

Research Article

Liming and Fertilization on the Growth of *Eucalyptus benthamii* and *Eucalyptus dunnii* in Brazil

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Received 25 August 2020; Revised 9 October 2020; Accepted 20 October 2020; Published 30 October 2020

Academic Editor: Qing Lai Dang

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The use of mineral fertilizers has shown substantial productivity gains for the vast majority of *Eucalyptus* forests. The objective of the present work is to evaluate the response of *Eucalyptus benthamii* and *Eucalyptus dunnii* at 48 months of age, to different doses of limestone, soluble NPK, and natural phosphates. The experiment was conducted in a plantation located in South Brazil. The experimental design was a randomized block with three replications, and the treatments consisted of combinations of doses of natural phosphate (NP) (0, 400, 600, and 800 kg ha⁻¹ of Gafsa reactive NP P₂O₅), limestone (0, 3, 5, 6, and 10 Mg ha⁻¹ of dolomitic limestone), and mineral fertilizer–NPK (0, 100, 133, and 167 kg ha⁻¹ of mixed mineral fertilizer 6-30-6). Height and diameter measurements were taken after 48 months. There was a positive response with the increase of NPK fertilizer dose, and the dose where the highest averages were obtained was 167 kg ha⁻¹. The doses of NP had significant effects on the increase of the variables up to 600 kg ha⁻¹, also the averages decreased with the increase of the dosage. For liming, positive results were observed from its absence to the maximum dose, justifying its use in minimum dose in order to supply the necessary amounts of Ca and Mg in the soil. The use of NPK, natural phosphate, and limestone is recommended, causing an increase in the growth of both species of *Eucalyptus* studied.

1. Introduction

The introduction of species from other regions is a process that needs studies aimed at assessing their adaptability and survival, as well as their reflexes on economic productivity. A combination of several factors is required for the establishment of productive forests, such as site-adapted genetic materials, favorable soil and climate conditions, proper management, and high-quality seedlings [1].

The need for fertilization in forest species comes from the fact that the soil is not always able to provide all the nutrients in quantity that the plants need for proper growth, and the amount depends on the nutritional needs, soil fertility, reaction of fertilizers with soil, and fertilizer efficiency. Proper nutrition in *Eucalyptus* plantations is essential for the establishment of high-yielding forests [2].

Eucalyptus species are considered nutrient-demanding, mainly phosphorus in the early phase and potassium in the juvenile and adult phase [3]. Given this feature, along with the fact that they are under subtropical conditions, it is relevant to promote rapid early development with gains in height and diameter, so that plants reach a size where frost damage is minimized. However, regarding nitrogen fertilization, Sette et al. [4] did not obtain increment for *E. grandis*, as well as no changes in wood structure.

Most Brazilian soils have inadequate chemical characteristics for intensive production, among them a high natural acidity, making it necessary to use limestone for its suitability, increasing the pH and calcium and magnesium levels in the soil, and allowing the full development of the culture [5]. According to Barros et al. [6], liming calcium is the second nutrient most absorbed by most forest species. The

most accumulated nutrients in components exported from the *Eucalyptus* production area are Ca and Mg, placed in order, with Ca occupying the first place, with approximately 75% of this element exported from the site with the harvest. Over several years of cultivation, nutritional deficiency can be promoted for plants and limits the productivity of future cycles due to Ca depletion [7]. In addition, nutritional imbalances may be produced by providing inadequate Ca²⁺ and Mg²⁺ ratios, which may induce plant deficiency and compromise growth.

Fertilization can increase the growth of *E. benthamii* and *E. dunnii* forests, resulting in an increased final yield and may even reduce the rotational cycle. There is a direct relationship between the different doses of liming, phosphating, and NPK with the growth of *Eucalyptus* species. In view of this, it is expected that different growth behaviors will be expressed as a function of fertilizer doses, and the higher the dose, the higher the growth of dendrometric variables.

Thus, the objective of the study was to quantify the growth of *E. benthamii* and *E. dunnii*, in response to fertilization, for the different doses of dolomitic limestone, reactive natural phosphate, and NPK, aiming to define the specific fertilization management for each studied species.

2. Materials and Methods

2.1. Study Area. The study was carried out in Rio Negrinho (latitude 26°06'41" south and longitude 49°48'19" west), located in the microregion of the northern plateau of Santa Catarina State (Brazil). With an average altitude of 800 m above the sea level, the municipality presents regular surface and plateau relief, with hills of small altimetric amplitude.

Regarding the climate, in the Köppen classification, the northern Santa Catarina plateau is Cfb (constantly humid temperate climate, no dry season, with cool summer). The average annual temperature ranges from 15.0°C to 17.0°C, with average maximum temperatures ranging from 24.0°C to 26.6°C and minimum from 10.8°C to 11.8°C. The average annual precipitation is 1720 mm, with maximum and minimum of 2500 mm and 1082 mm, respectively. The relative humidity can vary from 80.0% to 86.2% [8]. Considering the hydraulic demand of *Eucalyptus*, which is 800–1,200 mm [9], the study area has the amount of rain necessary to meet the average requirements of the genus.

Prior to the implementation of the experiment, no natural corrective or phosphates had been used in the field, only base fertilization in this area, which was cultivated with *E. viminalis* in the first planting cycle, planting in 1983 and clear-cutting in 2011.

Soil composite samples were collected in the 0–20 cm layer to characterize it in the experimental area (Table 1). Chemical analyses were performed according to the methodology described by Tedesco et al. [10] by the Soil Routine Analysis Laboratory of the Department of Soils and Natural Resources of Santa Catarina State University, Lages, SC (Brazil). The soil of the experiment site was classified as Humic Cambisol (Cambisols).

TABLE 1: Chemical and physical characteristics of the soil in the 0–20 cm depth layer of the study area.

Attributes	Values	Interpretation*
pH H ₂ O ⁽¹⁾ (1:1)	4.28	No pH for reference**
SMP buffer	4.20	—
Ca ⁽²⁾ (cmol _c dm ⁻³)	0.88	≥4.0 cmol _c dm ⁻³
Mg ⁽²⁾ (cmol _c dm ⁻³)	0.76	≥1.0 cmol _c dm ⁻³
Al ⁽²⁾ (cmol _c dm ⁻³)	4.64	—
P Mehlich ⁽²⁾ (mg dm ⁻³)	0.72	≥15.1 mg dm ⁻³
K ⁽²⁾ (mg dm ⁻³)	73.80	≥106 mg dm ⁻³
OM (%)	3.45	≥5.00%
Effective CEC (cmol _c dm ⁻³)	6.46	—
CEC pH 7.0 (cmol _c dm ⁻³)	36.32	15.1 a 30.0
Basis saturation (%)	5.00	—
Al saturation (%)	71.84	—
Clay (%)	18.50	Class 4

¹Methodology used by Tedesco et al. [10]; OM, organic matter. *Values are subjected to interpretation. **Culture tolerant to soil acidity and has no pH for reference.

2.2. Experimental Design and Treatments. The experiment was set up in a randomized block design with three replications of 15 trees each. The treatments consisted of combinations of doses of natural phosphate (0, 400, 600, and 800 kg ha⁻¹), limestone (0, 3, 5, 6, and 10 Mg ha⁻¹), and NPK mineral fertilizer (0, 100, 133, and 167 kg ha⁻¹), at planting fertilization, for *E. benthamii* and *E. dunnii*. *E. benthamii* seedlings of seminal origin produced in the region of São Bento do Sul, SC (Brazil), and clonal plants of *E. dunnii* produced in the region of Canoinhas, SC (Brazil), were used. For both species, the seedlings planted were approximately 30 cm height and had shoot diameter greater than 2 mm.

The amounts of nutrients used in the experiment were determined from soil analysis performed before planting. The 400 kg dosage of natural phosphate is the standard dosage of the company where the study was conducted, with 800 kg being double the dosage and 600 the average of the two doses. The NP used was the Tunisia-branched Gafsa reactive (NPGR) (28% total P₂O₅).

For the limestone factor, the company uses 3.5 Mg ha⁻¹ as the standard farm dosage. The dosage of 10 Mg ha⁻¹ is almost half the dosage of 19 Mg ha⁻¹, recommended by the Rede Oficial de Laboratórios de Análise de Solos (ROLAS) (Official Network of Soil Analysis Laboratories) [11], and as intermediate dose was used, 6 Mg ha⁻¹. For NPK, the dose of 133 kg ha⁻¹ is recommended by the interpretation of soil analysis, with 167 kg ha⁻¹, the maximum dose, and 100 kg ha⁻¹, the minimum dose. The source of NPK was mixed mineral fertilizer with formulation 6-30-6 (NPK), providing the amount of 6 kg ha⁻¹ of N and K₂O and 30 kg ha⁻¹ of P₂O₅ for 100 kg ha⁻¹ fertilizer dose, 8 kg ha⁻¹ of N and K₂O and 40 kg ha⁻¹ of P₂O₅ for 133 kg ha⁻¹ of fertilizer, and 10 kg ha⁻¹ of N and K₂O and 50 kg ha⁻¹ of P₂O₅ for 167 kg ha⁻¹ of fertilizer.

First, cultural treatments were made in the area in accordance with the company's operational plan. Operations began in November 2012 with the cleaning of the area by mechanized mowing and chemical weeding in the total area. The tillage was mechanized, performed in minimum

cultivation with subsoiling at 45–50 cm deep in the planting line, with spacing of 3.0 m between the rows. After subsoiling, dolomitic limestone (80% PRNT) was applied according to the treatments.

The planting, the application of NP, and the fertilization of planting were carried out in January 2013. The planting was performed manually in spacing of 3 × 3 m, and the NP was filleted over the subsoiling line. There was an application of 500 mL of hydrogel per planting pit. Planting fertilization was carried out in two lateral “pits” per plant, at a distance of 10–15 cm from them, using manual fertilizers adjusted at the dosages fixed in the treatments.

Coverage fertilization was carried out two months after planting, along with the surface replanting, in the crown projection, at a dose of 133 kg ha⁻¹ of mineral fertilizer with formulation 20-00-20 (N-P-K), providing the amount of 27 kg ha⁻¹ of N and K₂O. Coverage fertilization was performed at the same dose for all plots.

The fight against leaf-cutting ants was carried out by applying 4 kg ha⁻¹ of formicide bait at the time of planting and 20 days after planting. Ten months after planting, a mechanized mowing was performed between the rows to control weed competition.

2.3. Data Collection and Analysis. The dendrometric data of total tree height (m) and BHD diameter at breast height (cm) were collected with the help of the Haglöf and Suta clinometer, respectively, in February 2017. All diameters were collected within each portion and five heights. The other heights were estimated using a hypsometric equation, with the Kopecky–Gehrhardt model chosen for *E. benthamii*: $ht = \beta_0 + \beta_1 \cdot BHD^2$, with a coefficient of determination (adjusted R^2) of 0.3983; estimate standard error (Syx%) of 11.25%; and coefficients β_0 12.4166 and β_1 0.0178. For *E. dunnii*, the model chosen was Schneider’s $ht - 1.3 = \beta_0 + \beta_1 \cdot BHD$, with an adjusted R^2 of 0.5482; Syx% of 7.13, and β_0 5.3158 and β_1 0.6080. The volume was calculated by the expression, $V = g * h * f$, where V is the volume (m³); g is the basal area (m²); h is the height (m); and f is the artificial form factor considering 0.4624 [12]. After estimating the variables, the data were submitted to Tukey’s means test at 5% error probability. The analyses were performed using the variations between the treatments (NPK, natural phosphate, and limestone) and the two species (*E. benthamii* and *E. dunnii*).

3. Results

3.1. Species and NPK. Regarding the diameter, for *E. benthamii*, the highest average was observed for 167 kg ha⁻¹, not differing from 133 kg ha⁻¹ and being 13% higher in relation to the worst observed average, which was the control (Figure 1(a)). For *E. dunnii*, the highest average was presented by 167 kg ha⁻¹, which does not differ from 133 kg ha⁻¹. The lowest average was presented by the control, being 21% smaller, not differing from 100 kg ha⁻¹.

There was a statistical difference for treatments in *E. benthamii* in relation to height, where the lowest result

was observed for the control, with an average of 37% lower compared to the average of the other treatments (Figure 1(b)). For dosages of 100, 133, and 167 kg ha⁻¹, there were no differences. For *E. dunnii*, the lowest mean height was also observed for the control, being 19% lower, not differing from 100 kg ha⁻¹. The highest averages were observed with 133 kg ha⁻¹ and 167 kg ha⁻¹.

For the volume in *E. benthamii*, the lowest average was presented by the control, differing from all other treatments (Figure 1(c)). The highest average was presented by 167 kg ha⁻¹, not differing from 133 kg ha⁻¹, and 63% higher than the lowest average observed. *E. dunnii* obtained the highest average volume for the treatment 167 kg ha⁻¹, while the lowest average obtained was for the control treatment, 53% lower than the highest average, not differing from 100 kg ha⁻¹.

3.2. Species and Natural Phosphate (NP). Regarding the means of treatments with NP for *E. benthamii* in relation to BHD, the lowest mean observed was in the control treatment that did not differ from 400 kg ha⁻¹ (Figure 2(a)). The other treatments had the highest averages, 13% higher than the lowest average. For height (Figure 2(b)), the control also obtained the lowest average, being 37% lower than the others, which did not differ from each other. For *E. dunnii*, the lowest mean was observed for the control, both in relation to BHD and in relation to height, being 18% and 23%, respectively, lower than the other averages.

Regarding the volume, the highest average for *E. benthamii* was presented by 600 kg ha⁻¹, not differing from 0 kg ha⁻¹ and 800 kg ha⁻¹ (Figure 2(c)). The lowest average obtained was for the control treatment, which differed from the other averages, and was 62% lower than the best average. For *E. dunnii*, the treatment with 600 kg ha⁻¹ of NP also had the highest average; however, it differed from the other treatments. The lowest average was observed for the control treatment, which was 48% lower than the treatment with the highest average.

3.3. Species and Liming. For *E. benthamii* BHD, the control treatment presented the lowest average, 18% lower than the average of the other treatments (Figure 3(a)). For height, the same behavior was observed, with the control treatment obtaining the lowest average (Figure 3(c)). The other treatments showed no difference between them, being 38% superior in relation to the control. Regarding volume, the lowest mean was also for the control, differing from the other averages. The highest average obtained was for 6 Mg ha⁻¹, not differing from 0 Mg ha⁻¹, 61% higher than the lowest average obtained.

The mean BHD for *E. dunnii* did not differ for liming doses, being 19% higher when compared to the control with the lowest average (Figure 3(a)). Regarding height and volume (Figures 3(b) and 3(c)), the lowest average was observed for the control, 24% and 41%, respectively, lower than the other fertilizers, which did not differ from each other.

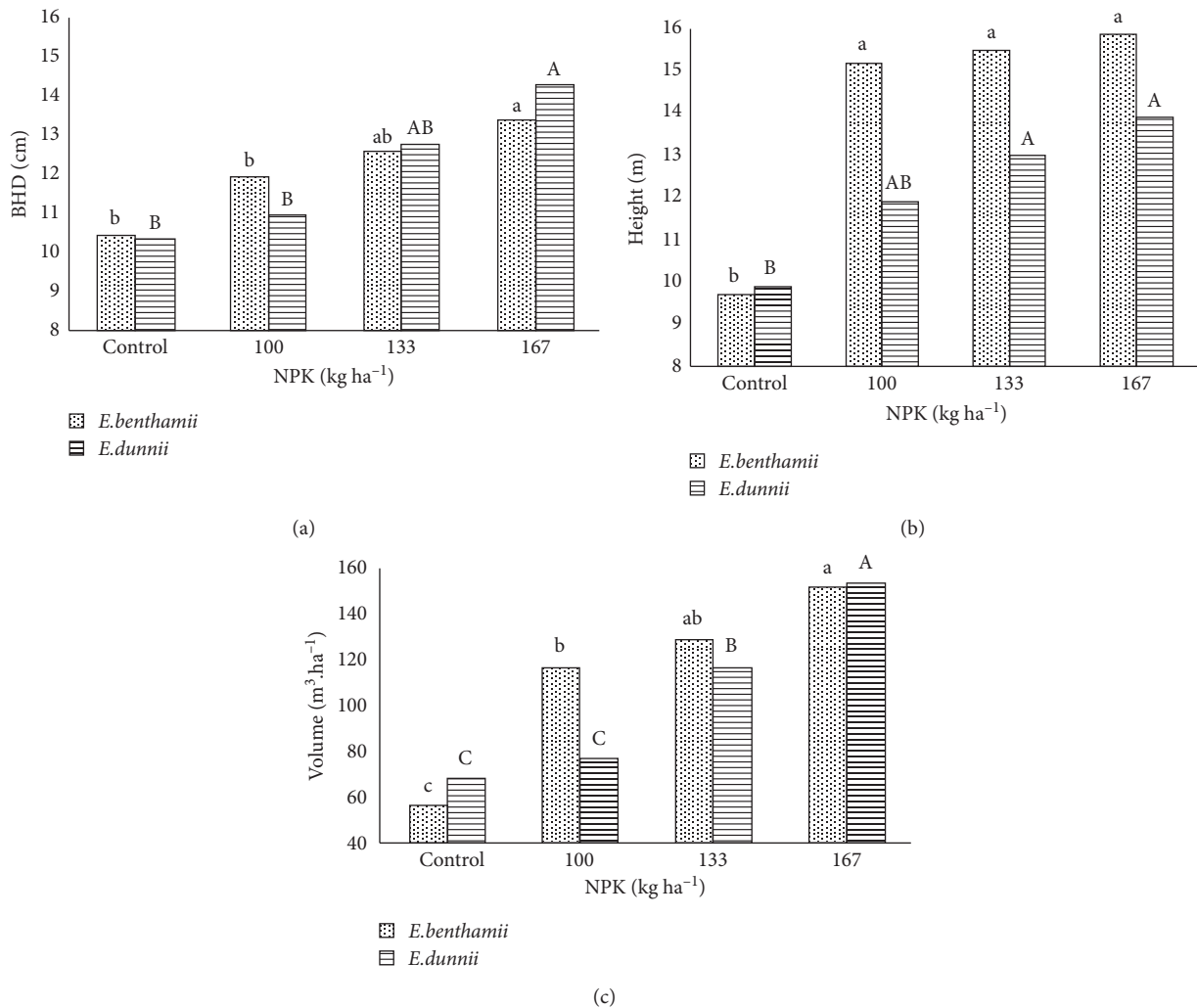


FIGURE 1: (a) Breast height diameter (BHD, cm), (b) height (m), and (c) volume (m³ ha⁻¹) in *Eucalyptus benthamii* and *Eucalyptus dunnii* in relation to NPK fertilizing. Averages followed by the same letter, lower and uppercase, do not differ between them by the Tukey test at 5% probability. Lowercase letters compare fertilization in relation to *E. benthamii*. Uppercase letters compare fertilization in relation to *E. dunnii*.

3.4. Averages of Treatments and Species. Regarding BHD, there was no statistical difference between species averages for all treatments (Figure 4). For height, there was a statistical difference between the species, and the highest averages were obtained for *E. benthamii*, around 16% higher when compared to the *E. dunnii* averages. The averages obtained for volume also present a statistical difference between species and behaved on an average 13% higher for *E. benthamii* when compared to *E. dunnii*.

4. Discussion

Positive results were observed in all NPK dosages applied to the treatments for both *E. benthamii* and *E. dunnii*, highlighting the 167 kg ha⁻¹ treatment, in diameter, height, and volume. It can be noted that with the omission of NPK application, the variables also suffer a reduction in response. Cicek et al. [13] working with the effect of NPK fertilization on initial field performance with *Fraxinus*

angustifolia (ash tree), with fertilization of 67 g plant⁻¹ NPK (10-10-10) and 133 g plant⁻¹ NPK (20-20-20), observed positive effects on increases in BHD and H during the first 36 months of growth, and when compared to the control (without fertilization), the averages were 24% higher. Bavoso and Bassaco [14], in their work with *E. dunnii* growth with increasing doses of NPK, stated that the absence of NPK limited the development of plants, and in contrast, growth had a positive relationship with increasing dosage. This positive growth response is due to the greater amount of nutrients essential for the development of the plant that are available to be absorbed by it. The decrease in plant growth without initial fertilization, as observed in our study with both species of *Eucalyptus*, is a function of the participation of elements in the structure of numerous molecules, being the main limitation of growth, being part of proteins, nucleic acids, and many other cellular constituents, such as membranes and hormones [15].

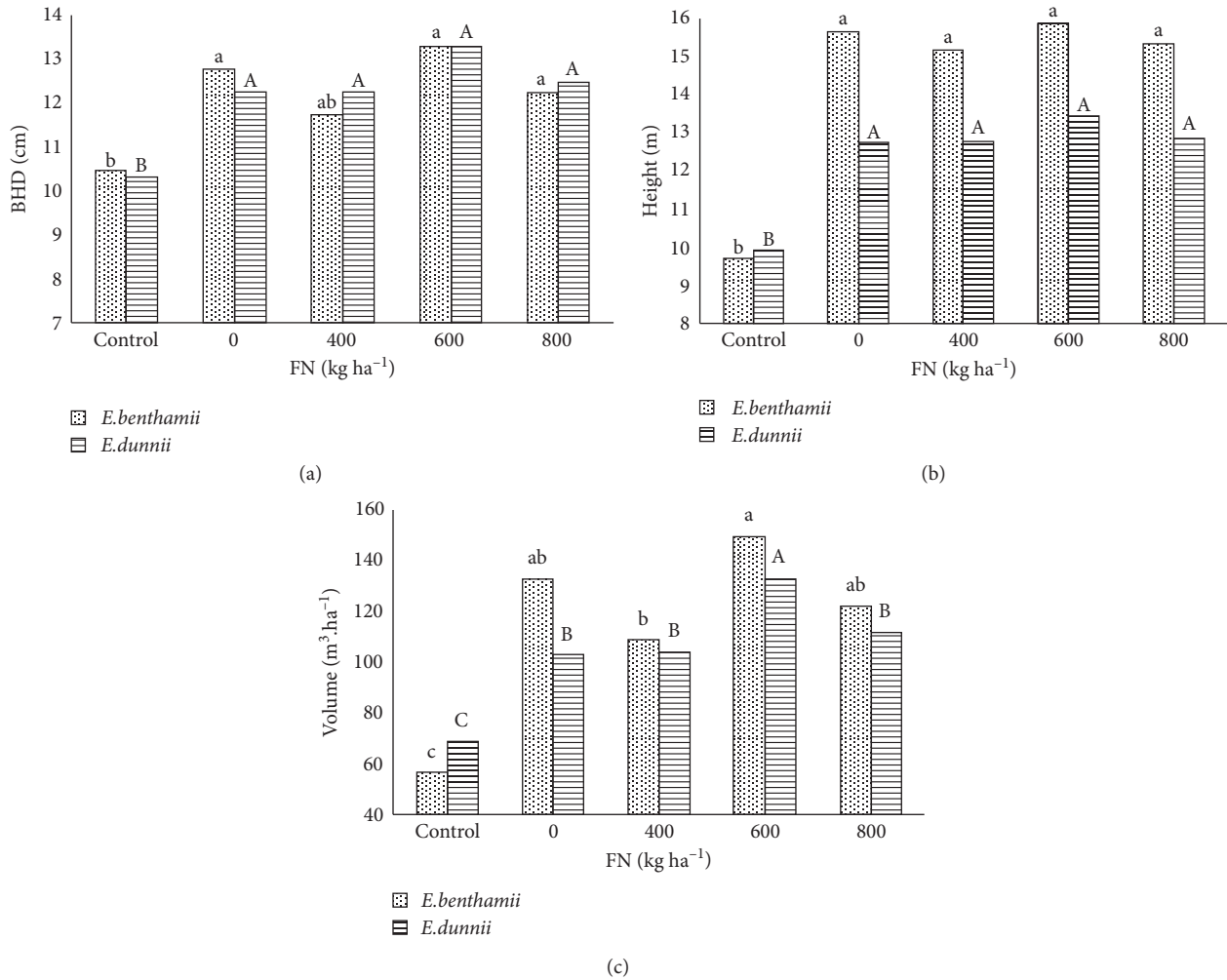


FIGURE 2: (a) Breast height diameter (BHD, cm), (b) height (m), and (c) volume (m³ ha⁻¹) in *Eucalyptus benthamii* and *Eucalyptus dunnii* in relation to natural phosphate (FN) fertilizing. Averages followed by the same letter, lower and uppercase, do not differ between them by the Tukey test at 5% probability. Lowercase letters compare fertilization in relation to *E. benthamii*. Uppercase letters compare fertilization in relation to *E. dunnii*.

Comparing the species, there is a difference in growth in relation to the variables height and volume. *E. benthamii* stands out with higher averages, and one of the possible explanations for the volume average to be higher is to be directly related to height, since the two species do not present differences in BHD. Moro et al. [16], in the study on response of *Pinus taeda* with different ages and NPK fertilization in the southern Santa Catarina plateau (Brazil), observed that the wood volume increased in all ages in response to NPK fertilization. According to the authors, adequate fertilization of the three chemical elements is important. Treatments that omitted some nutrients had lower volume averages.

Regarding the conditions of the present study, the positive response of mineral fertilization with NPK from the lowest doses can be explained by the low presence of P and K and O.M. content and clay (Table 1) in the soil, with data found by Muniz et al. [17] who consider that the amount of NPK fertilizer directly influences the development of

Eucalyptus change. According to Epstein and Bloom [18], the application of P is necessary to guarantee the production and the ideal quality of the plants, when still young and when the root system is not yet developed to explore larger soil volume. There is a response of K in the growth for *Eucalyptus* species [19] stressing that its application to the study soil was extremely important. Since one of the main sources of N in the soil comes from the O.M. contents, the application of this element may have been fundamental for the development of the planting in the study soil.

In treatments with natural phosphate (NP), a positive response of the averages above the control in BHD, height, and volume for both *E. benthamii* and *E. dunnii* can be observed at all applied doses. This may be related to the phosphorus (P) requirement that *Eucalyptus* has in the stand implementation phase, being the highest critical P level in the early development phase [3]. This response to P is likely to decrease for both species over time, decreasing the influence of nutrient on growth.

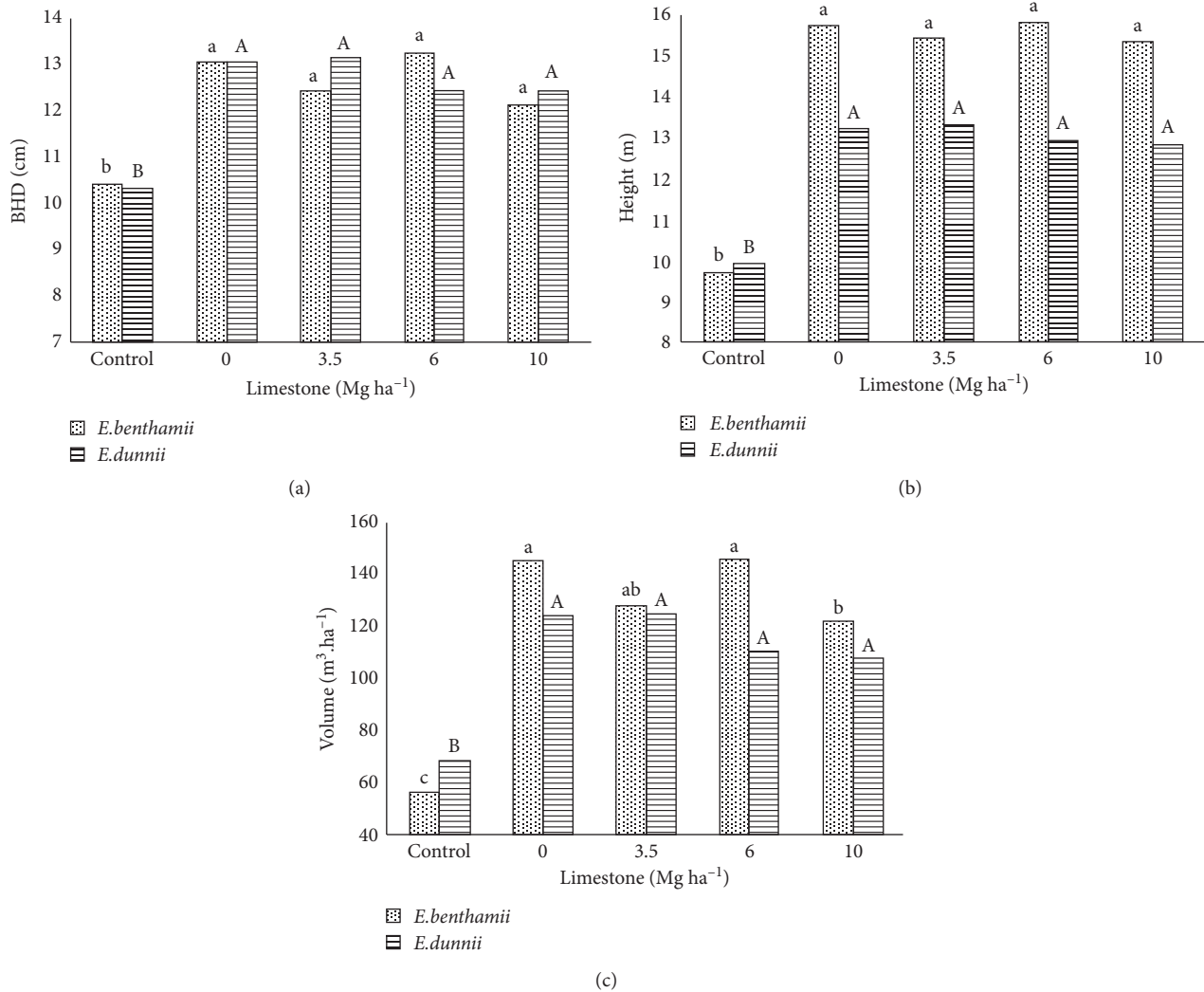


FIGURE 3: (a) Breast height diameter (BHD, cm), (b) height (m), and (c) volume (m³.ha⁻¹) in *Eucalyptus benthamii* and *Eucalyptus dunnii* in relation to liming. Averages followed by the same letter, lower and uppercase, do not differ between them by the Tukey test at 5% probability. Lowercase letters compare fertilization in relation to *E. benthamii*. Uppercase letters compare fertilization in relation to *E. dunnii*.

When comparing the species, *E. benthamii* stands out in height and volume, with no difference between the response for variable diameter. This behavior may be explained by the better response of *E. benthamii* to fertilization, while *E. dunnii* does not have such a strong but significant response.

Regarding liming, positive results were obtained at all dosages for *E. benthamii* and *E. dunnii* in relation to BHD and height, showing higher growth when compared to control, although the species is tolerant to soil acidity, as a function of low pH. However, the fact that the treatments presented higher averages than the control may be related to the Ca and Mg supply through liming, favoring the species development. Tucci et al. [20] observed a significant effect on the growth of forest species with liming from the application of 0.75 Mg ha⁻¹, also increasing Ca and Mg and decreasing Al content.

In the present study, there was also a positive relationship between the volume variable and liming. For both

species, the treatments with limestone application were superior to the control, showing that liming positively affected the growth. In a similar study, Maeda and Boghola [21] obtained a liming effect on *E. dunnii* growth, increasing shoot dry matter production, seedling growth, accumulation, and P use efficiency in *Eucalyptus*.

E. benthamii presented the highest averages of height and volume in the comparative between species, reinforcing the assumption that the response to fertilization of the species is higher when compared to *E. dunnii*. It can be said that under the conditions of the present study, fertilization was of supreme importance in plant growth, demonstrating that with the application of nutrients in the soil, the species responded to growth. This response may be directly related to Ca and Mg supply through liming and increase of N, P, and K levels with NPK application and phosphate fertilization, factors that mainly contributed to the initial development and establishment of the plantation.

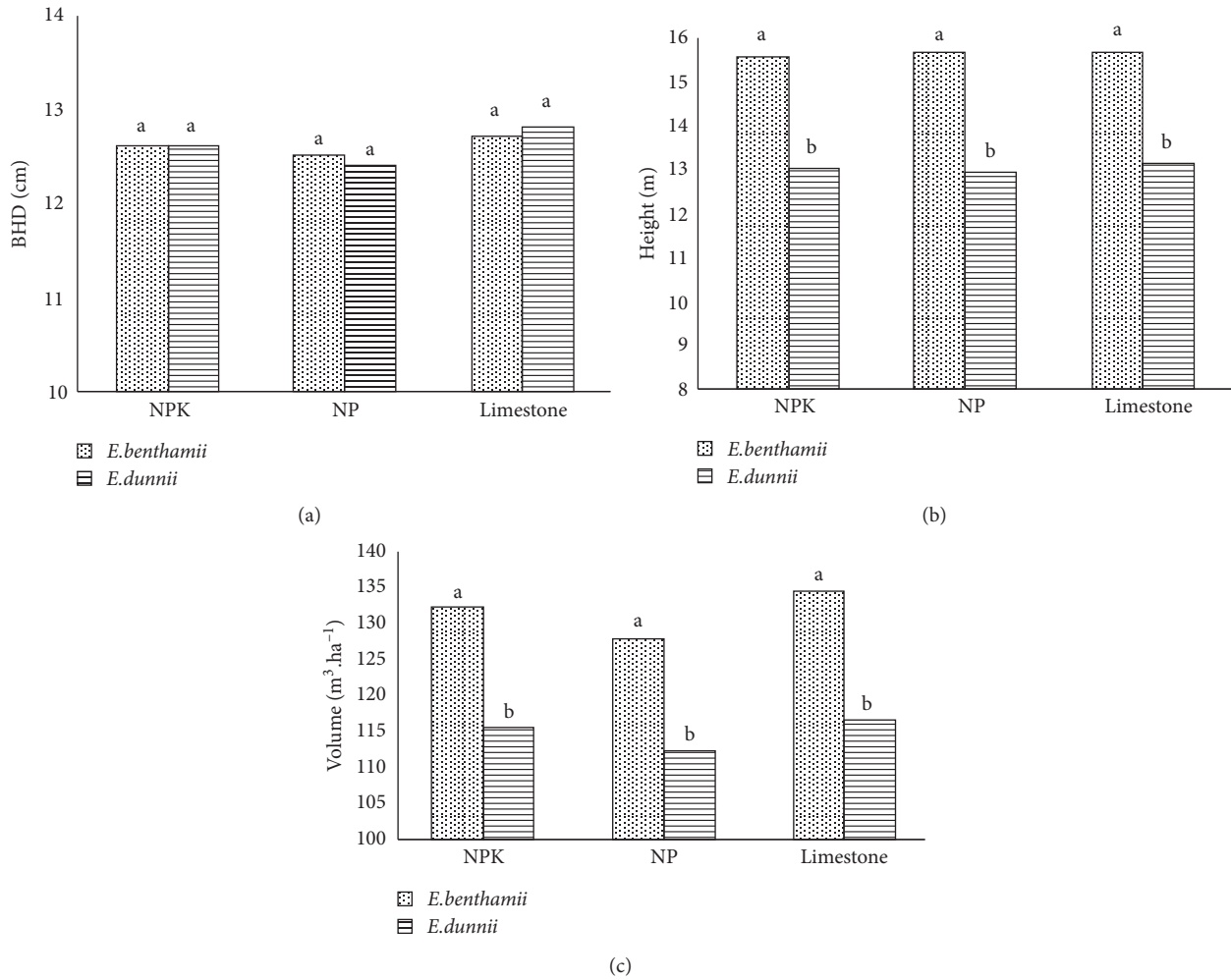


FIGURE 4: (a) Breast height diameter (BHD, cm), (b) height (m), and (c) volume ($\text{m}^3 \text{ha}^{-1}$) in *Eucalyptus benthamii* and *Eucalyptus dunnii*. Averages followed by the same letter, lower and uppercase, do not differ between them by the Tukey test at 5% probability. Lowercase letters compare fertilization in relation to *E. benthamii*. Uppercase letters compare fertilization in relation to *E. dunnii*.

Maximum growth limiting doses were not found for the studied species, but unnecessary liming may affect the availability of other nutrients and cause restrictions on plant growth, also increasing production costs.

5. Conclusions

For NPK, the recommendation is 167 kg ha^{-1} , which presented the highest growth averages for all variables.

For NP, the recommendation is 600 kg ha^{-1} , which is the dosage that presented the growth peak of the study variables.

For limestone, the dose application recommendation is 3.5 Mg ha^{-1} , aiming to supply the Ca and Mg amounts in the soil.

E. benthamii has the higher demand for NP, NPK fertilization, and liming than *E. dunnii*.

Data Availability

The data used to support the findings of this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors acknowledge the University of the State of Santa Catarina (UDESC) for the institutional support for conducting the master's research in Forest Engineering by Diego Pereira da Rosa (first author of the article), with a

dissertation entitled “Calagem e adubação no crescimento de *Eucalyptus benthamii* Maiden et. Cambage e *Eucalyptus dunnii* Maiden.” They would also like to acknowledge FAPESC for funding the research group Management of Planted and Natural Forests (PAP2019031000055) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for partial finance support, Brazil (Finance code 001). They also thank the company Souza Cruz®.

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