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Research Article

Eucalyptus grandis Response to Calcium Fertilization in Colombia

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Abstract

Calcium (Ca) is a critical plant nutrient typically applied at the time of planting in intensive *Eucalyptus* plantations in South America. At two sites in Colombia, we examined (1) calcium source by comparing growth after application of 100 kg ha^{-1} elemental Ca as lime or as pelletized highly reactive calcium fertilizer (HRCF) compared to a no application control, and (2) Ca rate by applying 0, 100, 200, and 400 kg ha^{-1} elemental Ca as HRCF with the addition of nitrogen, phosphorus, potassium, sulfur, and boron (NPKSB). We assessed height, diameter, and volume after 12 and 24 months. There were no growth differences from Ca source at the 100 kg ha^{-1} rate. We found increased volume after 24 months at the "Popayan" site with 200 and 400 kg ha^{-1} Ca HRCF+NPKSB treatments (112 and 113 m^3 ha^{-1}, respectively) compared to control (92 m^3 ha^{-1}), a 22% increase. In contrast, volume did not differ after 24 months at the "Darien" site, ranging from 114 m^3 ha^{-1} in the 0 kg ha^{-1} Ca HRCF+NPKSB treatment to 98 m^3 ha^{-1} in the control. Differences in response are likely due to soil characteristics, such as organic matter, emphasizing the importance of identifying site-specific nutrient deficiencies.

Study Implications: Operational applications may be over- or under-applying calcium carbonate in *Eucalyptus* plantations in South America. In the first two years of a seven-year rotation located in volcanic soils in Colombia, we found that one site with more organic matter at a greater depth did not need Ca additions, whereas the other site required greater than current operational applications to optimize productivity. Ca application rate trials across a gradient of soil conditions could establish critical values and improve recommendations of appropriate Ca application rates and emphasize the importance of understanding site-specific soil conditions to produce effective fertilization regimes.

Keywords: Eucalyptus, calcium, plantation management, intensive silviculture

Introduction

Calcium is a critical macronutrient required for plant growth and wood formation because it supports the strength of cell walls and other woody plant tissues. Plants with sufficient Ca available in the soil typically have shoot Ca concentrations between 1%–5% dry weight (Meharg and Marschner 2012). Ca deficiency may result in the disintegration of cell walls and the collapse of the affected tissues in the apical and upper parts of the stems or in new leaves. To address deficiencies, the soil environment can be modified through the addition of Ca to produce a more nutrient-rich soil solution, improving mineral absorption (Cheng et al. 2013, Fageria and Nascente 2014). However, critical levels are still not well defined for forest plantations (Leite et al. 2010).

Operationally, lime has become a regular addition at planting to most short-rotation (seven to 10 years) *Eucalyptus* plantations in South America due to concerns regarding potentially unsustainable nutrient removal during harvest, particularly for Ca and magnesium, and to prevent drops in pH (Stape et al. 2008, Leite et al. 2010). Recent work has shown no depletion in soil nutrient stocks, including Ca, after multiple rotations when Ca was added at elemental rates between 286 and 1,464 kg ha^{-1} in Brazil. There is also evidence that soil Ca is increasing over time (up to 500%) in some areas where current intensive forest production methods have been applied (McMahon et al. 2019). Application of Ca in the form of Ca carbonate ($CaCO_3$, commonly referred to as lime) increases soil pH, which affects other soil nutrient availability and may address soil deficiencies (Fageria et al. 2002, Cheng et al. 2013). High levels of soil organic matter will reduce the direct impact of lime application on pH because soil organic matter provides negatively charged sites that bind to H^+ in the soil, resulting in a more acidic soil solution (Fageria and Baligar 2008). Chemical and physical properties such as soil pH, cation exchange capacity (CEC), nutrient holding and availability, and aggregation may be affected by lime application (Rippy et al. 2007, Kassel 2009, Woodard and Bly

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2010). For example, soil acidity was typically reduced within three years of lime application (Pagani and Mallarino 2012, Li et al. 2019).

Aglime (ground or powdered limestone) is one of the most commonly used lime sources for neutralizing acidic soils throughout the world (Barber 1984, Fageria and Baligar 2008). The combination of particle size and chemical reactivity (as measured by $CaCO_3$ equivalence) influence the timing and efficiency of treatment for adjusting soil pH to the desired level (Higgins et al. 2012). Aglime and pelletized aglime can increase soil pH and crop yield (Kelling and Schulte 1988, Murdock 1997, Warncke and Pierce 1997). Highly reactive pelletized lime products produced from finely ground, high-purity $CaCO_3$ or calcium magnesium carbonate (dolomitic lime) provide Ca and react with soil pH more quickly than traditional aglime products. Whereas some studies have shown that broadcast pelletized lime is not more efficient than broadcast aglime at similar application rates (Godsey et al. 2007, Higgins et al. 2012), the granular nature of pelletized material enables easy transport, allows mixing with other fertilizers, and can be applied more conveniently.

Despite the importance of this critical macronutrient and its widespread use in plantation forestry, little information exists in the literature regarding Ca rate response or how different Ca sources influence response. The primary objectives of this study were to determine whether (1) the Ca source influenced growth response at the current operational rate and (2) the Ca application rate affected tree growth in *Eucalyptus* plantations at two sites in Colombia.

Table 1. Initial soil characteristics for the two sites in Colombia where *Eucalyptus grandis* was established prior to calcium application. For each row, different letters separate means at the $p < 0.05$ level per depth per soil characteristic to compare sites.

	Site	
Parameter	Darien	Popayan
Soil taxonomy	Loamy, mixed, thermic, Acrudoxic Hapludand	Loamy, mixed, thermic, Typic Melanudands
Parent material	Volcanic ash	Volcanic ash
Surface texture	Loam	Loam
Drainage	Well drained	Well drained
pH (0–15 cm)	4.3b	4.6a
pH (15–30 cm)	4.4b	5.0a
$N\text{-}NO_3$(ppm, 0–15 cm)	35.0a	24.4b
$N\text{-}NO_3$(ppm, 15–30 cm)	31.1a	10.8b
Phosphorus (ppm, 0–15 cm)	9.8a	9.7a
Phosphorus (ppm, 15–30 cm)	9.4a	9.4a
Potassium (ppm, 0–15 cm)	103.1b	128.3a
Potassium (ppm, 15–30 cm)	110.9a	110.9a
Calcium (ppm, 0–15 cm)	51.3b	57.7a
Calcium (ppm, 15–30 cm)	48.8b	55.4a
Cation exchange capacity (meq/100 gr, 0–15 cm)	39.4a	35.3b
Cation exchange capacity (meq/100 gr, 15–30 cm)	39.1a	34.3b

Methods

Experimental Design

Two studies were established in June 2018 on Smurfit Kappa Colombia property, one called "Darien" and the other one called "Popayan," both located on volcanic soils in the Colombian Andes and representing approximately 70% of the soils on the company land base. The soils at both sites are well-drained Andisols with a loamy texture (Table 1). The Darien site soil taxonomy is loamy, mixed, thermic Acrudoxic Hapludand, whereas soil taxonomy at the Popayan site is loamy, mixed, thermic Typic Melanudand. Both sites are located on the eastern slope of the western mountain range approximately 200 km apart. Sites had similar productivity in mean annual increment in the previous seven-year rotation based on direct production records of the harvested stand (Table 2). Although slight differences in productivity in the previous rotation could be attributed to operational management, care was taken in the current rotation to control all operational factors to isolate the effect of fertilization. There was no mechanical soil preparation at either site (i.e., no tilling, disking, bedding, or subsoiling). Both sites received broadcast preplanting chemical weed control with glyphosate (3.5 L ha^{-1}). In addition, shrubs, broadleaves, and sprouts were cleaned by manual operation 15 days prior to planting to maintain a clean experimental site (Figure 1A). All site preparation methods fall within industry standards so that results can be interpreted in the context of typical forest operations.

Three replications of six treatments (Table 3) were applied at each site in a randomized complete block design. Of the six treatments, one was a "true" control with no fertilizer additions, one received no Ca but all other nutrients, and the remaining four treatments received Ca and all other nutrients, but Ca varied in either source or rate. There was one powdered Ca treatment (dolomitic lime, 22% Ca, 13% Mg) applied at 100 kg ha^{-1} elemental Ca as the operational standard treatment and three pelletized Ca treatments applied at 100, 200, and 400 kg elemental Ca ha^{-1} as a highly reactive Ca fertilizer (HRCF). These micronized granules ranged between 2 and 6 mm in diameter with a weighted median particle size of d_{50} = 4.5 µm, 37% Ca, 0.6% Mg, tradename Omya Calciprill®). Additional elements that were applied to all treatments except the true control were nitrogen, phosphorus, potassium, sulfur, and boron (NPKSB). NPKSB were applied as ammonium sulfate (21% N, 24% S), diammonium phosphate (18% N, 20% P), potassium chloride (50% K 47% Cl,) and Campofert boron (10% B, 2.5% K) at planting, buried 20 cm down and away from the seedling (Figure 1B). All Ca applications were made manually around the base of the tree on the soil surface at planting to mimic operational application procedures (Figure 1C). All NPKSB fertilizers and elemental rates were similar to those used operationally. The fertilizers were applied by hand on May 28th and June 1st in 2018 at the Darien and Popayan sites, respectively, following commercial application procedures. Ca fertilizer is not typically buried with the NPKSB fertilizer but placed on the surface with the intention that it will slowly leach into the soil.

Eucalyptus grandis was planted at both sites at a density of 1,111 trees ha^{-1} on a 3 × 3 m spacing with the same genotype (clone 28-3). Species and clone were selected to be most appropriate for that elevation. Each study site was approximately 2.33 ha. Each treated plot contained 144 trees in a 12 × 12 grid. Measurement plots were centered in the

Table 2. Site characteristics and previous rotation (seven year) stand information for two sites in Colombia where *Eucalyptus grandis* was established and treatments with varying amounts of calcium were applied.

	Site	
	Darien	Popayan
County	Valle	Cauca
Nearest town	Darien	Popayan
Latitude	4.00	2.52
Longitude	−76.44	−76.57
Elevation (masl)	1614	1794
Slope	8.3%	12.1%
Precipitation (mm yr^{-1})	1428	2153
Mean annual temperature (°C)	19.7	17.7
Installation date	05/21/2018	05/23/2018
Fertilizer application date	05/28/2018	06/01/2018
Previous land use	*E. grandis* plantation	*E. grandis* plantation
Year entered into company land base	1975	1984
Number of previous rotations and species	4 (3 in *Eucalyptus*, 1 in pine)	4 (All in *Eucalyptus*)
Previous mean annual increment (m^3 ha^{-1} yr^{-1})	34	41
Previous site index, base age 7 years (m)	30.4	33.2
Previous volume under bark (m^3 ha^{-1})	297	361

treated plot and had 64 trees in an 8 × 8 grid. The plantation was successfully established, and the canopy was closed by 12 months (Figure 1D). For reference, trees in the background of Figure 1A are three years old.

Measurements

For all measurement trees, stem root collar diameter at 0.1 m height was measured at planting and at three and six months until diameter at breast height (DBH, 1.37 m) could be measured every six months after. Tree height was measured at three, six, 12, 18, and 24 months.

Soil samples were collected at both sites prior to fertilizer application and at six months after installation. Soil was sampled at 0–15 and 15–30 cm depths at five points across each measurement plot. Samples were composited by depth in each plot, air dried, and sieved through a 2 mm mesh prior to analysis. Soil chemical extraction was performed using Mehlich-3 procedures at Dr. Calderon Labs-Colombia, in Bogota, Colombia.

After 12 months, five mature leaves were collected from two branches in the upper crown of four dominant trees and composited by plot. Foliage was dried at 70°C to a constant weight, ground to pass through a 1 mm screen and analyzed for N, P, K, Ca, Mg, and B concentration. Laboratory analyses followed the methods specified in Sadzawka et al. 2004 and were performed at Waters Lab, Camilla, GA. N concentration was determined colorimetrically after Kjeldahl wet digestion. Samples were digested at 500°C and diluted in hydrogen chloride for the other elements. P and B concentrations were determined colorimetrically, and K, Ca, and Mg concentrations were determined by atomic absorption spectrophotometry.

Data Analysis

Tree volume was calculated from DBH and height measurements using a proprietary volume equation from Smurfit Kappa Colombia for *E. grandis* (Zapata 2011). The volume from all trees in each plot were summed and scaled to a ha area basis. Volume response was calculated by subtracting the volume of each treatment from the control (no fertilization) treatment. A mixed model approach was applied to analyze DBH, height, volume, and soil sampling data (Ca, N, P, K, pH, organic matter, and cation exchange capacity). Soil samples were analyzed within site per depth and across sites. In this model, treatment was considered a fixed effect and blocks were treated as random effects. If there was a significant treatment effect at an alpha level of 0.05, means were separated using a Tukey's HSD test. Data were examined at 12 and 24 months after planting by site. In a separate analysis, we included site as a factor in the model to examine site effects. We used a regression model analysis to examine the Ca rate response. Data were analyzed using RStudio (R Core Team 2021) and JMP (JMP, Version 14.0, SAS Institute Inc., Cary, NC, 1989–2019).

Results

Darien

All trees in the experiment survived to 24 months. At 12 months, there was a significant treatment effect on height ($p = 0.016$), where the 100, 200, and 400 kg ha^{-1} Ca HRCF+NPKSB were greater than the control. There was a significant treatment effect for diameter ($p < 0.01$) and volume ($p < 0.01$, Table 4, Figure 2), where all treatments receiving NPKSB were greater than the control. At 24 months after planting, only the 100 kg ha^{-1} Ca HRCF+NPKSB was significantly greater in height than the control ($p = 0.04$). Diameter ($p = 0.10$) and volume response ($p = 0.07$, Figure 3) showed no significant differences.

Popayan

All trees at this site survived to 24 months. After 12 months, there was a significant treatment effect on height ($p = 0.04$), where the 400 kg ha^{-1} Ca HRCF+NPKSB was greater than the control. The 200 and 400 kg ha^{-1}

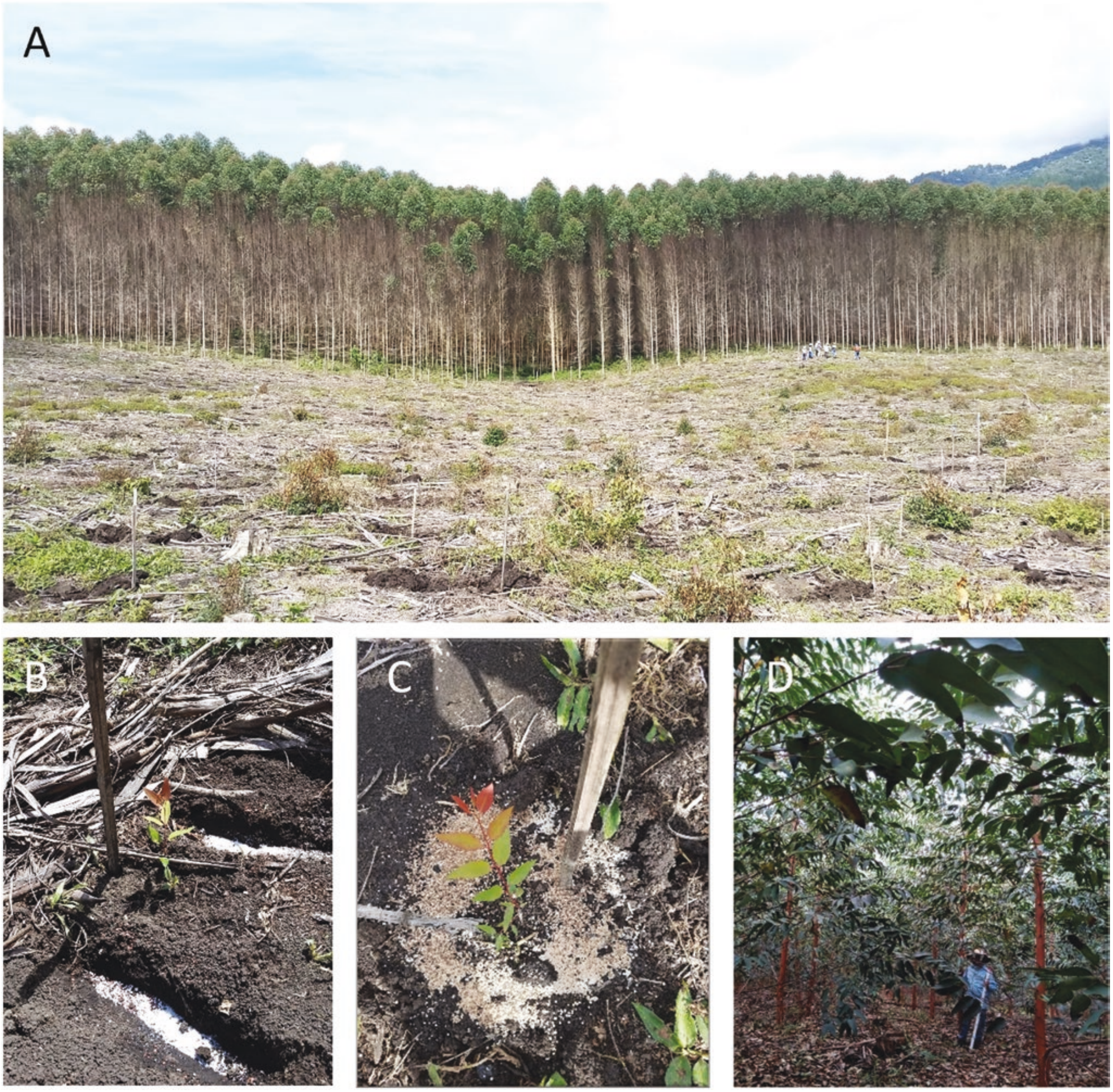

Figure 1. Site photos of (A) planting at Darien, (B) NPKSB fertilizer placement, (C) highly reactive calcium fertilizer placed at soil surface, and (D) *Eucalyptus* growth 12 months after planting.

Table 3. Treatment descriptions and nutrient application doses for *Eucalyptus grandis* in elemental rates. HRCF is highly reactive calcium fertilizer, a ground and pelletized calcium product. Magnesium (Mg) rate was higher with dolomitic lime due to source. Nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and boron (B) were added to all treatments except the control.

Treatment Name	Ca Source	Ca	Mg	N	P	K	S	B
	kg ha^{-1}							
Control		0	0	0	0	0		0
0 kg ha^{-1} Ca + NPKSB	0	0	0	38[a], 42[b]	33	12	43[a], 48[b]	2
100 kg ha^{-1} elemental Ca as lime + NPKSB	Dolomitic lime	100	59	38[a], 42[b]	33	12	43[a], 48[b]	2
100 kg ha^{-1} elemental Ca as HRCF + NPKSB	HRCF	100	16	38[a], 42[b]	33	12	43[a], 48[b]	2
200 kg ha^{-1} elemental Ca as HRCF + NPKSB	HRCF	200	32	38[a], 42[b]	33	12	43[a], 48[b]	2
400 kg ha^{-1} elemental Ca as HRCF + NPKSB	HRCF	400	65	38[a], 42[b]	33	12	43[a], 48[b]	2

[a] Darien
[b] Popayan

Ca HRCF+NPKSB treatments had significantly greater diameter than the control ($p = 0.01$). The 400 kg ha^{-1} Ca HRCF+NPKSB had significantly more volume than the control ($p = 0.04$; Figure 4).

After 24 months, height was still significantly greater in the 400 kg ha^{-1} Ca HRCF+NPKSB treatment than the control ($p = 0.05$). There was a significant treatment effect on diameter ($p = 0.02$), where the 200 and 400 kg ha^{-1} Ca HRCF+NPKSB

Table 4. Separation of height, diameter, and volume for each site at 12 months and 24 months after installation. HRCF is highly reactive calcium fertilizer, a ground and pelletized calcium product. NPKSB is nitrogen, phosphorus, potassium, sulfur, and boron. Means within a column followed by different letters indicated differences at $p < 0.05$ level of significance.

	12 month			24 month		
	Height (m)	Diameter (cm)	Volume (m³ ha⁻¹)	Height (m)	Diameter (cm)	Volume (m³ ha⁻¹)
	Darien					
Control	7.7b	6.3b	18.9b	17.5b	11.6a	98.4a
100 kg ha⁻¹ Ca as lime + NPKSB	8.5ab	7.4a	24.8a	17.8ab	12.2a	109a
100 kg ha⁻¹ Ca as HRCF + NPKSB	8.6a	7.5a	25.5a	18.3a	12.3a	111.7a
200 kg ha⁻¹ Ca as HRCF + NPKSB	8.7a	7.5a	25.8a	18.1ab	11.8a	105.1a
400 kg ha⁻¹ Ca as HRCF + NPKSB	8.7a	7.5a	25.6a	18.1ab	12.0a	105.5a
0 kg ha⁻¹ Ca + NPKSB	8.5ab	7.5a	25.2a	18.2ab	12.4a	114a
p value	0.016	0.003	0.007	0.041	0.103	0.07
	Popayan					
Control	5b	3.6b	9.8b	16b	11.8b	92.4b
100 kg ha⁻¹ Ca as lime + NPKSB	6.2ab	4.9ab	13ab	16.5ab	12.4ab	105.1ab
100 kg ha⁻¹ Ca as HRCF + NPKSB	6.3ab	5.0ab	13.4ab	16.9ab	12.3ab	105.4ab
200 kg ha⁻¹ Ca as HRCF + NPKSB	6.6ab	5.3a	14.2ab	17.0ab	12.7a	112.1a
400 kg ha⁻¹ Ca as HRCF + NPKSB	7.0a	5.5a	15.2a	17.4a	12.6a	112.9a
0 kg ha⁻¹ Ca + NPKSB	6.2ab	4.9ab	12.3ab	17ab	12.5ab	109.1ab
p value	0.040	0.014	0.044	0.053	0.016	0.041

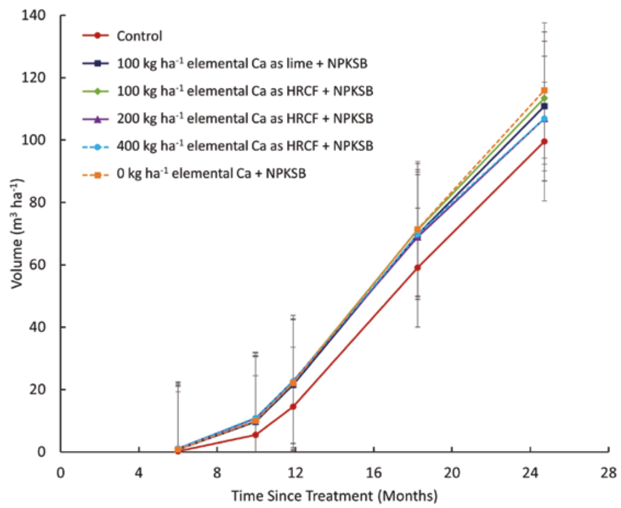

Figure 2. Volume (m³ ha⁻¹) since treatment using calcium fertilizer (either lime or pelletized highly reactive calcium carbonate fertilizer [HRCF]) and nitrogen, phosphorus, potassium, sulfur, and boron (NPKSB) treatments at Darien site.

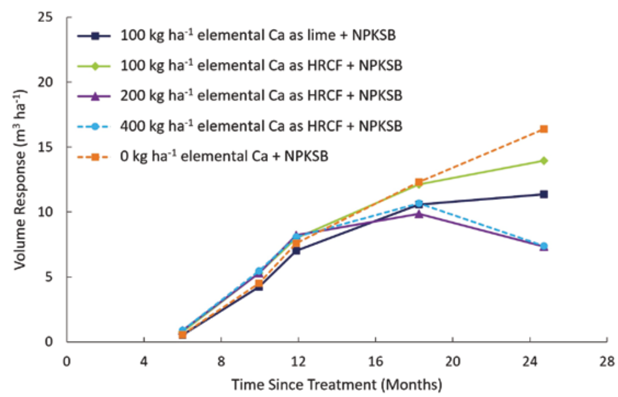

Figure 3. Darien site volume (m³ ha⁻¹) response to treatments compared to the control (no fertilization). HRCF, highly reactive calcium carbonate fertilizer.

treatments were greater than control (Table 4). The 200 and 400 kg ha⁻¹ Ca HRCF+NPKSB treatments were similar and produced 20 m³ ha⁻¹ more volume ($p = 0.04$) than the control (Figures 4 and 5).

Rate Response and Site Effect

There were no significant rate responses for volume at either site when examining linear and quadratic relationships (Figure 6). Site was a significant factor at 12 months ($p < 0.01$) where Darien produced more volume than Popayan on average across all treatments (21.0 m³ ha⁻¹ versus 7.5 m³ ha⁻¹, respectively). However, after 24 months, site was no longer a significant factor in explaining volume growth ($p = 0.71$). When examined across both sites, the treatment main effect for volume was significant at 12 months where all treatments receiving NPKSB had greater volume than control ($p < 0.01$), but treatment was not significant at 24 months ($p = 0.07$, Figure 7). There was no interaction between site and treatment at 12 or 24 months.

Effect of Ca Sources and NPKSB Fertilizers on Foliage Nutrient Concentrations and Soil Chemical Properties

There were no significant effects on foliar N, P, K, Ca, Mg, or S concentrations at Darien (Table 5) or Popayan (Table 6). At six months after treatment, there were no significant treatment effects at either depth on any soil nutrient or soil parameter at the Darien site (Table 7). At Popayan, significant treatment effects on CEC and organic matter were observed at the 15–30 cm depth (Table 8). CEC and organic matter

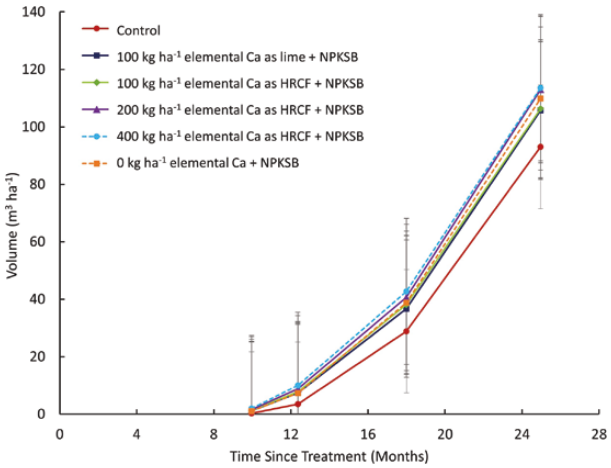

Figure 4. Volume (m³ ha⁻¹) since treatment using calcium fertilizers (either lime or pelletized highly reactive calcium carbonate fertilizer [HRCF]) and NPKSB treatments at Popayan site.

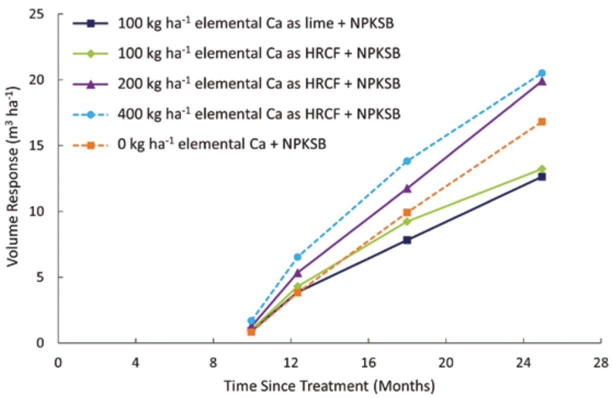

Figure 5. Popayan site volume (m³ ha⁻¹) response to treatment compared to the control (no fertilization). HRCF, highly reactive calcium carbonate fertilizer.

were significantly greater in the control than in the 100 kg ha⁻¹ Ca lime+NPKSB treatment.

There was no difference in organic matter, soil Ca, or CEC at 0–15 cm between sites but there was more organic matter, soil Ca, and CEC at the 15–30 cm depth at Darien than at Popayan ($p < 0.01$, $p = 0.01$, and $p = 0.03$, respectively). Darien had more soil P at the 0–15 cm depth ($p < 0.01$) and more total soil nitrogen at both soil depths ($p < 0.01$). Popayan, however, had greater soil K concentrations and higher pH than Darien at both the 0–15 and 15–30 cm depth ($p < 0.01$), similar to pre-treatment differences between sites.

Discussion

At the Darien site after 24 months, none of the treatments provided significant additional volume growth. These results indicate that operational Ca applications on some sites may not be necessary and may not provide a positive short-term return on investment. However, there is still concern that reductions or elimination of Ca additions may not be sustainable over repeated rotations, as reductions of soil Ca and pH have been shown previously over three rotations (21 years) of *Eucalyptus* production in Brazil where Ca inputs were lower than exports (Leite et al. 2010). In contrast, at Popayan, volume increased with application of 200 and 400 kg ha⁻¹ Ca in agreement with previous studies (Schönau and Herbert 1982, 1983, Herbert 1983). The 200 and 400 kg ha⁻¹ Ca applications proved equally effective, so from a management perspective, the operational application amount (100 kg ha⁻¹ Ca) may not be sufficient at this site but 400 kg ha⁻¹ Ca would be more than necessary. Results indicate that the addition of NPKSB is critical for *Eucalyptus* growth, but the study was not designed to determine which of these elements were most limiting. Similarly, whereas our study was not designed to examine the effect of an isolated Ca application, previous work indicated that $CaCO_3$ sources alone may not have a beneficial effect on the growth of *Eucalyptus grandis* (Mello et al. 1970, Schönau 1977).

There was no difference in growth response due to Ca sources at either site, but this result may be due to different drivers at each location. At Popayan, we postulate, as noted previously, that the 100 kg ha⁻¹ treatment was not enough to induce a response regardless of Ca source, given the growth response at higher rates, whereas at Darien, the site must have provided enough Ca that it was not the limiting resource. Similarly, we postulate that the lack of a rate response at Darien was likely due to higher soil quality and native nutrient availability, whereas at Popayan, perhaps higher Ca rates would have induced a greater response. Interestingly, the higher application rates at Popayan increased productivity to similar levels as those found at Darien after 24 months, showing the importance of understanding site-limiting resources to ameliorate limiting factors and the need for determination of critical values for nutrients.

Different responses at the two sites are most likely due to soil quality. Though the soil analysis at both sites (Darien and Popayan) differed little due to fertilizer additions, the soils differed in some chemical analyses between sites. Organic matter concentration was higher at the greater profile depth at the Darien site (14.6% at 15–30 cm depth) than at the Popayan site (8.9% at 15–30 cm depth). CEC was initially greater at Darien, potentially allowing for greater retention of soil Ca at 15–30 cm after treatments. We observed from describing soils to 1 m that at the Darien site the organic matter sometimes extended more than 92 cm in depth, whereas at Popayan, the organic matter tended to be shallower (5 to 25 cm depth). Compared with Darien, slightly steeper slopes at Popayan may have suffered greater past erosion, although compared with other sites in Colombia, both these sites had relatively gentle slopes. Organic matter is considered a critical soil property because of its influence on many characteristics of productive soil and has been shown to be linked with *Eucalyptus* yield (Menezes 2005). Organic matter can lead to increased nutrient and water holding capacity and decreased bulk density. Organic matter reduces bulk density, which will ultimately affect soil infiltration and root proliferation. In general, soils with higher organic matter content tend to be more productive (Shoji 1993). The difference in organic matter, CEC, and soil Ca levels at depth may help explain the response to nutrient additions. These results support other work (Albaugh et al. 2015) that suggests that treatment effects can be strongly influenced by soil characteristics, where soils with lower inherent nutrient availability are more likely to respond to fertilizer additions. Interestingly, although we did not see a difference in pH due to treatment effect, we did see greater pH at Popayan prior to and after treatments, suggesting there

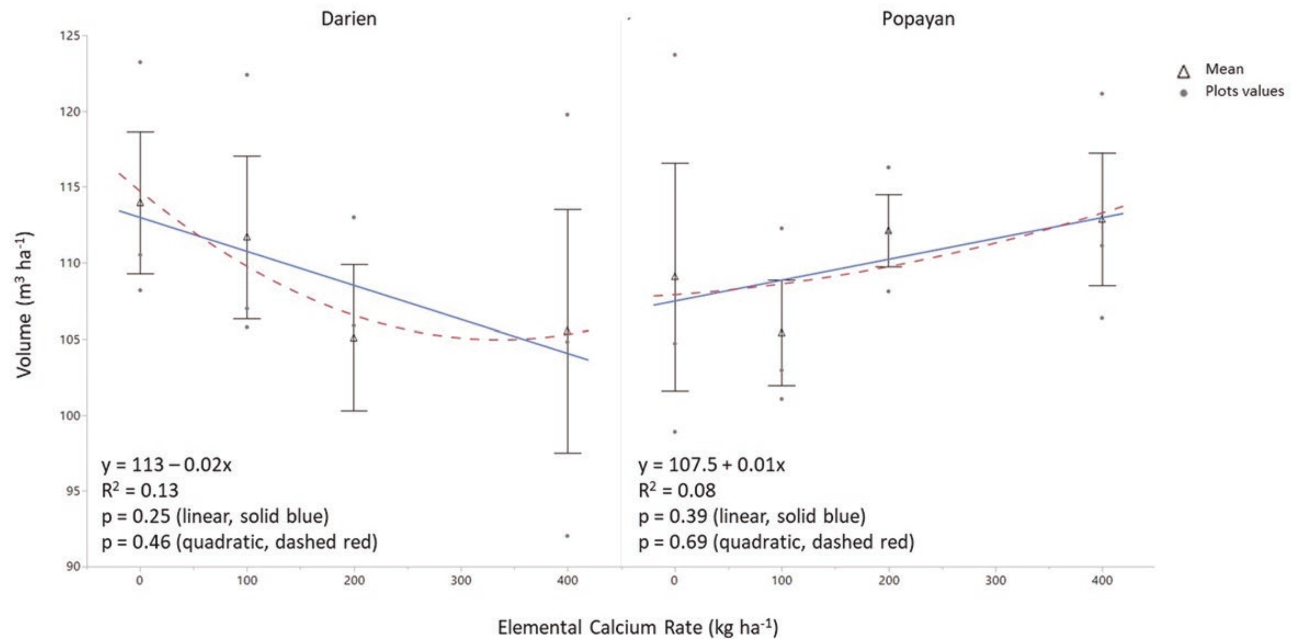

Figure 6. Tree volumes (m^3 ha^{-1}) measured at 24 months post planting at each site shown against quantity of rate of calcium fertilizer application from treatments. Values are fit against a linear (solid blue line) and quadratic (dashed red line) regression model. Plot-level values (gray circles) and treatment mean values (triangles) with standard error bars are shown. No regressions were significant.

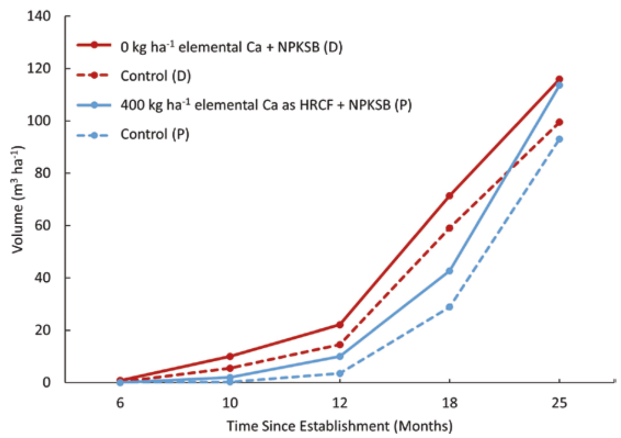

Figure 7. Control treatment volume and the treatment with the greatest volume (m^3 ha^{-1}) shown at Darien (D) and Popayan (P) sites. HRCF, highly reactive calcium carbonate fertilizer; NPKSB, nitrogen, phosphorus, potassium, sulfur, and boron.

may be some relationship to the greater treatment response seen, although we would have expected the site with the lower pH to potentially be more responsive. Volcanic soils have high P-fixation abilities, and changes in pH may relate to P availability. Soil P is typically quite limiting in these soils, and plant availability is particularly difficult to assess. Zapata (2017) found that approximately 60% of inorganic P is occluded and only 0.7% and 1.6% were rapidly available at Popayan and Darien, respectively.

We had originally expected to see greater differences in foliar nutrient concentrations due to treatment, but foliar concentrations were similar overall, even in treatments with greater growth response. Nutrient concentrations have been previously shown to have limitations in predicting productivity (Albaugh et al. 2015). Differences in site productivity may be attributed to higher leaf area or greater growth efficiency in treatments with greater growth but without higher nutrient concentrations.

Although the nature of this study was narrow in scope, the information provided should be useful for plantation managers looking for fast crown closure and capturing site resources for plantation development. Nutrients like Ca are often applied in a prophylactic manner in South American *Eucalyptus* plantations, and this study highlights the need for a better understanding of site-specific nutrient limitations rather than a one-size-fits-all approach. Some sites may need more than is currently being applied, and others could be equally productive with less. Additionally, the current ability to predict response based on soil chemical extractions and analysis is essentially unknown for forest plantations across a broad gradient of soils in South America. A better understanding of soil supply and fertilizer response will allow for optimizing resource allocation on a site-specific basis and enhance the sustainability of forest operations.

Conclusion

Site and soil characteristics likely had an impact on differences in response to Ca fertilization. The differences in soil organic matter likely contributed to different responses to Ca additions. In general, sites like Darien may not be as resource limited and therefore are less likely to respond to Ca applications, whereas sites like Popayan may be more likely to show responses to Ca additions at higher rates than currently applied. These trends emphasize the importance of using site-specific information to guide management and fertilization regimes and the need for greater understanding of the drivers of response.

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Table 5. Summary of posttreatment foliar element concentrations (% or ppm) across treatments at the Darien site. HRCF is highly reactive calcium fertilizer, a ground and pelletized calcium product. NPKSB is nitrogen, phosphorus, potassium, sulfur, and boron. Different letters indicate differences among treatments for a given foliar nutrient. Means within a column followed by different letters indicated differences at $p < 0.05$ level of significance.

	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Mn (ppm)	Zn (ppm)	Cu (ppm)
P value	0.31	0.69	0.97	0.20	0.20	0.94	0.52	0.88	0.07
Standard error	0.039	0.002	0.012	0.045	0.004	0.001	22.166	0.272	0.189
Treatment									
Control	2.60a	0.11a	0.95a	1.08a	0.17a	0.18a	699.09a	17.65a	7.43a
100 kg ha^{-1} Ca as lime + NPKSB	2.45a	0.10a	0.96a	1.12a	0.17a	0.17a	756.55a	17.24a	6.49b
100 kg ha^{-1} Ca as HRCF + NPKSB	2.31a	0.09a	0.96a	1.26a	0.18a	0.18a	685.44a	16.25a	6.15b
200 kg ha^{-1} Ca as HRCF + NPKSB	2.43a	0.10a	1.02a	1.13a	0.18a	0.18a	610.09a	17.74a	6.83b
400 kg ha^{-1} Ca as HRCF + NPKSB	2.40a	0.10a	0.99a	1.38a	0.20a	0.18a	685.40a	18.24a	6.43b
0 kg ha^{-1} Ca + NPKSB	2.47a	0.11a	0.95a	1.19a	0.18a	0.18a	755.17a	17.51a	7.04b

Table 6. Summary of posttreatment foliar element concentrations (% or ppm) across treatments at the Popayan site. Different letters indicate differences among treatments for a given foliar nutrient. Means within a column followed by different letters indicated differences at $p < 0.05$ level of significance.

	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Mn (ppm)	Zn (ppm)	Cu (ppm)
P value	0.53	0.21	0.50	0.31	0.06	0.50	0.44	0.24	0.68
Standard error	0.031	0.002	0.022	0.034	0.002	0.002	65.028	0.952	0.113
Treatment									
Control	2.19a	0.10a	1.17a	1.15a	0.22a	0.167a	844.29a	20.19a	6.81a
100 kg ha^{-1} as lime+NPKSB	2.20a	0.09a	1.11a	1.01a	0.22a	0.17a	484.79a	15.63a	6.99a
100 kg ha^{-1} as HRCF+NPKSB	1.99a	0.09a	1.13a	1.06a	0.22a	0.17a	413.59a	14.07a	6.43a
200 kg ha^{-1} as HRCF+NPKSB	2.17a	0.01a	1.09a	1.00a	0.22a	0.18a	479.99a	14.01a	6.39a
400 kg ha^{-1} as HRCF+NPKSB	2.16a	0.01a	1.01a	1.20a	0.22a	0.18a	610.39a	15.23a	7.02a
0 kg ha^{-1} Ca+NPKSB	2.16a	0.01a	1.09a	1.15a	0.23a	0.17a	677.38a	17.09a	6.86a

Table 7. Soil analysis six months after treatment for the Darien site, separated into 0–15 and 15–30 cm soil depth. Letters separating values within a column are significantly different. CEC is cation exchange capacity. HRCF is highly reactive calcium fertilizer, a ground and pelletized calcium product. NPKSB is nitrogen, phosphorus, potassium, sulfur, and boron. Means within a column followed by different letters indicated differences at $p < 0.05$ level of significance.

Treatment	Ca (ppm)	N (%)	P (ppm)	K (ppm)	pH	Organic matter (%)	CEC (cmol$_c$ 100 kg^{-1})
	0–15 cm						
Control	145.33	1.20	5.33	10.40	4.36	15.38	24.98
100 kg ha^{-1} elemental Ca as lime + NPKSB	82.00	1.25	4.33	11.70	4.23	15.96	25.63
100 kg ha^{-1} elemental Ca as HRCF + NPKSB	108.67	1.10	4.00	19.50	4.33	15.13	24.82
200 kg ha^{-1} elemental Ca as HRCF + NPKSB	106.00	1.19	4.00	13.00	4.32	13.66	23.27
400 kg ha^{-1} elemental Ca as HRCF + NPKSB	108.00	1.13	3.00	11.70	4.37	13.09	22.73
0 kg ha^{-1} elemental Ca + NPKSB	89.33	1.22	4.67	10.40	4.32	15.58	25.18
p value	0.68	0.98	0.86	0.83	0.48	0.41	0.41
	15–30 cm						
Control	88.00	0.94	2.00	3.90	4.52	17.56	27.22
100 kg ha^{-1} elemental Ca as lime + NPKSB	53.33	1.04	2.00	7.80	4.56	14.94	24.60
100 kg ha^{-1} elemental Ca as HRCF + NPKSB	58.67	0.90	2.00	10.40	4.60	12.96	22.47
200 kg ha^{-1} elemental Ca as HRCF + NPKSB	63.33	1.01	2.00	3.90	4.59	13.07	22.84
400 kg ha^{-1} elemental Ca as HRCF + NPKSB	66.67	0.78	2.33	6.50	4.61	14.49	24.15
0 kg ha^{-1} elemental Ca + NPKSB	56.67	0.95	2.33	6.50	4.68	14.68	24.22
p value	0.70	0.73	0.57	0.36	0.77	0.96	0.96

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Table 8. Soil analysis six months after treatment for the Popayan site, separated into 0–15 and 15–30 cm soil depth. CEC is cation exchange capacity. HRCF is highly reactive calcium fertilizer, a ground and pelletized calcium product. NPKSB is nitrogen, phosphorus, potassium, sulfur, and boron. Means within a column followed by different letters indicated differences at $p < 0.05$ level of significance.

Treatment	Ca (ppm)	N (%)	P (ppm)	K (ppm)	pH	Organic matter (%)	CEC (cmol$_c$ 100 kg^{-1})
	0–15 cm						
Control	198.00	0.91	2.33	46.80	4.69	17.73	27.39
100 kg ha^{-1} elemental Ca as lime + NPKSB	70.67	0.68	2.00	57.20	4.92	12.45	22.13
100 kg ha^{-1} elemental Ca as HRCF + NPKSB	61.33	0.72	2.00	39.00	4.95	14.87	24.55
200 kg ha^{-1} elemental Ca as HRCF + NPKSB	54.67	0.85	2.00	40.30	4.71	12.55	22.24
400 kg ha^{-1} elemental Ca as HRCF + NPKSB	45.33	0.75	2.00	22.10	4.90	11.49	21.31
0 kg ha^{-1} elemental Ca + NPKSB	119.33	0.93	2.33	32.50	4.71	14.96	24.68
p value	0.43	0.44	0.57	0.21	0.91	0.86	0.87
	15–30 cm						
Control	51.33	0.59	2.00	28.60	5.01	14.62a	24.55a
100 kg ha^{-1} elemental Ca as lime + NPKSB	41.33	0.50	2.00	40.30	5.47	4.83b	14.65b
100 kg ha^{-1} elemental Ca as HRCF + NPKSB	50.67	0.39	2.00	35.10	5.56	5.60b	15.40b
200 kg ha^{-1} elemental Ca as HRCF + NPKSB	40.67	0.54	2.00	31.20	5.24	7.29b	16.84b
400 kg ha^{-1} elemental Ca as HRCF + NPKSB	40.00	0.63	2.67	18.20	4.89	12.53b	22.17b
0 kg ha^{-1} elemental Ca + NPKSB	52.67	0.47	2.00	28.60	5.28	8.78b	18.79b
p value	0.57	0.52	0.46	0.72	0.15	0.03	0.03

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Conflict of Interest

None declared.

Literature Cited

Albaugh, T.J., R.A. Rubilar, T.R. Fox, H. Lee Allen, J.B. Urrego, M. Zapata, and J.L. Stape. 2015. Response of *Eucalyptus grandis* in Colombia to mid-rotation fertilization is dependent on site and rate but not frequency of application. *For. Ecol. Manage.* 350(August):30–39. https://doi.org/10.1016/j.foreco.2015.04.030.

Barber, S.A. 1984. Liming materials and practices. In F. Adams (ed.) *Soil acidity and liming*. Agronomy Monographs: John Wiley & Sons, Ltd. 171–209 p. https://doi.org/10.2134/agronmonogr12.2ed.c4.

Cheng, Y., J. Wang, B. Mary, J.-B. Zhang, Z.-C. Cai, and S.X. Chang. 2013. Soil pH has contrasting effects on gross and net nitrogen mineralizations in adjacent forest and grassland soils in Central Alberta, Canada. *Soil Biol. Biochem.* 57(February):848–857. https://doi.org/10.1016/j.soilbio.2012.08.021.

Fageria, N.K., and V.C. Baligar. 2008. Chapter 7 Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production. *Adv. Agron.* 99:345–399. Academic Press. https://doi.org/10.1016/S0065-2113(08)00407-0.

Fageria, N.K., V.C. Baligar, and R.B. Clark. 2002. Micronutrients in crop production. *Advances in Agronomy*. 77: 185–268. https://doi.org/10.1016/S0065-2113(02)77015-6

Fageria, N., and A. Nascente. 2014. Management of soil acidity of South American soils for sustainable crop production. *Adv. Agron.* 128:221–275. https://doi.org/10.1016/B978-0-12-802139-2.00006-8.

Godsey, C.B., G.M. Pierzynski, D.B. Mengel, and R.E. Lamond. 2007. Management of soil acidity in no-till production systems through surface application of lime. *Agron. J.* 99(3):764–772. https://doi.org/10.2134/agronj2006.0078.

Herbert, M.A. 1983. The response of *Eucalyptus grandis* to fertilising with nitrogen, phosphorus, potassium and dolomitic lime on a mispah soil series. *South. Afr. For. J.* 124(1):4–12. https://doi.org/10.1080/00382167.1983.9628859.

Higgins, S., S. Morrison, and C.J. Watson. 2012. Effect of annual applications of pelletized dolomitic lime on soil chemical properties and grass productivity. *Soil Use Manag.* 28(1):62–69. https://doi.org/10.1111/j.1475-2743.2011.00380.x.

JMP. 1989–2019. *Version 14.0.* SAS Institute Inc., Cary, NC.

Kassel, P.C. 2009. *Report on the effects of eggshells and aglime on soil pH and crop yields. 3905025.* Iowa State University Digital Repository. Ames, IA. https://doi.org/10.31274/farmprogressreports-180814-1173.

Kelling, K.A., and E.E. Schulte. 1988. Pelletized lime for Wisconsin. Paper presented at the *Proceedings of the 1988 Wisconsin Forage Council's 12th Forage Production and Use Symposium,* Wisconsin Dells, WI; p. 147–149.

Leite, F.P., I.R. Silva, R.F. Novais, N.F. De Barros, and J.C.L. Neves. 2010. Alterations of soil chemical properties by eucalyptus cultivation in five regions in the Rio Doce Valley. *Rev. Bras. Ciência do Solo* 34:821–831.

Li, Y., S. Cui, S.X. Chang, and Q. Zhang. 2019. Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: A global meta-analysis. *J. Soils Sediments* 19(3):1393–1406. https://doi.org/10.1007/s11368-018-2120-2.

McMahon, D.E., L. Vergütz, S.V. Valadares, I.R. da Silva, and R.B. Jackson. 2019. Soil nutrient stocks are maintained over multiple rotations in Brazilian *Eucalyptus* plantations. *For. Ecol. Manage.* 448(September):364–375. https://doi.org/10.1016/j.foreco.2019.06.027.

Meharg, A., and P. Marschner. 2012. Marschner's mineral nutrition of higher plants. *Exp. Agric.* 48(2):305. http://dx.doi.org.prox.lib.ncsu.edu/10.1017/S001447971100130X.

Mello, H.A., J.M. Sobrinho, J.W. Simões, and H.D. Couto. 1970. Resultados da aplicação de fertilizantes minerais na produção de madeira de *Eucalyptus saligna sm*. em solos de cerrado do estado de São Paulo. *IPEF, Piracicaba* (1):7–26.

Menezes, A.A. 2005. *Produtividade do eucalipto e sua relação com a qualidade e a classe de solo*. Universidade Federal de Viçosa, Viçosa, Brazil. 98 p. (Doctoral dissertation).

Murdock, L.W. 1997. Pelletized Lime - How Quickly Does It React. *Soil Science News and Views*. 13. https://uknowledge.uky.edu/pss_views/13

Pagani, A., and A.P. Mallarino. 2012. Soil PH and crop grain yield as affected by the source and rate of lime. *Soil Sci. Soc. Am. J.* 76(5):1877–1886. https://doi.org/10.2136/sssaj2012.0119.

R Core Team. 2021. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rippy, J.F.M., P.V. Nelson, D.L. Hesterberg, and E.J. Kamprath. 2007. Reaction times of twenty limestones. *Commun. Soil Sci. Plant Anal.* 38(13–14):1775–1783. https://doi.org/10.1080/00103620701435530.

Shoji, S., and M. Nanzyo. 1993. *Volcanic ash soils: Genesis, properties, and utilization*. Developments in Soil Science. Elsevier, Amsterdam. 21 p. https://catalog.lib.ncsu.edu/catalog/NCSU829500.

Sadzawka, A., M.A. Carrasco, R. Grez, M.L. Mora, H. Flores, and A. Neaman. 2004. *Métodos de análisis recomendados para los suelos de Chile. Revisión 2004*. Instituto de Investigaciones Agropecuarias, Serie Actas INIA No 34, Santiago, Chile, 164p.

Schönau, A.P.G. 1977. Initial responses to fertilizing *Eucalyptus grandis* at planting are sustained until harvesting. *South. Afr. For. J.* 100(1):72–81. https://doi.org/10.1080/00382167.1977.9629437.

Schönau, A.P.G., and M.A. Herbert. 1982. Relationship between growth rate and foliar concentrations of nitrogen, phosphorus and potassium for *Eucalyptus grandis*. *South. Afr. For. J.* 120(1):19–23. https://doi.org/10.1080/00382167.1982.9630235.

Schönau, A.P.G., and M.A. Herbert. 1983. Relationship between growth rate, fertilizing and foliar nutrient concentrations for *Eucalyptus grandis*; preliminary investigations. *Fertil. Res.* 4(4):369–380. https://doi.org/10.1007/BF01054010.

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(3):920–930. https://doi.org/10.1016/j.foreco.2007.09.085.

Warncke, D.D., and F.J. Pierce. 1997. Pelletized lime reacts slower than dolomitic aglime. *Crop Soil Sci. Newsletter* 23(231): 4–6.

Woodard, H., and A. Bly. 2010. Soil pH change and crop responses with long-term liming applications in tilled and untilled systems. *Commun. Soil Sci. Plant Anal.* 41(14):1723–1739. https://doi.org/10.1080/00103624.2010.489136.

Zapata, C.M. 2011. *Fractovolumen*. Smurfit Kappa Colombia, Yumbo, Colombia.

Zapata, C.M. 2017. *Dinámica del fósforo en el suelo y su relación con el crecimiento del Eucalyptus grandis para la región alto andina de Colombia. Capítulo 2. Fracciones y adsorción de fósforo en suelos volcánicos de la región alto andina de Colombia*. Universidad Nacional de Colombia.