response relative to the control treatment for three of the six sites in Colombia where *Eucalyptus grandis* was fertilized.

Site	Treatment code	Diameter				Height				Basal area				Volume				Survival	
		Growth cm	Response			Growth m	Response			Growth m ² ha ⁻¹	Response			Growth m ³ ha ⁻¹	Response			%	%
			cm		%	m	m		%	m ² ha ⁻¹	m ² ha ⁻¹		%	m ³ ha ⁻¹	m ³ ha ⁻¹		%		%
1	0	11.8	a			16.0	a			15.5	a			156	a			95	a
1	106	13.3	ab	1.5	13	16.6	ab	0.6	4	18.5	ab	3.0	19	196	ab	40	26	92	a
1	112	14.0	b	2.2	19	18.7	ab	2.7	17	20.9	ab	5.4	35	225	ab	69	44	96	a
1	124	15.4	b	3.6	30	20.7	b	4.7	29	24.8	b	9.3	60	298	b	142	91	93	a
1	224	15.1	b	3.3	28	20.8	b	4.8	30	23.8	b	8.3	54	278	b	122	78	92	a
1	506	15.0	b	3.2	28	20.3	ab	4.3	27	23.5	b	8.0	52	278	b	123	79	91	a
1	512	15.1	b	3.3	28	20.0	ab	4.0	25	24.0	b	8.5	55	279	b	123	79	94	a
2	0	14.2	a			19.8	a			19.4	a			236	a			90	a
2	106	14.0	a	-0.1	-1	19.2	a	-0.6	-3	20.7	a	1.3	7	263	a	26	11	93	a
2	112	14.1	a	-0.1	0	20.0	a	0.2	1	19.5	a	0.0	0	248	a	11	5	89	a
2	124	14.7	a	0.6	4	18.9	a	-1.0	-5	19.8	a	0.4	2	252	a	16	7	85	a
2	224	14.1	a	0.0	0	18.3	a	-1.5	-8	20.6	a	1.1	6	262	a	26	11	92	a
2	506	13.3	a	-0.8	-6	18.5	a	-1.3	-7	19.9	a	0.5	3	231	a	-5	-2	100	a
2	512	14.1	a	-0.1	-1	19.7	a	-0.1	-1	17.2	a	-2.3	-12	206	a	-30	-13	82	a
3	0	15.6	a			22.0	a			23.0	a			266	a			97	a
3	106	15.7	a	0.1	0	21.1	a	-0.9	-4	22.4	a	-0.5	-2	267	a	1	0	94	a
3	112	16.0	a	0.5	3	22.0	a	0.0	0	24.5	a	1.6	7	301	a	35	13	98	a
3	124	15.4	a	-0.2	-1	21.4	a	-0.6	-3	20.8	a	-2.2	-10	248	a	-18	-7	89	a
3	224	15.6	a	0.1	0	21.5	a	-0.5	-2	22.9	a	-0.1	0	276	a	10	4	94	a
3	506	16.1	a	0.5	3	22.3	a	0.3	1	24.9	a	1.9	8	301	a	35	13	98	a
3	512	16.2	a	0.6	4	21.4	a	-0.6	-3	24.4	a	1.5	6	299	a	32	12	95	a

Table 6b. Three year survival and growth measurements (treatment mean) and response and percent response relative to the control treatment for three of the six sites in Colombia where *Eucalyptus grandis* was fertilized.

Site	Treatment code	Diameter				Height				Basal area				Volume				Survival	
		Growth cm	Response cm		%	Growth m	Response m		%	Growth m ² ha ⁻¹	Response m ² ha ⁻¹		%	Growth m ³ ha ⁻¹	Response m ³ ha ⁻¹		%	%	
4	0	15.4	a			21.8	a			20.9	a			208	a			98	a
4	109	17.0	b	1.6	10	24.2	ab	2.4	11	25.6	b	4.7	22	281	b	73	35	98	a
4	112	17.5	b	2.1	13	25.1	b	3.3	15	27.0	b	6.1	29	301	b	93	45	99	a
4	118	17.5	b	2.1	14	25.1	b	3.3	15	28.8	b	7.9	38	324	b	116	56	100	a
4	212	17.2	b	1.7	11	23.7	ab	1.9	9	26.0	b	5.1	24	286	b	79	38	99	a
4	218	17.5	b	2.0	13	25.3	b	3.5	16	27.1	b	6.2	30	304	b	96	46	100	a
4	224	17.4	b	2.0	13	24.6	ab	2.8	13	26.9	b	6.0	29	302	b	94	45	99	a
4	506	17.3	b	1.9	12	25.3	b	3.5	16	26.2	b	5.2	25	290	b	82	39	98	a
4	509	16.7	b	1.2	8	23.9	ab	2.1	10	25.5	b	4.5	22	280	b	72	35	100	a
5	0	15.0	a			18.3	a			15.6	a			160	a			100	a
5	107	15.2	a	0.2	1	18.6	a	0.3	2	14.9	a	-0.7	-5	157	a	-3	-2	98	a
5	109	15.5	a	0.5	3	18.6	a	0.3	1	16.9	a	1.3	8	180	a	20	12	100	a
5	112	14.6	a	-0.4	-3	18.0	a	-0.3	-2	15.3	a	-0.3	-2	156	a	-4	-3	100	a
5	115	15.6	a	0.6	4	18.9	a	0.6	3	16.4	a	0.8	5	177	a	17	10	99	a
5	118	15.0	a	0.0	0	18.5	a	0.1	1	14.8	a	-0.8	-5	153	a	-7	-5	100	a
5	212	14.6	a	-0.4	-3	18.4	a	0.1	0	14.7	a	-0.9	-6	149	a	-11	-7	99	a
5	218	14.9	a	-0.1	-1	18.2	a	-0.2	-1	15.3	a	-0.3	-2	156	a	-4	-2	100	a
5	224	14.9	a	-0.1	-1	17.8	a	-0.5	-3	16.0	a	0.4	2	167	a	7	4	100	a
6	0	16.6	a			19.8	ab			22.2	a			250	a			100	a
6	107	16.5	a	-0.1	0	19.1	a	-0.7	-4	21.7	a	-0.5	-2	245	a	-4	-2	100	a
6	109	17.3	a	0.7	4	19.7	ab	-0.1	-1	23.0	a	0.8	4	267	a	17	7	98	a
6	112	16.8	a	0.2	1	20.2	ab	0.4	2	22.9	a	0.7	3	262	a	12	5	100	a
6	115	16.7	a	0.1	1	20.2	ab	0.3	2	21.8	a	-0.4	-2	250	a	0	0	100	a
6	118	16.6	a	0.0	0	20.1	ab	0.2	1	22.2	a	0.1	0	250	a	0	0	100	a
6	212	16.4	a	-0.2	-1	20.7	b	0.8	4	21.4	a	-0.7	-3	236	a	-14	-6	100	a
6	218	17.2	a	0.6	3	20.2	ab	0.4	2	23.2	a	1.1	5	267	a	17	7	100	a
6	224	17.3	a	0.8	5	20.2	ab	0.3	2	22.6	a	0.4	2	266	a	16	6	98	a
6	225	16.8	a	0.3	2	20.0	ab	0.1	1	22.0	a	-0.1	-1	250	a	0	0	100	a
6	324	17.2	a	0.7	4	20.5	ab	0.6	3	22.7	a	0.5	2	262	a	12	5	100	a

Table 7. Summary of statistical significance (p values) for diameter, height, basal area, volume increments and survival three years after study initiation for the six sites in Colombia where *Eucalyptus grandis* was fertilized. Linear and quadratic effects determine the form of the rate effect (linear or quadratic). Values in bold are less than 0.05.

Site	Diameter	Height	Basal Area	Volume	Survival
Linear effects					
1	0.001	0.009	0.001	0.004	0.304
2	0.388	0.421	0.478	0.495	0.121
3	0.664	0.501	0.416	0.344	0.479
4	0.000	0.001	0.000	0.000	0.842
5	0.741	0.735	0.723	0.720	0.938
6	0.865	0.999	0.678	0.457	0.909
Quadratic effects					
1	0.020	0.080	0.047	0.091	0.356
2	0.282	0.510	0.322	0.378	0.055
3	0.647	0.384	0.369	0.347	0.386
4	0.000	0.012	0.013	0.003	0.334
5	0.683	0.645	0.717	0.779	0.956
6	0.999	0.858	0.714	0.536	0.847

Table 8. Contrasts (p values) where the same cumulative dose was applied using different frequencies and doses at the six sites in Colombia where fertilizer was applied in *Eucalyptus grandis* stands. NT indicates the specified contrast was not tested for this site. Values in bold are less than 0.05.

Site	Cumulative Dose (kg N ha					
	360	720	360	540	360	240
	Frequencies and doses compared					
	3 doses of 120	3 doses of 240	3 doses of 120	3 doses of 180	3 doses of 120	2 doses of 120
	6 doses of 60	6 doses of 120	2 doses of 180	6 doses of 90	2 doses of 180	1 dose of 240
	6 doses of 60					
	Treatments compared					
	112 vs 506	124 vs 512	112 vs 218 vs 506	118 vs 509	112 vs 218	212 vs 324
1	0.089	0.548	NT	NT	NT	NT
2	0.434	0.100	NT	NT	NT	NT
3	0.936	0.223	NT	NT	NT	NT
4	NT	NT	0.825	0.023	NT	NT
5	NT	NT	NT	NT	0.746	NT
6	NT	NT	NT	NT	0.649	0.110

References

- Adams, P.R., C.L. Beadle, N.J. Mendham and P.J. Smethurst. 2003. The impact of timing and duration of grass control on growth of a young *Eucalyptus globulus* Labill. plantation. *New Forests*, **26** (2): 147-165.
- Bennett, L.T., C.J. Weston and P.M. Attiwill. 1997. Biomass, nutrient content and growth response to fertilisers of six-year-old *Eucalyptus globulus* plantations at three contrasting sites in Gippsland, Victoria. *Aust. J. Bot.*, **45** (1): 103-121.
- Birk, E.M. and J. Turner. 1992. Response of flooded gum (*E. grandis*) to intensive cultural treatments: biomass and nutrient content of eucalypt plantations and native forests. *For.Ecol.Manage.*, **47**: 1-28.
- Boyd, E. 1998. *A compilation of forest plantations statistics for selected African and Latin American countries*. Oxford Forestry Institute: London.
- Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.*, **59**: 39-45.
- Campion, J.M., L.J. Esprey and M.C. Scholes. 2005. Application of the 3-PG model to a *Eucalyptus grandis* stand subject to varying levels of water and nutritional constraints in KwaZulu-Natal, South Africa. *Southern African Forestry Journal*, **203**: 3-13.
- Campion, J.M., M. Nkosana and M.C. Scholes. 2006. Biomass and N and P pools in above- and below-ground components of an irrigated and fertilised *Eucalyptus grandis* stand in South Africa. *Aust.For.*, **69** (1): 48-57.
- Cannell, M.G.R. 1989. Physiological basis of wood production: a review. *Scand.J.For.Res.*, **4**: 459-490.
- Cromer, R.N., D.A. Cameron, S.J. Rance, P.A. Ryan and M. Brown. 1993. Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *For.Ecol.Manage.*, **62**: 211-230.
- Da Silva, H.D., C.A. Ferreira and A.F.J. Bellote. 2001. Quantification of the biomass in the trunk of *Eucalyptus grandis* at different ages. In *Rehabilitation of degraded tropical forest ecosystems: Workshop proceedings 2-4 November 1999, Bogor, Indonesia*. S. Kobayashi, J.W. Turnbull, T. Toma, T. Mori and N.M.N.A. Majid (eds.), CIFOR, pp. 164-171.
- Dell, B. 1996. Diagnosis of nutrient deficiencies in eucalypts. In *Nutrition of Eucalyptus*. P.M. Attiwill and M.A. Adams (eds.), CSIRO, Collingwood, pp. 417-440.
- Dell, B. and N. Malajczuk. 1994. Boron deficiency in eucalypt plantations in China. *Can.J.For.Res.*, **24**: 2409-2416.
- Dye, P.J. 1996. Response of *Eucalyptus grandis* trees to soil water deficits. *Tree Physiol.*, **16**: 233-238.
- FAO. 2010. Global forest resources assessment 2010. *FAO Forestry Paper* 163. Rome, p. 378.
- FAO. 2015. Planted forests in Colombia. <http://www.fao.org/forestry/country/18316/en/col/>.

- Goncalves, J.L., C.A. Alvares, A.R. Higa, L.D. Silva, A.C. Alfenas, J. Stahl, S.F. Ferraz, W.P. Lima, P.H. Brancalion, A. Hubner, J.P. Bouillet, J.P. Laclau, Y. Nouvellon and D. Epron. 2013. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. *For.Ecol.Manage.*, **301**: 6-27.
- Goncalves, J.L., J.L. Gava and M.C.P. Wichert. 2004. Sustainability of wood production in eucalypt plantations of Brazil. In *Site management and productivity in tropical plantation forests: Proceedings of workshops in Congo July 2001 and China February 2003*. E.K.S. Nambiar, J. Ranger, A.E. Tiarks and T. Toma (eds.), CIFOR, Bogor, Indonesia, pp. 3-14.
- Goncalves, J.L., J.L. Stape, J.P. Laclau, P.J. Smethurst and J.L. Gava. 2004. Silvicultural effects on the productivity and wood quality of eucalypt plantations. *For.Ecol.Manage.*, **193** (1-2): 45-61.
- Herbert, M.A. 1983. The response of *Eucalyptus grandis* to fertilising with nitrogen, phosphorus, potassium and dolomitic lime on a Mispah soil series. *South African Forestry Journal*, **124**: 4-12.
- Herbert, M.A. 1990. Fertilizer/site interactions on the growth and foliar nutrient levels of *Eucalyptus grandis*. *For.Ecol.Manage.*, **30**: 247-257.
- Herbert, M.A. 1996. Fertilizers and Eucalypt plantations in South Africa. In *Nutrition of Eucalypts*. P.M. Attiwill and M.A. Adams (eds.), CSIRO, Collingwood, pp. 303-325.
- Hitchcock, D.I. and R.C. Belden. 1933. An accurate semimicro-Kjeldahl method. *Ind. Eng. Chem. Anal. Ed.*, **5** (6): 402-402.
- Huang, C.L. and E.E. Schulte. 1985. Digestion of plant tissue for analysis by ICP emission spectroscopy. *Commun.Soil Sci.Plant Anal.*, **16** (9): 943-958.
- Judd, T.S. 1996. Simulated nutrient losses due to timber harvesting in highly productive eucalypt forests and plantations. In *Nutrition of eucalypts*. P.M. Attiwill and M.A. Adams (eds.), CSIRO, Collingwood, pp. 249-258.
- Judd, T.S., P.M. Attiwill and M.A. Adams. 1996. Nutrient concentrations in *Eucalyptus*: A synthesis in relation to differences between taxa, sites and components. In *Nutrition of eucalyptus*. P.M. Attiwill and M.A. Adams (eds.), CSIRO, Collingwood, pp. 123-153.
- Kimmins, J.P. 1997. Biogeochemistry, cycling of nutrients in ecosystems. In *Forest ecology, a foundation for sustainable management*. J.P. Kimmins (ed.). 2nd Ed., Prentice Hall, Saddle River, N.J., pp. 71-129.
- Knecht, M.F. and A. Göransson. 2004. Terrestrial plants require nutrients in similar proportions. *Tree Physiol.*, **24**: 447-460.
- Landsberg, J.J. and P.J. Sands. 2011. *Physiological ecology of forest production Principles, processes and models*. Academic Press: London.
- Linder, S. 1995. Foliar analysis for detecting and correcting nutrient imbalances in Norway spruce. *Ecological Bulletins*, **44**: 178-190.
- Little, K.M. and C.A. Rolando. 2002. Post-establishment vegetation control in a *Eucalyptus grandis* x *E. camaldulensis* stand. *South African Forestry Journal*, **193**: 77-80.
- Miller, H.G. 1981. Forest Fertilization: Some Guiding Concepts. *Forestry*, **54** (2): 157-167.

Myers, B.J., S. Theiveyanathan, N.D. O'Brien and W.J. Bond. 1996. Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Physiol.*, **16**: 211-219.

Nzila, J.D., P. Deleporte, J.P. Bouillet, J.P. Laclau and J. Ranger. 2004. Effects of slash management on tree growth and nutrient cycling in second-rotation *Eucalyptus* replanted sites in the Congo. In *Site management and productivity in tropical plantation forests: Proceedings of workshops in Congo July 2001 and China February 2003*. E.K.S. Nambiar, J. Ranger, A.E. Tiarks and T. Toma (eds.), CIFOR, Bogor, Indonesia, pp. 15-30.

Prado, J.S. and J. Toro. 1996. Silviculture of eucalypt plantations in Chile. In *Nutrition of Eucalypts*. P.M. Attiwill and M.A. Adams (eds.), CSIRO, Collingwood, pp. 357-370.

Schonau, A.P.G. 1983. Fertilisation in South African Forestry. *South African Forestry Journal*, **125** (1-19).

Schonau, A.P.G. and M.A. Herbert. 1989. Fertilizing eucalypts at plantation establishment. *For.Ecol.Manage.*, **29**: 221-244.

Shorrocks, V.M. 1997. The occurrence and correction of boron deficiency. *Plant and Soil*, **193** (1-2): 121-148.

Smethurst, P.J., C. Baillie, M. Cherry and G. Holz. 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. *For.Ecol.Manage.*, **176** (1-3): 531-542.

Stape, J.L., D. Binkley and M.G. Ryan. 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *For.Ecol.Manage.*, **193** (1-2): 17-31.

Stape, J.L., D. Binkley and M.G. Ryan. 2008. Production and carbon allocation in a clonal *Eucalyptus* plantation with water and nutrient manipulations. *For.Ecol.Manage.*, **255**: 920-930.

Stape, J.L., D. Binkley, M.G. Ryan, S. Fonseca, R.A. Loos, E.N. Takahashi, C.R. Silva, S.R. Silva, R.E. Hakamada, J.M.A. Ferreira, A.M.N. Lima, J.L. Gava, F.P. Leite, H.B. Andrade, J.M. Alves, G.G.C. Silva and M.R. Azevedo. 2010. The Brazilian Eucalyptus Potential Productivity Project: Influence of water, nutrients and stand uniformity on wood production. *For.Ecol.Manage.*, **259**: 1684-1694.

Stone, E.L. 1990. Boron deficiency and excess in forest trees: A review. *For.Ecol.Manage.*, **37**: 49-75.

Tamm, C.O. 1964. Determination of nutrient requirements of forest stands. *Int.Rev.Forest Research*, **1**: 115-170.

Turner, J. and M.J. Lambert. 1996. Nutrient cycling and forest management. In *Nutrition of eucalypts*. P.M. Attiwill and M.A. Adams (eds.), CSIRO, Collingwood, pp. 229-248.

Walkley, A. 1947. A critical examination of a rapid method for determining organic carbon in soils - effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science*, **63** (4): 251-264.

Whitehurst, G.B. and B.M. Whitehurst. 2004. Volatility-inhibited urea fertilizers. C05C 9/00 (20060101) Ed., Whitehurst Associates, Inc., New Bern, NC.

Whitesell, C.D., D.S. De Bell, T.H. Schubert, R.F. Strand and T.B. Crabb. 1992. Short-rotation management of *Eucalyptus*: Guidelines for plantations in Hawaii. *General Technical Report PSW-GTR-137*, P.S.R. Station. Albany, California, p. 30.

Yuan, T.L. and J.G.A. Fiskell. 1959. Aluminum determination, aluminum studies: Soil and plant analysis of aluminum by modification of the aluminon method. *J.Agric.Food Chem.*, **7** (2): 115-117.

Zerpa, J.L. and T.R. Fox. 2011. Controls of volatile ammonia losses from loblolly pine plantations fertilized with urea in the southeast USA. *Soil Sci.Soc.Am.J.*, **75** (1): 257-266.

Figure 1.

Figure 2.

Figure 3.