

Articles

How can we increase the supply of high-quality native forest species seedlings in forest nurseries?

Como aumentar a oferta de mudas de espécies florestais nativas de alta qualidade nos viveiros florestais?

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ABSTRACT

Seedling quality at the time of shipping influences field performance. However, those interested in native species seedlings rarely plan their requirements in advance, posing a challenge for nursery operators. This study aimed to characterize the development patterns of seedlings from four pioneer Fabaceae species to assess the potential for shipping them together when cultivated over the same period. Morphological attributes were assessed at 180 d, coinciding with the average shipping time for forest seedlings grown in tubes, and supplemented by assessments at 300 d. The results showed distinct development patterns among the species, with height showing little correlation to the root system. Conversely, there was a large positive correlation (92%) between stem diameter and root dry mass, despite incomplete root-substrate aggregation at 180 d. However, seedlings from the same batch exhibited a cohesive root ball by 300 d. Thus, species within the same successional group display distinct growth patterns, and stem diameter, root ball quality, and height should be considered together to assess the quality of native seedlings. This highlights the need for planning and, consequently, prior communication between consumers and nurseries to ensure high-quality seedlings for forest plantings.

Keywords: Morphological attributes; species seasonality; Root ball quality; Forest plantings

RESUMO

A qualidade das mudas no momento da expedição influencia seu desenvolvimento no campo. Apesar disso, os interessados em mudas de espécies nativas não costumam planejar suas demandas com antecedência, o que representa um desafio para os viveiristas. O objetivo do estudo foi caracterizar o padrão de desenvolvimento de mudas de quatro espécies pioneiras da família Fabaceae, a fim de avaliar o potencial de sua expedição conjuntamente, quando cultivadas no mesmo período. Atributos morfológicos foram avaliados aos 180 dias, período que coincide com o tempo médio de expedição de mudas florestais produzidas em tubete, complementando-se com avaliações aos 300 dias. A partir disso, constatamos que as espécies apresentaram padrão de desenvolvimento diferenciado e a altura esteve pouco correlacionada com o sistema radicular. Por outro lado, a correlação foi alta e positiva (92%) entre diâmetro do coleto e a massa seca radicular, apesar da incompleta agregação das raízes ao substrato aos 180 dias. Entretanto, mudas do mesmo lote aos 300 dias apresentaram torrão agregado. Assim, as espécies pertencentes ao mesmo grupo sucessional apresentam padrões de crescimento distintos, e sugere-se que o diâmetro do coleto, a qualidade do torrão e a altura sejam considerados conjuntamente para avaliar a qualidade das mudas nativas. Isso implica a necessidade de planejamento e, conseqüentemente, de comunicação prévia dos consumidores com os viveiros a fim de garantir mudas com qualidade nos plantios florestais.

Palavras-chave: Atributos morfológicos; Sazonalidade das espécies; Qualidade do torrão; Plantios florestais

1 INTRODUCTION

Environmental degradation is a driver of climate change and can lead to extreme weather events (Menegat, 2025) that negatively affect natural ecosystems (Herrmann et al., 2023). To reverse this situation, area restoration practices serve as a strategy for recovering biodiversity and ecosystem services (Stahl et al., 2025b). Although natural regeneration and direct seeding are low-cost strategies prioritized in forest restoration, active planting accelerates the process, but it requires high-quality seedlings and species diversity (Vidal et al., 2020).

Given the Brazilian government's report at COP 30, which stated that 3.4 million hectares of degraded land have been recovered (MMA, 2025), against the target of 12 million hectares by 2030 set at COP 13, it is crucial to understand the various stages and gaps involved in achieving this goal, including seedling production. In this context, there is a limited number of nurseries cultivating native species, many with low diversity,

which frustrates silviculturists and restoration practitioners. But why does this occur? This supply-demand mismatch is believed to stem from a sectoral bottleneck: unlike the procurement of standardized inputs, ecological restoration requires a floristic composition that reflects regional diversity. However, the market often operates under a logic of urgency, where restoration practitioners face tight deadlines and are required to deliver seedlings immediately. This immediacy disregards the biological development time of native species and the need for advance planning, creating uncertainty for nursery operators and frustration for silviculturists due to a lack of prior alignment between the two parties.

The production of native forest seedlings presents multiple challenges, considering factors such as the representation of regional species using propagules that preserve genetic diversity, the difficulty of seed collection (Brancalion et al., 2012; Araujo et al., 2018b), the need for skilled labor (Vidal et al., 2020), the determination of species arrangements (Piotto et al., 2020; Stahl et al., 2025b), and the high cost of inputs used by nursery operators (Melo et al., 2021). These factors increase production costs and hinder nurseries from planning ahead amidst market uncertainty. Thus, the need to provide information for the conservation and use of these species, as well as for the restoration of altered areas, demands continuous research on the silviculture of native species (Stahl et al., 2026). Moreover, the Atlantic Forest boasts high forest species diversity (De Lima et al., 2024) with distinct physiological responses (Lima et al., 2021) and complex growth patterns. Consequently, mastering nursery production knowledge is crucial, as seedling development can vary among species even under similar management and environmental conditions (Dutra et al., 2016, 2018; Lima et al. 2021)..

Seasonality is another key factor determining plant growth (Ballestreri et al., 2021; Stahl et al., 2025a). Brazil's subtropical climate includes hot summers ($>22^{\circ}\text{C}$) and cold winters ($3\text{--}18^{\circ}\text{C}$) (Alvares et al., 2013). Thus, year-round climatic variation is a decisive factor in production planning and shipping schedules. In the subtropical region, peak demand for planting seedlings occurs in late winter and spring after the frost season as temperatures and water availability increase. To meet this demand, nursery operators must contend with varying environmental conditions, as well as the complex requirements of many species.

In general, seedlings of native forest species intended for restoration are often produced in containers ranging from 110 to 300 cm³ and, in some cases, are shipped at 180 d when they have a minimum height of 20 to 35 cm and a stem diameter between 2.5 and 3.5 mm. However, when evaluated in isolation, these attributes may not accurately indicate seedling quality, as even a well-developed and apparently vigorous shoot system must correspond to a high-quality root system and an adequately formed root ball (Araujo et al., 2018a), which will promote faster plant establishment after outplanting. Furthermore, these assessments must be quick and easy to perform so they can be incorporated into growth monitoring and decision-making processes by nursery managers regarding whether to ship seedlings to the field or retain them in the nursery for a longer period.

Calliandra brevipes Benth., *Schizolobium parahyba* (Vell.) Blake, *Inga vera* Willd., and *Enterolobium contortisiliquum* (Vell.) Morong belongs to the Fabaceae family and are species native to the Atlantic Forest biome. These species are considered heliophilic, pioneer and are fast-growing (Carvalho 2003, 2008; Sousa et al. 2023), providing effective soil cover and protection. Therefore, species with similar characteristics are used as a framework (initial structuring) in restoration projects (Ballestreri et al., 2021; Elliott et al., 2023) due to their multiple purposes. *C. brevipes* is also recognized as a rheophyte and is used in soil and water bioengineering works and slope stabilization (Sutuli et al., 2018; Kettenhuber et al., 2023). However, empirical observations in the nursery reveal varied morphophysiological characteristics, even among species belonging to the same successional group and family.

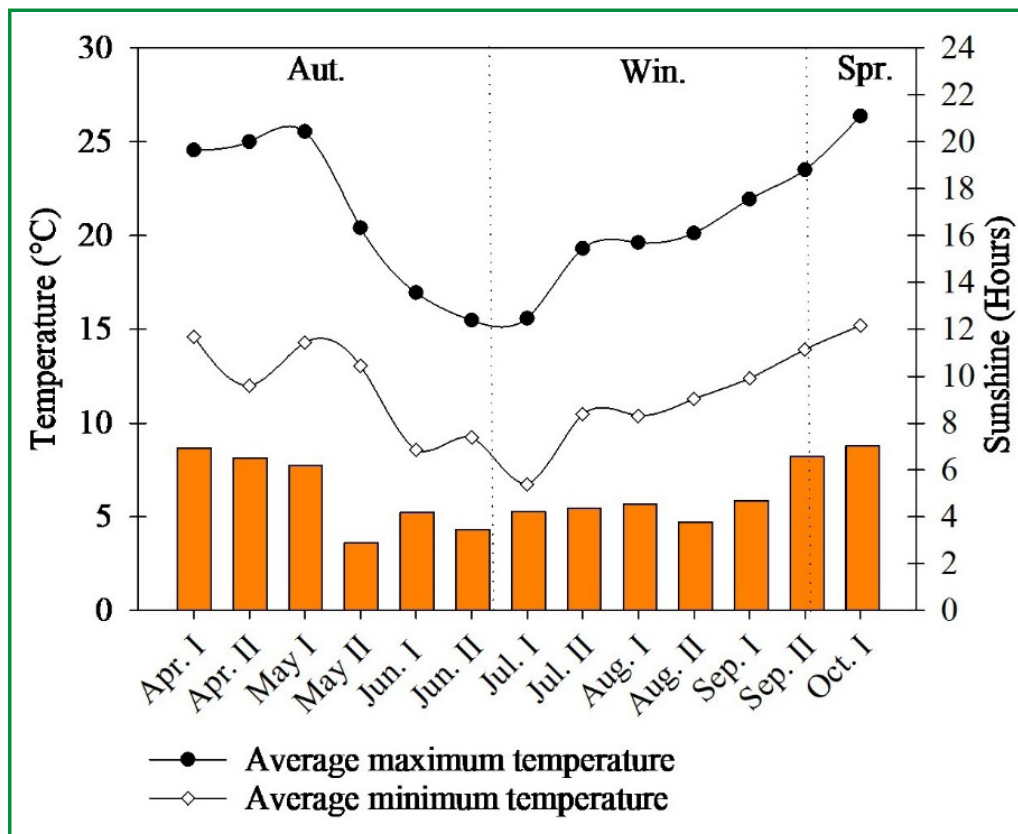
The hypothesis of this study is that native species exhibit different growth behaviors, requiring enhanced planning between the consumer and the nursery operator to ensure successful delivery and planting of high-quality seedlings for restoration projects. The objectives were: a) to determine whether the growth, quality, and substrate-root aggregation (root ball) of seedlings from different native species, belonging to the same successional group and produced under identical management, exhibit patterns that allow for rapid dispatch after 180 d; and b) to identify attributes indicative of quality standards for native species seedlings.

2 MATERIALS AND METHODS

2.1 Environmental characterization

The study was conducted in Santa Maria (29°43'13" S, 53°43'17" W) in southern Brazil. The climate is characterized as humid subtropical (Köppen classification Cfa type), with average winter temperatures of between 3 and 18 °C above 22 °C in summer, with an average annual precipitation of 1,700 mm (Alvares et al., 2013). The average minimum and maximum air temperatures recorded during the study period were 11.27 and 20.4 °C, respectively (Figure 1).

Figure 1 – Average minimum and maximum air temperatures and sunshine hours recorded during the study period in Santa Maria, Brazil



Source: BDMET-INMET (2025)

In where: Aut. – Autumn; Win. – Winter; Spr. – Spring; I – First half of the month; II – Second half of the month.

2.2 Seedling production

Seedling production of the pioneer species *C. brevipes*, *S. parahyba*, *I. vera*, and *E. contortisiliquum*, (Fabaceae), occurred in early April 2025 (autumn in subtropical region of Brazil) to enable outplanting in early spring (late September to October). The substrate consisted of a mixture of pine bark and carbonized rice husks (4:1), supplemented with 4 g/L of controlled-release fertilizer (Osmocote® 18-5-9 Mini Prill) and 3 g/L of PG MIX® (14-16-18). The mixture was homogenized and moistened with water in a concrete mixer before being placed into 180 cm³ polypropylene tubes. To trigger germination in *S. parahyba* and *E. contortisiliquum*, seeds were scarified using No. 60 sandpaper on the upper lateral section, opposite the micropyle.

Seeds of all four species were sown directly into the substrate-filled tubes. The tubes were placed on metal racks inside a greenhouse equipped with a micro sprinkler system ($\approx 6 \text{ mm day}^{-1}$); the average temperature ranged from 17 to 25°C, occasionally exceeding 25°C during the day.

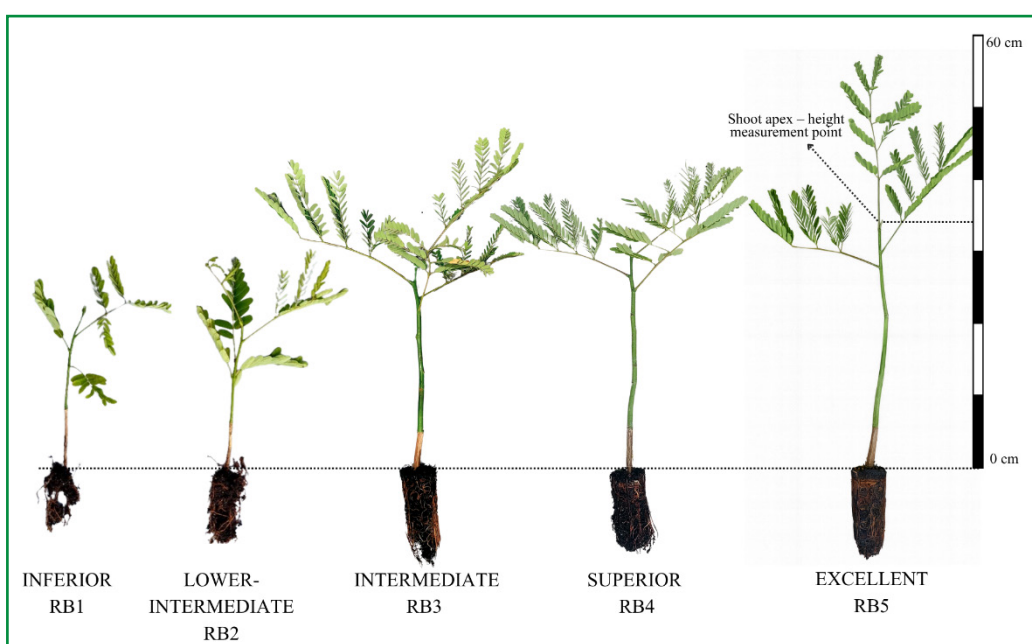
2.3 Experimental design and quality analysis of seedlings

The experiment was conducted using a completely randomized design, with treatments consisting of four species: *Calliandra brevipes* (CB), *Schizolobium parahyba* (SP), *Inga vera* (IV), and *Enterolobium contortisiliquum* (EC). The study utilized five replicates of 15 seedlings each; the three central seedlings served as the net plot for analysis, while the remaining seedlings acted as border plants, resulting in a total of 20 experimental units.

Seedling quality was assessed at 180 d (first half of October 2025), coinciding with spring in southern Brazil (Figure 1) and the period of increased demand for seedlings at regional forest nurseries. Height (H) and stem diameter (SD) were measured using a graduated ruler and a digital caliper, respectively; these data were then used to calculate the H/SD ratio.

To evaluate root-substrate aggregation, seedlings were removed from their containers and dropped from a height of one meter (Wendling; Guastala; Dedecek, 2007) to assess root ball quality (RB). However, we modified the impact surface; whereas the original authors dropped the seedlings onto crushed stone, we used a smooth concrete floor, releasing the seedling after tapping the upper rim (flange) of the container three times. Furthermore, our classification system used five scores rather than the ten applied by the original authors. To facilitate characterization, we defined the following scores: excellent (RB5 – intact root ball with few substrate particles scattered on the impact surface); superior (RB4 – slight crumbling at the root ball tip, showing flattening of the lower end); intermediate (RB3 – crumbling at the tip and/or one side of the root ball, exposing up to 20% of the root system free of substrate); lower-intermediate (RB2 – significant crumbling at the tip and sides of the root ball, with substrate retained mainly in the inner portion of the root system); and inferior (RB1 – visibly disintegrated root ball with substantial substrate loss, exposing $\geq 80\%$ of the root system, reflecting poor root formation). To illustrate this methodology and the assigned scores, we used *Schizolobium parahyba* seedlings taken from the same batch at different growth stages to create a visual reference (Figure 2).

Figure 2 – Root ball quality classes (RB) using *Schizolobium parahyba* seedlings



Source: Authors (2026)

To evaluate seedling dry mass at 180 d, the shoot was severed to separate it from the root system. The roots were washed under running water over sieves to remove adhering substrate. The materials were placed separately in Kraft paper bags, labeled, and oven-dried (65 ± 2 °C) to constant weight. Afterward, they were weighed on a precision balance to obtain shoot dry mass (SDM) and root dry mass (RDM). The sum of these values yielded the total dry mass (TDM). Based on H, SD, SDM, RDM, and TDM, the Dickson Quality Index (DQI) was calculated (Dickson; Leaf; Hosner, 1960; Araujo et al., 2018a).

Additionally, ten seedlings per species, representing the mean height and stem diameter of their respective treatments, were kept in the nursery under 50% shade for 300 d to assess H, SD, and RB. *C. brevipes* and *E. contortisiliquum* were not evaluated at this stage due to a lack of available seedlings, as they had been reserved for use in a restoration experiment conducted in parallel.

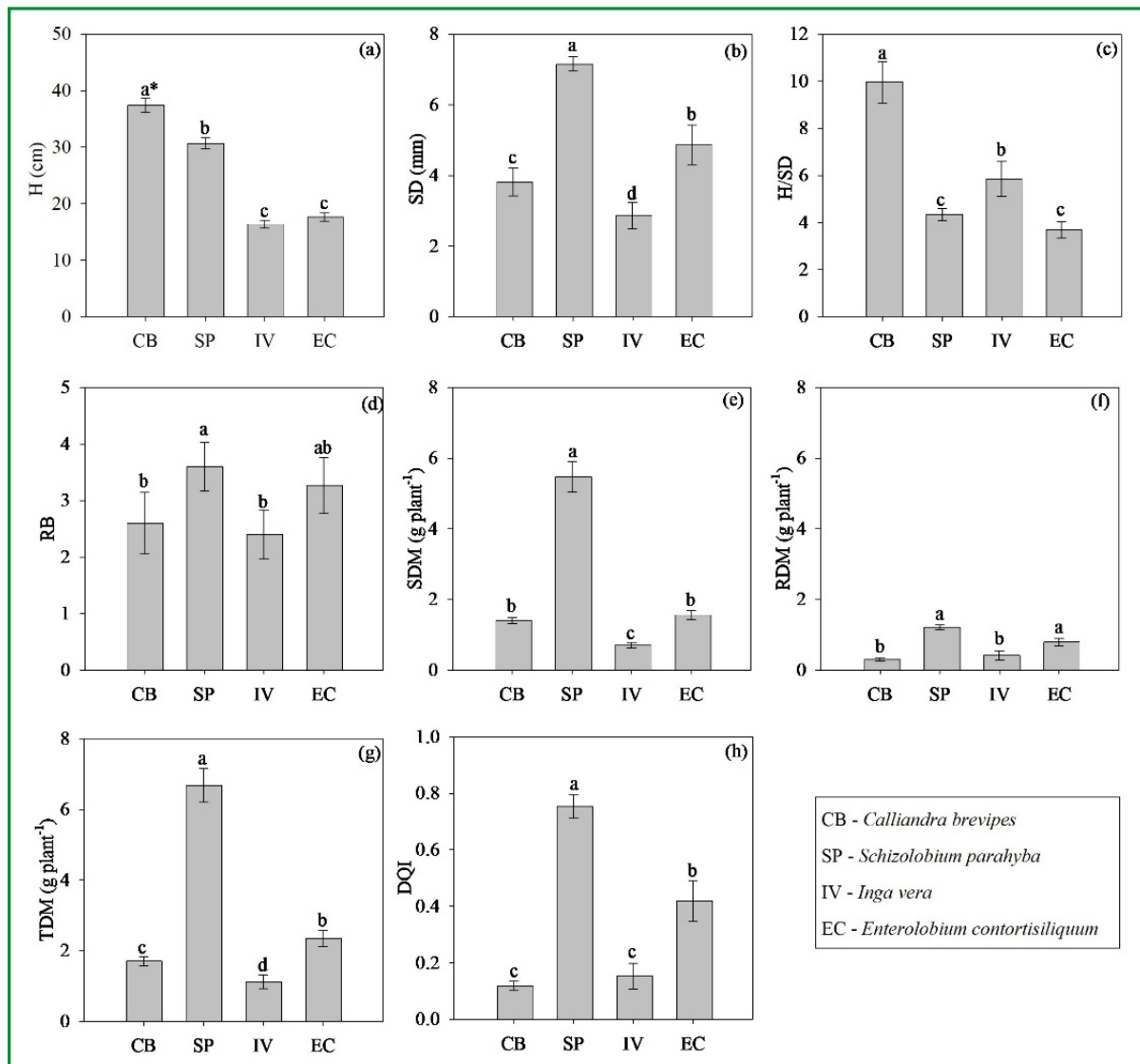
2.4 Statistical analysis

The data were checked for normality of errors and homogeneity of variances using the Shapiro-Wilk and Bartlett tests, respectively. Subsequently, analysis of variance (ANOVA) was performed, followed by Tukey's test ($p=0.05$) (Ferreira; Cavalcanti; Nogueira, 2014). Data were transformed using the Box-Cox when they did not meet the assumptions. Pearson's correlation analysis was performed using the metan package (Olivoto; Lúcio, 2020). All analyses were performed using RStudio (R Core Team, 2023).

3 RESULTS

At 180 d, the highest mean height (H) was observed in *C. brevipes* (37.44 cm), followed by *S. parahyba* (30.69 cm). *E. contortisiliquum* (17.67 cm) and *I. vera* (16.36 cm) did not differ regarding this variable (Figure 3a). Conversely, the greatest stem diameter (SD) was found in *S. parahyba* (7.15 mm), followed by *E. contortisiliquum* (4.77 mm), *C. brevipes* (3.81 mm), and *I. vera* (2.87 mm) (Figure 3b). Regarding the H/SD ratio, *C. brevipes* showed the highest mean (9.88), followed by *I. vera* (5.77), while *S. parahyba* and *E. contortisiliquum* did not differ for this variable (4.29 and 3.65, respectively) (Figure 3c).

Figure 3 – Morphological variables obtained from 180-day-old seedlings of four native forest species cultivated under the same management regime (autumn-winter, 2025)

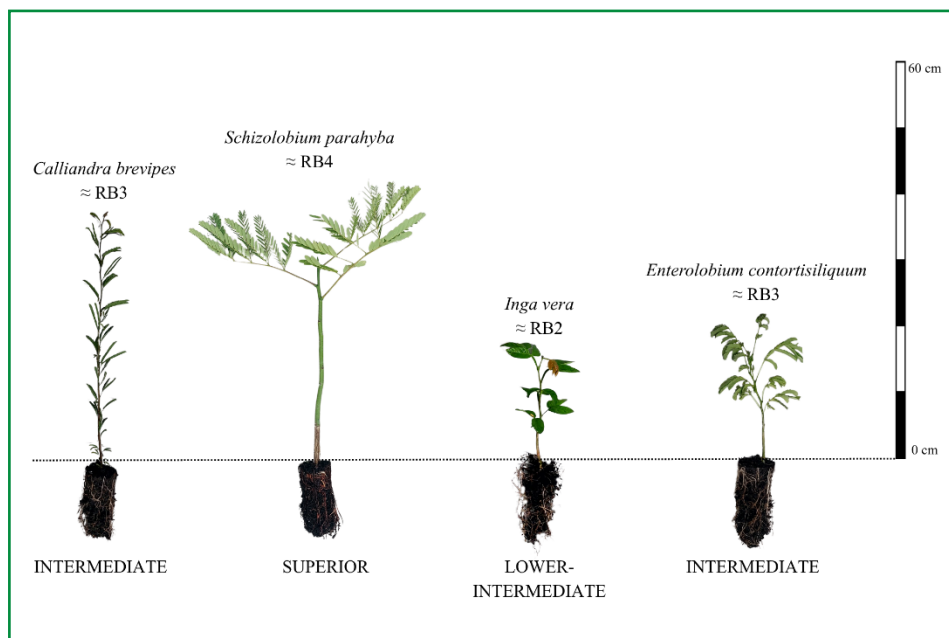


Source: Authors (2026)

In where: *Means followed by the same letter do not differ significantly according to Tukey's test ($p > 0.05$). Vertical bars represent the standard deviation. H – height; SD – stem diameter; H/SD – height-to-stem diameter ratio; RB – root ball quality; SDM – shoot dry mass; RDM – root dry mass; TDM – total dry mass; and DQI – Dickson Quality Index.

Superior root ball quality (aggregation of roots with the substrate) was observed in *S. parahyba*, with a mean seedling score of 3.6 (≈ 4). The greatest disintegration occurred in the root balls of *C. brevipes* (2.6) (≈ 3) and *I. vera* (2.4) (≈ 2) seedlings. The RB of *E. contortisiliquum* did not differ from that of the other species, with a score of 3.2 (≈ 3) (Figures 3d and 4).

Figure 4 – Root ball quality of 180-day-old seedlings of four native forest species cultivated under the same management regime, autumn-winter 2025



Source: Authors (2026)

The highest shoot dry mass (SDM) was observed in *S. parahyba* seedlings ($5.47 \text{ g plant}^{-1}$), and the lowest in *I. vera* specimens ($0.70 \text{ g plant}^{-1}$) (Figure 3e). *S. parahyba* and *E. contortisiliquum* exhibited the highest root dry mass (RDM), with no significant difference between them (1.10 and $0.88 \text{ g plant}^{-1}$, respectively), whereas *I. vera* and *C. brevipes* showed lower RDM values (0.41 and $0.30 \text{ g plant}^{-1}$, respectively) (Figure 3f). Total dry mass (TDM) was highest in *S. parahyba* seedlings ($6.68 \text{ g plant}^{-1}$), followed by *E. contortisiliquum* ($2.34 \text{ g plant}^{-1}$), *C. brevipes* ($1.70 \text{ g plant}^{-1}$), and *I. vera* ($1.11 \text{ g plant}^{-1}$) (Figure 3g).

A similar trend was found for the Dickson Quality Index (DQI), with *S. parahyba* seedlings showing the highest value (0.75), followed by *E. contortisiliquum* (0.41). However, the order was inverted for *I. vera* (0.15) and *C. brevipes* (0.11), reflecting the imbalance between shoot and root systems (higher H and SDM in *C. brevipes*) although there was no statistical difference between these two species (Figure 3h). Correlation analysis revealed a significant, positive relationship between SD and RB, SDM, RDM, TDM, and DQI (Table 1). In this context, we highlight the importance of the correlation between SD and RDM; while RDM is a key attribute for seedling performance after planting, it is a destructive measurement that is more difficult to assess.

Table 1 – Correlation analysis among variables obtained from 180-day-old seedlings of four native forest species cultivated under the same management, autumn-winter, 2025

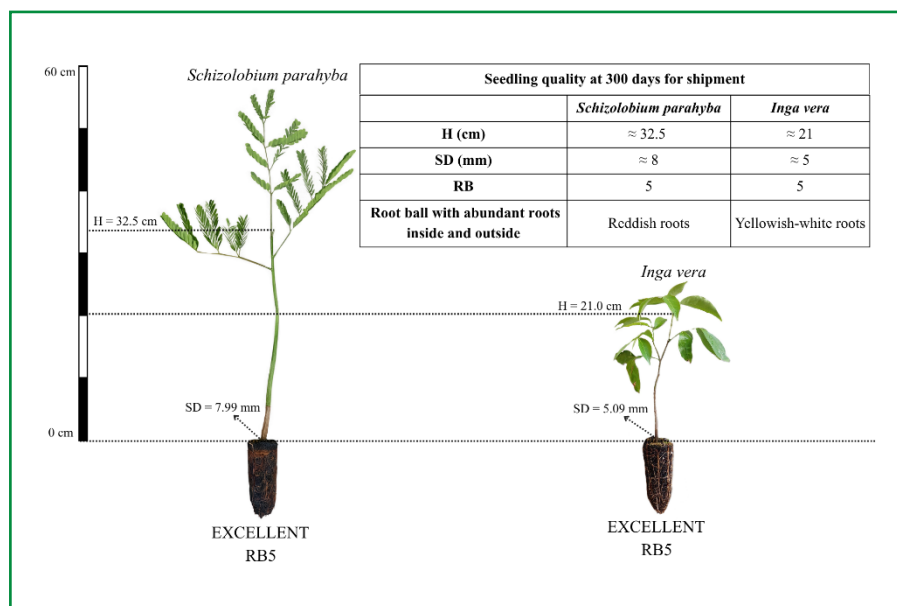
	H	SD	H/SD	RB	SDM	RDM	TDM	DQI
H	1.00	0.31	0.65**	0.057	0.39	-0.011	0.33	0.065
SD		1.00	-0.51*	0.73***	0.93***	0.92***	0.95***	0.95***
H/SD			1.00	-0.56*	-0.37	-0.73***	-0.44	-0.68***
RB				1.00	0.64**	0.76***	0.67**	0.75**
SDM					1.00	0.87***	1.00***	0.91**
RDM						1.00	0.91***	0.99***
TDM							1.00	0.94***
DQI								1.00

Source: Authors (2026)

In where: H – height; SD – stem diameter; H/SD – height-to-stem diameter ratio; RB – root ball quality; SDM – shoot dry mass; RDM – root dry mass; TDM – total dry mass; and DQI – Dickson Quality Index. * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$.

At 300 d, *S. parahyba* and *I. vera* seedlings were ready for shipment as both reached RB5 although they maintained structural differences (Figure 5). Keeping *S. parahyba* seedlings longer than 300 d could compromise their performance due to excessive root confinement and the resulting restriction on water and nutrient uptake.

Figure 5 – Quality assessment of seedlings of two native forest species 300 d after sowing (April 2025 to January 2026), produced in a subtropical region



Source: Authors (2026)

3 DISCUSSIONS

Species from the same family and successional group exhibited variations in growth, suggesting that this difference would be even more pronounced if compared to late-secondary and climax species. Consequently, nurseries producing multiple species rely on extensive knowledge, planning, and careful management tailored to each species' characteristics to meet the requirements of forest restoration projects. Furthermore, regional seasonality (autumn-winter) acts as a limiting factor for growth (Stahl et al., 2025a); even when greenhouses are used, a longer period is required to produce high-quality seedlings.

In general, nurseries use height as the primary attribute to determine when seedlings are ready for shipment, as it is easy to measure and reflects the development of the plant's shoot system and its photosynthetic potential. However, height must be evaluated in conjunction with the root system (Dumroese; Luna; Landis, 2009), which exhibits varying growth patterns and root ball formation times that are species dependent (Griebeler et al., 2021). Stem diameter is also a predictor of seedling performance in the field (Ritchie et al., 2010).

C. brevipes and *S. parahyba* appeared ready for outplanting at 180 days (height >30 cm and SD >3.5 mm) but had insufficient root development and incipient root ball formation (Figure 4). Furthermore, height showed a negative correlation with RDM (-0,011) and a low correlation with RB (0,057) (Table 1), reinforcing the importance of identifying complementary variables as indicators of seedling quality. In this context, we confirmed that SD contributed to determining seedling quality, showing a strong, direct correlation with RDM, DQI, and RB (Figure 3, Table 1). The positive relationship between SD and RDM had previously been theorized by Birchler et al. (1998) and subsequently observed by Griebeler et al. (2023) in their study of *Citharexylum montevidense* (Spreng.) Moldenke seedling development. However, a joint analysis of multiple species in a single study has not yet been conducted; thus, this finding

represents a technical-scientific advancement, supporting the inference that seedlings with larger diameters possess more abundant root systems.

In contrast, it is worth noting that seedlings with an SD of 3.5 mm, such as those mentioned above, did not achieve the root ball quality required for out planting (RB5). Therefore, for fast-growing species, replacing 180 cm³ tubes with 110 cm³ containers could be an alternative for achieving root ball formation in a shorter timeframe ($\approx$ 180 days), even under the less favorable environmental conditions found in subtropical regions. However, this decision depends on planning between the forester/restoration practitioner and the nursery operator. Given the uncertainties surrounding seedling sales, the use of larger containers is common practice, as it allows seedlings to be kept in the nursery for a longer period. In contrast, those with a smaller volume and diameter (110 cm³ tube and 35 mm, respectively) may compromise the hydration and nutrition of seedlings that exhibit a large stem diameter (e.g., *S. parahyba* = 7.99 mm) (Figure 5).

High-quality seedlings which are ready for dispatch feature a firm stem, an intact and cohesive root system showing evidence of both structural and physiologically active roots, adequate nutritional status, and an absence of pests and diseases (Araujo et al., 2018a; Berghetti et al., 2026). A well-formed root ball is directly linked to survival and initial establishment in the field (Dumroese; Luna; Landis, 2009). Consequently, high-quality seedlings optimize post-planting growth, accelerate site coverage and, in turn, the control of weed competition (Silva et al., 2022). This leads to a moderate microclimate, facilitating the establishment and diversification of other species within the restoration area (Stahl et al., 2025b).

The results also highlight that caution is required when comparing seedlings of different native forest species, especially with commercial species (e.g., *Eucalyptus* spp.). This is because large-scale production relies on coordinated advance planning, allowing for the use of smaller substrate volumes (containers of $\approx$ 50 cm³) and shipping within 120 days (Schumacher; Viera, 2015), specifically once seedlings reach

a height of 15–30 cm and a stem diameter of >2 mm (Wendling; Dutra, 2010; Gomes; Paiva, 2012). Interpretations of this nature can lead to erroneous generalizations which, combined with a lack of communication with the nursery manager, who possesses the expertise regarding the complexities of native seedling production, can compromise restoration projects.

Therefore, the results indicate that using simple attributes makes it possible to manage and ship high-quality seedlings to the field. Thus, the adoption of consistent and easily observable parameters is suggested, such as stem diameter as an indicator of dry mass (net photosynthesis), particularly root mass; root ball cohesion as a means to facilitate and expedite planting; and height as a strategy to outgrow weed competition (Andivia et al., 2021). However, achieving these parameters requires varying amounts of time depending on the species and management practices. This should be coordinated through prior communication between the forester or restoration practitioner and the nursery manager.

5 CONCLUSIONS

Seedlings of pioneer species in the Fabaceae family exhibit distinct growth patterns. After 180 d, *C. brevipes* and *S. parahyba* show height and stem diameter values suitable for shipping; however, the inferior root ball quality indicates that the seedlings should be kept in the nursery for a longer period.

Stem diameter is a morphological attribute that is easy to measure and correlates directly with the quality of the root system and the root ball. However, variation among species precludes the use of a generalized reference value for native species. Height alone is not a suitable attribute for assessing seedling quality, although it is an important indicator of above-ground biomass. Therefore, it is suggested that stem diameter, root ball quality, and height be considered together to assess the quality of native seedlings and determine if they are ready for dispatch.

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