ABSTRACT

ZELAYA ANDINO, ARIEL SAUL. Highly Reactive Calcium Fertilizer Response on the Growth and Nutrient Availability of *Eucalyptus grandis*. (Under the direction of Dr. Rachel L. Cook).

Challenges such as the fast-growing global population and increased demand for wood products will require the expansion of tree plantations grown under proper intensive regimes. Consequently, fast growing species such as *Eucalyptus grandis* have been used in South American countries to supply more wood products while allowing increased profits. *Eucalyptus* plantations on Andisols under proper fertilization have demonstrated dramatic increases in wood yield, however, Andisols have also been associated with phosphorus deficiency leading to reduced *Eucalyptus* wood production. The addition of calcium carbonate may enhance soil properties by raising pH, supplying calcium and improving nutrient availability. Calcium is an important nutrient needed for proper tree nutrition, health, and development, but the requirements for *Eucalyptus,* particularly in Andisols, are not well understood.

The objectives of the studies were to assess the effects of different rates and sources of calcium carbonate with and without nutrient additions such as Nitrogen, Phosphorus, Potassium, Sulfur and Boron (NPKSB) on growth of *Eucalyptus grandis.* A pot trial ran for five months and was destructively sampled for plant tissue nutrient concentration and content. In the field, the response of *Eucalyptus grandis* production to the addition of calcium carbonate sources and NPKSB was assessed every three months for one year in two different locations in Colombia (Popayan and Darien). Tree measurements were taken to assess tree growth and foliar tissue and soil samples were taken and analyzed after six months to assess the impact of added nutrient concentration on plant tissues and soil nutrient availability. Additionally, a laboratory incubation trial was established with different calcium carbonate rates and sources (Lime and Calciprill) to

determine the reactivity of the products and the soil chemistry change in Andisols following calcium carbonate application.

Results from the pot trial indicated that any addition of NPKSB significantly improved plant nutrient concentration, nutrient mass, plant height and root collar diameter, even when calcium carbonate was not applied. The field studies also showed a response to the addition of NPKSB, which improved plant height and diameter breast height but not soil nutrient availability at Darien. At the Darien site, tree volume increased with all treatments that received NPKSB either with or without calcium additions compared to the Control from 9.03 $m^3 ha^{-1}$ to 14.47 $m^3 ha^{-1}$ in the presence of 400 kg ha^{-1} Ca Calciprill + NPKSB. At the Popayan site, the tree volume increased from 2.23 $m^3 ha^{-1}$ in the Control to 6.41 $m^3 ha^{-1}$ in the presence of 400 kg ha^{-1} Ca Calciprill + NPKSB. In the incubation trial, the addition of NPKSB had a significant effect on most measured nutrients (P, K, Ca, S, B, Zn, Mn, and Fe) as well on soil pH and cation exchange capacity 32 days after treatment.

Based on our findings, the addition of nutrients (NPKSB) increases tree growth and soil nutrient availability in the pot trial (K and Ca), at 0-15 cm depth at the Popayan site (K), and in the incubation trial (P, K, Ca, S, B, Zn, Mn, and Fe). These results highlight the importance of matching the appropriate soil and fertilization schemes in order to maximize wood yields on tree plantations.

Highly Reactive Calcium Fertilizer Response on the Growth and Nutrient Availability of *Eucalyptus grandis*

by
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DEDICATION

To my family and friends.

BIOGRAPHY

Ariel Zelaya was born on December 09, 1991 in Tegucigalpa, Honduras. He started his undergraduate studies in Agronomic Engineering in 2009. Ariel Zelaya received his Agronomic Engineering Degree at the National Agriculture University of Honduras, Catacamas on December 20, 2012.

In 2013, Ariel worked as an Agriculture Quarantine Official for OIRSA (International Sanitary Agricultural Organization, Honduras) reviewing agricultural imports and exports.

In January 2015, Ariel Zelaya moved to North Carolina, USA and began working as a Research Assistant for North Carolina State University in the department of Crop Science. He also worked as a Research Assistant in soybean breeding for the US Department of Agriculture and NC State University. In 2017, his extensive experience in growing plants made him decide to pursue a Master of Science at NC State University, researching forest soils and plant nutrition for tropical species.

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INTRODUCTION

Production and global demand

Traditional forest plantations and natural forests alone cannot provide enough wood products to fulfill worldwide demand (Boyle and Coleman, 2005). Additionally, the creation of new tree plantations and adoption of proper intensive production regimes to supply wood products could prevent illegal exploitation in native woodlands as well as protect endangered species (Sedjo and Botkin, 1997; Cacho et al., 2005). Natural forests cannot fulfill all demand for wood products, but fortunately today's forest plantations are producing more wood products than natural forests (Bettinger et al., 2009). The use of forest fertilization to increase nutrient availability is one of the primary factors which has led to the increased productivity and use of intensive plantations (Fox et al., 2007). Fertilization is often required because some soils are nutrient deficient by nature, while other soils have become nutrient deficient as a consequence of the overuse for agricultural production. Some sites, with uneven topography and nutrient deficiencies, do not favor agriculture usage but could be appropriated for wood production (Wadsworth, 1997). These sites would require proper intensive management regimes in order to supply resources for optimal wood production (Bettinger et al., 2009).

Tree plantations

With an increase in demand for wood products, tree plantations are becoming more appealing as a wood product source because of their potential to maximize yields and livelihoods (Wadsworth, 1997). According to the Food and Agriculture Organization, just 5% of forest plantation lands supply 35% of the wood products produced globally (FAO, 2006). The use of forest plantations is also growing rapidly. Forest plantation area increased from 167.6 million

hectares in 2010 to 227.9 million hectares in 2015. Those areas yielded around 5.26 m^3 ha^{-1} yr^{-1} volume production of wood products in 2015 (Payn et al., 2015). Even with this growth in production, wood product supplies might be unable to meet global demand if forest plantations are unable to increase at a rate of 2.4% per year (WWF and IIASA, 2012).

Plantation forestry with fast-growing cycles is also important from a financial point of view (Earl, 1972). Intensive plantations are turning into a significant source of income for rural areas (Strauss and Bradshaw, 2004). Forest plantations also create conditions for carbon storage, nutrient cycling, and water and air purification while providing 45.14 million jobs around the globe and supporting livelihoods worth more than $580 billion a year (FAO, 2018). Multiple nations rely on the economic development opportunity provided by tree plantations as a significant source of income (Köhl et al., 2015). Marsha (1962) concluded that plantations and short rotation species are well-suited to meet wood demand compared to native vegetation, which provides less opportunity for economic development. Additionally, the removal of wood products from natural forests in remote locations is generally complicated or not feasible for wood extraction. To address this, access to forest products can be made more efficient by establishing plantations adjacent to wood processing facilities.

Eucalyptus plantations

Eucalyptus plantations provide a significant contribution to meeting global wood product demand. Currently, there are around 20 million hectares of *Eucalyptus* in production around the world. South American countries (Brazil, Venezuela, Colombia, Chile, Uruguay, and Argentina) are the most significant producers of *Eucalyptus* wood products (Carrero et al., 2018). In 2017, worldwide production of *Eucalyptus* wood pulp was approximately 183,000,000 tonnes while

worldwide consumption was around 184,464,000 tonnes (FAO, 2019). The cellulose industry is highly concentrated in subtropical countries because of the availability of under-utilized land, long periods of sunlight, and temperature for proper tree growth (Campinhos, 1999).

In the late 1980's to the early 2000's in Brazil, there was significant disapproval of the expansion of *Eucalyptus* plantations (Wadsworth, 1997). Spears (1987) suggests that there are many misconceptions about *Eucalyptus* plantations, such as that they (1) create nutrient deficiencies in the soil, (2) endanger the water equilibrium, (3) have a negative impact on the rhizosphere of plants, (4) take over croplands, and (5) reduce local labor. Despite these claims, it was demonstrated that *Eucalyptus* plantations are efficient, readily adaptable, and have rapid growth capabilities (Campinhos, 1999). *Eucalyptus* has been described as a good production species because of multiple properties including that (1) it is adaptable to variable environmental conditions, (2) it has short-rotation cycles from 7 to 10 years, (3) it produces a well-formed canopy structure, (4) it exhibits good compatibility between species for breeding, and (5) multiple markets exist for the wood products (FAO, 1988). The high monetary value for *Eucalyptus* produced as pulp and paper is because of its great durability, strength, abundance, and convenience (Campinhos, 1999). Additionally, intensive management regimes can be implemented to correct limiting conditions that may directly affect forest productivity (Carrero et al., 2018).

Eucalyptus **plantations in Colombia**

Tree farms supply around 60% of the wood products generated in Colombia. In 2017, Colombia provided 405,000 hectares (0.22%) of the world consumption of wood pulp (FAO, 2019). Of the tree plantations in Colombia, *Eucalyptus* plantations are one of the primary sources

of renewable wood production (Rodas et al., 2009). *E. grandis* and *E. globulus* represent 19% of the 405,000 hectares of the total established plantations in Colombia (FAO 2010, 2015). Improved plant material such as *Eucalyptus* clonal plants have become useful because they provide increased productivity and improved wood properties for wood products (Rodas et al., 2009). Supplying the appropriate soil nutrients to these new tree plantations with clonal plants could further increase wood production and help diminish the demand for harvesting from native forests (Albaugh et al., 2015).

Volcanic soils

The quality of soil is also an important factor to consider when establishing forest plantations. The presence of volcanos in the Colombian Andes have contributed to a predominance of volcanic soils, or Andisols, in the region (Herrera et at., 2007). Andisols are well known as one of the most productive soil orders. Shoji et al (1994) noted that the primary reasons why Andisols are very productive is because (1) the parent material has ashes that contain basalt or andesite and are abundant in clay minerals and nutrients which help to supply nutrients to plants, (2) they have an unrestricted rooting zone, (3) they contain humus horizons with large amounts of organic N, (4) Apatite (calcium phosphate) is relatively abundant in the parent material, and (5) they contain sufficient capacity for holding water which is available for plants. One challenge to using Andisols is that the soils are able to fix large amounts of phosphorus and therefore their use in continuous subsistence cultivation requires applications of P fertilizers for continuous production. Phosphorus deficiency in volcanic soils can potentially compromise crop production (Gijsman and Sanz, 1998; Rao et al., 1999). Calcium, sodium, and silicon uptake in Andisols are also affected by weathering processes and the high concentration

of aluminum in the soil (Nanyo, 2004). These simultaneous soil leaching and weathering processes can also lead to increased soil acidification (Herrera et al., 2007). Volcanic soils do not have many physical limitations unless they become dry for an extended period of time.

While tree plantations on volcanic soils may be affected by nutrient deficiencies, such problems can be ameliorated by using proper management regimes (Coyle and Coleman, 2005). A potential management approach involves supplying necessary nutrients to improve the production and efficiency of plant growth (Ericsson, 1994). One challenge with this approach is that anticipating the rate of soil supply of each nutrient in conjunction with plant demand requires site-specific understanding of soil nutrient availability over the length of the stand rotation cycle.

Calcium needed by plants

Calcium is a critical macronutrient required for plant growth and health. Calcium supports plant cell walls (apoplasm) where it is transported between the cell walls and the plasma membrane. Calcium is very important for wood formation since it supports the strength of cell walls and other woody plant tissues. Calcium is absorbed from the soil as Ca^{2+} by mass flow and root interception and binds to the middle lamella of cell walls as pectate for strength and support (Havlin et al., 2014; Marschner, 1995). Calcium moves mostly through the xylem, while its mobility throughout other parts of the plant is usually low (Marschner, 1995).

Plants with sufficient calcium available in the soil usually have shoot calcium concentrations between 1-5% dry weight (Marschner, 1995). The variability in this concentration depends on calcium availability in the environment and on each plant’s calcium requirements.

Deficiency of calcium in soil is not common but may occur when the soil has low base saturation or high acidic deposition (McLaughlin and Wimmer, 1999).

Poor calcium distribution in plants can result in poor plant growth and development. This distribution can be influenced by soil moisture, root pressure, and hormone activity. (Kirby and Pilbeam, 1984). Calcium uptake is also affected by other ions in the soil. The presence of positive ions such as NH_4^+, K^+, Mg^{2+}, Mn^{2+} and Al^{3+} all reduce calcium uptake, whereas counter anions such as NO_3^-, Cl^-, and SO_4^{2-} have been shown to aid calcium uptake (Kirby and Pilbeam, 1984). Root health is also important for calcium uptake. Plants with small root systems or poor root growth may experience calcium deficiency (Havlin et al., 2014).

In general, calcium deficiency may result in the disintegration of cell walls and the collapse of the affected tissues in apical and upper parts of the stems. Calcium deficiency can also result in symptoms in new leaves, in enclosed tissues or in tissues fed by the phloem rather than the xylem. Many of these symptoms are evident in vegetables and fruits as physical abnormalities such as leaf tipburn, fruit cracking, end rot, and other physical deficiencies (White and Broadley, 2003). To address deficiencies, the soil environment can be modified through the addition of calcium elements to produce a more nutrient-rich soil solution, hence improving mineral absorption (Cheng et al., 2013; Fageria and Nascente, 2014).

Calcium Sources and pH

The addition of calcium carbonate ($CaCO_3$) or lime is recommended as a method to increase the soil pH and add calcium to soil (Cheng et al., 2013; Fageria, 2002). High levels of soil organic matter will reduce the direct impact of the lime application on pH because the soil organic matter offers many negatively charged sites to bind to H^+ in the soil, pushing the soil

solution toward acidic levels (Fageria and Baligar, 2008). Both chemical and physical properties such as soil pH, cation exchange capacity, nutrient holding and availability, and aggregation may be affected when using lime and gypsum (Rippy et al., 2007; Kassel, 2009; Woodard and Bly, 2010). Multiple studies have shown that soil acidity was reduced within three years of application of lime amendments (Pagani and Mallarino, 2012a; Li et al., 2016). Moreover, many trials in field and greenhouse studies have shown improvement in crop and tree plantation growth as well as in soil properties when using lime applications (Jiang et al., 2016).

Various sources of lime are commonly used including ground limestone (aglime), hydrated lime, industry by-products, and water treatment plant waste. Different lime treatments have different chemical and physical properties, and this makes it important to choose the appropriate lime treatment to meet objectives. Aglime is one of the most commonly used lime sources for neutralizing acidic soils throughout the world (Barber, 1984). The combination of aglime particle size and chemical reactivity (as measured by calcium carbonate equivalence) will influence the time and efficiency of the treatment in adjusting the soil pH to the desired level (Higgins, 2012). The most efficient aglime products have particle sizes within a specified range. For example, aglime particles that are filtered by a mesh of 100-200 (particles from 0.15 to 0.075 mm) are nearly equivalent to pure calcium carbonate or hydrated lime treatments. Larger aglime particles, such as those filtered by size 8-20 mesh (particles from 2.36-0.85 mm) are slow to react with the soil due to the smaller surface area to volume ratio (Beacher and Merkle, 1949). Pelleted aglime was developed as an alternative to using direct aglime in order to aid the application of ground aglime. Pelleted aglime is produced by pelletizing ground aglime and binding it with a water-soluble coating (usually clay or synthetic binders). This method enables easy application of aglime with specific particle sizes, which are released more quickly into

moist soil or following rainfall. These pellets can also be easily broken down by microbial processes in the soil yet are durable during fertilizer transport. Prior extension research has shown that aglime and pelleted aglime perform well at increasing soil pH and crop yield (Kelling and Schulte, 1988a, 1988b; Murdock, 1997; Warncke and Pierce, 1997). Further research is needed to develop techniques for evaluating the efficiency of aglime and pelleted aglime products at adjusting the pH of different types of soil, particularly outside of major agricultural areas (Jones and Mallarino, 2018).

Calciprill

Calciprill is a 2-5 mm pelletized calcium source produced from finely ground high purity calcium carbonate or calcium magnesium carbonate (Dolomitic lime). Calciprill differs from pelletized lime because it is ground into finer particles than typical pelletized lime. This granulized product is highly reactive and is marketed as being as effective as standard aglime using application rates that are 80-90% lower. Prior research has shown that broadcast pelletized lime is not more efficient than broadcast regular aglime at similar application rates (Godsey et al., 2007; Higgins et al., 2012). Even so, there are other benefits to using pelletized lime products such as Calciprill. The granular nature of the material enables easy transport and allows the Calciprill to be easily mixed with other fertilizers and seeds and distributed using standard sowing and fertilizing machinery. The micronized powder granules also do not produce clouds of dust when applied, due to the larger effective size of the pellets.

Even though calcium is known to be an essential nutrient for cell wall development, especially in fast growing species such as *E. grandis*, previous research has shown that calcium application did not have a significant effect (Mello et al. 1970; Schonau, 1977a) or showed a

negative impact on plant growth (Herbert, 1983; Schonau and Herbert. 1983). Alternatively, applications of Dolomitic lime have previously been shown to produce growth development in *E. grandis*, depending on the nutrients such as (K and N) applied together with the Dolomitic lime (Schonau and Herbert. 1983).

The primary objectives of this study were to assess (1) the potential growth response of *E. grandis* to calcium fertilizer additions from different sources (highly reactive Calciprill vs traditional Dolomitic lime) at different rates and (2) how these calcium fertilizer additions affect nutrient availability in these volcanic soils. To achieve these objectives, we conducted (1) a containerized pot trial, (2) a field trial at two locations, and (3) a laboratory incubation study.

MATERIALS AND METHODS

Pot Trial

Containerized experiments were established on May 23, 2018 in Restrepo, Colombia (3.856394 lat and -76.507623 long) on an open-air pad. The average annual precipitation for the site is 1024 mm yr^{-1} and the average daily maximum and minimum air temperature are 24.44°C and 15.55°C, respectively. The soil utilized was obtained from the Darien trial location (Table 1). For this, well drained Andisol and loamy soil was collected from a soil depth of 0-30 cm. *Eucalyptus grandis* seedlings (clonal cuttings from one selected clone) were transplanted in 3-gallon containers and were used for all the treatments. Containers were hand watered to maintain consistent moisture.

Treatments and Measurements

This study was executed as a randomized complete block design with four subsamples of each treatment, eight treatments, and six blocks of each treatment leading to a total of 192 trees. Each experimental block was fertilized at planting with nitrogen, phosphorus, potassium, sulfur and boron (Table 2) which were buried 5-10 cm deep next to the seedlings. The fertilizer was applied as ammonium sulfate (N, S), diammonium phosphate (N, P), potassium chloride (K) and a boron-containing fertilizer (K and B). Eight different treatments were applied for the pot trial experiments (Table 3). Calcium as Calciprill was applied at rates equivalent to 0, 100, 200 and 800 kg calcium ha^{-1}. Calcium as Dolomitic lime was applied at rates equivalent 100 and 160 kg calcium ha^{-1}. Calcium source applications were made around the base of the tree after dilution using one liter of water per tree and were applied two days after the application of additional nutrients. The fertilization was performed manually in June at planting, simulating the

commercial fertilization application procedure. Individual root collar diameter (RCD) at 0.1 m height and tree height (Ht) were measured prior to treatment initiation and monthly in all blocks. At harvest, the tree components were measured from four plants per treatment per block.

Soil Measurements

Composite soil samples were taken for each treatment. Four soil samples from each treatment in every block were collected and homogeneously mixed to form composite samples (6 composite samples consisting of four soil samples each). In total, 60 soil samples were collected and analyzed for chemical and physical properties. Complete soil testing and analysis was performed using the Mehlich-3 soil nutrient extraction procedure. Exchangeable base cations (calcium, magnesium, and potassium) were extracted using ammonium nitrate and nitric acid. Micronutrients (copper, zinc, manganese and iron) were extracted using ammonium and the chelating agent EDTA. The Flame Atomic Absorption Spectroscopy (FAAS) method was used to measure the micronutrient concentration. Potassium concentration was determined using Flame Atomic Emission Spectroscopy (FAES). Calcium and magnesium concentrations were determined by FAAS in an air-acetylene flame after dilution in the presence of lanthanum. Phosphorus concentration was determined by using the ascorbic-ammonium molybdate method. All soil analyses were performed at the Dr. Calderon Laboratory, in Bogota, Colombia.

Destructive Harvest

After 5 months of growth, the tree components from 192 harvested trees were divided into plant components (leaves, stem, branch, and roots). All component samples were dried at 70 °C to a constant dry weight. The foliage, stem, branch and root samples were then ground to pass

through a 1 mm screen in order to be analyzed for nitrogen, phosphorus, potassium, calcium, magnesium and boron content. Laboratory analyses followed the methods specified in Sadzawka et al., 2004. Nitrogen content of the samples was determined colorimetrically after Kjeldahl wet digestion. To analyze phosphorus, potassium, calcium, magnesium and boron, the samples were dry digested at 500 °C and diluted in HCl. After digestion, phosphorus and boron were determined colorimetrically, and potassium, calcium, and magnesium were determined by atomic absorption spectrophotometry.

Data Analysis

A mixed model approach was applied to analyze the root collar diameter, height, nutrient concentration, nutrient masses and soil sampling data from the containerized experiments. Four seedlings were averaged within each treatment to get observations for each block. The corresponding treatment was the fixed effect and the blocks were treated as random effects. If there was a significant interaction or significant treatment effect at an alpha level of 0.05, the means were separated using Tukey's HSD test. All data were analyzed using the JMP statistical analysis package (JMP Pro, Version 14, SAS Institute Inc., NC, 1989-2019).

Field trials

Field experiments were established in June 2018 at two sites (Darian and Popayan) located in the Colombian Andes (Table 4.) The soils at both sites were well drained Andisols with a loamy texture (Table 1). The Darien site soil taxonomy is loamy, mixed, thermic Acrudoxic Hapludand, while soil taxonomy at the Popayan site is loamy, mixed, thermic Typic Melanudand. The species planted at each site was *Eucalyptus grandis*. Each study site was approximately 2.33 hectares (5.57 acres) in size. Each study site was setup to have 18 plots, with six plots for

each of the three replicates. The plots for each replicate were assigned randomly based on elevation. Each treated plot contained 144 trees, arranged in a 12 by 12 configuration. The measurement plots contained 64 trees in an eight by eight configuration centered within the treated plot. Initial stocking consisted of 1111 trees ha^{-1} on a three by three meter spacing.

Treatments

Each site was fertilized with nitrogen, phosphorus, potassium, sulfur, and boron (Table 5) applied at planting (buried 20 cm from the seedling). Fertilizer was applied as ammonium sulfate, diammonium phosphate, potassium chloride and boron-containing fertilizer. Fertilizer rates were selected to match operational use in these regions. Six treatments were applied at each site in a randomized complete block design (Table 5). Calcium as Calciprill (37% Ca, 0.6% Mg) was applied at rates of 0, 100, 200 and 400 kg elemental calcium ha^{-1}. Calcium as Dolomitic lime (22% Ca, 13% Mg) was applied at a rate of 100 kg elemental calcium ha^{-1}. All calcium source applications were made around the base of the tree on the soil surface. The fertilization was performed manually on May 28th and June 1st in 2018, at the Darien and Popayan sites, respectively. The fertilizer application was executed at planting, simulating commercial application procedures (Table 6).

Soil and Stand Measurements

Soil samples were collected at both locations (Darien and Popayan) prior to fertilizer application and every 6 months after installation. Ten soil samples from each plot were collected and homogeneously mixed to form composite samples (2 composite samples consisting of five soil samples each). As no site prep or bedding took place on these sites, there was no distinction

between bed/interbed. Only one composite sample from 0-15 cm and one from 15-30 cm was analyzed for soil chemical and physical properties for each plot. The two composite samples for each were air dried and sieved through a 2 mm mesh prior to analysis. Soil extraction was performed using Mehlich-3 procedures and analysis was performed as previously described at Dr. Calderon Labs-Colombia, in Bogota, Colombia.

The individual root collar diameter at 0.1 m height and tree height (Ht) were measured prior to treatment initiation and every three months in all the measurement plots. Tree diameter at breast height (DBH) was measured only after trees had attained sufficient height ($\geq$ 0.1 m).

Data analysis

Tree volume was calculated from DBH and height measurements using proprietary equations. The volume from all trees within each plot were summed and this value was scaled up to produce a per hectare approximation. A mixed model approach was applied to analyze the root collar diameter, DBH, height, volume and soil sampling data. In this model, the treatment was the fixed effect and blocks were treated as random effects. If there was a significant interaction or significant treatment effects at an alpha level of 0.05, the means were separated using Tukey's HSD test. All data were analyzed using the JMP statistical analysis package (JMP Pro, Version 14, SAS Institute Inc., NC, 1989-2019).

Laboratory incubation

Laboratory experiments were established in March 2019 in Raleigh, North Carolina. The experiment was designed as a randomized complete block experiment. The soils used were obtained from the Darien site (Table 1) and were well-drained, loamy Andisols. The soil was

collected from the site at a depth of 0 to 20 cm in July 2018. The soil was air dried, crushed, mixed well, passed through a 2 mm sieve and then divided into jars in quantities of 150 g of soil in each jar. Soil fertilizer treatments consisted of calcium fertilizer treatment rates similar to the field trial application to test the effects on soil properties over time (Table 7). Each jar was fertilized with nitrogen, phosphorus, potassium, sulfur and boron (Table 8) and mixed at field capacity. Fertilizer was applied as ammonium sulfate, diammonium phosphate, potassium chloride, and boron-containing fertilizer. Calcium as Calciprill was applied at rates of 0, 112, 226 and 565 kg calcium ha^{-1}. Calcium as Dolomitic lime was applied at a rate of 226 kg calcium ha^{-1}. Treatments were replicated three times and incubated for six different time periods (0, 0.5, 2, 4, 16, and 32 days). Soil and fertilizer material were thoroughly mixed for each treatment combination and incubated in 300 ml jars (7.5-cm diameter and 11.2-cm height). The jars were distributed according to a randomized design in a dark room maintained at a constant temperature of 25°C.

Soil measurements

Soil pH of samples was measured in a 1:1 water slurry with an electrode pH meter at 0, 0.5, 2, 4, 16 and 32 days. The soils were also sampled destructively at 0, 0.5 and 32 days and extracted using the Mehlich-3 procedure for analysis. Soil analyses were performed at Waters Agricultural Laboratories, Georgia, USA.

Data analysis

A mixed model approach was applied to analyze the pH and soil sampling data separately for each time point (0, 0.5 and 32 days). The treatment was the fixed effect and the blocks were

treated as random effects. If there was a significant interaction or significant treatment effects at an alpha level of 0.05, the means were separated using Tukey's HSD test. All data were analyzed using the JMP statistical analysis package (JMP Pro, Version 14, SAS Institute Inc., NC, 1989-2019)

RESULTS

Pot Trial

Tree growth response to calcium carbonate and NPKSB fertilization

The curves of root collar diameter and height over time show that the treatments with NPKSB and NPKSB + calcium sources begin to show more growth than the Control and the 800 kg ha^{-1} Ca + NP treatment, especially following month three (Figures 1, 2). At the end of the experiment, there was a significant effect ($P < 0.0001$), showing that every fertilized treatment increased both tree height and RCD compared to the control, except the 800 kg ha^{-1} Ca + NP treatment (Figures 3, 4).

Effect of calcium carbonate and NPKSB application on plant biomass

The application of NPKSB either with or without calcium carbonate sources showed a significant ($P < 0.05$) effect on the measured biomass in foliage, branch, stem and root components (Figures 5, 6, 7, and 8, respectively). A separation of means showed that NPKSB only and all NPKSB + calcium carbonate source treatment groups except the 800 kg ha^{-1} Ca Calciprill + NP treatment had greater mass than the control. The Dolomitic lime treatments did not show a significant difference in plant component biomass compared to the other treatments including those with Calciprill. Additionally, the rates of Calciprill and Dolomitic lime that were applied did not have a significant impact on any of the measured biomass components (Figures 5, 6, 7, and 8).

Nutrient concentration and nutrient mass by plant component

The effect of different treatments on nutrient concentration and nutrient mass were evaluated in the foliage, branch, stem, and root for six nutrients (N, P, Ca, K, B, and S). Three of

the measured nutrients (P, K, and B) showed a statistically significant difference in content and mass in all measured plant components. The treatment significantly affected nitrogen content in all four tree components although it did not significantly affect nitrogen concentration (Table 9). Nitrogen content in the foliage and the root components was approximately three to four times higher in all treatments with NPKSB, than in the control treatment and the 800 kg ha^{-1} Ca Calciprill + NP treatment. Nitrogen content in the foliage, branch and stem was slightly higher in the NPKSB only treatment than in other treatments with NPKSB.

Phosphorus concentration in the foliage, branches, and stem was higher in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatment than in all other treatments. Phosphorus concentration in the roots was similar in the 200 kg ha^{-1} Ca Calciprill + NPKSB treatment, the 800 kg ha^{-1} Ca Calciprill + NP treatment and the control treatment (Table 10). Phosphorus content in the foliage was significantly higher for all treatments that included NPKSB. Phosphorus content in the branches and the stem was highest in the 800 kg ha^{-1} Ca Calciprill + NP treatment. The phosphorus content in the branches was slightly higher in the NPKSB only treatment, compared to the other treatments. The phosphorus content in the roots was highest for the 200 kg ha^{-1} Ca Calciprill + NPKSB treatment, and lowest in the control treatment, with all other treatments showing similar results between the two (Table 10).

Potassium concentration in the foliage and the roots was significantly higher for all treatments with NPKSB. Potassium concentration in the branches and the stem was similar for all treatments with NPKSB and slightly higher than in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments. Potassium content in the foliage, the branches, the stem and the roots was significantly higher for all treatments with NPKSB. For all of these foliage components, the

treatments with NPSKB had a potassium content approximately five times greater than in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatment (Table 11).

The addition of nutrients and calcium carbonate sources showed an impact on calcium concentration in the foliage and stem, as well as on calcium content in all tree components (Table 12). Calcium concentration in the foliage and the stem was significantly lower for all treatments with NPKSB, however, calcium concentration in the branches and the roots was not statistically different between different treatment groups. Calcium content in all four plants components was significantly higher for all treatments with NPKSB (Table 12).

Sulfur concentration in the foliage was slightly lower in the control treatment, the 160 kg ha^{-1} Ca Dolomitic lime + NPKSB treatment, and the 800 kg ha^{-1} Ca Calciprill + NP treatment, however, the standard error of the model (0.01%) is relatively large compared to the measured range. Sulfur concentration in the branch, stem, and root did not show a significant difference between the treatments. Sulfur content in all the plant components was significantly higher for all treatments with NPKSB than in the other two treatments (Table 13).

Boron concentration in the foliage, branches, stem and roots was also significantly higher for all treatments with NPKSB. The boron concentration in the foliage was more than five times higher in the NPKSB treatments than in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments. Boron content in the foliage, the branches, the stem and the roots was also significantly higher for all treatments with NPKSB (Table 14).

Soil analysis

The effect of different treatments such as soil pH, CEC, organic matter and soil nutrients (N, P, K, and Ca) were evaluated. Soil pH was significantly impacted five months after

application. Soil pH was higher in the 800 kg ha^{-1} Ca Calciprill + NP and the 800 kg ha^{-1} Ca Calciprill treatments. Soil pH was similar in the 160 kg ha^{-1} Ca Dolomitic lime + NPKSB treatment, the 100 kg ha^{-1} Ca Dolomitic lime + NPKSB treatment, and the control. The lowest pH level of around 4.4 was observed in the NPKSB only treatment. The control treatment and the 100 kg ha^{-1} Ca Dolomitic lime + NPKSB treatment also exhibited a lower pH than all other treatments (Figure 9).

Only two of the measured soil nutrients (K and Ca) showed a statistically significant difference due to treatment. Soil potassium was statistically higher in all treatments with NPKSB than in the control treatment (Figure 10). Soil calcium was higher in the 800 kg ha^{-1} Ca Calciprill + NP and 800 kg ha^{-1} Ca Calciprill + NPKSB treatments than in all other treatments (Figure 11). The rate of calcium application also led to an increase in soil calcium availability in treatments with a higher dose of calcium carbonate sources.

Fields studies

Tree growth response to calcium carbonate and NPKSB fertilization during establishment

Site 1: Darien

At the Darien site, tree height increased throughout the one-year period and the height of different treatments began to diverge at three months after planting (Figure 12). At twelve months after planting, separation of means showed that the control group height was significantly lower than the 200 kg ha^{-1} Ca Calciprill +NPKSB treatment, while all other treatments were not significantly different ($P < 0.0001$; Figure 13). A significant effect of treatment ($P < 0.0001$) on tree diameter at breast height was observed twelve months after planting (Figure 14). Tree diameter at breast height was significantly higher for the NPKSB

treatment and all other calcium source treatments compared to the control (Figure 14). There was also a significant effect of treatment on the measured tree volume ($P < 0.05$) twelve months after planting. The treatments containing NPKSB either with or without calcium carbonate produced a larger tree volume compared to the control (Figure 15). Among different rates of calcium carbonate application there was no significant difference in tree height, DBH, or volume. There was also no significant difference in tree height or volume between calcium carbonate sources (Dolomitic lime vs Calciprill) when applied at the same rate.

Site 2: Popayan

At the Popayan site, analysis of tree height over time showed that plots treated with NPKSB only and NPKSB + calcium sources exhibited consistently higher tree height than other plots following month three (Figure 16). At 12 months after planting, tree height was significantly greater in the 400 kg ha^{-1} Ca Calciprill + NPKSB treatment group than in the control treatment (Figure 13). There was also a significant effect of treatment on tree diameter at breast height 12 months after planting ($P < 0.05$; Figure 14). Tree DBH was significantly higher in the treatments with 200 kg ha^{-1} Ca Calciprill + NPKSB and 400 kg ha^{-1} Ca Calciprill + NPKSB compared to the control. There was also a significant effect of treatment on calculated tree volume twelve months after planting at Popayan ($P < 0.05$; Figure 15). The 400 kg ha^{-1} Ca Calciprill + NPKSB treatment produced larger tree volume than the control while all other treatments were not significantly different (Figure 15). No significant difference in tree volume was observed between treatment groups treated with different rates of calcium carbonate application or different calcium carbonate sources.

Effect of calcium carbonate sources and NPKSB fertilizers on nutrient availability in soil

The effects of different treatments on parameters such as soil pH, CEC, organic matter and soil nutrients (N, P, K, and Ca) were evaluated. There was no significant effect from the addition of calcium carbonate and NPKSB fertilizer on any soil nutrient or soil parameter at the Darien site, however, soil analysis showed significant differences in soil potassium at 0-15 cm depth at the Popayan site. At Popayan, the soil potassium was significantly higher in the 100 kg ha^{-1} Ca Dolomitic lime + NPKSB treatment than in the 400 kg ha^{-1} Ca Calciprill + NPKSB treatment. All other treatments at the Popayan site showed no significant difference in soil potassium (Figure 17). Soil analysis showed significant differences in CEC and organic matter only at 30 cm depth at the Popayan site. CEC and organic matter were significantly higher in the control than in the 100 kg ha^{-1} Ca Dolomitic lime + NPKSB treatment, which showed the lowest CEC and organic matter (Figures 18 and 19, respectively).

Incubation study

Effect of calcium carbonate sources and NPKSB fertilizers on nutrient availability in soil

The effect of fertilizer on soil nutrient availability of eleven different nutrients (N, P, K, Mg, Ca, S, B, Zn, Mn, Fe, and Cu), pH, cation exchange capacity, and organic matter was evaluated for differences over time during 32 days of incubation in the laboratory. Fertilizer treatments had a statistically significant impact on soil nutrient availability for eight of the measured nutrients (P, K, Ca, S, B, Zn, Mn, and Fe) 32 days after treatment. Fertilizer treatment also had a significant impact on soil pH and cation exchange capacity.

Soil phosphorus availability was significantly higher for all treatments compared to the control except the 112 kg ha^{-1} Ca Calciprill + NPKSB treatment (Figure 20). Soil potassium

availability was significantly higher in the NPKSB only and calcium carbonate source + NPKSB treatments than in the NP only and the control treatments (Figure 21). Soil calcium availability was significantly higher in all calcium carbonate source treatments than in the NPKSB only, NP only, and the control treatments (Figure 22). Application of different rates of Calciprill produced a significant difference in soil calcium content with a ranking of 565 kg ha^{-1} Ca Calciprill + NPKSB > 226 kg ha^{-1} Ca Calciprill + NPKSB > 112 kg ha^{-1} Ca Calciprill + NPKSB. Soil magnesium availability was significantly higher in all calcium carbonate source treatments compared to the NPKSB only, the NP only, and the control treatment (Figure 23). There was a rate effect observed in soil magnesium when applying different rates of Calciprill. The corresponding ranking for soil magnesium was 565 kg ha^{-1} Ca Calciprill + NPKSB > 226 kg ha^{-1} Ca Calciprill + NPKSB > 112 kg ha^{-1} Ca Calciprill + NPKSB. Soil sulfur availability was significantly higher in the 565 kg ha^{-1} Ca Calciprill + NPKSB treatment compared to all other treatments (Figure 24). Soil boron availability was significantly higher in all treatments with NPKSB compared to the NP only and the control treatments (Figure 25). Soil zinc availability was higher in the NP only treatment, the 112 kg ha^{-1} Ca Calciprill + NPKSB treatment and the 565 kg ha^{-1} Ca Calciprill + NPKSB treatment compared to all other treatments (Figure 26). Soil iron availability was significantly lower in the treatment with 565 kg ha^{-1} Ca Calciprill + NPKSB compared to all other treatments (Figure 27).

The soil pH measurements in the incubation study indicated a significantly higher pH in soil treated with 226 kg ha^{-1} Ca Dolomitic lime + NPKSB or 565 kg ha^{-1} Ca Calciprill + NPKSB Calciprill than in the NP only, NPKSB only and the control group (Figure 28). All soils treated with different doses of Calciprill had an increased soil pH although there was no significant difference among different Calciprill treatment rates. The curves of soil pH over time show that

all of the treatments began to show consistently higher soil pH immediately (Day zero) following the treatment application (Figure 29). After 32 days, the 565 kg ha^{-1} Ca Calciprill + NPKSB and the 226 kg ha^{-1} Ca Dolomitic lime + NPKSB treatments exhibited the highest soil pH of all the treatments.

The cation exchange capacity of soils treated with calcium carbonate follows the same trend as pH. Soils with calcium carbonate sources have a significantly higher CEC than the NPKSB only, the NP only and the control treatment (Figure 30). CEC was significantly higher in the 565 kg ha^{-1} Ca Calciprill + NPKSB treatment than all other treatments. CEC was lowest, yet similar in the NPKSB, the NP only, and the control treatments. Application of different rates of Calciprill produced a significant difference in CEC with a ranking of 565 kg ha^{-1} Ca Calciprill + NPKSB > 226 kg ha^{-1} Ca Calciprill + NPKSB > 112 kg ha^{-1} Ca Calciprill + NPKSB.

DISCUSSION

Pot Trial

Tree growth response

The findings from the greenhouse study suggest that adding nutrients (NPKSB) may improve height and root collar diameter, albeit to a moderate degree. Additionally, there was no notable further effect from adding calcium carbonate sources in addition to nutrients. The 800 kg ha^{-1} Ca + NP and control treatment groups had consistently smaller height and root collar diameter of *Eucalyptus grandis* than any treatment with NPKSB either with or without calcium carbonate additions. This indicates that limited seedling growth was potentially associated with the lack of nutrients (potassium, sulfur and boron) in the NP treatment or due to a slightly lower rate of N (2 g less per plant) in the 800 kg ha^{-1} Ca + NP treatment. As a result, over 37% more height and 70% larger root collar diameter was observed in the seedlings treated with NPKSB + calcium carbonate sources compared to those treated with 800 kg ha^{-1} Ca + NP and the control treatments. Research suggests that calcium carbonate sources alone may not have a beneficial effect on the growth of *Eucalyptus grandis* (Herbert, 1983; Schönau and Herbert, 1982, 1983), however, in those experiments the calcium carbonate was only effective when applied together with K or when the application of N was omitted. Our results show that NPKSB provides the greatest benefit to early tree growth.

The pot trial also investigated the impact of applying different calcium carbonate sources and doses on *Eucalyptus grandis*. We expected that seedlings treated with Calciprill would have better growth, because higher reactivity would increase pH more rapidly and added calcium would improve root growth and increase nutrient availability. The application of Dolomitic lime and Calciprill showed no significant difference in either tree growth measurement over time as

result of calcium carbonate source. This result was surprising because we expected treatments with Calciprill would react faster than Dolomitic lime. Previous research suggested that pelletized calcium carbonate products may reduce the pH reaction effect in the soil, which would also reduce the efficiency of soil nutrient availability (Murdock, 1997; Warncke and Pierce, 1997). Less surprisingly, the dose of calcium carbonate source also did not show a significant difference on either tree growth measurement. These results are in agreement with previous experiments (Mello et al., 1970; Schönau, 1977a) which showed no significant differences in *E. grandis* growth response when adding limestone and ammonium nitrate fertilizer. Those studies used rates of calcium (112 and 223 kg ha^{-1}) which were similar to the rates used in this study.

The pot trial also showed that addition of NPKSB either with or without calcium carbonate sources produced a significant impact on the growth beyond two months after treatment. All treatments with calcium carbonate and NPKSB showed a similar rate of growth, regardless of the calcium source and doses. After month two, the root collar diameter of these treatments grew at a rate of about 4.3 mm per month, and the tree height grew at a rate of about 30 cm per month. In comparison, in the 800 kg ha^{-1} Ca + NP and the control treatments, the root collar diameter grew at a rate of 2.3 mm per month and the tree height grew at a rate of 20 cm per month. This result was surprising because we expected that adding highly reactive calcium carbonate would improve nutrient availability and, subsequently, nutrient uptake. Our results are in disagreement with multiple studies which observed a growth response of *E. grandis* after fertilizer application containing P (Mello, 1968; Mello et al., 1970; Simões et al., 1972; De Rezende et al., 1982; Mattos and Maciel, 1984; Carrero et al., 2018). In contrast, our results did not show a significant response to the 800 kg ha^{-1} Ca + NP treatment. Other research has shown that adding potassium fertilizer produced increased growth response of *E. grandis* (Heiberg-

Jurgensen and Pennefather, 1966; Mello, 1968; Pennefather and MacGillivray, 1971; Schönau and Pennefather, 1975; Carrero et al., 2018). One potential reason for this discrepancy is that plant response will be soil and site dependent according to what nutrients are limited, and these sites must also be deficient in K, S, and/or B.

Plant biomass

Biomass parameters such as the dry weight of plant components (foliage, stem, branch, and roots) follow a similar trend to the root collar diameter and tree height. All of these parameters also show that treatments with calcium carbonate sources and nutrients (NPKSB) produce significantly more biomass than the 800 kg ha^{-1} Ca + NP and the control treatments. Although we expected that seedlings treated with Calciprill would have increased biomass, plants treated with Dolomitic lime + NPKSB or NPKSB only showed no differences in plant component biomass of the plant components (foliage, stem, branch, and roots) compared to plants treated with Calciprill. Surprisingly, the doses of calcium carbonate sources did not produce a significant difference in any of the four plant components measured. Our results are in agreement with results reported by Mello et al. (1970) which also showed no differences in the growth response of *E. grandis* to calcium carbonate. In their studies located in Brazil, they used a different soil type (Oxisol) and tree spacing density. They also used two metric tons of calcium carbonate per hectare whereas we used lower dosage in our experiments. This suggests that it is possible that even though the plants are receiving added nutrients to build biomass, they may still be lacking other nutrients needed to fully express the maximum increase in biomass. Additionally, plants will not develop biomass if one or more of the nutrients required for plant

tissue growth is not met. This lack of required nutrients could have led to the observed deficiency in the plant tissues.

Nutrient concentration and nutrient mass

Nutrient analysis of plant components showed some differences in uptake of the six nutrients analyzed (N, P, K, Ca, S and B). Nitrogen concentration in all four plant components (foliage, branch, stem, and root) showed no significant difference among treatments, possibly indicating that sufficient nitrogen was available in all soils including the control. The nitrogen content was significantly lower in the control and the 800 kg ha^{-1} Ca Calciprill + NP (and 4.623 g P $plant^{-1}$) treatment in all four plant components. This is likely because these plants were smaller, resulting in smaller plant component samples. The nitrogen rate was also two grams lower per plant in the 800 kg ha^{-1} Ca Calciprill + NP treatment than in other treatments containing NPKSB (4.14 g N $plant^{-1}$ vs 6.03 g N $plant^{-1}$, respectively) (Table 2).

Phosphorus nutrient concentration was higher in the plant components of the control and 800 kg ha^{-1} Ca Calciprill + NP treatments. It is possible that concentrations were higher as a result of the dilution effect. Nutrient concentrations may increase in plant components even when the biomass development may be compromised by another nutrient in short supply (Ulrich and Hills, 1973; Jarrell and Beverly, 1981). Even plant treatments that receive significant P, such as the 800 kg ha^{-1} Ca Calciprill + NP treatment, might have less biomass because another nutrient is limiting. There is a good chance that nutrient concentration will change after application of NPKSB, but it is unclear what direction this trend will follow. This reaction will depend on the other nutrients that are ready for uptake and the effect that each specific nutrient might have on plant development (Munson and Nelson, 1973).

Potassium concentration was higher in all four plant components in treatments with NPKSB and calcium carbonate sources than in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments. The addition of NP seemed to slightly inhibit uptake of potassium into certain plant components. This might be due to the dilution effect occurring with potassium, as described previously. Similar results on a red pine study were found by Timmer and Armstrong (1987) where adding N and P produced a reduction in K uptake in seedlings. Again, the nutrient mass was much lower in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments, likely due to smaller overall tree sizes.

The results for calcium nutrient concentration only show a significant difference in two plant components (foliage and stem), with higher concentrations appearing in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments. Once again, the dilution effect might have occurred due to biomass development. This effect likely occurs because plant components did not get enough calcium to support plant development in the rapidly growing regions of the plant, such as the foliage. This typically occurs because calcium mobility in plants is low. Moreover, plants cannot develop biomass because there are one or more nutrients that have not met the tissue requirements to develop more plant growth and plant tissues are still deficient in those nutrients.

Sulfur concentration did not show a significant difference between treatments in most plant components, although the foliage measurements showed slightly lower sulfur concentration in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments. The omission of sulfur as a nutrient added by fertilizer in the 800 kg ha^{-1} Ca Calciprill + NP treatment resulted in lower sulfur concentration because there was a lack of sufficient soil sulfur supply.

Relative boron nutrient concentrations were similar to potassium nutrient concentration. All treatments except the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments showed a

significantly higher concentration of boron in all four plant components. This result indicates that the soil boron availability was probably not sufficient and thus adding B as fertilizer in the treatments via NPKSB could increase the plant's ability to uptake boron. Again, the boron content is much smaller in all plant components in the control and the 800 kg ha^{-1} Ca Calciprill + NP treatments than in the other treatments due to the smaller plant sizes.

Soil analysis

We expected soil treated with a higher dosage of Calciprill and Dolomitic lime would have higher soil pH. Indeed, the dose of calcium carbonate source did produce a significant difference in pH for all the soil treated with calcium carbonate sources. Moreover, the greater the dose, the larger the increase in soil calcium availability. Treatments of 800 kg ha^{-1} Ca Calciprill + NP and 800 kg ha^{-1} Ca Calciprill + NPKSB had the highest soil pH compared to all the other treatments. The addition of NP along with Calciprill increased the soil pH slightly. This may have occurred because diammonium phosphate tends to increase soil pH temporarily. As expected, the treatments indicated that higher doses of calcium carbonate sources increased the soil pH. Dolomitic lime and Calciprill sources did not show a significant difference in soil calcium availability indicating that the calcium source had little impact on pH.

Soil potassium availability was statistically the same in all treatments where calcium carbonate sources and nutrients were applied (as NPKSB) as well as the control treatment, with the exception of the 100 kg ha^{-1} Ca Calciprill + NPKSB treatment. Dolomitic lime and Calciprill treatments showed no significant difference in soil potassium availability based on calcium source. The dose of calcium carbonate also did not show a significant impact on soil potassium

availability. These results are in agreement with results reported by (Tamimi et al., 1975; Han et al., 2019) who observed that calcium carbonate application resulted in lower soil K availability.

We expected higher soil calcium availability with higher rates of Calciprill and Dolomitic lime application. The dose of calcium carbonate source did have a significant impact on all the soil treated with calcium carbonate sources. Higher doses of calcium carbonate sources produced an increase in soil calcium availability, with the 800 kg ha^{-1} Ca Calciprill + NP and Calciprill + NPKSB treatments showing the greatest soil calcium availability. These results indicated that higher doses of calcium carbonate sources led to an increase in soil calcium levels. Unsurprisingly, the dose of calcium carbonate source did not show a significant impact on CEC. This result was expected because Andisols tend to have a permanent charge. This result is due to the isomorphic substitution charge which is distributed uniformly over the clay surface and is thus unaffected by changes in soil solution pH.

Field studies

Though the soil analysis of both field sites (Darien and Popayan) were fairly similar (Table 1), the soil profiles show different organic matter depth. Organic matter (Appendix A) was much deeper at the Darien site (14.6% at 30 cm depth) than at the Popayan site (8.9% at 30 cm depth). Visually, we observed that at the Darien site the organic matter extended more than 92 cm in depth in the soil profiles, while in Popayan, the organic matter was much less deep (ranges from 5 to 25 cm depth). The site slope in Popayan was also steeper than the slope in Darien. These two factors may contribute to the difference in results that we obtained at each site. For example, we expected that Darien would have higher tree height, DBH and volume, while Popayan would be generally less productive. In agreement with this result, the Darien site

was more responsive to calcium carbonate and NPKSB fertilizers than Popayan. The high amounts of organic matter (OM) present on volcanic soils generally supply organic nitrogen in large amounts. OM is considered a critical soil property, because of its influence on many characteristics of a productive soil. OM can lead to increased nutrient and water holding capacity and decreased bulk density. Bulk density will ultimately affect soil infiltration and root proliferation. In general, soil with higher OM content will be more productive (Shoji et al., 1994). Steep slopes can cause erosion, resulting in removal of nutrients and OM and causing sites to have less organic matter and lower productivity. Those eroded sites may be more responsive to nutrient additions. Organic matter, as well as noncrystalline clay materials, contribute to the unique chemical and physical properties of Andisols such as permanent charge, high phosphate retention (reaction with Al complexed with OM), low bulk density, notable friability, weak stickiness, and formation of stable soil aggregates. OM also influences the productivity of Andisols by supplying important nutrient elements, retaining available water, and improving the rooting environment (Shoji et al., 1994).

Tree growth response - Darien

At the Darien site, the DBH after one year showed no difference between the NPKSB only treatment and treatments with calcium carbonate sources + NPKSB. There was also no difference in DBH due to different calcium carbonate doses. The tree height response at one year showed slightly higher growth in the treatment with 200 kg ha^{-1} Ca Calciprill + NPKSB compared to the control. We originally expected that the treatment with a higher dose of 400 kg ha^{-1} Calciprill + NPKSB would have the greater response, however, the highest dose of calcium did not increase growth further. The addition of NPKSB treatment alone also induced a response

in tree growth, indicating that the high dose of calcium carbonate may have caused luxury consumption.

There was a significant effect of calcium carbonate sources and NPKSB on the tree volume of *Eucalyptus grandis* compared to the control. Nonetheless, there was a pronounced trend for the control, which has reduced volume of *Eucalyptus grandis*, indicating that limited tree volume was associated with the lack of nutrients (NPKSB). These results are in agreement with results found by (Mello et al., 1970; Schönau, 1977a) who observed that calcium carbonate sources alone may not have a beneficial effect on the growth of *Eucalyptus grandis*.

Tree growth response - Popayan

Tree growth at the Popayan site showed different results than at the Darien site, possibly because of the different soil profile and site slope. At Popayan, both the DBH and tree height were higher in all the treatments with NPKSB (with or without calcium carbonate) than in the control group. The Calciprill dose also had a significant impact on the tree growth. The two highest doses resulted in larger DBH than the control and the highest dose resulted in the greatest tree height. Additionally, there was a significant effect of treatment on the tree volume of *Eucalyptus grandis* compared to the control. The 400 kg ha^{-1} Ca Calciprill + NPKSB treatment had increased volume also indicating that volume response was associated with the combined addition of nutrients (NPKSB) and calcium sources. These results are in agreement with the results found by (Herbert, 1983; and Schönau and Herbert, 1982, 1983) that reported *Eucalyptus grandis* had a response to calcium carbonate (Aglime) and NPKSB. Additionally, they reported that calcium carbonate was only effective when applied together with K.

Over time, the growth rate was similar for all treatments with calcium carbonate sources and NPKSB only. The tree height and volume after 12 months were twice as big at Darien than at Popayan for the control treatments. The growth rate was fastest between months 6-9 but slowed down after month 9. Overall, trees at Popayan showed less growth than trees at Darien, possibly because of the higher slope and less organic matter. Steep slopes cause erosion, and consequently, the nutrients and OM are eroded, making sites with less organic matter less productive. Such less productive sites can be more responsive to nutrient additions.

Nutrient availability in soil Darien/ Popayan

The soil nutrient and soil parameter measurements after 6 months showed no significant difference among treatments at the Darien site and few significant differences among treatments at the Popayan site. Measurements of the soil parameters did, however, vary significantly between the two sites. This result was expected due to differing initial soil pH, buffering capacity, and organic matter content between the sites, and especially due to the differences in organic matter and slope. The results show a different response of soils depending on treatment due to differences in the initial soil parameters. Similar soil behavior was observed by Jones and Mallarino, 2018 on soil incubations where lime treatments were applied to different soils. For example, soil with higher CEC will require a higher dose of calcium carbonate before pH rises in response to lime products compared to soil with low CEC. The Popayan site showed a significant difference in soil potassium 6 months after treatment at the 15-30 cm depth. The Dolomitic lime treatment showed the highest level of soil potassium and, surprisingly, the 400 kg ha^{-1} Calciprill + NPKSB treatment showed a significantly lower soil potassium. The decrease of K in soil where lime was used was also observed by Mora et al. (1999) and Das and Saha (2014). This

result could be due to the large flow of cations with charge $^{+2}$ from the applied calcium which has the potential to displace K ions at exchange sites (Kirkman et al. 1994). Cation exchange capacity, and organic matter percentage were also significantly lower at a depth of 30 cm at the Popayan site than at the Darien site. Nutrient soil availability data in both locations from depths of 0-15 cm did not shown significant differences in any soil nutrient measured (data not shown). Surprisingly, the control group showed a significantly higher CEC and organic matter than all other treatments. We were expecting that CEC would be affected by calcium carbonates sources. Calcium carbonate tends to have an impact on CEC of soils with variable negative charge depending on pH, ionic strength, and nutrient availability (van Raij & Peech 1972; Gillman & Bell 1976; Parfitt 1978). In some soils, the manipulation of this variable charge could be used as a management factor to control the nutrient holding capacity of the soils (Tamimi et al. 1975; Wann & Uehara 1978).

Incubation study

Nutrient availability in soil

We expected soil treated with Calciprill and Dolomitic lime would have better soil phosphorus nutrient availability than the NP only and NPKSB only treatments. This result could occur because of the effect the treatments would have on pH, however, there was not evidence of a statistically significant effect due to different calcium carbonate sources on the soil phosphorus availability of the Andisol incubations. The dose of calcium carbonate sources also did not show a significant difference in phosphorus availability on the soil treated with calcium carbonate sources. This result is unexpected based on the observed differences in pH measurements for each treatment group and the relationship between P availability and pH. Unsurprisingly, there

was evidence of a statistically significant effect on soil phosphorus availability in all the soil treated with NP and NPKSB (including the calcium carbonate treatments) compared to the control treatment. This likely occurred because the control was the only treatment that did not receive any phosphorus application.

All treatments with calcium carbonate + NPKSB showed significantly higher phosphorus availability than the control. This result occurred because the fertilizer (NPKSB) supplied added phosphorus to these soils while the phosphorus in the control was less available because there was no phosphorus addition. Additionally, Andisols are well known for P fixation capabilities (Nanzyo, 1987). These results agreement with the result found by (Rahman et al., 2002), which found that calcium carbonate alone increases P availability. A significant difference in that study and the study presented here is that Rahman et al (2002) used a higher dose of calcium carbonate (1 and 2 tons per hectare).The experimental purpose was also different because the experiment was evaluating the impact of acidic soil cultivation on rice-wheat. The difference in results may indicate that we did not use high enough rates of calcium sources to affect P availability.

As we expected, soil potassium availability increased more where nutrients (NPKSB) were applied than in the NP and the control treatments. This happens because the treatments with NP (0.013 g N, 0.015 g P) and NPKSB (0.017 g N, 0.015 g P, 0.0053 g K) have different amounts of N and K nutrients. Also, the control and the NP only treatments were the only two treatments that did not receive K, S and B sources. This result is also in agreement with results reported by Rutkowska et al (2014), despite the differences between the purpose and doses used in the study. In that study, they report that using different sources of potassium on loamy sand increased the potassium availability. The use of Dolomitic lime and Calciprill showed no significant difference in soil potassium availability due to calcium carbonate source. The dose of

calcium carbonate source also did not produce a significant difference on soil potassium availability.

Soil magnesium availability increased where calcium carbonate sources were applied compared to the NP, the NPKSB and the control treatments. This result is in agreement with results reported by Adams and Henderson (1962), despite the differences in the studies. They report that calcium carbonate + silicate, or phosphogypsum applied on a clay-textured Typic Acrustox soil increased the magnesium availability. In our study, the Dolomitic lime and Calciprill treatments all showed significantly higher soil magnesium availability than the NPKSB, NP and control treatments, which is unsurprising considering both Dolomitic lime and Calciprill have magnesium present (Table 2). Interestingly, a smaller dose of Calciprill which represent 0.03 g per jar^{-1} of elemental Mg (112 kg ha^{-1} Ca Calciprill + NPKSB) has the same effect of increasing magnesium availability as a larger dose of Dolomitic lime which represented 0.22 g per jar^{-1} of elemental Mg (226 kg ha^{-1} Ca Dolomitic lime + NPKSB). The dose also showed a significant difference on soil magnesium availability. The 565 kg ha^{-1} Ca Calciprill + NPKSB (0.15 g per jar^{-1} of elemental Mg) treatment shows more soil magnesium availability than 112 kg ha^{-1} Ca Calciprill + NPKSB (0.03 g per jar^{-1} of elemental Mg), 226 kg ha^{-1} Ca Calciprill + NPKSB (0.06 g per jar^{-1} of elemental Mg), and 226 kg ha^{-1} Ca Dolomitic lime + NPKSB (0.22 g per jar^{-1} of elemental Mg) treatments. Calciprill contains 0.6% magnesium versus 13% magnesium in Dolomitic lime. These results show that soil magnesium in Calciprill become available more quickly.

Soil calcium availability increased where calcium carbonate sources and nutrients (NPKSB) were applied compared to the NP, the NPKSB and the control treatments. This result is in agreement with the result reported by Rahman et al (2002). They report that adding high

rates of calcium carbonate on acidic soil would result in higher measured calcium. The use of Dolomitic lime versus Calciprill treatments also showed a significant difference in soil calcium availability. Surprisingly, soil incubations treated with 226 kg ha^{-1} Ca Dolomitic lime + NPKSB showed more soil calcium availability than the 226 kg ha^{-1} Ca Calciprill + NPKSB treatment. This result was surprising because Calciprill should have a faster reaction (immediately after application) while Dolomitic lime will release nutrients more slowly. The dose of calcium carbonate source (Calciprill) also showed a significant difference in soil calcium availability. Soil incubations treated with 565 kg ha^{-1} Ca Calciprill + NPKSB showed more soil calcium availability than the rest of the treatments. As expected, all treatments that did not receive a calcium carbonate source showed very low amounts of available soil calcium.

As we were expecting, soil sulfur availability increased more where 565 kg ha^{-1} Ca Calciprill + NPKSB was applied than in all other treatments. This could have occurred because of an increased pH in that treatment, which can increase sulfur availability (Havlin et al., 2014). The control and NP treatments did not receive any added sulfur yet they showed similar sulfur availability to all other treatments except for the 565 kg ha^{-1} Ca Calciprill + NPKSB. Unsurprisingly, the Dolomitic lime and Calciprill treatments with lower doses (except the 565 kg ha^{-1} Ca Calciprill + NPKSB treatment) did not show a significant difference in soil sulfur availability compared to the control, NP, and NPKSB only treatments. All treatments with Calciprill and Dolomitic lime received equal amounts of sulfur from the NPKSB application. This indicates that an even larger dose of calcium carbonate sources + NPKSB is required to increase the pH, thus making soil sulfur more available (Havlin et al., 2014).

Soil boron availability showed the same trend as soil potassium. These results are also in agreement with results reported by Rahman et al. (2002). They report that using high rates of

calcium carbonate on acidic soil increases boron availability. Soil boron increased where calcium carbonate sources and nutrients (NPKSB) were applied more than in the NP and the control treatments. This is expected because the NP treatment and the control did not receive S and B. Additional previous research (Arora and Chahal, 2005) has found significant positive correlation between soil pH and available B content. Our study did not show this effect due to increase in pH, however, all treatments with NPKSB showed higher boron availability than the control and the NP only treatments. This confirms that in our study, NPKSB was a primary source of boron. Dolomitic lime and Calciprill treatments showed no significant difference on soil boron availability due to calcium carbonate source. Unsurprisingly, the dose of calcium carbonate source also did not show a significant difference on soil boron availability because NPKSB is the primary source of boron.

Soil zinc availability, similar to most micronutrients, was expected to be reduced in treatments with a higher pH (Havlin et al., 2014; Fageria et al., 2010). Soil zinc availability did not show a clear trend correlating to the measured soil pH in the treatments. Zinc availability in the NP only treatment was significantly higher than in the control, the NPKSB only, the 226 kg ha^{-1} Ca Calciprill + NPKSB, and the 226 ha^{-1} Ca Dolomitic lime + NPKSB treatments. These results are in agreement with results reported by (Rahman et al., 2002). They report that using high rates of calcium carbonate on acidic soil did not increase soil zinc availability. In our study, Dolomitic lime and Calciprill showed no significant differences in soil zinc availability due to calcium carbonate source.

Unsurprisingly, the soil iron concentration shows lower nutrient availability in the treatment with the higher dose of 565 kg ha^{-1} Ca Calciprill + NPKSB. This result was expected because iron is less available at high pH (Havlin et al., 2014; Fageria et al., 2010). The treatment

with 226 kg ha^{-1} Ca Dolomitic lime + NPKSB also showed reduced availability of soil iron. Again, this result is in agreement with Foncesa et al (2010) which observed that liming could cause a linear decrease in iron availability.

Of the other measured soil nutrients, manganese and copper showed no significant difference in any of the treatments. Neither Calciprill nor Dolomitic lime treatments contain these nutrients. Since the soil pH was somewhat similar across all treatments (5.6-6.2) there is not a significant difference in availability of these two nutrients. In most soil, P, K, S and Zn are more available when the soil pH is around 7.00, Ca is more available in neutral and alkaline soil, B tends to be available in all three pH categories (acid, neutral and alkaline), and lastly Fe and Mg are more available in acid soil (Havlin et al., 2014). Soil organic matter (%) also did not show a significant difference in any of the treatments. Since organic matter requires certain weather conditions and microbial activity to develop, the short duration of this trial does not show a difference in organic matter for the treatments.

Cation exchange capacity (CEC) showed a similar trend to calcium availability. This result was expected because CEC is calculated by the sum of available Ca, Mg, K and Na in the soil solution. As we were expecting, CEC increased more where calcium carbonate sources and nutrients (NPKSB) were applied compared to the NP, NPKSB and the control treatments. These results are in agreement with results reported by (Mite et al., 2010). They report that using high rates of calcium carbonate on Andisol soil increased CEC. This reaction happens because calcium carbonate will neutralize either aluminum or hydrogen by the CO_3^{2-} while the Ca will increase in the soil solution resulting in higher CEC. This effect reported by Mite et al (2010) primarily occurs when using higher doses of calcium carbonate (1.5, 3.0, 4.5, 6.0, 7.5, 9.0 and 10.5 tons per hectare). A difference in that study is that the experimental goal was to evaluate

cultivation of pineapple on Ecuadorian Andisol. In our study, soils treated with 226 kg ha^{-1} Ca Dolomitic lime + NPKSB and 226 kg ha^{-1} Ca Calciprill + NPKSB showed similar CEC (16.66 vs 15.19 mmhos cm^{-1}). The dose of calcium carbonate source (Calciprill) showed a significant impact on CEC, with soil incubations treated with 565 kg ha^{-1} Ca Calciprill + NPKSB showing higher CEC than the rest of the treatments. As expected, all treatments that did not receive calcium carbonate showed lower rates of CEC.

Soil pH 32 days after treatment was higher in all treatments where calcium carbonate sources were applied compared to the control, NP only, and NPKSB only treatments. This result is in agreement with the results from Mite et al, (2010), which indicates that using high rates of calcium carbonate on Andisol soil increased soil pH. Unsurprisingly, the only difference in pH observed in our study was between Calciprill treatments with different doses. Treatments with higher doses showed a higher pH than treatment with lower doses. At a rate of 112 kg ha^{-1} Ca Calciprill + NPKSB the soil pH increased by 0.76 units, at a rate of 226 kg ha^{-1} Ca Calciprill + NPKSB the soil pH increased by 0.56 units and at a rate of 565 kg ha^{-1} Ca Calciprill + NPKSB the soil pH increased by 0.26 units. Surprisingly, Calciprill and Dolomitic lime treatments with the same dose (226 kg ha^{-1} Ca) show a similar soil pH level, even though Calciprill has a higher percentage of calcium carbonate and is expected to produce higher soil pH.

CONCLUSIONS

In these studies, we showed that the addition of NPKSB to *Eucalyptus grandis* plantations on Colombian Andisols produces overall increased biomass. In the pot trial, the addition of NPKSB only as well as calcium carbonate sources with NPKSB resulted in increased overall growth after five months. There was not a significant difference in growth between the Calciprill and Dolomitic lime treatments in the pot trial. Calciprill treatments showed a greater increase in soil pH compared to treatments with Dolomitic lime in the pot trial.

Application of pelletized lime (Calciprill) with nutrients produced greater volume than the control at Popayan but not at Darien. Tree volume in the 400 kg ha^{-1} Ca Calciprill treatment (6.41 m^3 ha^{-1}) was greater than in the Control (2.23 m^3 ha^{-1}) after twelve months at the Popayan site. The presence of soil organic matter likely contributed to overall higher yield at the Darien site and lack of differences among fertilizer treatments. In the pot trials, the impact of highly reactive calcium fertilizer versus Dolomitic lime was not as significant. The pot trials were shorter in duration (5 months) which could be the reason why the type of lime treatment was not as significant. Further analysis of the field trials after a longer duration is necessary to further understand the impact of calcium source and rate on production.

In soil incubation trials, the addition of NPKSB or NP along with calcium carbonate sources resulted in an increase in measured soil nutrient concentrations (for P, K, and B). Soil Mg, Ca and pH also showed an increasing positive correlation with the addition higher doses of calcium carbonate sources. These increases in soil nutrient concentration were likely not observed in the field trials because of the uncontrolled variables such as moisture, temperature and soil physical properties that contribute changes in the field soils over time.

Overall, the three studies presented here suggest that for Colombian Andisols, the application of nutrient (NPKSB) treatments can improve overall growth and yield of *Eucalyptus grandis* for wood production in field conditions where nutrients are limiting.

Table 1. Soil characteristics for the two sites in Colombia (Darien and Popayan).

Site	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
Bulk density (g cm^{-3})	0.54	0.61
pH	4.57	4.82
Total Nitrogen (%)	0.66	0.64
Phosphorus (ppm)	9.58	9.55
Potassium (meq/100)	0.29	0.30
Calcium (meq/100)	0.26	0.28
CEC (meq/100)	37.04	34.86

Table 2. Doses of elemental nutrients applied by treatments for the pot trial in Colombia on *Eucalyptus grandis.*

	Amount of nutrient applied (g plant^{-1})						
Treatment	N	P	K	Ca	Mg	S	B
Control	0	0	0	0	0	0	0
NPKSB	6.03	4.623	1.569	0	0	2.16	0.3
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	6.03	4.623	1.569	14.08	8.32	2.16	0.3
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	6.03	4.623	1.569	24.86	14.69	2.16	0.3
100 kg ha^{-1} Ca Calciprill + NPKSB	6.03	4.623	1.569	14.44	0.228	2.16	0.3
200 kg ha^{-1} Ca Calciprill + NPKSB	6.03	4.623	1.569	28.88	0.456	2.16	0.3
800 kg ha^{-1} Ca Calciprill + NPKSB	6.03	4.623	1.569	57.38	0.906	2.16	0.3
800 kg ha^{-1} Ca Calciprill + NP	4.14	4.623	0	57.38	0.906	0	0

Table 3. Doses of fertilizer applied by treatments for the pot trial in Colombia on *Eucalyptus grandis*.

Treatment	Amount of fertilizer applied (g plant^{-1})					
	KCL	DAP	Ammonium sulfate	Boron	Dolomitic lime	Calciprill
Control	0	0	0	0	0	0
NPKSB	3	23	9	3	0	0
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	3	23	9	3	64	0
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	3	23	9	3	113	0
100 kg ha^{-1} Ca Calciprill + NPKSB	3	23	9	3	0	38
200 kg ha^{-1} Ca Calciprill + NPKSB	3	23	9	3	0	76
800 kg ha^{-1} Ca Calciprill + NPKSB	3	23	9	3	0	151
800 kg ha^{-1} Ca Calciprill + NP	0	23	0	0	0	151

Table 4. Site location characteristics for two sites in Colombia where *Eucalyptus grandis* was established.

	Site	
	1	2
County	Valle	Cauca
Nearest town	Darien	Popayan
Latitude	4.00	2.52
Longitude	-76.44	-76.57
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
Tree age (months)	12	12
Elevation (masl)	1614	1794
Precipitation (mm yr^{-1})	1428	2153
Mean annual temperature (°C)	19.7	17.7

Table 5. Fertilizer application doses by treatments in the field study in Colombia for *Eucalyptus grandis*.

	Amount of fertilizer applied (g plant^{-1})					
Treatment	KCL	DAP	Ammonium sulfate	Boron	Dolomitic lime	Calciprill
Control	0	0	0	0	0	0
NPKSB	21	149	38[a], 56[b]	20	0	0
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	21	149	38[a], 56[b]	20	409	0
100 kg ha^{-1} Ca Calciprill + NPKSB	21	149	38[a], 56[b]	20	0	242
200 kg ha^{-1} Ca Calciprill + NPKSB	21	149	38[a], 56[b]	20	0	484
400 kg ha^{-1} Ca Calciprill + NPKSB	21	149	38[a], 56[b]	20	0	968

[a] Darien
[b] Popayan

Table 6. Elemental nutrient application doses by treatments in the field study in Colombia for *Eucalyptus grandis*.

	Amount of nutrient applied (g plant^{-1})						
Treatment	N	P	K	Ca	Mg	S	B
Control	0	0	0	0	0	0	0
NPKSB	34.8[a], 38.6[b]	29.9	11.0	0	0	9.1[a], 13.4[b]	2
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	34.8[a], 38.6[b]	29.9	11.0	90.0	53.2	9.1[a], 13.4[b]	2
100 kg ha^{-1} Ca Calciprill + NPKSB	34.8[a], 38.6[b]	29.9	11.0	92.0	1.4	9.1[a], 13.4[b]	2
200 kg ha^{-1} Ca Calciprill + NPKSB	34.8[a], 38.6[b]	29.9	11.0	183.9	2.9	9.1[a], 13.4[b]	2
400 kg ha^{-1} Ca Calciprill + NPKSB	34.8[a], 38.6[b]	29.9	11.0	367.8	5.8	9.1[a], 13.4[b]	2

[a] Darien

[b] Popayan

Table 7. Doses of fertilizer applied by treatments for the incubation study using Colombian Andisol soil.

	Amount of fertilizer applied (g jar-^{1})					
Treatment	KCL	DAP	Ammonium sulfate	Boron	Dolomitic lime	Calciprill
Control	0	0	0	0	0	0
NPKSB	0.010	0.073	0.019	0.0098	0	0
226 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.010	0.073	0.019	0.0098	1	0
112 kg ha^{-1} Ca Calciprill + NPKSB	0.010	0.073	0.019	0.0098	0	0.5
226 kg ha^{-1} Ca Calciprill + NPKSB	0.010	0.073	0.019	0.0098	0	1
565 kg ha^{-1} Ca Calciprill + NPKSB	0.010	0.073	0.019	0.0098	0	2.5
NP	0.010	0.073	0	0	0	0

Table 8. Doses of elemental nutrients applied by treatments for the incubation study using Colombian Andisol soil.

	Amount of fertilizer applied (g jar^{-1})						
Treatment	N	P	K	Ca	Mg	S	B
Control	0	0	0	0	0	0	0
NPKSB	0.017	0.015	0.0053	0	0	0.0045	0.00098
226 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.017	0.015	0.0053	0.22	0.13	0.0045	0.00098
112 kg ha^{-1} Ca Calciprill + NPKSB	0.017	0.015	0.0053	0.19	0.003	0.0045	0.00098
226 kg ha^{-1} Ca Calciprill + NPKSB	0.017	0.015	0.0053	0.38	0.006	0.0045	0.00098
565 kg ha^{-1} Ca Calciprill + NPKSB	0.017	0.015	0.0053	0.95	0.015	0.0045	0.00098
NP	0.013	0.015	0.0050	0	0	0	0

Table 9. Summary of mean nitrogen concentration (%), nitrogen content (g kg⁻¹), the statistical significance (P value) and standard error of nitrogen on each plant component. Within a plant component, means with different letters are significantly different.

Nitrogen	Nutrient concentration				Nutrient content			
	Foliage	Branch	Stem	Root	Foliage	Branch	Stem	Root
P value	0.38	0.83	0.32	0.59	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Standard error	0.12	0.06	0.08	0.11	7.4	1.6	4.8	5.7
Treatment	%				g kg ⁻¹			
Control	1.11a	0.47a	0.37a	0.64a	21.2b	2.6c	5.8c	9.6b
NPKSB	1.21a	0.48a	0.49a	0.66a	92.4a	14.7a	28.3a	41a
100 kg ha⁻¹ Ca Dolomitic lime + NPKSB	1.19a	0.39a	0.45a	0.75a	88.5a	10.8ab	24.1ab	44.4a
160 kg ha⁻¹ Ca Dolomitic lime + NPKSB	1.05a	0.44a	0.42a	0.7a	80.9a	12.4a	24ab	38.8a
100 kg ha⁻¹ Ca Calciprill + NPKSB	1.27a	0.41a	0.4a	0.82a	89.1a	10ab	19.5ab	40.5a
200 kg ha⁻¹ Ca Calciprill + NPKSB	1.19a	0.4a	0.44a	0.76a	81a	9.3abc	23.1ab	39.2a
800 kg ha⁻¹ Ca Calciprill + NPKSB	1.22a	0.37a	0.41a	0.69a	80.6a	8.3abc	19.8ab	33.4a
800 kg ha⁻¹ Ca Calciprill + NP	1.07a	0.36a	0.49a	0.61a	22.4b	4bc	11.7bc	11.9b

Table 10. Summary of mean phosphorus concentration (%), phosphorus content (g kg^{-1}), the statistical significance (P value) and standard error of phosphorus on each plant component. Within a plant component, means with different letters are significantly different.

Phosphorus	Nutrient concentration				Nutrient content			
	Foliage	Branch	Stem	Root	Foliage	Branch	Stem	Root
P value	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.002**	**0.0001**	**0.0016**
Standard error	<0.00	0.01	0.01	0.01	0.3	0.1	0.3	0.3
Treatment	%				g kg $^{-1}$			
Control	0.08a	0.1a	0.09b	0.05ab	1.5b	0.5b	1.4b	0.8c
NPKSB	0.06b	0.03b	0.02c	0.03bc	4.3a	0.8ab	1.3b	1.6ab
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.05b	0.02b	0.02c	0.03bc	3.9a	0.5b	1b	1.4abc
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.05b	0.02b	0.02c	0.02c	4a	0.5b	1.2b	1.3abc
100 kg ha^{-1} Ca Calciprill + NPKSB	0.06b	0.02b	0.02c	0.02c	4a	0.5b	0.8b	1.1bc
200 kg ha^{-1} Ca Calciprill + NPKSB	0.06b	0.02b	0.02c	0.05abc	3.8a	0.4b	1b	2a
800 kg ha^{-1} Ca Calciprill + NPKSB	0.06b	0.02b	0.02c	0.03bc	3.8a	0.5b	0.9b	1.3abc
800 kg ha^{-1} Ca Calciprill + NP	0.08a	0.1a	0.12a	0.06a	1.6b	1a	2.3a	1.2bc

Table 11. Summary of mean potassium concentration (%), potassium content (g kg^{-1}), the statistical significance (P value) and standard error of potassium on each plant component. Within a plant component, means with different letters are significantly different.

Potassium	Nutrient concentration				Nutrient content			
	Foliage	Branch	Stem	Root	Foliage	Branch	Stem	Root
P value	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Standard error	0.1	0.07	0.07	0.03	8.5	2.4	4	2.2
Treatment	%				g kg $^{-1}$			
Control	0.88b	0.56bc	0.41bc	0.32b	16.8b	3.1b	6.4b	4.7b
NPKSB	1.4a	0.76ab	0.6a	0.5a	110.4a	23.1a	34.4a	30.9a
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	1.52a	0.91a	0.59a	0.55a	115.2a	25.6a	30.9a	31.9a
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	1.44a	0.83a	0.54ab	0.5a	111a	23.1a	29.4a	28.1a
100 kg ha^{-1} Ca Calciprill + NPKSB	1.39a	0.78ab	0.55ab	0.5a	99.4a	19.6a	27.7a	25.2a
200 kg ha^{-1} Ca Calciprill + NPKSB	1.45a	0.83a	0.57ab	0.51a	102.2a	19.6a	29.4a	26.4a
800 kg ha^{-1} Ca Calciprill + NPKSB	1.54a	0.85a	0.65a	0.54a	103.3a	19.5a	29.7a	25.8a
800 kg ha^{-1} Ca Calciprill + NP	0.79b	0.42c	0.33c	0.28b	15.6b	5b	6.8b	5.5b

Table 12. Summary of mean calcium concentration (%), calcium content (g kg^{-1}), the statistical significance (P value) and standard error of calcium on each plant component. Within a plant component, means with different letters are significantly different.

Calcium	Nutrient concentration				Nutrient content			
	Foliage	Branch	Stem	Root	Foliage	Branch	Stem	Root
P value	**0.0001**	0.2185	**0.0001**	0.0696	**0.0001**	**0.0007**	**0.0001**	**0.0001**
Standard error	0.05	0.09	0.06	0.07	3.6	2.9	2.8	3.3
Treatment	%				g kg $^{-1}$			
Control	0.83a	0.96a	0.69ab	0.7a	16b	5.3c	10.6c	10.2b
NPKSB	0.53b	0.61a	0.51b	0.51a	41.3a	18.3abc	29.6ab	31.4a
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.6b	0.85a	0.57b	0.75a	45.6a	23.9a	30a	43.2a
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.65b	0.84a	0.56b	0.73a	50.7a	23.3ab	29.5ab	41.3a
100 kg ha^{-1} Ca Calciprill + NPKSB	0.61b	0.87a	0.51b	0.62a	43.2a	21.9ab	24.8ab	30.7a
200 kg ha^{-1} Ca Calciprill + NPKSB	0.61b	0.72a	0.53b	0.78a	42.5a	17abc	26.6ab	39.2a
800 kg ha^{-1} Ca Calciprill + NPKSB	0.64b	0.83a	0.68ab	0.81a	43.4a	19.1ab	31.6a	38.2a
800 kg ha^{-1} Ca Calciprill + NP	0.85a	0.91a	0.86a	0.76a	17.2b	10.4bc	17.9bc	14.4b

Table 13. Summary of mean sulfur concentration (%), sulfur content (g kg^{-1}), the statistical significance (P value) and standard error of sulfur on each plant component. Within a plant component, means with different letters are significantly different.

Sulfur	Nutrient concentration				Nutrient content			
	Foliage	Branch	Stem	Root	Foliage	Branch	Stem	Root
P value	**0.0021**	0.1473	0.7112	0.2916	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Standard error	0.01	<0.01	<0.01	<0.01	0.7	0.1	0.2	0.3
Treatment	%				g kg^{-1}			
Control	0.12b	0.04a	0.04a	0.06a	2.2b	0.2b	0.6b	0.9b
NPKSB	0.13ab	0.04a	0.04a	0.05a	9.8a	1.3a	2.1a	3.3a
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.13ab	0.05a	0.04a	0.06a	9.4a	1.4a	1.8a	3.5a
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	0.11b	0.05a	0.04a	0.06a	8.9a	1.3a	1.9a	3.1a
100 kg ha^{-1} Ca Calciprill + NPKSB	0.13a	0.05a	0.03a	0.06a	9.5a	1.1a	1.6a	2.9a
200 kg ha^{-1} Ca Calciprill + NPKSB	0.12ab	0.05a	0.04a	0.07a	8.6a	1.1a	1.8a	3.3a
800 kg ha^{-1} Ca Calciprill + NPKSB	0.12ab	0.05a	0.04a	0.07a	8.1a	1.1a	1.7a	3.1a
800 kg ha^{-1} Ca Calciprill + NP	0.11b	0.04a	0.04a	0.06a	2.3b	0.4b	0.7b	1.2b

Boron	Nutrient concentration				Nutrient content			
	Foliage	Branch	Stem	Root	Foliage	Branch	Stem	Root
P value	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Standard error	19.46	1.99	2.41	6.29	<0.001	<0.001	<0.001	<0.001
Treatment	ppm				µg kg $^{-1}$			
Control	39.7d	15.4b	8.7b	11b	0.0008d	0.00008b	0.00013b	0.00016b
NPKSB	325.7a	26a	21.9a	49.9a	0.025a	0.00079a	0.0012a	0.0030a
100 kg ha^{-1} Ca Dolomitic lime + NPKSB	289.4ab	30.2a	21.5a	67.6a	0.021ab	0.00085a	0.0011a	0.0039a
160 kg ha^{-1} Ca Dolomitic lime + NPKSB	287ab	26.8a	17.9a	55.2a	0.021ab	0.00074a	0.00094a	0.0030a
100 kg ha^{-1} Ca Calciprill + NPKSB	234bc	24.7a	19.2a	59.6a	0.016bc	0.00062a	0.00094a	0.0029a
200 kg ha^{-1} Ca Calciprill + NPKSB	193.4c	24.9a	18.4a	51.5a	0.013c	0.00059a	0.00092a	0.0025a
800 kg ha^{-1} Ca Calciprill + NPKSB	193.9c	26.1a	21.5a	59.7a	0.013c	0.0006a	0.00098a	0.0027a
800 kg ha^{-1} Ca Calciprill + NP	36.1d	12.5b	9.3b	11.2b	0.0007d	0.00015b	0.0002b	0.00022b

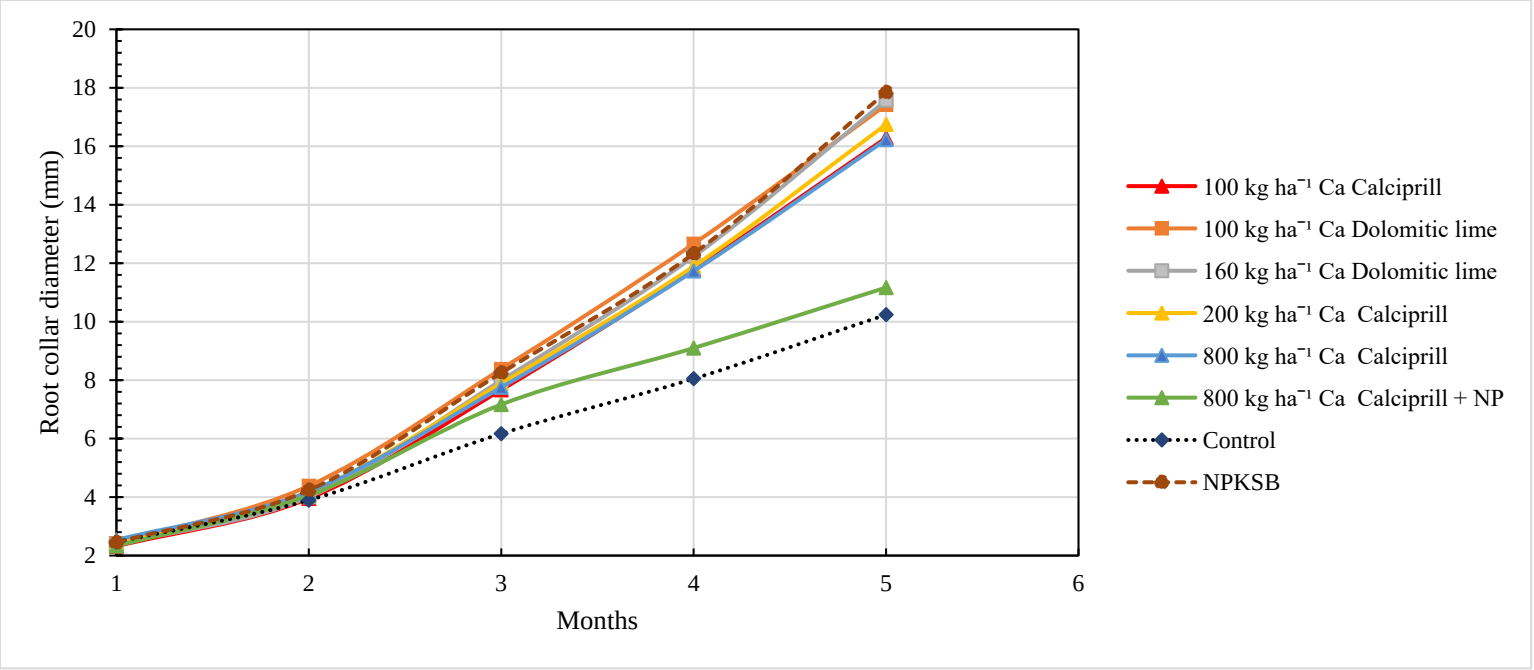

Figure 1. Root collar diameter (mm) at months since treatment using calcium carbonate sources and NPKSB treatments in pot trial. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha⁻¹ Ca Calciprill + NP.

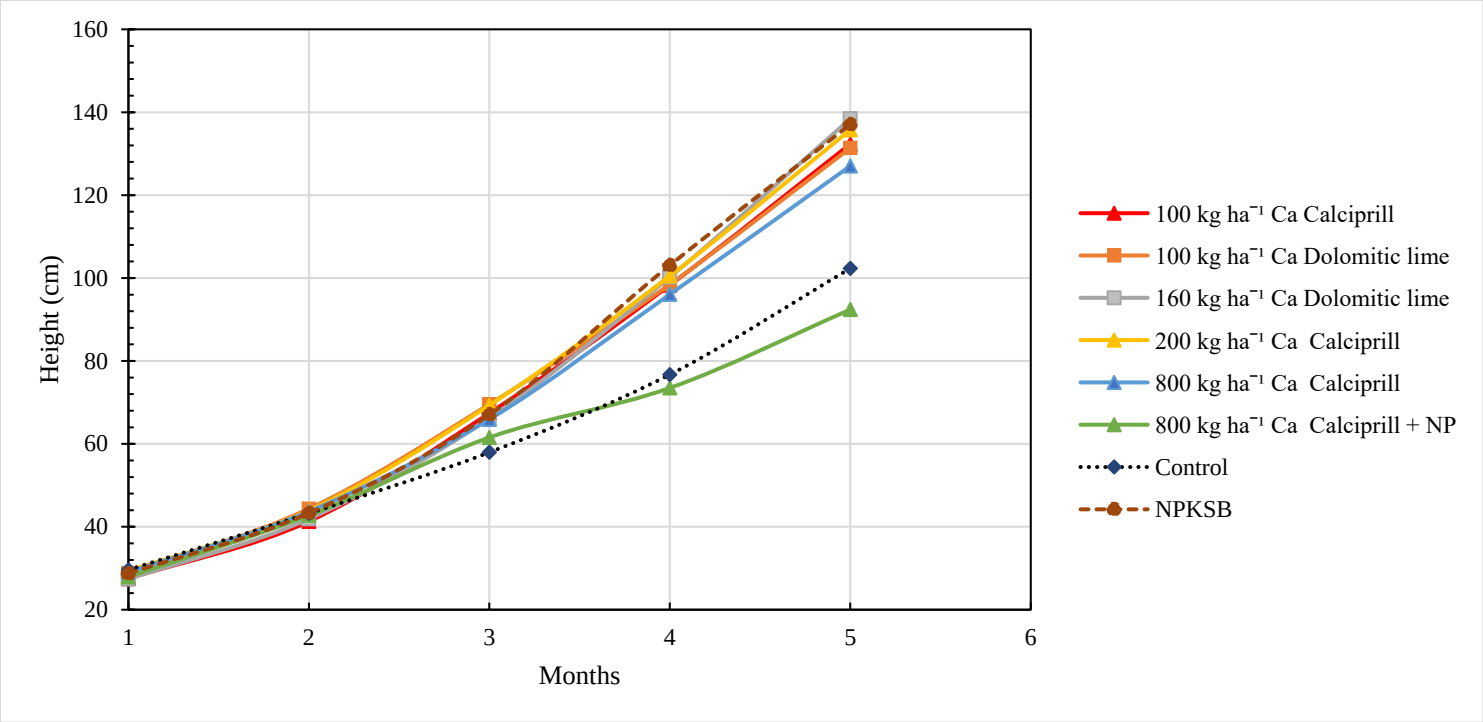

Figure 2. Height (cm) at months since treatment using calcium carbonate sources and NPKSB treatments in pot trial. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha⁻¹ Ca Calciprill + NP.

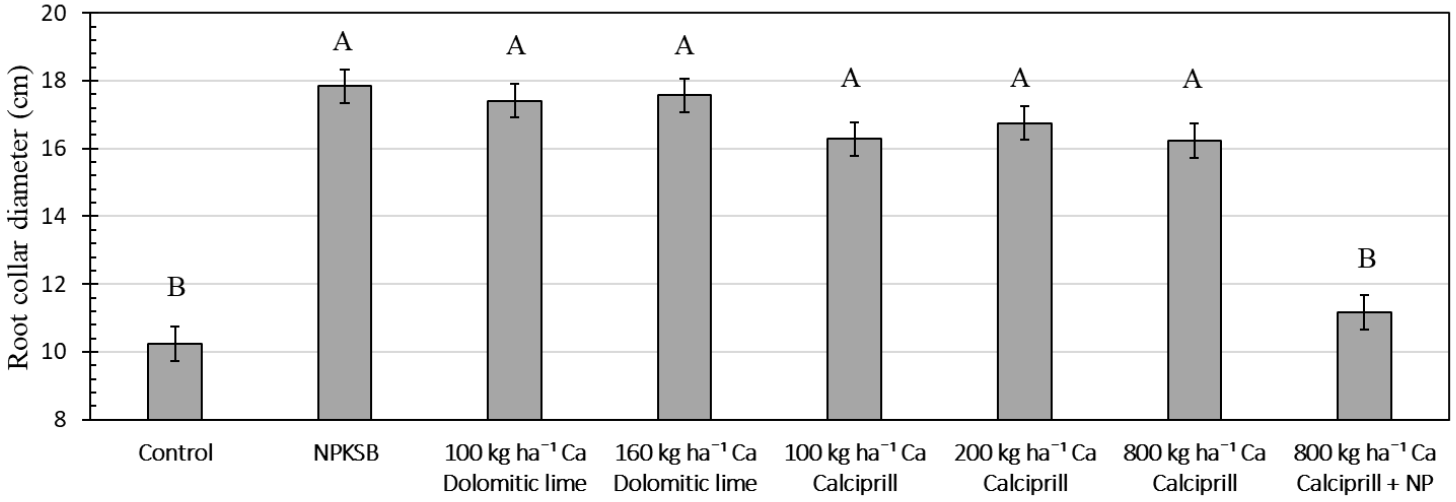

Figure 3. Root collar diameter (cm) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha $^{-1}$ Ca Calciprill + NP.

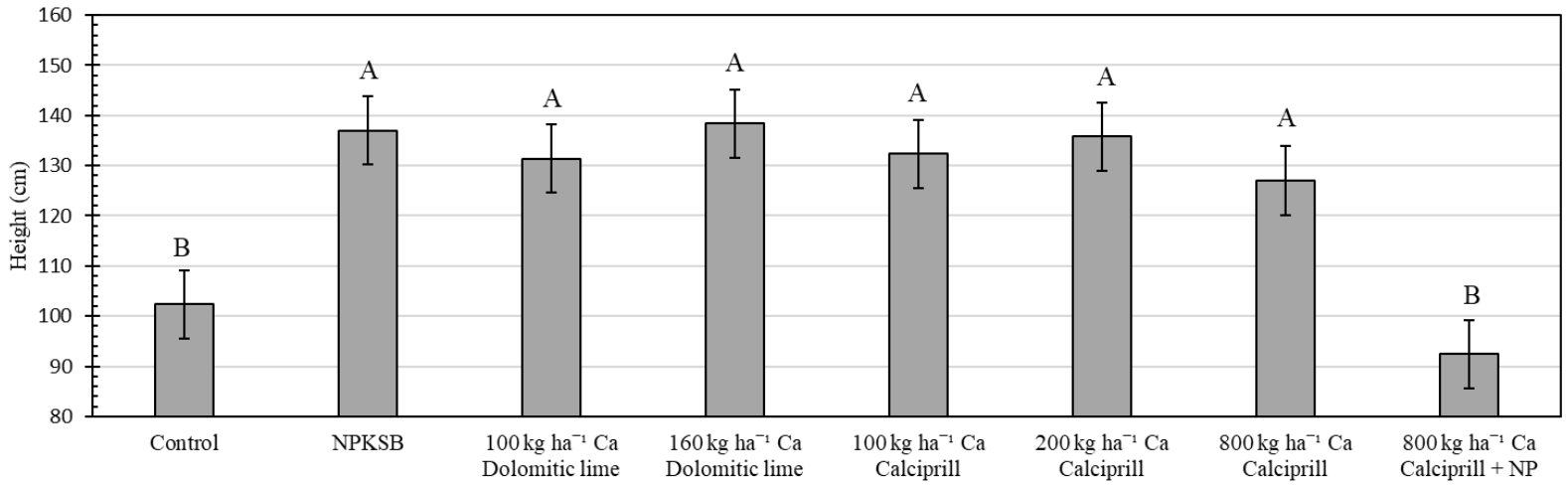

Figure 4. Height (cm) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha $^{-1}$ Ca Calciprill + NP.

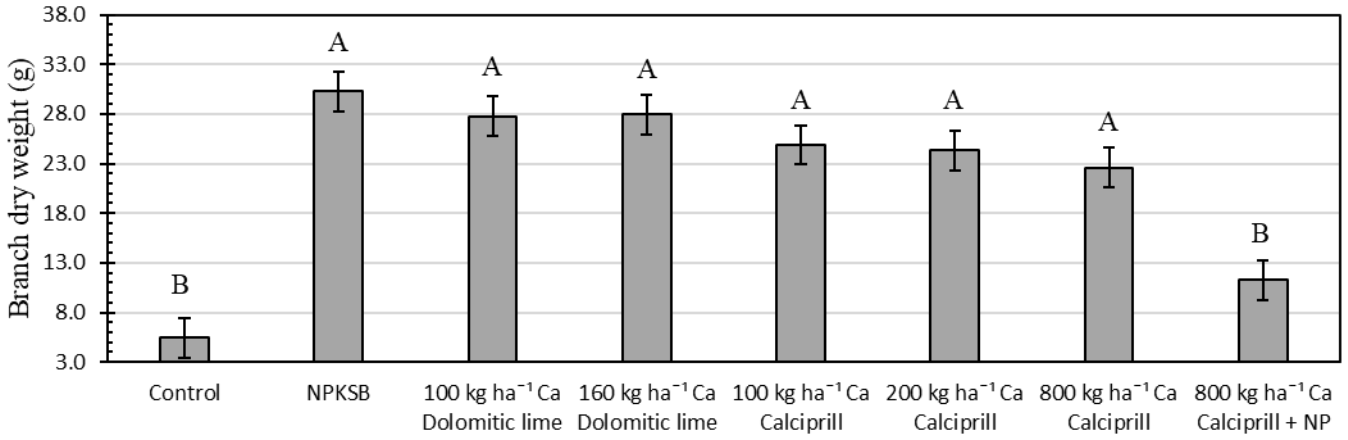

Figure 5. Branch dry weight (g) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

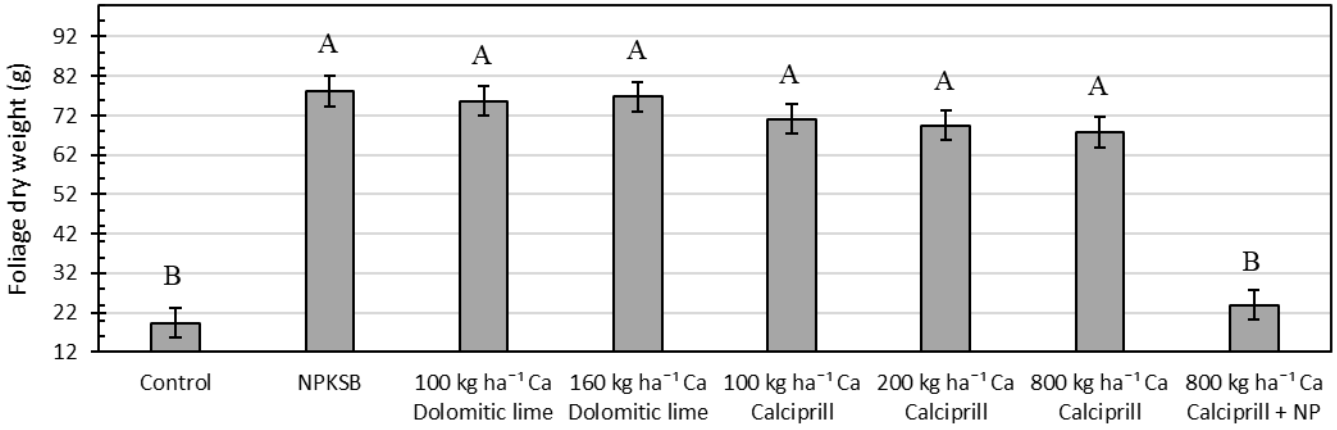

Figure 6. Foliage dry weight (g) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

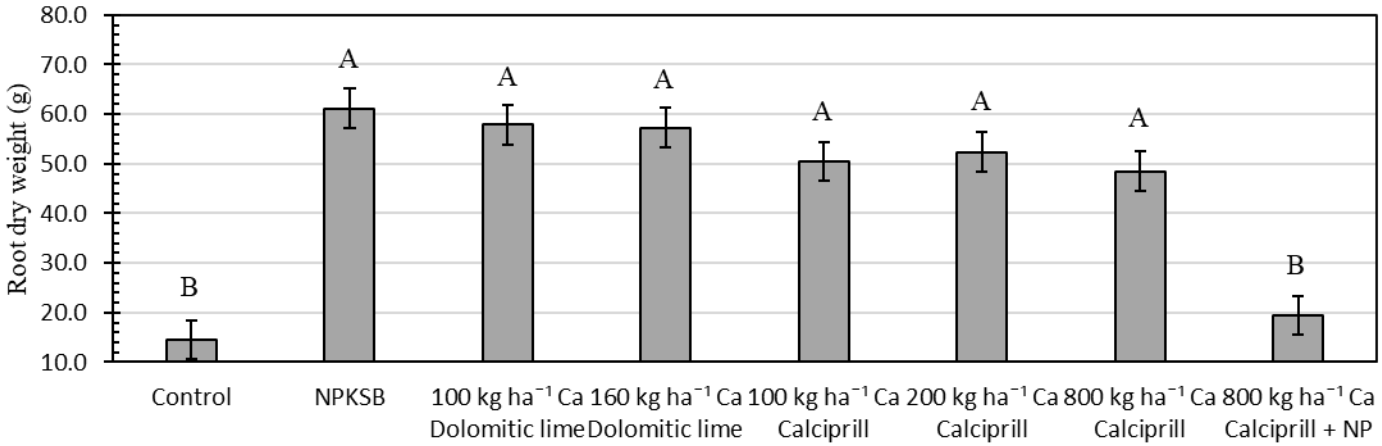

Figure 7. Root dry weight (g) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

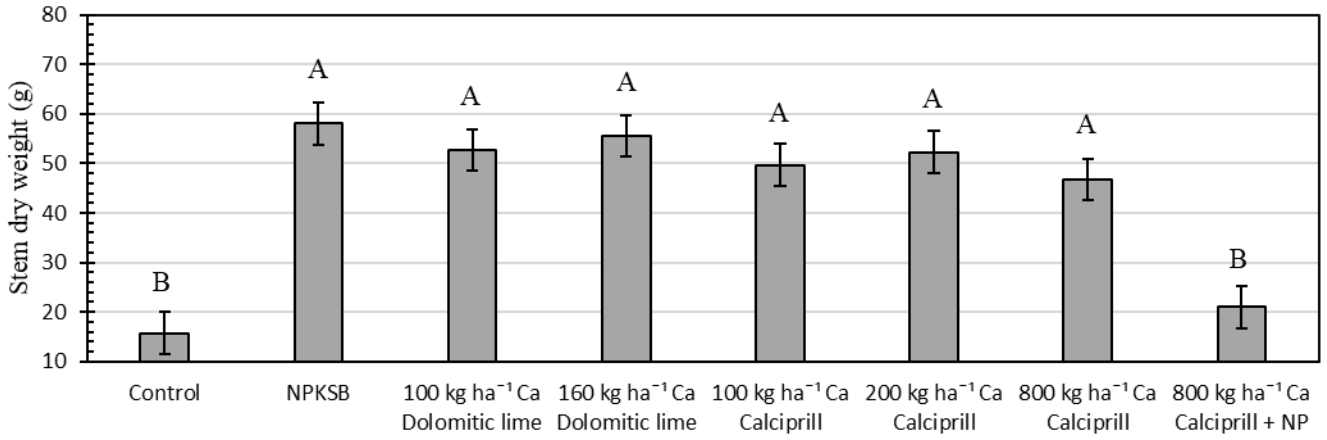

Figure 8. Stem dry weight (g) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

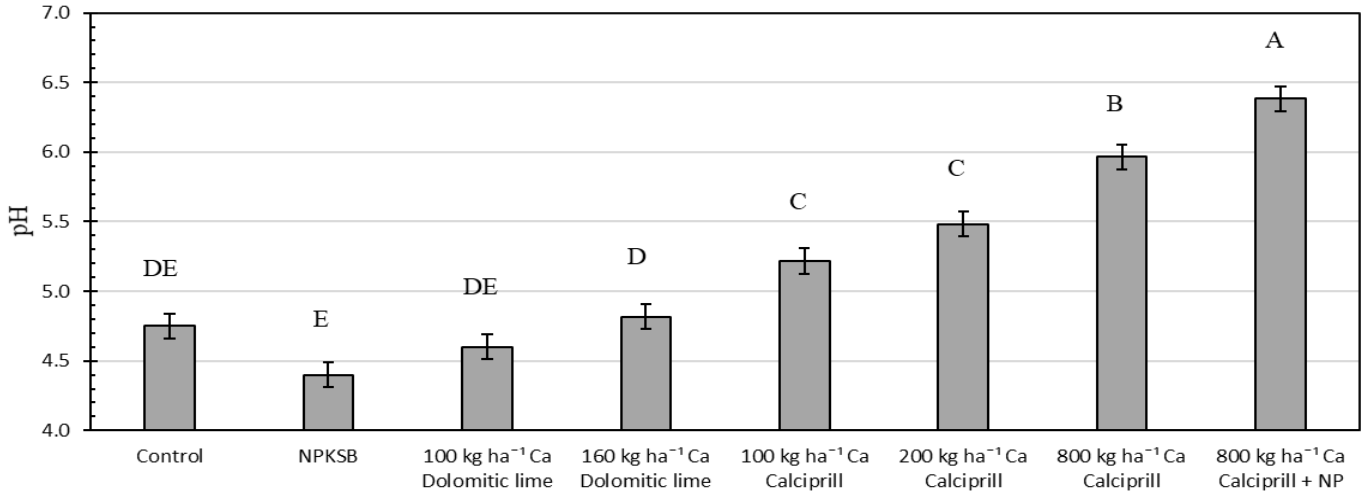

Figure 9. Soil pH treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

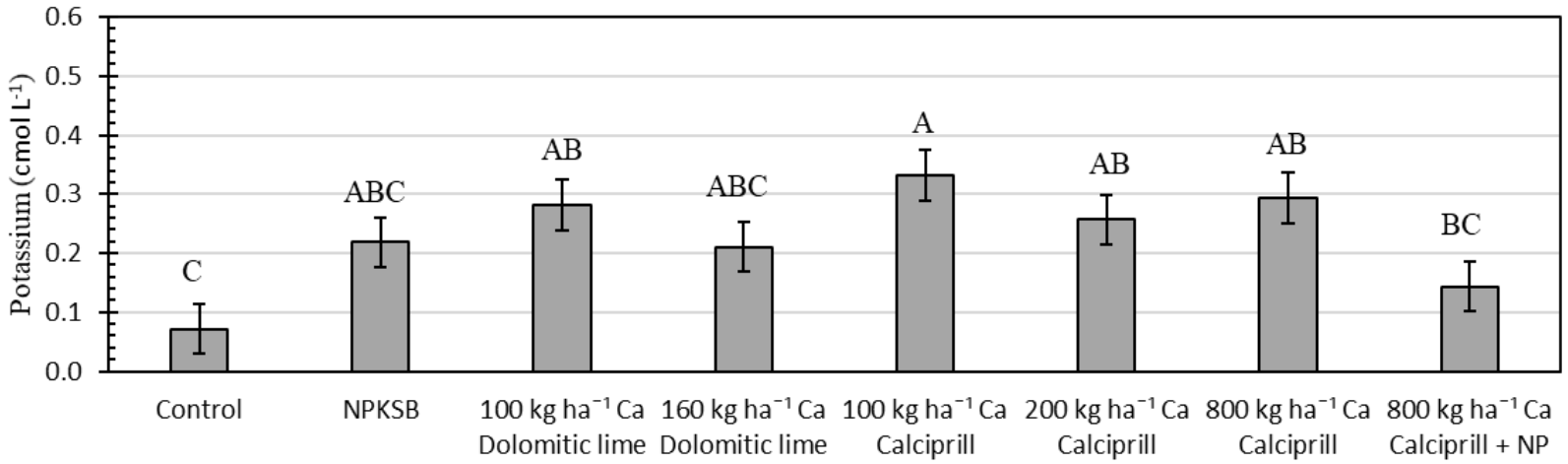

Figure 10. Soil potassium (cmol L^{-1}) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

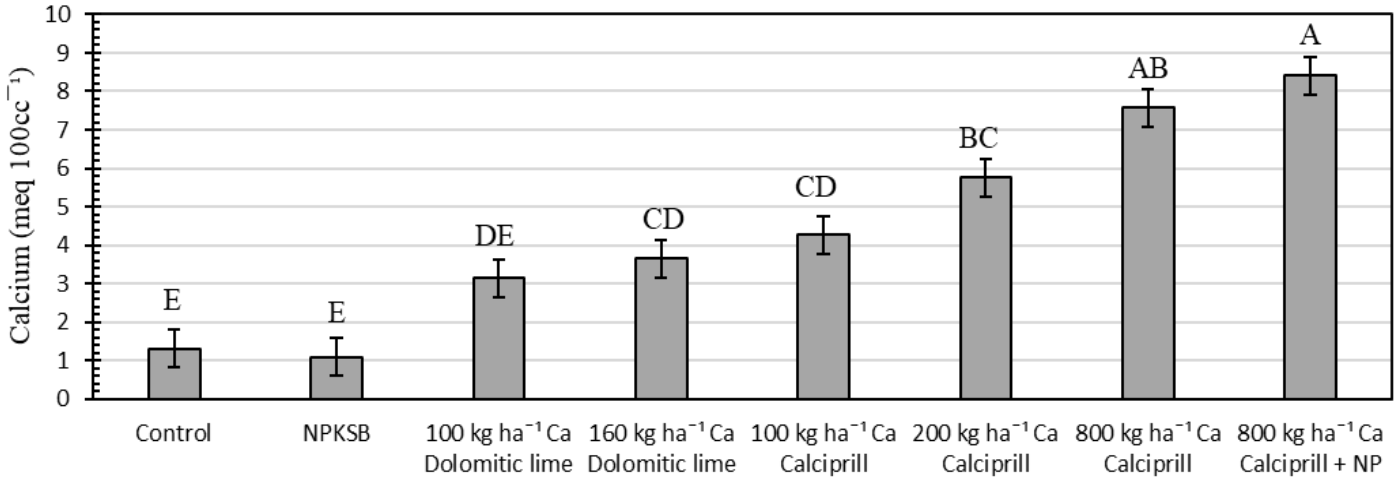

Figure 11. Soil calcium (meq 100 cc^{-1}) treatment means and standard error five months after treatment application in pot trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the 800 kg ha^{-1} Ca Calciprill + NP.

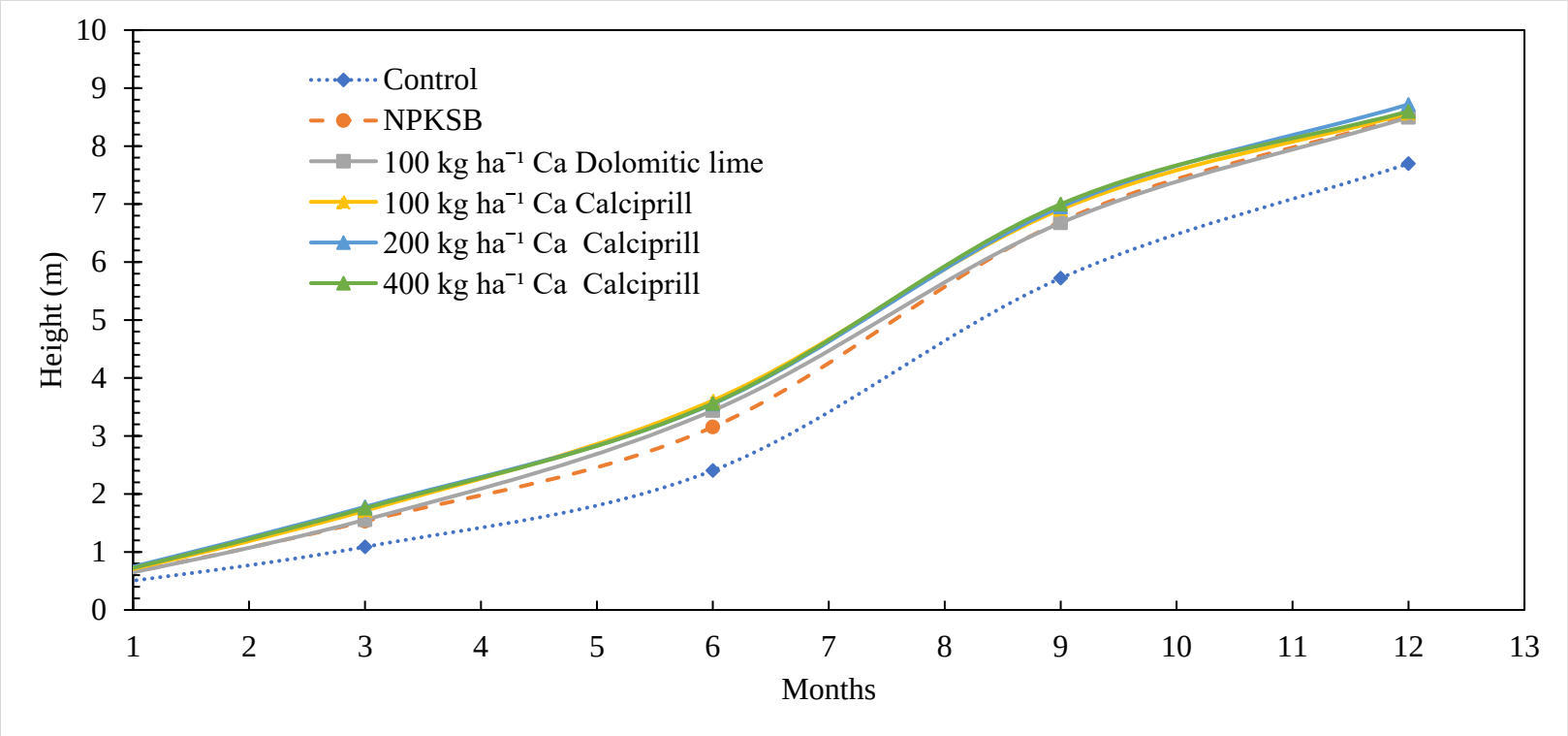

Figure 12. Height (m) at months since treatment using calcium carbonate sources and NPKSB treatments at Darien site. All Calciprill treatments received an equivalent amount of NPKSB.

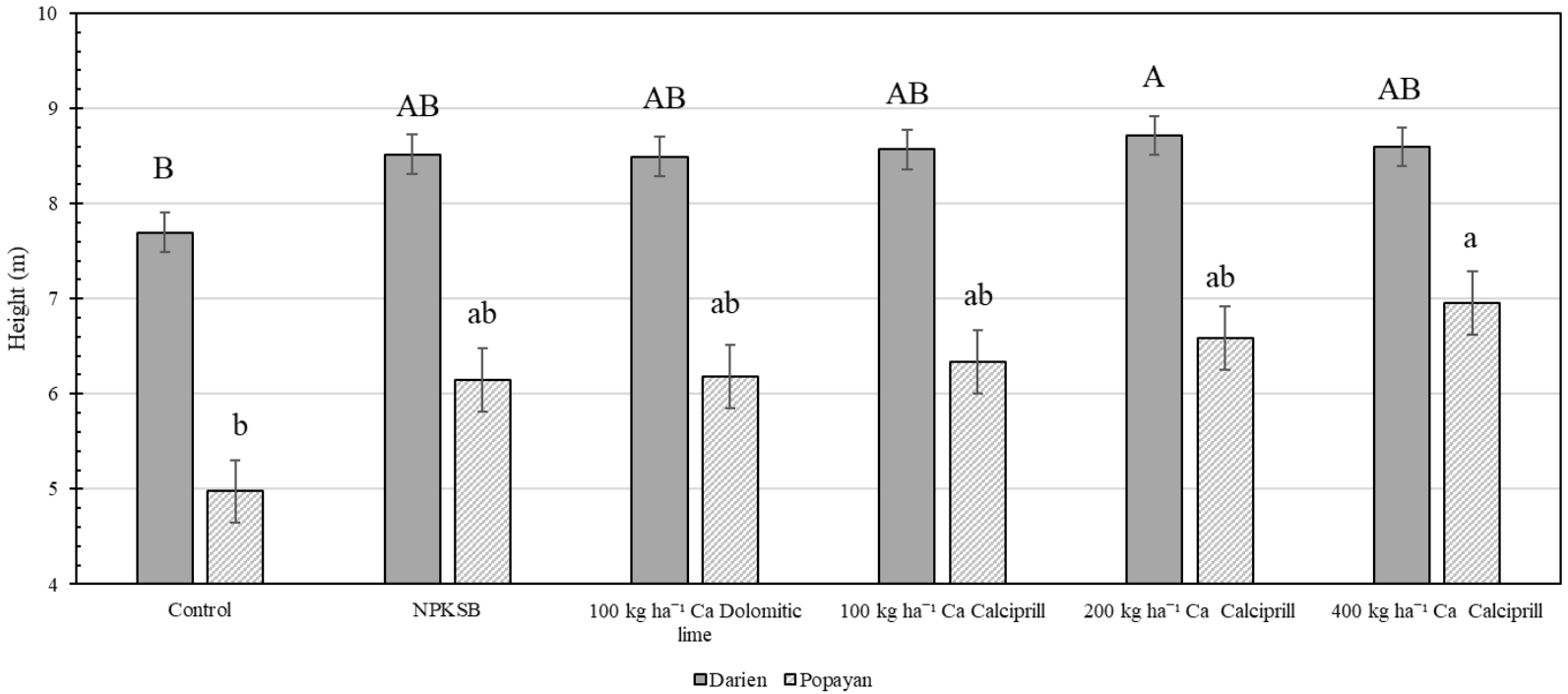

Figure 13. Height (m) treatment means and standard error twelve months after treatment application at Darien and Popayan trials. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB. Statistical analysis within site.

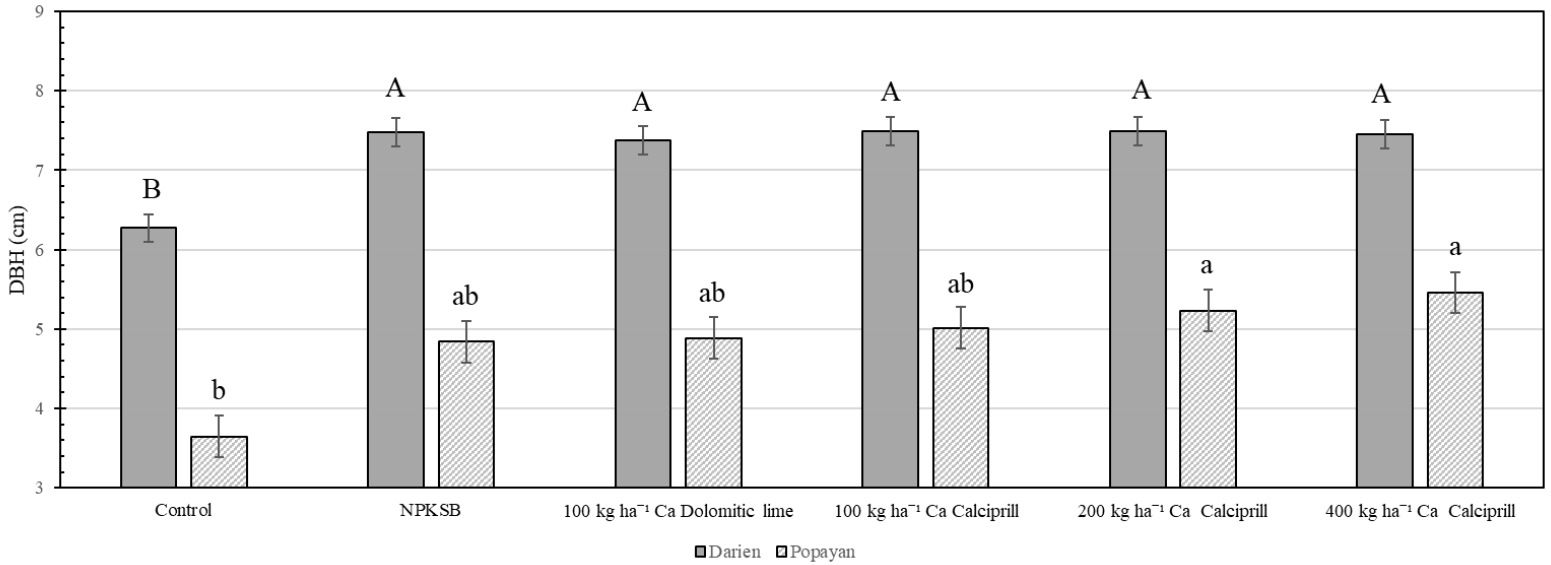

Figure 14. DBH (cm) treatment means and standard error twelve months after treatment application at Darien and Popayan trials. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB. Statistical analysis within site.

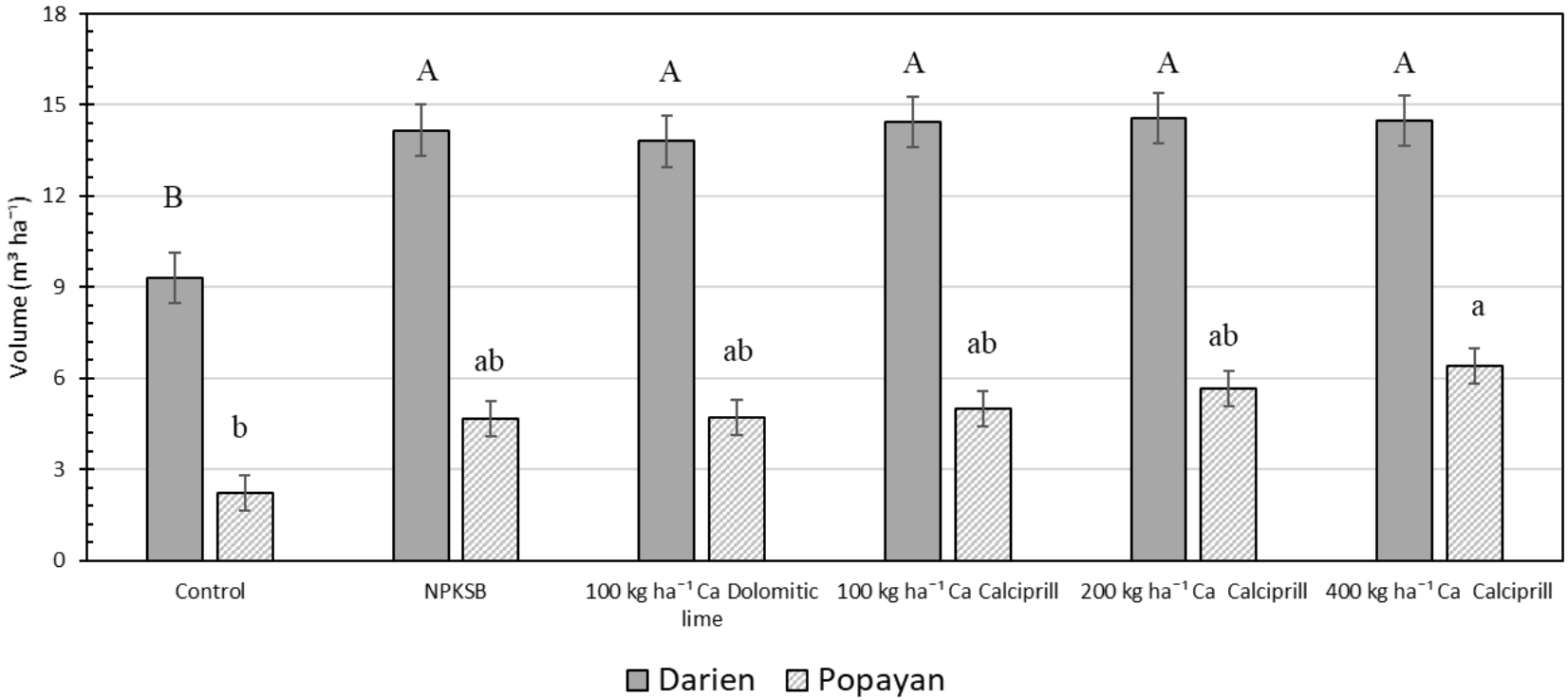

Figure 15. Volume ($m^3 ha^{-1}$) treatment means and standard error twelve months after treatment application at Darien and Popayan trials. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB. Statistical analysis within site.

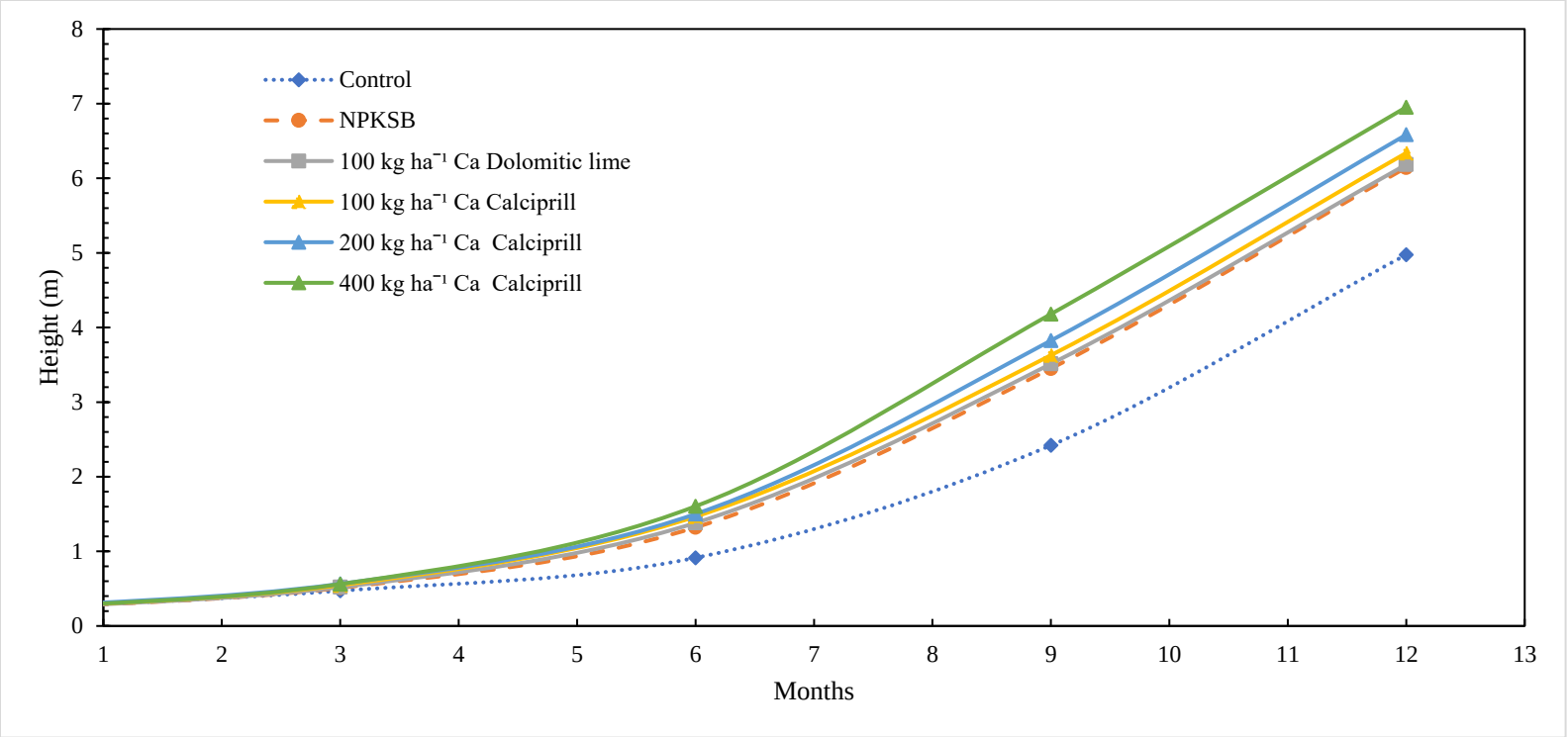

Figure 16. Height (m) months since treatment using calcium carbonate sources and NPKSB treatments at Popayan site. All Calciprill treatments received an equivalent amount of NPKSB.

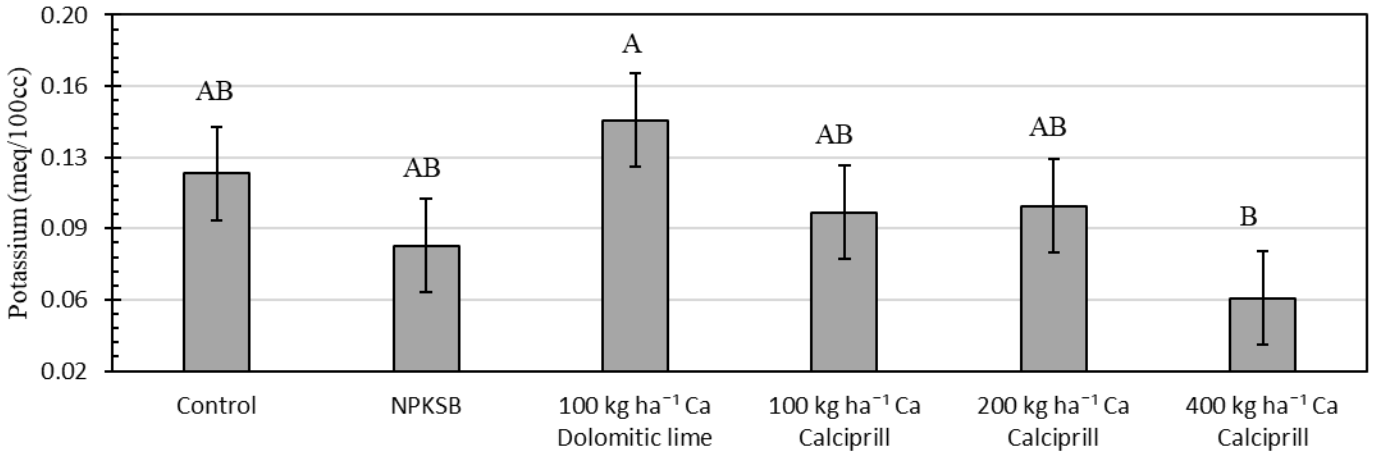

Figure 17. Soil potassium (meq/100cc) treatment means and standard error six months after treatment application in Popayan field trial. Letters show significant differences, $P < 0.05$. (0-15 cm depth). All Calciprill treatments received an equivalent amount of NPKSB.

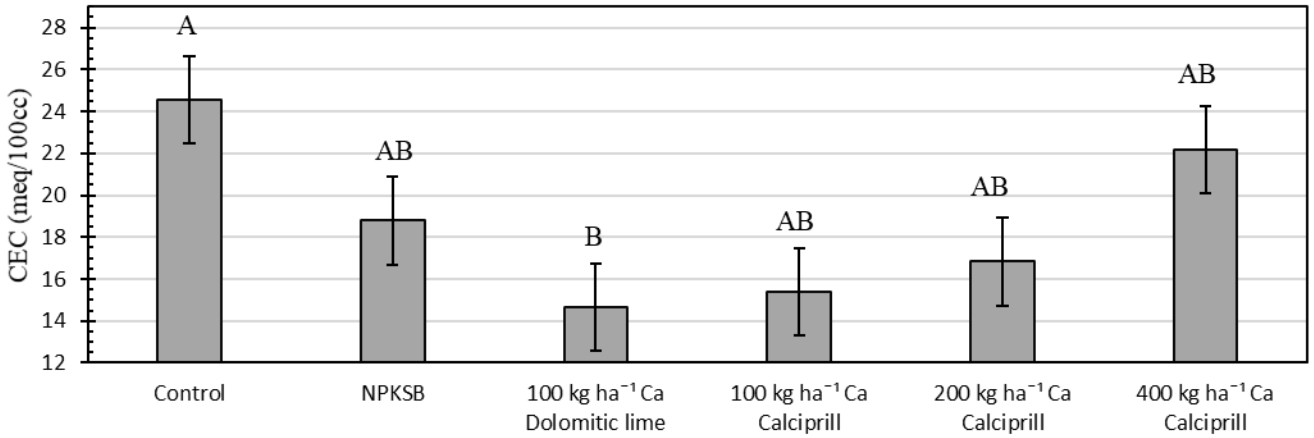

Figure 18. Soil CEC (meq/100cc) treatment means and standard error six months after treatment application in Popayan field trial. Letters show significant differences, $P < 0.05$. (15-30 cm depth). All Calciprill treatments received an equivalent amount of NPKSB.

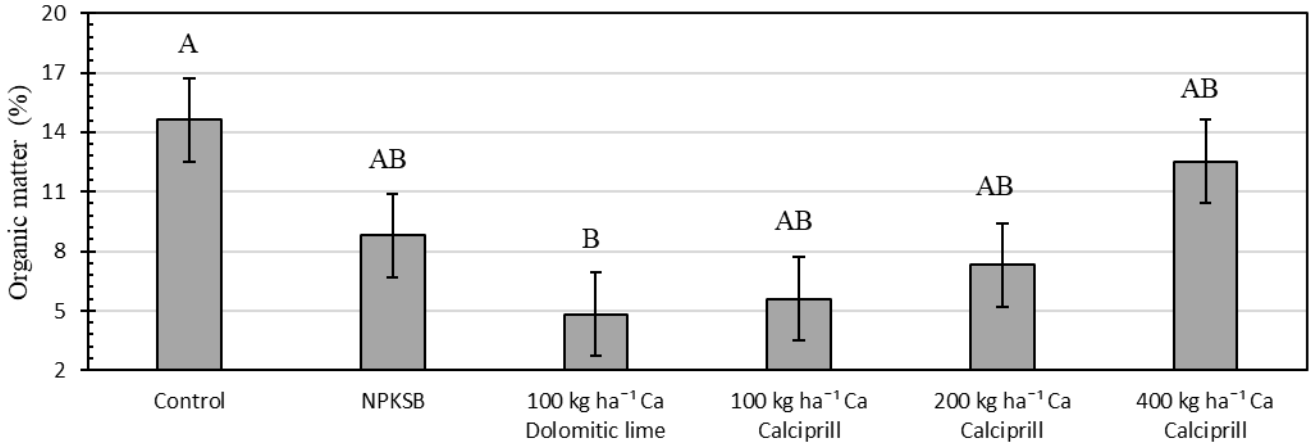

Figure 19. Organic matter (%) treatment means and standard error six months after treatment application in Popayan field trial. Letters show significant differences, $P < 0.05$. (15-30 cm depth). All Calciprill treatments received an equivalent amount of NPKSB.

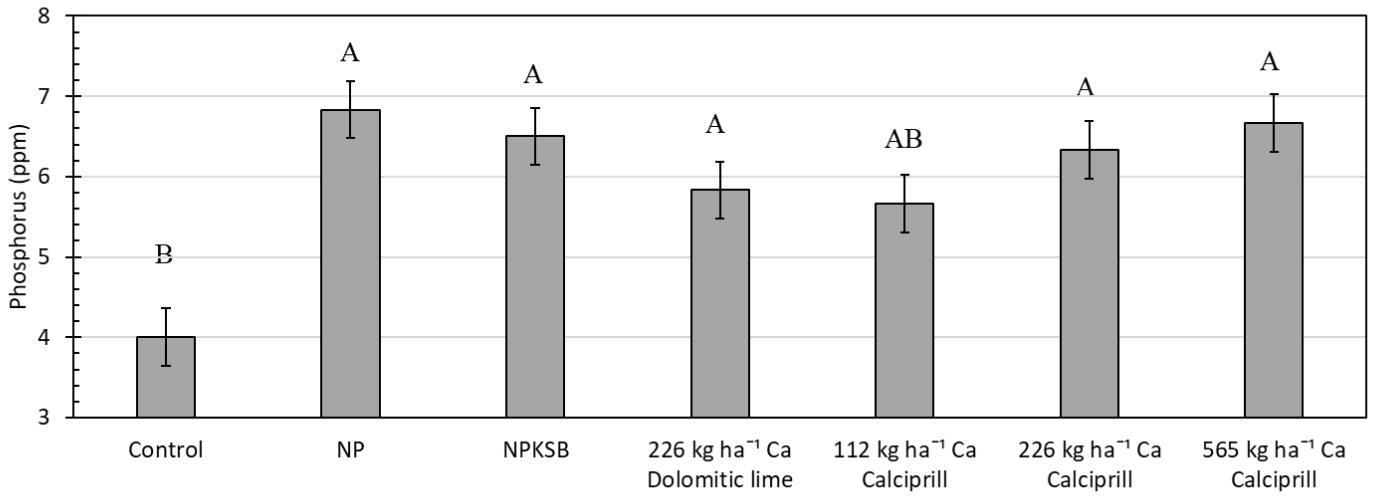

Figure 20. Soil phosphorus (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP treatment.

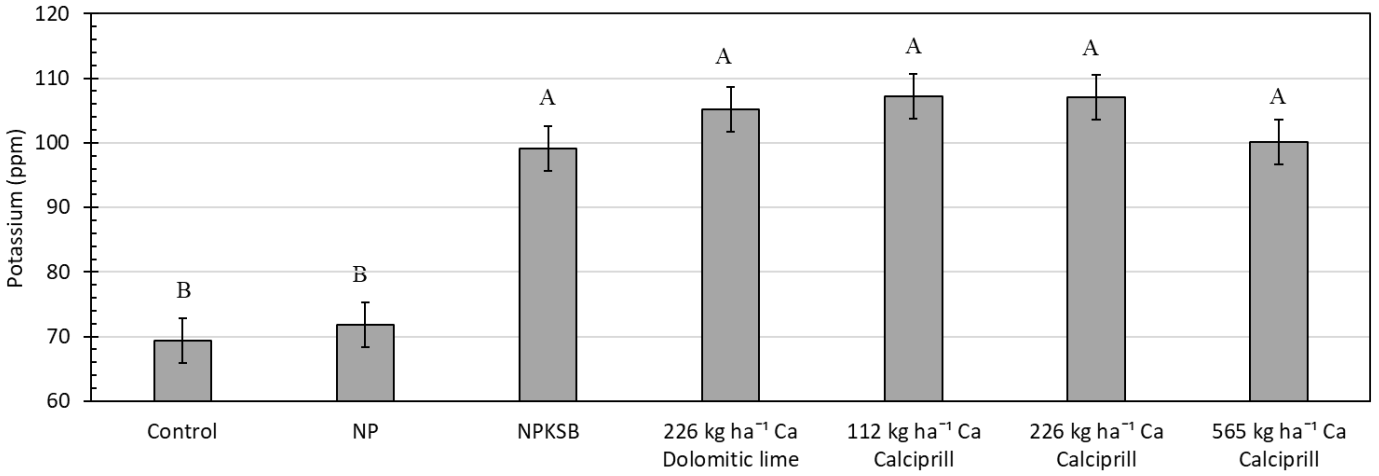

Figure 21. Soil potassium (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP treatment.

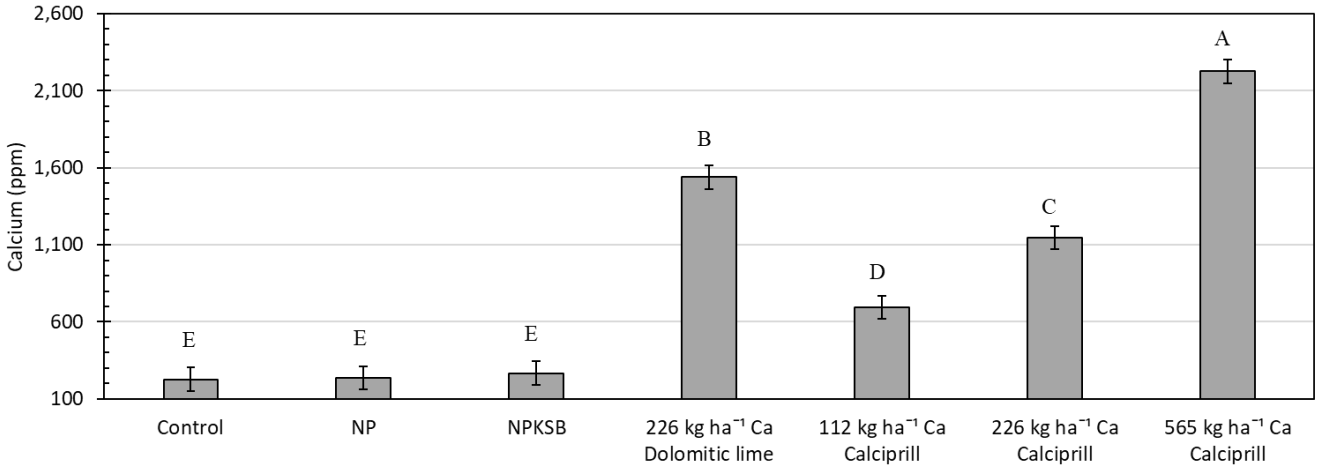

Figure 22. Soil calcium (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

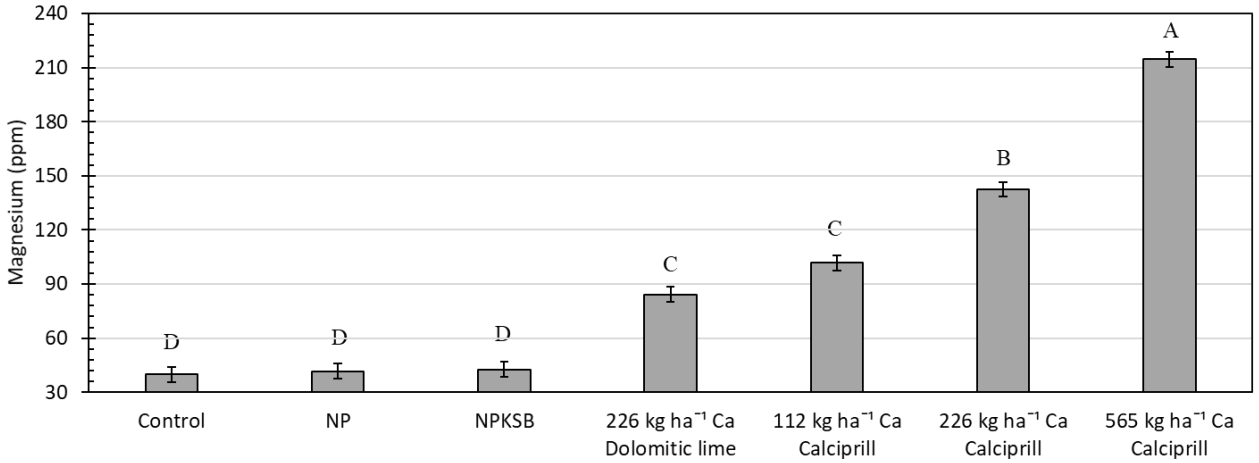

Figure 23. Soil magnesium (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

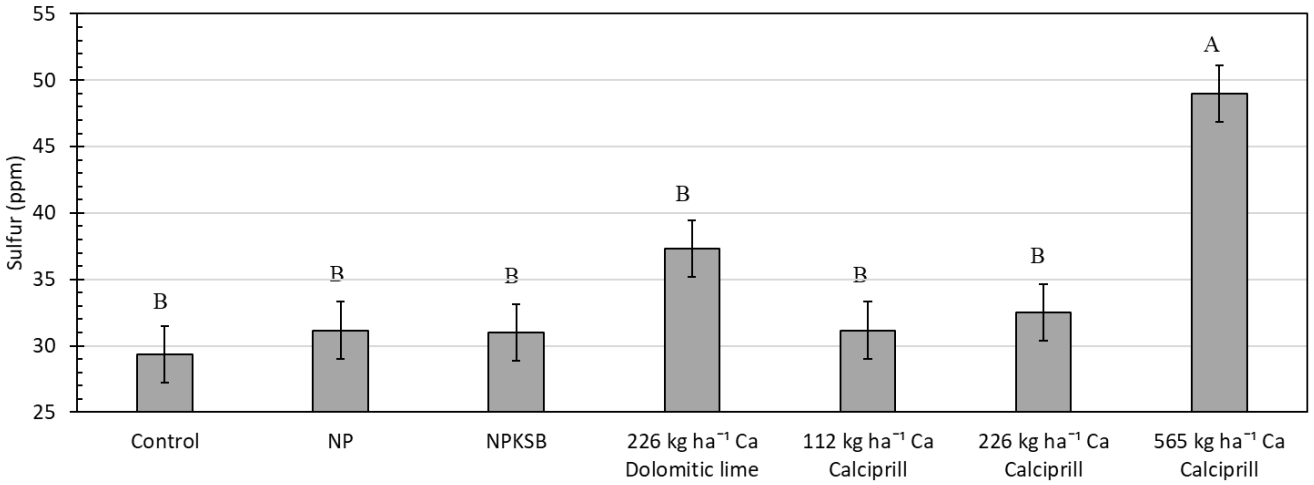

Figure 24. Soil sulfur (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

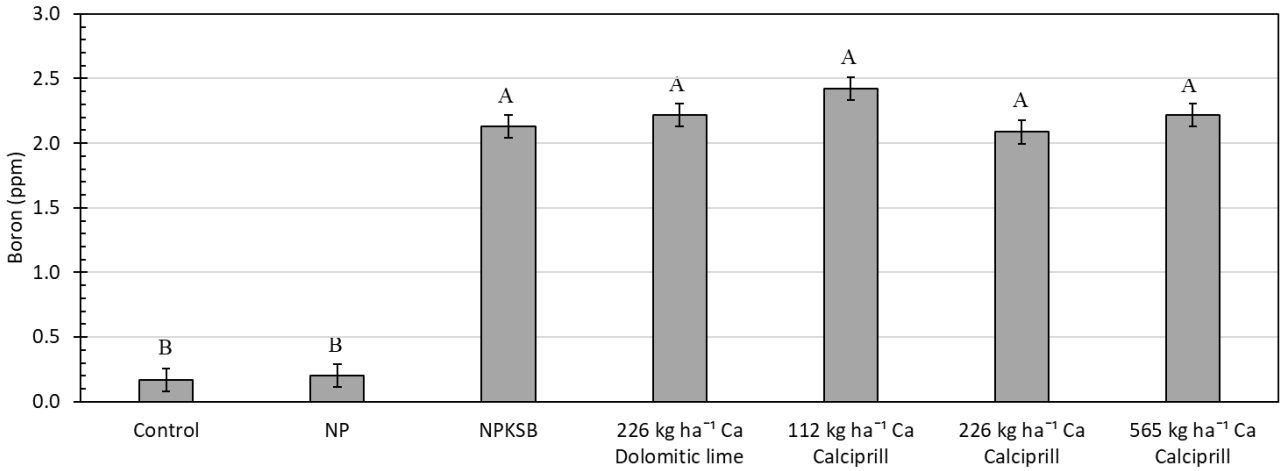

Figure 25. Soil boron (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

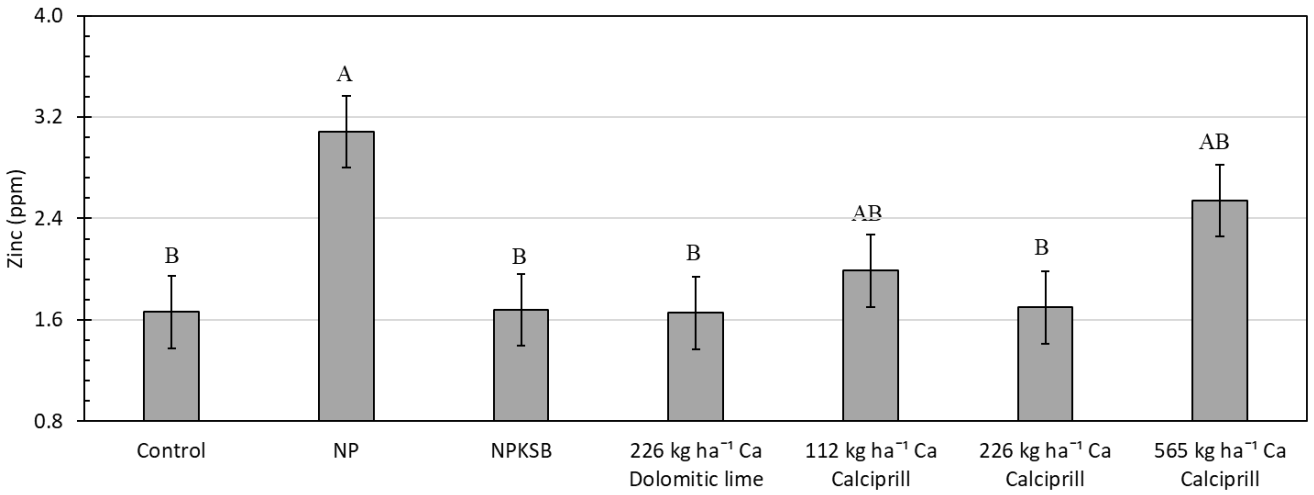

Figure 26. Soil zinc (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

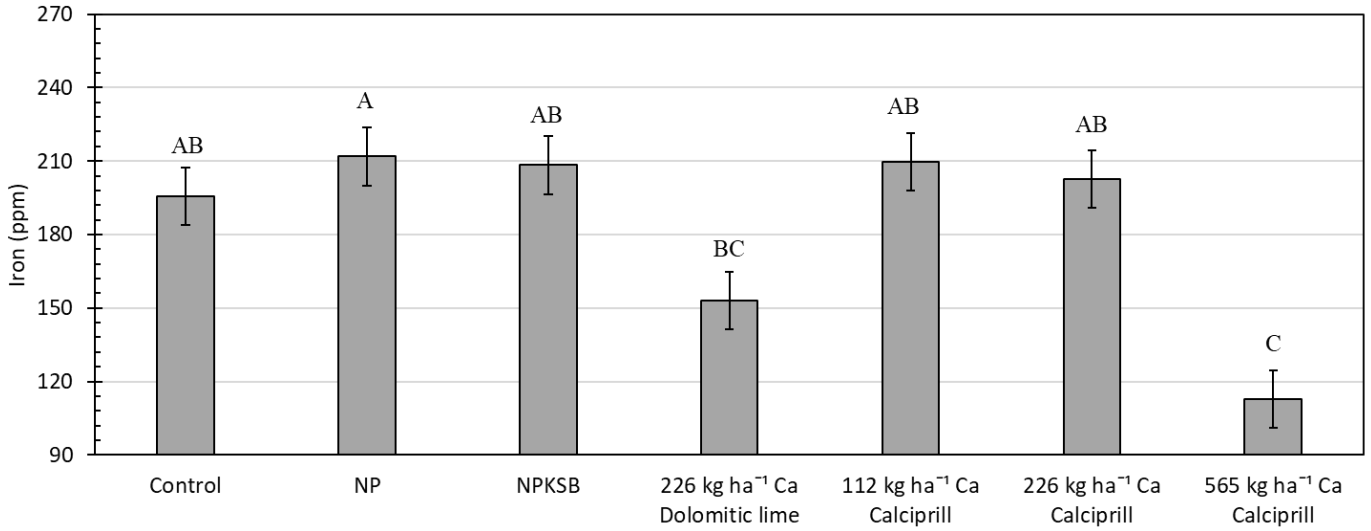

Figure 27. Soil iron (ppm) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

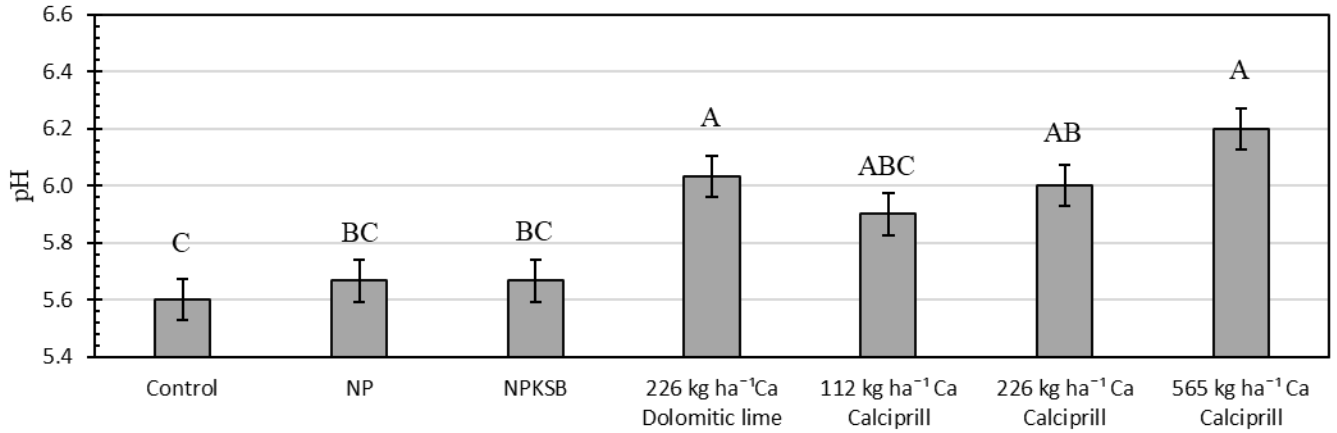

Figure 28. Soil pH treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

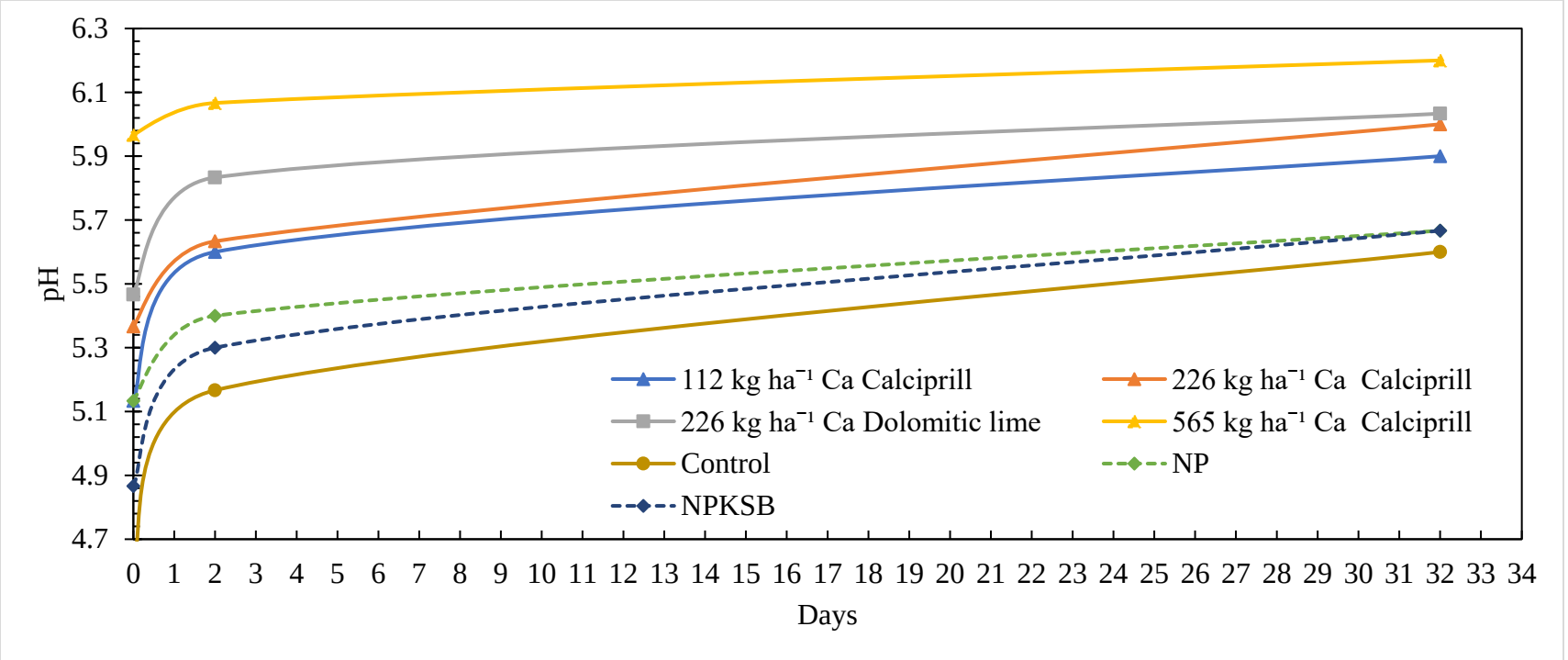

Figure 29. Soil pH, days since treatment using calcium carbonate sources and element fertilizers on soil incubation trial. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

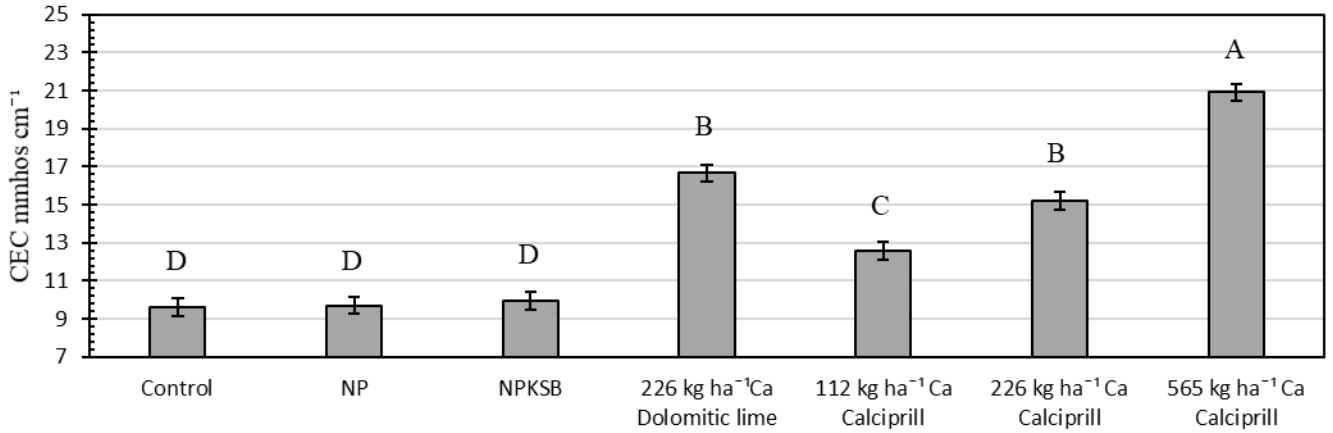

Figure 30. Cation exchange capacity (mmhos cm^{-1}) treatment means and standard error 32 days after treatment application on soil incubation trial. Letters show significant differences, $P < 0.05$. All Calciprill treatments received an equivalent amount of NPKSB, except the NP.

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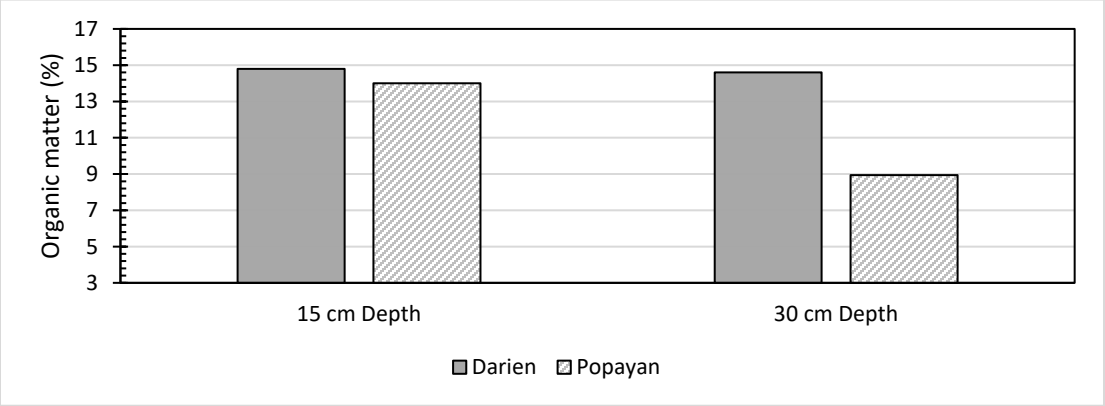
APPENDIX



Appendix A. Organic matter (%) six months after treatment application in Darien and Popayan trials. (15-30 cm depth).