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Potential of high- or low-solubility calcium to correct stem sinuosity in fast-growing *Pinus radiata* D. Don

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Abstract

Background: *Pinus radiata* D. Don is widely planted in Chile due to its fast growth and adaptability to various soil types and environmental conditions. However, the species is prone to stem sinuosity due to factors such as genetics, environmental stresses including nutrient availability, and management practices. This study assessed the efficacy of either low- or high-solubility calcium (Ca) additions in reducing stem sinuosity in young radiata pine plantations grown on Andisols.

Methods: We compared growth and stem sinuosity of a 3-year-old pine plantation subject to two types of Ca sources: agricultural low-solubility crushed lime (ag-lime), and finely ground pelletised high-solubility lime (pell-lime), applied at three concentrations (300 kg Ca ha^{-1}, 600 kg Ca ha^{-1}, 1,200 kg Ca ha^{-1}) alongside a control.

Results: Our findings revealed that both calcium sources increased the soil Ca content post-application but was only significant for the highest concentration in each case (1,200 Kg Ca ha^{-1}). The soil Ca availability rate was higher in pell-lime treatments. Agricultural lime had no effect on growth, whereas two of the pell-lime treatments increased the basal area, the lowest concentration increased the cumulative diameter at the root collar, and the highest concentration reduced tree height. Interestingly, while pell-lime did not mitigate stem sinuosity in 3-year-old pine trees, ag-lime reduced stem sinuosity severity although this result was not correlated with soil Ca content. Notably, the ag-lime treatment at 600 kg Ca ha^{-1} was most effective, decreasing the proportion of severely deformed trees from 32% to 14%.

Conclusions: The application of both low-solubility calcium (ag-lime) or high-solubility calcium (pell-lime) calcium increased the soil Ca content. Ag-lime treatments showed no adverse impact on stand growth and led to a reduction in stem sinuosity being the most effective treatment applying 600 kg Ca ha^{-1}. Pell-lime treatments had mixed effects on growth: diameter at root collar (DRC) and basal area increment (BAI) increased, and height decreased. Pell-lime treatments did not reduce stem sinuosity. Our results suggests that stem sinuosity might be more closely associated with deficiencies in trace metals like Cu and Mn rather than Ca content alone.

Keywords: stem sinuosity, liming, calcium, Andisols, Chile

Introduction

Pinus radiata D. Don (radiata pine) is the most common commercially grown species in Chile with an area of 1,886,664 ha (CONAF 2023). Radiata pine, known for its rapid growth and versatility in adapting to a range of soil types (Álvarez et al. 2013; Mead 2013), is nonetheless prone to stem sinuosity.

Stem sinuosity quantifies the stem displacement from its straight original direction over the total length of the stem. Sinuous growth causes tension/compression wood, which is detrimental for both pulp and solid wood due to higher specific gravity and an increased lignin content. These properties pose challenges in terms of milling and lumber processing potentially leading to large economic losses (Dwivedi et al. 2019).

The occurrence of stem sinuosity results from a complex interplay of factors including nutrient imbalances and deficiencies such as copper (Cu), zinc (Zn), manganese (Mn), and boron (B), genetic traits, environmental variables and silvicultural practices such as weed control, fertilization, pruning and thinning, phytohormone activity, and physiology (Birk 1991; Espinoza et al. 2012).

Intensively managed fast-growing radiata pine plantations often develop moderate to severe stem sinuosity (Espinoza et al. 2012) and are found on the most productive sites for radiata pine sawtimber production in Chile, particularly on soils derived from recent volcanic ash (Andisols). Andisols are characterised by clay mineralogy dominated by a non-crystalline mineral structure (mostly allophane) with a high anion exchange capacity and high amounts of active aluminum (Al) and iron (Fe) (Sadao Shoji & Takahashi 2002; Pizarro et al. 2017). As a result, volcanic ash derived soils have a strong capacity to retain phosphorus (P) and nitrogen (N) by anion exchange reactions (Escudey et al. 2001; Sadao Shoji & Takahashi 2002). Thus, these soils commonly exhibit low P content (which limits growth) and high organic carbon (C) (Álvarez et al. 2013). Soil organic matter (SOM), active Al and Fe and variable charge are the most prominent attributes regulating chemical reactions in volcanic ash soils. Particularly, SOM influences many soil chemical and physical properties (medium texture, low bulk density, friable consistency, well-developed soil structure, and large water holding capacity) enhancing soil biological activity and productivity in Andisols, which unsurprisingly are among the most productive soils in the world (S. Shoji et al. 1993).

The incidence of stem sinuosity increases with site fertility, and severity of sinuosity has been directly correlated with the concentration of mineral soil N, particularly tied to soil N mineralization and nitrification processes (Birk 1991; Hopmans et al. 1995). Accordingly, N addition has been found to significantly increase stem sinuosity, whereas calcium (Ca) additions mitigates the negative effects of N (Espinoza et al. 2012). Thus, stem sinuosity is linked to excess nitrate availability and calcium deficit combined with potential micronutrient deficiencies such as Cu, Mn and B (Espinoza et al. 2012).

Calcium is a critical macronutrient for plant growth and wood formation due to its involvement in secondary cell wall synthesis (supports the strength of cell walls), lignification (along with Cu, Mn, and B), and cell wall stabilization (Littke & Zabowski 2007; Caisley 2021; Grover et al. 2021). As a result, radiata pine plantations demand large quantities of Ca in short periods of time to reach high levels of productivity (Rocha et al. 2019).

The application of lime, often perceived as a pH-modifying practice, primarily enhances the availability of Ca and magnesium (Mg). Lime application may, subsequently, increase stand growth, not because of its effect on reducing soil acidity but as a source of Ca and Mg (Rocha et al. 2019). Furthermore, changes in pH are not desirable in established pine plantation triggering adverse effects on soil microbiology and the availability of N and B with a subsequent potential reduction in stand growth. Therefore, high rates of lime are not recommended (Rocha et al. 2019) and Ca and Mg requirements should be supplied in small amounts with low reactivity (low solubility) lime such as the agricultural lime (ag-lime) (Rocha et al. 2019) to prevent drastic changes in pH.

Also, recent studies have reported some success in controlling the stem sinuosity with highly soluble Ca sources such as finely-ground pelletised lime (pell-lime) at rates lower than 1,000 kg Ca ha^{-1} (Caisley 2021). Thus, given the contradictory results reported in the literature from lime applications, this study seeks to answer the following question: How does the solubility and concentration of Ca interact with growth patterns and stem sinuosity of young radiata pine intensively managed plantations? Therefore, understanding the efficiency of low and high soluble Ca on reducing stem sinuosity is vital for making informed decisions in the establishment and management of pine plantations on volcanic-derived soils.

The aim of this research was to evaluate the effectiveness of low-solubility ag-lime and high-solubility pell-lime at varying concentrations in reducing stem sinuosity in fast-growing radiata pine plantations established on Andisol soils.

Methods

Study site

The study was conducted west of Mulchén city, in the Biobio region of south-central Chile (37°52’6”S, 72° 0’39”W) where stem sinuosity in plantations is widespread (Figure 1). The soils are classified as Andisols in the Santa Bárbara soil series (CIREN 1999; Stolpe 2006), with recent volcanic ash in the top soil. These soils are deep to very deep, well drained along the profile, and well-structured with silty loam soil texture, and 6.2 % organic matter in the first 20 cm (CIREN, 1999). The soils are moderately acid ranging from a pH of 4.93 to 5.05 with low levels of P and B as the main growth limiting factors.

The mean annual temperature from 2019 to 2023 at the study site was 12.1 °C with a minimum temperature of 6.6 °C in July and a maximum of 18.5 °C in February, and the mean annual precipitation during this time

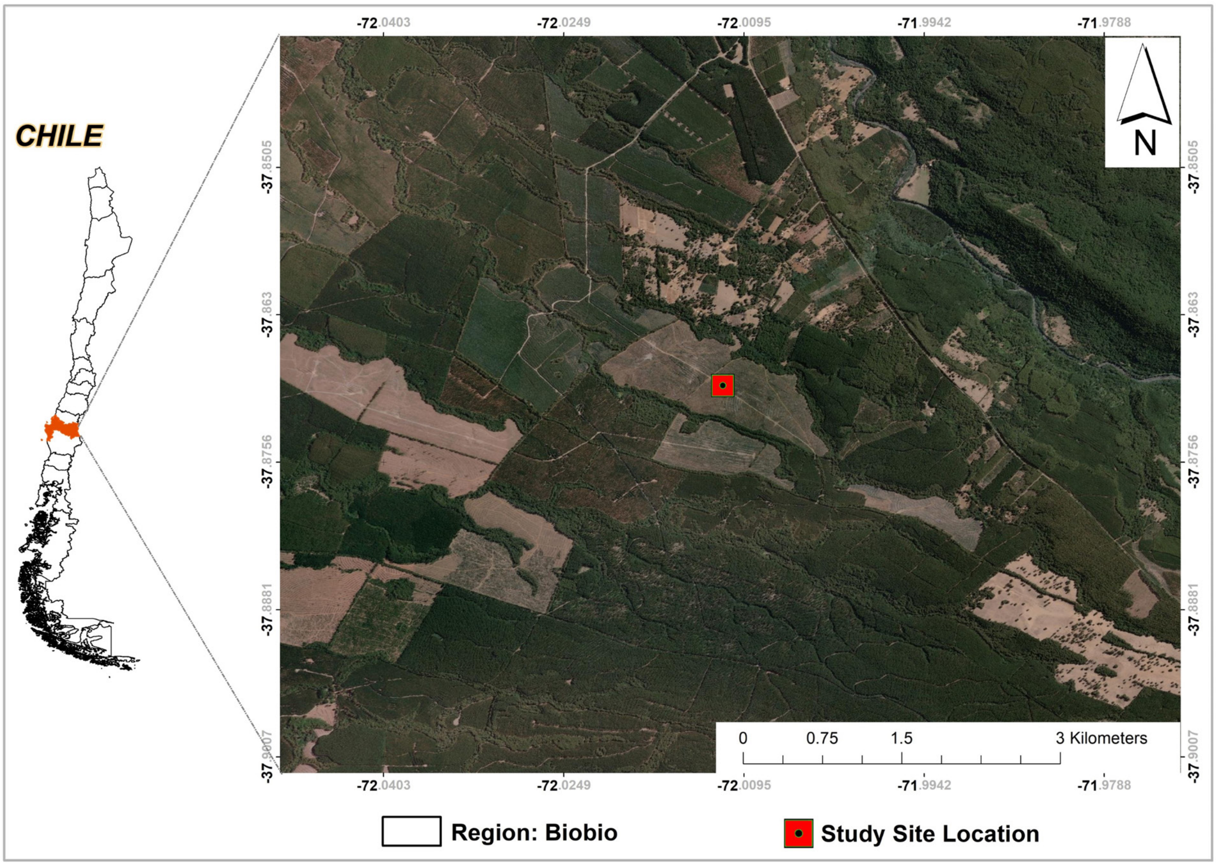

FIGURE 1: Study site.

period was1,283 mm. Radiata pine plantations in central Chile, require a minimum annual rainfall in the range 600-750 mm (Álvarez et al. 2013; Mead 2013). Given the high soil water holding capacity of Andisols and the site precipitation, water availability is likely not a limiting growth factor at the study site.

The previous rotation at the study site was an Eucalyptus plantation, harvested at 22 years of age with an average volume (over bark) production of 612 m^3 ha^{-1}. The study began in June 2021 in an already established 1-year old radiata pine plantation planted at 2.2 m along the planting row and 3.5 m between planting rows (1,250 trees ha^{-1}).

Pre-planting soil preparation consisted on subsoiling to 80 cm and disking using a D6 bulldozer in September 2019. Weed control focused on shrubs and pre-emergent grass treatment and was applied in November 2019 with 0.3 L ha^{-1} of Triclopyr + 0.04 kg ha^{-1} of Metsulfuronmethyl + 3 kg ha^{-1} of Glyphosate + 6 kg ha^{-1} of Simazine.

A post planting weed control was carried out in November 2020 with 2.3 kg ha^{-1} of Glyphosate + 0.4 L ha^{-1} of Triclopyr +20 gr ha^{-1} of Metsulfuron; 2.1 kg ha^{-1} of Glyphosate + 2 kg ha^{-1} of Hexaninone.

Boron fertilization was applied in August 2021 with 3.8 kg ha^{-1} of B (38 kg ha^{-1} of Boronatrocalcite ($NaCaB_5O_6(OH)_65H_2O$) broadcast over the planting band.

Experimental design

The experiment consisted of a complete randomised block design (3 blocks) that included a control and six Ca addition treatments comparing pell-lime ($CaCO_3$ 91%; $MgCO_3$ 2%; SiO_2 2.5%; Fe_2O_3 0.2%; Al_2O_3 0.3%) and ag-lime ($CaCO_3$ 91%; MgO 1.2%; S 1.2%) at increasing rates (Table 1).

TABLE 1: Treatments applied according to product, Ca solubility, and elemental calcium concentration (kg ha^{-1}).

Treatment	Product	Ca solubility	Ca (kg ha^{-1})
T1	Control		0
T2	Ag-lime	Low	300
T3	Ag-lime	Low	600
T4	Ag-lime	Low	1,200
T5	Pell-lime	High	300
T6	Pell-lime	High	600
T7	Pell-lime	High	1,200

For the six Ca additions treatments, a mechanised application was used to obtain a homogeneous distribution of the material applied.

The experimental units (blocks) consisted of 9 trees per row and 6 planting rows totalling 54 trees per treatment plot with an approximate area of 420 m^2. The measurements were carried out in the 2 central planting rows, resulting in 16 (for border plots) and 18 (for central plot) trees designated for measurement in each plot. The outer row of trees serves as buffers zones to minimise edge effects between treatments.

Measurements and sampling

Individual tree growth and stem sinuosity

At ages two and three (2022 and 2023 respectively) we measured diameter at root collar (DRC, ± 0.1 cm) at 10 cm above ground, diameter at breast height (DBH, ± 0.1 cm) at 1.3 m height (after trees reached heights ≥1.5 m) and total tree height (HT, ± 1 cm) using a height pole. We also estimated individual tree volume (iVol) with the following relationship:

$$iVol = 1/3\pi\ DRC^2\ HT$$

Finally, we estimated the basal area increment (BAI) for individual trees using the following relationship:

$$BAI = \pi\ (r^2_{t0} - r^2_{t1})$$

Where rt_0 and rt_1 are the tree radius at the root collar in 2023 (t_0) and the year 2022 (t_1), respectively.

Stem sinuosity was also evaluated 3 years after establishment. For each measurement plot tree stem sinuosity was evaluated in 1 m height sections up to a maximum height of 5 m. Using a marked pole every 1 meter and aligned vertically next to each tree, we recorded a stem sinuosity score as: no stem sinuosity (0, straight, without sinuosity along the stem section); slight stem sinuosity (1, slight angle of inclination or slight curvature along the stem section); moderate stem sinuosity (2, greater angle of inclination or a greater curve along the stem section); and severe stem sinuosity (3, stem section presents a curve and countercurve) (Figure 2). The score for each section was agreed by two people, with the process taking approximately one minute per section. The total stem sinuosity score (SS) of each tree was the sum of the stem sinuosity score of each stem section and ranged from 0 to 15. Because not all trees had the 5 sections to compare stem sinuosity between treatments, we also estimated the stem sinuosity proportion (SSP) and the maximum stem sinuosity score (SS_{max}). The SSP was determined as the sum of the ratios of each section's sinuosity score to the maximum possible score (3) (with ranges from 0 to 1) and SS_{max} was calculated as the highest score recorded among all the measured stem sections (with ranges from 0 to 3).

Soil analyses

Soil samples were collected 5 and 10 months after liming. The first soil samples were taken during the dry season (December) 5 months after liming, while the

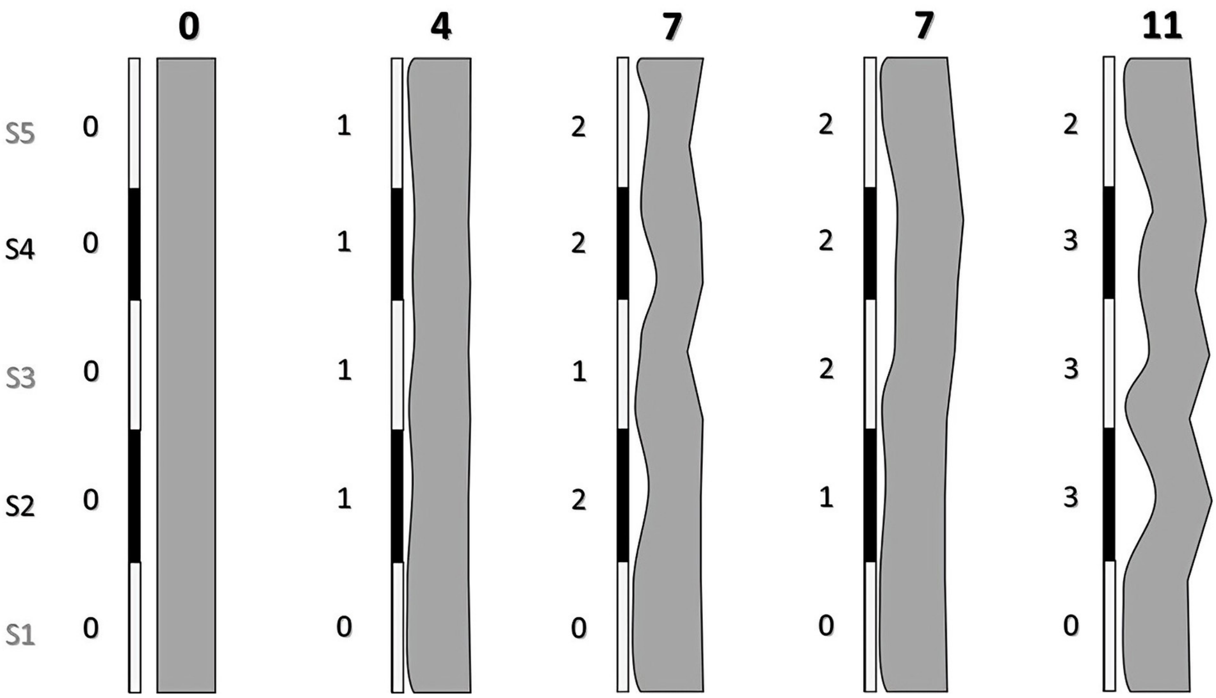

FIGURE 2: Representation of the evaluation of stem sinuosity using a marked pole in sections (S1 to S5) of 1 m in height, up to a maximum height of 5 m. The sections scores correspond to 0 (completely straight), 1 (slight stem sinuosity), 2 (moderate stem sinuosity) and 3 (severe stem sinuosity, with curve and counter-curve). The number above the stem corresponds to the sum of the scores for each section, with a minimum of 0 (completely straight stem) to 15 (stem with curves and counter-curves in all sections).

second samples were collected during the rainy season (May) 10 months after liming to evaluate soil nutrient contents within the first year after liming for low and high solubility lime.

In each plot, 15 soil samples were taken at a depth of 0 to 20 cm and mixed to obtain a 500 g composite soil sample. Soil samples from each plot were stored in plastic bags, labeled, transported to the laboratory, air-dried at 30 °C and sieved to pass < 2 mm.

A 10 g soil aliquot was extracted from each sample, which was dried at 70°C for 24 hours and subsequently ground. A 5 g subaliquot was used for carbon and nitrogen concentration determination using an IRMS analyzer (Infrared Mass Spectroradiometer, SERCON Scientific Inc.). Available phosphorus (P) and Boron (B) were analyzed using a Shimadzu UV-mini 1240 spectrophotometer, while available Mg, Ca, K, sodium (Na), Mn, Cu, Fe and Zn were analyzed on a PerkinElmer AAnalyst 400 Atomic Absorption Spectrometer (Sadzawka et al. 2006). All soil samples were analyzed at the Soil, Water, and Forest Research Laboratory (LISAB) of the University of Concepción (Concepción, Chile).

Statistical analysis

Analysis of Variance (ANOVA) along with Fisher's least significant difference (LSD) test ($p>0.05$) were carried out in 3 data sets: i) All treatments (n=7); ii) ag-lime (low solubility Ca) treatments + Control (n=4); and iii) pell-lime (fast solubility Ca) treatments + Control (n=4) to evaluate differences in soil Ca content, growth variables (height, DRC, DBH, volume, and BAI) and stem sinuosity (total, proportion, and maximum) among the treatments. Results are reported as means ± SD.

Correlation (Pearson correlation coefficient) and regression analyses were conducted to evaluate the relationship between nutrients, growth, and stem sinuosity. The effects of the Ca addition treatments (n=7) were analyzed at the site level because there was no block effect.

Results

Soil Ca contents

Overall, a positive correlation was observed between Ca additions (kg ha^{-1}) and the resulting increase in soil Ca concentration (mg kg^{-1}) both 5 and 10 months after liming treatments. The rate of Ca availability was higher for the pell-lime treatments 5 and 10 months after liming, with a notable increase in Ca availability rate observed for both pell-lime and ag-lime 10 months after application (Figure 3).

All ag-lime treatments exhibited an increased soil Ca concentration 5 months after the application. However, it was only in the highest concentration (1,200 kg Ca ha^{-1}) treatment where the increase was significantly greater than the observed in the control. There were no significant differences in soil Ca concentration for all ag-lime treatments 10 months after the application. Even though data for the highest concentration of pell-lime treatment was not available 5 months after liming, our results suggest that a significant increase in soil Ca content was primarily associated to the higher Ca addition treatments (600 kg Ca ha^{-1} and 1,200 kg Ca ha^{-1}) at this time, whereas 10 months after liming only at the highest pell-lime addition treatment exhibited a significant increase in soil Ca availability (Figure 3).

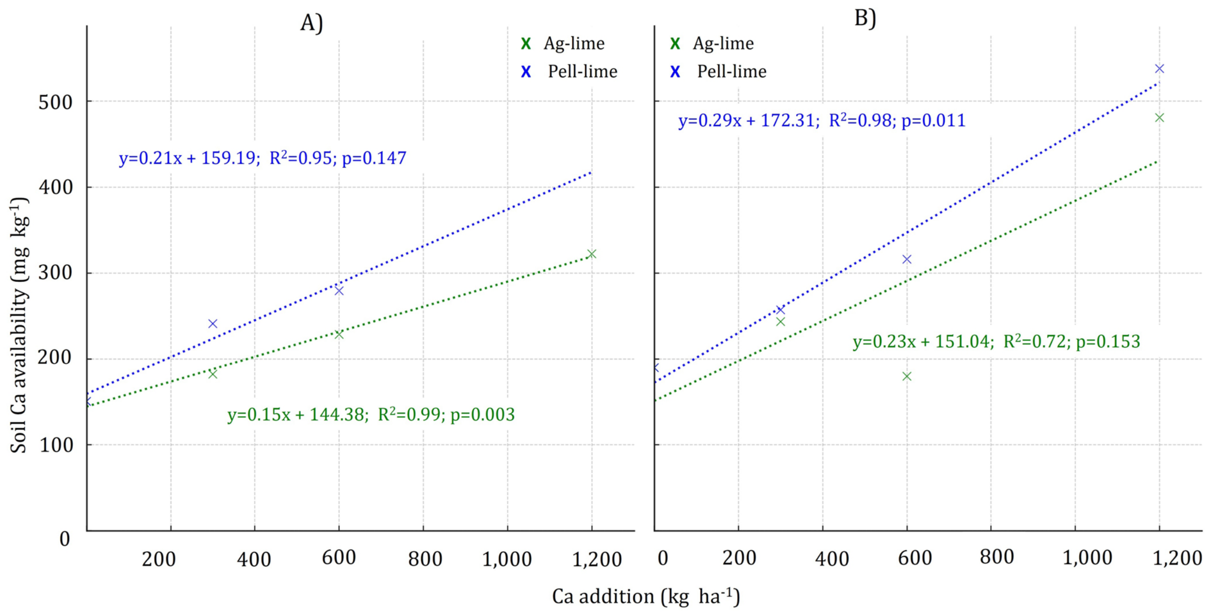

FIGURE 3: Relationship between soil Ca availability (mg kg^{-1}) and Ca addition treatments (kg ha^{-1}). A) 5 months after liming and B) 10 months after liming for pell-lime (finely ground pelletised lime) and ag-lime (agricultural lime) treatments.

Growth variables

There was no difference in cumulative DBH and volume between the Ca addition treatments and the control. Nevertheless, for DRC the pell-lime (300 Kg ha^{-1}) treatment showed greater cumulative gain compared to the control with no difference with the rest of the Ca treatments. For individual tree BAI, pell-lime treatments at the lowest and highest concentration (300 and 1,200 Kg ha^{-1} respectively) exhibited significantly greater BAI than the control while there was no difference between the control and the ag-lime treatments.

Although the pell-lime 1,200 kg treatment resulted in a greater BAI compared to the control, it also showed lower cumulative height growth than the control (Table 2).

Overall, our findings indicate no direct relationship between soil Ca content and growth variables. Nonetheless, tree height showed a negative correlation with K levels (r=-0.53; p=0.019), while DBH was positively correlated with P content (r=0.51; p=0.025).

Particularly, in the case of the pell-lime treatments, a negative correlation was observed between soil Ca content and both height (r=-0.64; p= 0.024) and DBH (r=-0.51; p=0.024). Also, within these treatments, the soil Ca/P ratio showed a strong negative association with both height (r= -0.84; p =0.0007) and DBH (r=-0.62; p=0.032). Furthermore, soil N levels were negatively correlated with height (r=-0.55; p=0.062), DBH (r=-0.56; p=0.060) and DRC (r=-0.63; p=0.027).

In contrast, for the ag-lime treatments, no significant relationship was found between soil Ca content and growth variables. However, height exhibited a negative correlation with K (-0.77; p=0.009), and DBH showed a positive correlation with P (r=0.64; p=0.044) (Appendix Table A1)

Soil N content showed no correlation to growth variables for ag-lime treatments whereas for the pell-lime treatments, N was negatively associated with height (r=-0.55; p=0.062), DBH (r=-0.56; p=0.060) and DRC (r=-0.63; p=0.027).

Conversely, the association between soil P content and growth was positive. The ag-lime treatments exhibited a more pronounced increase in soil P availability compared to the pell-lime treatments.

Five months after treatment application, soil levels of Ca (242 mg kg^{-1}), P (3.34 mg kg^{-1}) and K (37,90 mg kg^{-1}) were very low compared to values in the literature (Sandoval et al., 2020). The level of Ca and K remained very low (329 mg kg^{-1} and 31.34 mg kg^{-1} respectively) 10 months post-liming. P content 10 months after treatment application was low (5.60 mg kg^{-1}). Notably, the ag-lime (1,200 kg) treatment was the only one that effectively elevated P levels to a moderate range (Appendix Tables S2 and S3).

Stem sinuosity

Overall, in terms of the SS_{max}, the analysis revealed that only 2% of the trees were completely straight (score 0), whereas 33% exhibited severe sinuosity (score 3) somewhere along the stem. Notably, all ag-lime treatments resulted in the lowest number of trees with severe sinuosity and the highest number of trees with light stem sinuosity. In contrast, all pell-lime treatments showed a higher proportion of severe stem sinuosity than the control treatment (Figure 4).

The greatest SSP was observed in the control, and the pell-lime treatments at 300 and 600 kg ha^{-1}, which also exhibited the highest proportion of severe and moderate stem sinuosity. Contrastingly, the 3 ag-lime additions displayed lower SSP values compared to the control, aligning with the SS_{max} findings. Furthermore, the pell-lime (1,200 kg ha^{-1}) showed lower SSP than the control, attributed to a higher number of completely straight trees and a much lower proportion of moderate sinuosity trees (Figure 5).

In the overall analysis of growth variables, DRC showed a positive correlation with both SS (r=0.49; p=0.023) and SS_{max} (r=0.46; p=0.034). Across all Ca treatment, the soil Ca/Mg ratio was negatively correlated

TABLE 2: Individual tree cumulative root collar diameter (DRC), diameter at breast height at 1.3 m (DBH), total height (Height), volume, and basal area increment (BAI) growth for 2023. Distinct letters indicate significant differences among the treatments according to LSD test (P ≤ 0.05). T1: Control – 0 kg Ca ha^{-1}. T2 Ag-lime – 300 kg Ca ha^{-1}. T3: ag-lime – 600 kg Ca ha^{-1}. T4: ag-lime – 1,200 kg Ca ha^{-1}. T5: pell-lime – 300 kg Ca ha^{-1}. T6: pell-lime – 600 kg ha^{-1}. T7: pell-lime – 1,200 kg ha^{-1}.

Treatment	DRC (cm)		DBH (cm)		Height (m)		Volume (cm^3)		BAI (cm^2 year^{-1})	
T1	8.1±1.0	bc	4.9±1.2	ab	3.6±0.6	ab	25,469±9,415	ab	1.79	bc
T2	7.9±0.8	c	4.5±1.0	b	3.4±0.4	bc	22,413±6,176	b	1.75	c
T3	7.9±1.1	c	4.8±0.9	ab	3.5±0.5	abc	23,649±8,322	b	1.85	ab
T4	8.4±1.2	ab	5.0±1.1	a	3.7±0.5	a	27,584±10,110	a	1.83	abc
T5	8.5±1.3	a	5.0±1.2	a	3.6±0.6	abc	27,667±11,157	a	1.91	a
T6	8.2±1.2	abc	4.8±1.2	ab	3.4±0.5	abc	25,245±9,801	ab	1.86	ab
T7	8.1±1.1	bc	4.6±1.0	ab	3.4±0.4	c	24,374±8,633	b	1.92	a

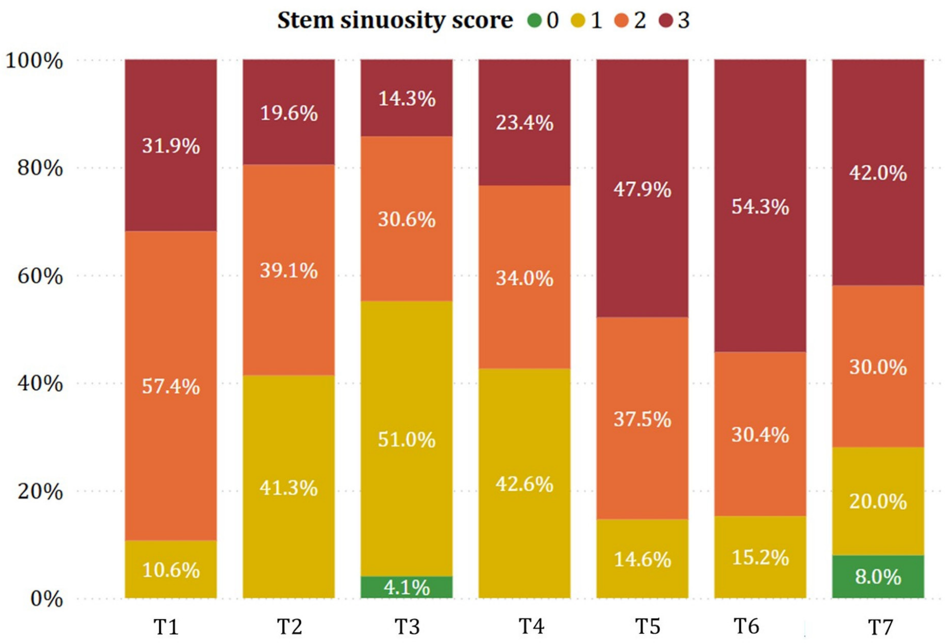

FIGURE 4: Maximum stem sinuosity score (SS_{max}): i) 0-scored (completely straight), ii) 1-scored (light stem sinuosity), iii) 2-scored (moderate stem sinuosity), and iv) 3-scored (severe stem sinuosity). T1: Control – 0 Kg Ca ha^{-1}. T2: ag-lime – 300 Kg Ca ha^{-1}. T3: ag-lime – 600 Kg Ca ha^{-1}. T4: ag-lime – 1,200 Kg Ca ha^{-1}. T5: pell-lime – 300 Kg Ca ha^{-1}. T6: pell-lime – 600 Kg ha^{-1}. T7: pell-lime – 1,200 Kg ha^{-1}. ag-lime (agricultural lime) and pell-lime (finely ground pelletised lime).

with SS (r=-0.41; p=0.081), SSP (r=-0.41; p=0.078), and SSmax (r=-0.42; p=0.078) and the soil C concentration was also negatively correlated with SSP (r=-0.46; p=0.048). Although Cu was deficient in the site study (>1 mg L^{-1}), it showed a negative association with SSP (r= -0.41; p=0.080) and SS_{max} (r=-0.42; p=0.073) (Figure 6).

For pell-lime treatments, SS showed a significant negative correlation to Ca additions, soil C concentration and soil C/Mg ratio. For the ag-lime treatments there were no significant correlations between Ca addition and SS (r=-0.44; p=0.206), SSP (r=-0.51; p=0.132), and SS_{max} (r=-0.49; p=0.154) (Figure 6).

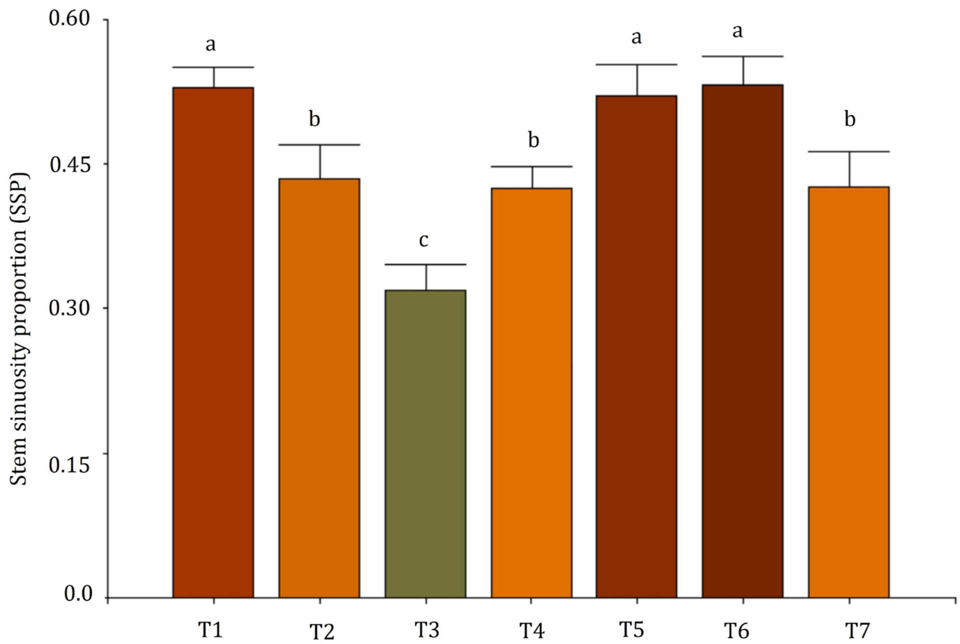

FIGURE 5: Mean stem sinuosity proportion (SSP). Distinct letters indicate significant differences between SSP among the treatments according to LSD test ($P \leq 0.05$). T1: Control – 0 kg Ca ha^{-1}. T2: ag-lime – 300 kg Ca ha^{-1}. T3: ag-lime – 600 kg Ca ha^{-1}. T4: ag-lime – 1,200 kg Ca ha^{-1}. T5: pell-lime – 300 kg Ca ha^{-1}. T6: pell-lime – 600 kg ha^{-1}. T7: pell-lime – 1,200 kg ha^{-1}. ag-lime (agricultural lime) and pell-lime (finely ground pelletised lime).

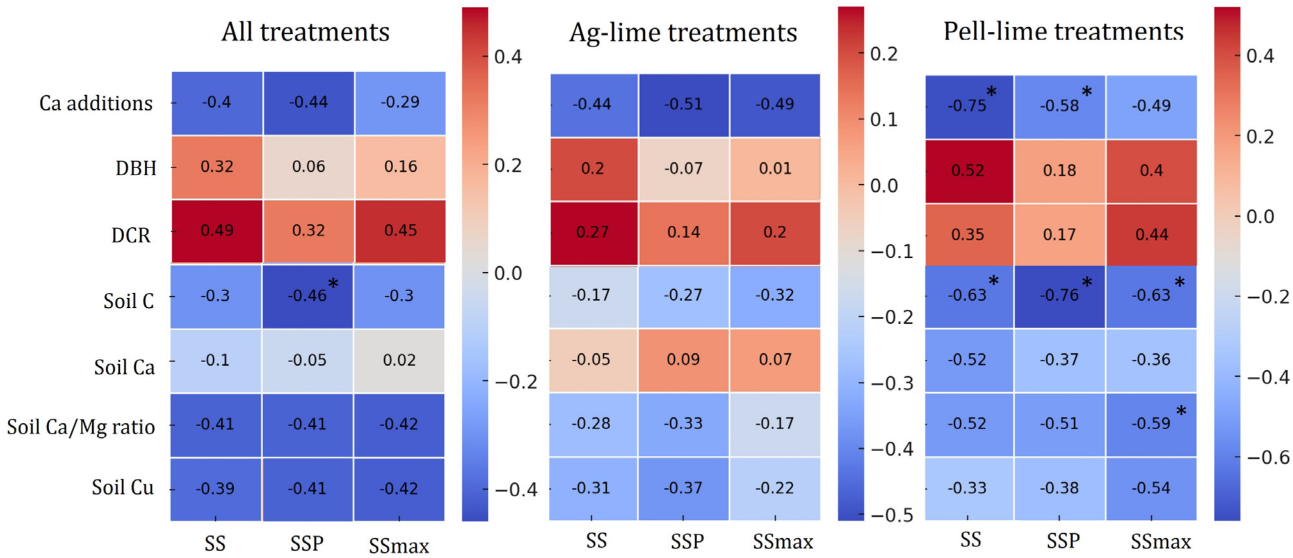

FIGURE 6: Pearson correlation among growth variables, stem sinuosity and soil nutrients for all treatments (n=7), the ag-lime treatments + control (n=4), and the pell-lime treatments + control (n=4). SS: stem sinuosity score; SSP: stem sinuosity proportion; SS_{max}: maximum stem sinuosity score; DBH: diameter at breast height; DCR: diameter at root collar. The symbol * indicates significant correlation (p<0.05).

Discussion

Individual tree cumulative growth variables were not influenced by ag-lime treatments. This aligns with other studies (Prietzel et al. 2008; Rocha et al. 2019; Caisley 2021) which have reported varied responses to lime application, ranging from decreased stand growth, negligible growth differences to modest increases.

Although, increases in tree growth following lime application are not typically expected in younger soils, such as these recent volcanic soils (Rocha et al. 2019), changes in growth are often linked to sudden changes in soil pH caused by high rates of lime applications in line with height growth reduction and greater BAI observed for the pell-lime 1,200 kg ha^{-1} treatment, and the increased DRC and BAI found for the pell-lime 600 kg ha^{-1}. Pell-lime treatments pH was 0.12 higher than ag-lime treatments, explaining a potential alteration in nitrogen dynamics that likely influenced tree growth (Prietzel et al. 2008; Rocha et al. 2019).

Soil P availability (a known growth-limiting factor in these soils) exhibited a more pronounced increase in ag-lime treatments compared to the pell-lime treatments. Thus, using slow-release Ca lime can improve the availability of these essential nutrients in volcanic soils.

The deficiency of Cu and its negative correlation with SS and SS_{max} supports previous reports where Cu has been associated to stem sinuosity as it could cause poor lignification of woody tissue (Gartner & Johnson 2006; Espinoza et al. 2012).

Soil C content was negatively related to stem sinuosity. Given the role of high SOM in the chemical and physical soil properties of Andisols, we may infer that soil C content alleviated unbalanced nutrients and thus reduced stem sinuosity.

Highly soluble Ca additions (pell-lime) and growth were negatively associated with stem sinuosity. These relationships between Ca, growth and stem sinuosity are similar to what was reported for a Douglas-fir plantation (Espinoza et al. 2012). Nonetheless, Ca addition through pell-lime treatments did not reduce SS_{max} or SSP as reported in other studies where seedlings were fertilised with Ca (Littke & Zabowski 2007). These results reinforce the recommendation of not using highly reactive lime in established pine plantations because the applications might alter pH and worsen nutrient imbalances (Rocha et al. 2019).

Although ag-lime treatments exhibited better performance in reducing stem sinuosity, this could not be associated to soil Ca or other nutrients. This suggests that ag-lime treatments may increase soil Ca content, and at the same time influence nutrient dynamics, to reduce the nutrient imbalances and deficiencies (Dwivedi et al. 2019) responsible for stem sinuosity.

Conclusions

The application of lime, whether the lime was low or high solubility calcium (Ca), effectively increased the soil Ca content. However, the high solubility Ca treatments (pell-lime) had mixed effects on growth: DRC and BAI increased, and height decreased. Also, pell-lime treatments did not effectively reduce stem sinuosity. Therefore, the use of high solubility Ca is not recommended for mitigating stem sinuosity in radiata pine plantations established on Andisols.

In contrast, the application of low-solubility Ca (ag-lime) showed no adverse impact on stand growth and led to a reduction in stem sinuosity. The most effective treatment in minimizing stem sinuosity was ag-lime applied at 600 kg Ca ha^{-1}. Furthermore, this treatment also recorded the lowest pH, Ca, and Mg levels, and the highest Cu and Mn contents among all treatments. This suggests that stem sinuosity might be more closely associated with deficiencies in trace metals like Cu and Mn rather than Ca content alone. Thus, a clear link between stem sinuosity and soil Ca or another specific nutrient could not be definitively established.

List of abbreviations

ag-lime	agricultural low-solubility crushed lime
Al	aluminum
ANOVA	Analysis of variance
B	boron
BAI	Basal area increment (based on DRC)
C	carbon
Ca	calcium
Cu	copper
DBH	diameter at breast height
DRC	diameter at root collar
Fe	iron
IRMS	Infrared mass spectroradiometer
K	potassium
LISAB	Forest research laboratory
LSD	Least significant difference
Mg	magnesium
Mn	manganese
SS_{max}	maximum stem sinuosity score
N	nitrogen
Na	sodium
P	phosphorus
pell-lime	finely ground pelletised high-solubility lime
SSP	stem sinuosity proportion
SS	stem sinuosity score
SOM	soil organic matter
Zn	zinc

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

CGR perform the statistical analysis and wrote de manuscript. RR contributed to the conception and design of the experiment and data analysis. DB contributed to data acquisition and writing the manuscript. DRC and TA contributed to the conception and design of the experiment and revising the manuscript. RR, MP, AZ, JO, RC, DRC and OC contributed to the conception and design of the experiment.

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Appendix

TABLE A1: Correlation between growth variables and soil nutrients. DBH: Diameter at breast height. DRC: Diameter at Root Collar. ag-lime treatments (agricultural lime -low solubility). Pell-lime treatments (finely ground pelletised lime – high solubility)

Variables		All treatments		Ag-lime treatments		Pell-lime treatments	
1	2	r	p	r	p	r	p
Height	Ca	-0.19	0.428	0.13	0.722	**-0.64**	**0.024**
Height	P	0.40	0.091	0.35	0.324	0.41	0.190
Height	Ca/P ratio	-0.29	0.230	0.03	0.928	**-0.84**	**0.0007**
Height	N	-0.10	0.671	0.52	0.127	-0.55	0.062
Height	K	**-0.53**	**0.019**	**-0.77**	**0.0093**	-0.20	0.531
Height	Cu	-0.41	0.078	**-0.64**	**0.044**	-0.29	0.355
DBH	Ca	-0.24	0.0325	-0.04	0.910	**-0.51**	**0.024**
DBH	P	**0.51**	**0.025**	**0.64**	**0.045**	0.29	0.360
DBH	Ca/P ratio	-0.34	0.149	-0.15	0.672	**-0.62**	**0.032**
DBH	K	**-0.43**	**0.065**	-0.52	0.120	-0.19	0.559
DBH	N	-0.07	0.762	0.55	0.098	-0.56	0.060
DBH	C/N ratio	0.21	0.388	-0.14	0.693	**0.60**	**0.039**
DRC	B	**0.47**	**0.040**	0.51	0.135	**0.64**	**0.024**
DRC	K	-0.42	0.073	-0.42	0.225	-0.17	0.605
DRC	N	0.018	0.99	0.63	0.053	**-0.63**	**0.027**
DRC	C/N ratio	0.06	0.794	-0.32	0.369	0.65	0.023

TABLE A2: Key soil nutrients evaluated 5 months after liming. Results are presented as mean ± SD. Low-solubility agricultural lime = ag-lime. Pell-lime treatments Finely ground, high-solubility pelletised lime = pell–lime. T1: Control – 0 kg Ca ha^{-1}; T2: ag-lime – 300 kg Ca ha^{-1}; T3: ag-lime – 600 kg Ca ha^{-1}; T4: ag-lime – 1,200 kg Ca ha^{-1}; T5: pell-lime – 300 kg Ca ha^{-1}; T6: pell-lime – 600 kg ha^{-1}; T7: pell-lime – 1,200 kg ha^{-1}. NA: data not available (missing).

Soil nutrients (5 months after liming)	Control	Ag-lime			Pell-lime		
	0 Ca kg ha^{-1}	300 Ca kg ha^{-1}	600 Ca kg ha^{-1}	1,200 Ca kg ha^{-1}	300 Ca kg ha^{-1}	600 Ca kg ha^{-1}	1,200 Ca kg ha^{-1}
	T1	T2	T3	T4	T5	T6	T7
pH (KCl)	4.8±0.0	4.7±0.0	4.9±0.0	4.8±0.0	4.8±0.1	4.8±0.0	NA
Ca (mg kg^{-1})	241.2±10.8	322.3±45.9	150.5±68.2	228.6±24.4	279.4±62.2	279.4±30.8	NA
Mg (mg kg^{-1})	59.8±23.6	40.4±13.1	62.1±15.4	63.2±22.3	47.5±47.8	36.6±12.8	NA
P (mg kg^{-1})	3.5±0.4	4.1±0.2	3.5±0.5	3.3±0.3	3.1±0.3	2.9±0.3	NA
B (mg kg^{-1})	0.3±0.0	0.4±0.1	0.4±0.2	0.5±0.2	0.3±0.2	0.8±0.4	NA
K (mg kg^{-1})	30.8±0.4	55.4±10.5	26.8±7.3	28.6±3.8	41.6±21.1	47.7±13.6	NA
Na (mg kg^{-1})	18.0±0.6	21.4±6.7	23.0±15.6	17.6±3.1	21.7±6.6	41.5±17.7	NA
N (%)	0.7±0.0	0.5±0.2	0.7±0.1	0.6±0.2	0.4±0.1	0.6±0.1	NA
C (%)	9.9±0.3	7.1±1.4	9.7±2.3	8.4±1.6	7.1±1.2	10.2±0.8	NA
Mn (mg L^{-1})	5.4±0.7	3.6±0.1	4.7±0.2	4.3±0.0	2.2±1.7	2.0±1.5	NA
Cu (mg L^{-1})	0.2±0.5	1.0±0.1	0.0±0.6	0.8±0.0	0.6±0.7	1.1±0.3	NA
Fe (mg L^{-1})	0.5±0.1	4.6±0.0	1.9±2.3	1.8±1.9	1.2±1.0	3.1±2.2	NA
Zn (mg L^{-1})	2.9±0.9	1.6±0.3	3.6±1.6	2.4±0.8	2.3±0.5	2.1±1.1	NA

TABLE A3: Key soil nutrients evaluated 10 months after liming. Results are presented as mean ± SD. Low-solubility agricultural lime = ag-lime. Pell-lime treatments Finely ground, high-solubility pelletised lime = pell–lime. T1: Control – 0 kg Ca ha^{-1}; T2: ag-lime – 300 kg Ca ha^{-1}; T3: ag-lime – 600 kg Ca ha^{-1}; T4: ag-lime – 1,200 kg Ca ha^{-1}; T5: pell-lime – 300 kg Ca ha^{-1}; T6: pell-lime – 600 kg ha^{-1}; T7: pell-lime – 1,200 kg ha^{-1}.

Soil nutrients (10 months after liming)	**Control**	**Ag-lime**			**Pell-lime**		
	0 Ca kg ha^{-1}	**300 Ca kg ha^{-1}**	**600 Ca kg ha^{-1}**	**1,200 Ca kg ha^{-1}**	**300 Ca kg ha^{-1}**	**600 Ca kg ha^{-1}**	**1,200 Ca kg ha^{-1}**
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**
pH (KCl)	4.8±0.0	4.8±0.0	4.8±0.0	4.9±0.1	4.8±0.1	4.9±0.0	4.9±0.1
Ca (mg Kg^{-1})	189.7±92.8	243.6±15.4	179.7±0.0	480.8±225.8	257.2±116.3	316.0±183.3	538.1±77.7
Mg (mg Kg^{-1})	49.1±26.1	24.6±6.1	17.9±0.0	66.4±49.0	78.2±41.9	57.0±34.5	100.7±32.1
P (mg Kg^{-1})	4.3±2.3	4.1±0.3	5.2±0.0	9.0±7.7	3.2±0.2	8.0±6.7	5.2±1.7
B (mg Kg^{-1})	0.2±0.1	0.3±0.1	0.3±0.0	0.6±0.3	0.6±0.1	0.2±0.0	0.3±0.1
K (mg Kg^{-1})	29.6±11.7	44.8±15.5	40.0±0.0	26.5±9.1	26.6±11.4	30.6±2.0	27.2±15.2
Na (mg Kg^{-1})	25.3±14.7	12.4±7.1	5.3±0.0	62.2±69.5	12.1±9.5	11.0±1.1	12.5±4.5
N (%)	0.7±0.1	0.4±0.1	0.5±0.0	0.7±0.1	0.4±0.1	0.8±0.1	0.8±0.1
C (%)	8.2±1.4	7.6±2.0	8.1±0.0	8.4±2.1	7.5±0.8	8.4±2.4	9.4±0.9
Mn (mg L^{-1})	3.0±1.7	3.1±1.8	4.4±0.0	2.2±1.8	4.0±1.3	3.4±2.3	2.2±1.9
Cu (mg L^{-1})	-0.4±1.0	0.5±1.1	1.6±0.0	-0.3±1.3	-0.2±0.9	-0.9±0.3	-0.2±1.2