Floresta Ambient., Rio de Janeiro, 2024; 31(3): e20230050
https://doi.org/10.1590/2179-8087-FLORAM-2023-0050
ISSN 2179-8087 (online)

ORIGINAL ARTICLE – Silviculture

Effect of spacing and genetic material on *Eucalyptus* growth for solid-wood and cellulose production in Uruguay

Paulina Siri[1]
Cecilia Bruno[2]
Mónica Balzarini[2]
Valentina Benitez[3]
Andrés Hirigoyen[4]
Luciana Ingaramo[5]
Juan Pedro Posse[6]
Jean Kassio Fedrigo[3]
Pablo Gonzalez Barrios[1]

[1]Universidad de la República, Facultad de Agronomía, Biometría y Estadística, Montevideo, Uruguay.
[2]Universidad Nacional de Cordoba, Facultad de Ciencias Agropecuarias, Estadística y Biometría, Córdoba, Argentina.
[3]Universidad de la Republica Uruguay, Casa de la Universidad de Cerro Largo, Cerro Largo, Uruguay.
[4]Instituto Nacional de Investigación Agropecuaria Estación Experimental Las Brujas, Canelones, Uruguay.
[5]Lumin, Tacuarembo, Uruguay.
[6]Instituto Nacional de Investigación Agropecuaria, Tacuarembó, Uruguay.

Abstract

The impact of forestry practices was evaluated on *Eucalyptus's* growth variables and mortality dynamics. An experiment was conducted in Uruguay over sixteen years, sixteen spacing and thinning treatments were compared depending on the genetic material and productive objective. Tree height and diameter at breast height were assessed annually. All variables were analyzed using linear mixed models. Kaplan-Meier survival analysis and the Log Rank test were used to compare tree survival. 460 trees ha^{-1} from seed material resulted in the highest individual basal area (0.023 m^2), while treatments with 2000 trees ha^{-1}, without thinning, generated a greater yield per hectare (1014 m^3 ha^{-1}). Variations in mortality were detected in higher-density treatments (above 800 trees ha^{-1}). This study underscores the critical importance of managing spacing, genetic material, and thinning practices to optimize *Eucalyptus* growth.

Keywords: Forest management, stand density, survival rate, thinning.

1. INTRODUCTION AND OBJECTIVES

In the past few decades, forestry has emerged as a globally significant field, critically influencing both economic and ecological dynamics. Notably, *Eucalyptus*, a widely planted hardwood specie, covers over 25 million hectares worldwide (Elli et al., 2020). In Uruguay, there has been a remarkable expansion of areas designated for fast-growing species, particularly *Eucalyptus*, which now dominates 70% of the area (Dieste et al., 2019). The *Eucalyptus* genus boasts various enticing characteristics, including rapid growth rates, ready access to genetic material, abundant seed availability, and versatile end-products (Resquin et al. 2019). The potential productivity of forest systems is primarily influenced by management practices, such as genetic selection, soil preparation, stand density (SD), weed and pest control, and thinning, rather than environmental variations (Binkley et al., 2019). Understanding the complex dynamics of forest stands is challenging and requires the examination of multiple interactions (Lintz et al., 2016; Pires et al., 2020). However, research efforts in the region have primarily focused on isolated evaluations of genetic merit and different management factors in productive stands. Situations where both have been evaluated together have predominantly been with a focus on bioenergy (Resquin et al., 2019).

Establishing new *Eucalyptus* plantations requires carefully assessing SD, a significant factor influencing wood attributes (Cassidy et al., 2012; Bentancor et al., 2019). These species favor environments with abundant light (Resquin et al., 2019; Lie & Xue, 2019), underscoring the importance of adjusting SD to match the desired end products (West & Smith, 2019; André et al., 2021). In Uruguay, higher-density stands, exceeding 1200 trees per hectare, are aimed at pulp production, while solid wood typically sources from lower-density stands of 900–1000 trees per hectare (Resquin et al., 2018). Appropriate SD is key for silvicultural decisions, affecting individual tree dimensions and stand yield (Forrester et al., 2013). The choice of SD has a profound effect on the type, quantity, and quality of products over the rotation period. Additionally, optimizing SD and rotation duration according to site conditions and selecting suitable genotypes is essential for maximizing productivity within the limits of available land resources.

Competition among trees plays a crucial role in shaping their growth trajectories, significantly influencing individual development in productive cycles and the final product (DeBell et al., 2001; Resquin et al. 2019; West & Smith, 2019). *Eucalyptus* plantations are particularly susceptible to the competence dynamic, which reverberates throughout the ecosystem (Akhtar et al., 2008). The consequential impact on volume and tree size is well-documented (Forrester, 2019; Bhandari et al., 2021), with the intricacies of mortality varying across stand ages (Binkley, 2017; Lie & Xue, 2019). Appropriate thinning time can enhance wood quality, consistency, and size (Qu et al., 2022). Silvicultural practices, such as spacing, fertilization, and thinning, play a crucial role in enhancing both quantitative and qualitative yields. Thinning redistributes resources, increasing stand value over volume (Cassidy et al., 2012), with thinned *Eucalyptus* stands leading to faster growth in the individual tree diameter (Forrester, 2013). Comprehending the effects of thinning on stands that have diverse objectives and utilize different genetic materials is key for the optimization of silvicultural system designs.

In terms of genetic origin, many studies have shown the disparities in growth and production dynamics between pure and hybrid *Eucalyptus* clones, serving various product purposes (Griffin, 2014). Evaluating the interplay of genotype and management practices, notably spacing, is achievable through commonly employed experimental designs (Binkley et al. 2017; Ferraz et al. 2018; Stape et al. 2022). Although seed-source trees are also employed in plantation design, the internal variability of plantations tends to be higher compared to clone-based plantations (Griffin, 2014). Nevertheless, this variability becomes less critical when the production objective is cellulose pulp rather than solid wood. In such scenarios, it can be effectively utilized to achieve broader and more varied production outcomes, starting with a focus on pulp production before transitioning to the utilization of solid wood.

Our hypothesis centers on the critical relationship between initial and final density and genetic material to effectively implement management practices aligned with production goals. The relevance of conducting studies with a dual purpose (cellulose and solid wood) is emphasized, as limited research has been conducted on evaluating the combined impact of tree spacing and genetic materials on *Eucalyptus* growth in common South American scenarios, especially in long-term experiments where factors can be studied over several years (Fernandes et al., 2023). Therefore, this study aims to evaluate the effect of tree spacing, genetic material (E. *grandis* grown by seed or clones, and pure or hybrid E. *grandis* × E. *camaldulensis*), and thinning practices on stand growth, considering two different end uses: cellulose pulp or solid wood.

2. MATERIALS AND METHODS

2.1. Experimental site

The experiment was installed in the Department of Rivera, Uruguay, at coordinates 30º54‘S and 50º33‘W (152 masl) (Figure 1). The experimental site experiences an average annual precipitation of 1500 mm, evenly distributed throughout the year. The average temperature is around 18 ºC, with the highest mean temperature in January (22 ºC), and the lowest in June (10 ºC). The predominant soils are moderately deep Melanic/Umbric Inceptisols with a sandy loam-loam texture, characterized by low fertility and good drainage (classified as CONEAT 7.2 in the Uruguay System of Soil Aptitude). Additionally, there are Umbric Ochric Dystric Planosols with a deep loamy-sandy texture and imperfect drainage (CONEAT G03.21).

2.2. Experimental design and data collection

We analyzed a *Eucalyptus* trial planted in 2003 that encompassed diverse genetic materials and productivity objectives. To enhance comparability, the original trial dataset was partitioned into three datasets (Table 1) based on the intended productivity goals and the genetic material used.

Table 1. Overview of the assessed treatments, including details on initial and final stand density, spacing between trees (m × m), thinning timing, and genetic material across the three datasets.

Dataset	Treatment code	Genetic material	Initial density (trees ha^{-1})	Thinning *	Final density (trees ha^{-1})	Distance among trees (m × m)
A	400_400_C1	*E. grandis (C1)*	400	-	400	5 × 5
A	500_350_C1	*E. grandis (C1)*	500	8	350	4.5 × 4.5
A	622_444_C1	*E. grandis (C1)*	622	8	444	4 × 4
A	622_622_C1	*E. grandis (C1)*	622	-	622	4 × 4
A	800_333_C1	*E. grandis (C1)*	800	2 / 8	333	3.5 × 3.5
A	800_800_C1	*E. grandis (C1)*	800	-	800	3.5 × 3.5
A	800_333_S	Seed	800	2 / 8	333	3.5 × 3.5
A	800_333_S	Seed	800	-	800	3.5 × 3.5
B	400_400_C2	*E. grandis x E. camandulensis (C2)*	400	-	400	6 × 5
B	500_350_C2	*E. grandis x E. camandulensis (C2)*	500	8	350	4.5 × 4.5
B	622_444_C2	*E. grandis x E. camandulensis (C2)*	622	8	444	4 × 5
B	622_622_C2	*E. grandis x E. camandulensis (C2)*	622	-	622	4 × 5
B	800_333_C2	*E. grandis x E. camandulensis (C2)*	800	2 / 8	333	3.5 × 3.5
B	800_800_C2	*E. grandis x E. camandulensis (C2)*	800	-	800	3.5 × 3.5
C	1111_460_S	Seed	1111	2 / 8	460	3 × 3
C	1111_1111_S	Seed	1111	-	1111	3 × 3
C	1600_1033_S	Seed	1600	2 / 8	1033	2.5 × 2.5
C	1600_640_S	Seed	1600	8	640	2.5 × 2.5
C	2000_2000_S	Seed	2000	-	2000	2 × 2

* Years after planting

Dataset A focused on solid wood production and consisted of seed material and Clon 1 (C1), which represents pure *E. grandis*. Dataset B, also for solid wood production, included Clon 2 (C2), a hybrid of *E. grandis* and *E. camaldulensis*. Lastly, dataset C had a dual objective of producing pulp cellulose and solid wood at different times. The genetic material in dataset C was seed material (*E. grandis)*. Thinning was carried out in specific treatments (Table 1). The thinned trees were sold for pulp production, while the remaining trees were designated for solid wood production.

Datasets A and B maintained an SD ranging from 400 to 800 trees ha^{-1}, while dataset C had an initial SD ranging from 1111 to 2000. After eight years, specific treatments underwent thinning with varying intensities, depending on the specific treatment and end-product goal (Table 1). The experimental design was a randomized complete block design with three replications, and the experimental units were of fixed dimensions, measuring 900 square meters (30 m × 30 m).

Annual measurements of diameter at breast height (DBH) and individual tree height were recorded for all the trees from 2005 (two years after implantation) until 2021. The border trees of each experimental unit were excluded from this study. Since fixed-size plots were used and treatments were associated with different SD, a varying number of trees per plot were observed. In dataset C, individual tree volumes were calculated for each treatment using the taper functions described by Hirigoyen et al. (2021). The per-hectare volumes were obtained by multiplying the individual volumes by survival rates and final SD of each treatment. Basal area (BA) was determined on an individual tree basis. Due to measurement issues in two evaluation years, the data from these years were estimated by taking the average of the values from the years before and after (2015, 2019). Additionally, residual values above three times the standard deviation were defined as outliers and removed from each specific dataset.

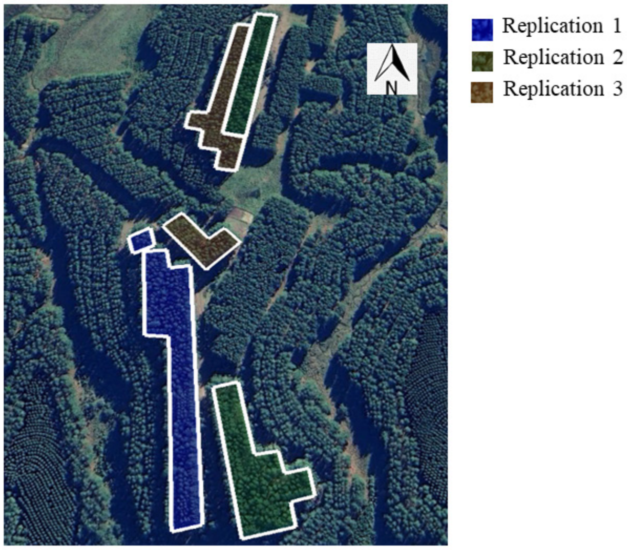

Figure 1. Satellite image of the experimental site, where replications are differentiated by color, and treatments from each dataset are distributed in each replication. Each experimental unit is a square of 30 meters by 30 meters.

2.3. *Statistical analysis*

For data analysis, linear mixed models for repeated measures were used incorporating information from all the evaluated years (Littel et al., 2006, Equation 1).

$$y_{ijk} = \mu + \tau_i + \delta_j + \tau_{ij} + \tau\delta_{ij} + \beta_1 x_k + \beta_2 x_k{}^2 + \tau x_{ik} + \varepsilon_{ijk} \qquad [1]$$

where: y_{ijk} is the response variable, μ is the overall mean, τ_i: is the effect of the *i-th* SD, δ_j is the effect of *j-th* replication, $\beta_1 x_k$: x and x^2 are the k-th year and squared year, respectively, defined as a covariate, β and β^2 are the corresponding (unknown) regression parameters, and ε_{ijk} is the residual random error term. Two scenarios were evaluated in the analysis. One with independent residuals and the other with residuals consider a temporally correlated structure modeled by a first-order continuous autoregressive process (AR(1)), with the tree serving as subject.

For each variable, an analysis of variance was conducted, followed by a post hoc Tukey test ($\alpha = 0.05$) to determine significant differences. To further investigate the dynamics of the treatments over time, annual predictions were made, allowing for the assessment of treatment impacts across years. To compare the survival rate among treatments, Kaplan-Meier survival analysis and Log Rank test ($\alpha = 0.05$) were employed. The survival analysis was performed for all three databases, considering thinned and unthinned treatments. The analysis focused on the time at which the final density was reached (8 years) for the thinning treatments. Statistical analyses were conducted using the InfoStat statistical software (Di Rienzo et al., 2021) and its R interface (R core, 2021), in addition to SAS 9.3 (SAS Institute, Cary NC).

3. RESULTS

3.1. *Basal area*

Significant differences were observed among treatments regarding BA at both eight and sixteen years of age across all three datasets. Dataset A revealed notable differences among treatments at both time points (Figure 2). Moreover, as time progressed, additional distinctions among treatments became apparent (Figure S1). However, across both age groups, it consistently appeared that treatment 800_800_C1 exhibited the lowest individual BA. Additionally, the treatment 800_333_S outperformed treatments that initially began with 800 trees per hectare but were not thinned (800_800_C1 and 800_800_S) during both evaluation periods. Specifically, under the 800_800 and 800_333 treatments, seed material exhibited a higher BA than the evaluated clone C1 at sixteen years. The most interesting aspect was the considerable variability within treatments, with significant differences between the seed and clone treatments.

Eight years after plantation, noteworthy distinctions between treatment 500_350_C2 and 800_800_C2 were identified in dataset B (Figure 3). However, at sixteen years, the 400_400_C2 exhibited a greater BA compared to 800_800_C2. The remaining treatments were grouped without significant differences, and the trajectories of the treatments over time were similar (Figure S2). Figure 4 illustrates that the spacing treatment with the lowest final SD (1111_460_S) displayed the best BA performance at the age of eight in dataset C. Nevertheless, at the age of sixteen, three distinct groups emerged. Treatment 1111_460_S continued to demonstrate the best performance, while treatment 2000_2000_S exhibited the lowest BA. The more surprising aspect of the results was the more differences observed at age sixteen compared to eight, underscoring the influence of age on the observed variations (Figure S3).

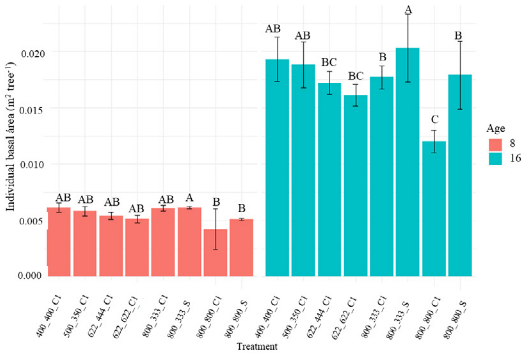

Figure 2. Adjusted means and standard error for individual basal area (m^2 $tree^{-1}$) for each treatment evaluated in dataset A at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$).

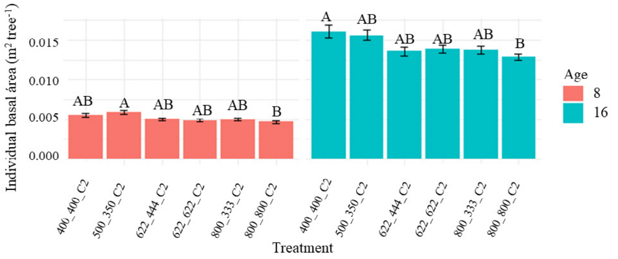

Figure 3. Adjusted means and standard error for individual BA (m^2 $tree^{-1}$) for each treatment evaluated in dataset B at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$).

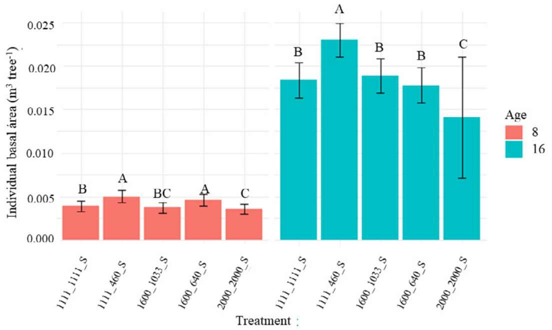

Figure 4. Adjusted means and standard error for individual basal area (m^2 $tree^{-1}$) for each treatment evaluated in dataset C at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$).

3.2. Stand Volume

The analysis of volume was exclusively conducted on the seed genetic material treatments, specifically designed for thinning at the age of eight to facilitate pulp production. As depicted in Figure 5, the impact of thinning is evident, with treatment 1111_460_S displaying the highest individual tree volume. Interestingly, this treatment maintains the same initial SD as treatment 1111_1111_S. Despite increased disparities at sixteen years, treatment 2000_2000_S consistently exhibited the lowest individual volume values at both time points. Notably, individual tree volume showed a clear trend, as treatments with higher SD consistently had lower average volumes per tree than those with a lower initial SD (Figure S4).

Concerning volume per hectare (Figure 6), the results reveal a contrasting trend compared to individual tree volume, as denser treatments demonstrate higher performance. Specifically, treatments 1111_1111_S and 2000_2000_S exhibit higher volumes per hectare at ages eight and sixteen, respectively. As the years progress, fewer differences become apparent, and changes in ranking emerge (Figure S5). While at eight years, the treatment that resulted in the fewest post-thinning number of trees (1111_460_S) displayed the lowest wood productivity, by the age of sixteen, an intermediate treatment, such as 1600_640_S, had the lowest production.

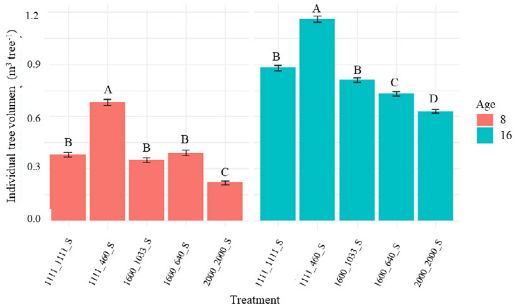

Figure 5. Adjusted means and standard error for individual tree volume (m^3 $tree^{-1}$) for each treatment evaluated in dataset C at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$).

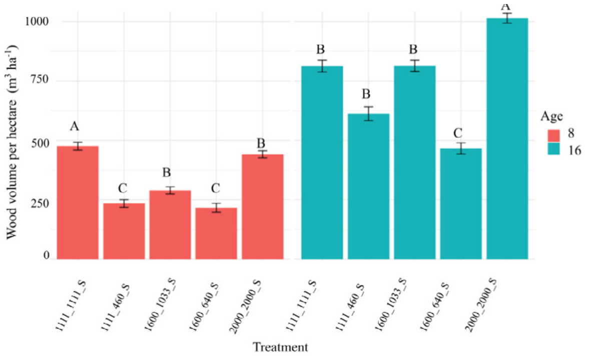

Figure 6. Adjusted means and standard error for wood volume per hectare (m^3 ha^{-1}) for each treatment evaluated in dataset C, at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$).

3.3. Survival analysis

In dataset B without thinning, no significant differences in tree survival were detected (Figure 7). However, in datasets A, both with and without thinning, and in dataset B with thinning, significant differences were found. Treatments with an initial density of 800 trees per hectare exhibited lower survival rates. In dataset C, significant differences were observed for both thinned and unthinned treatments (Figure 8). It is evident in all cases that a higher initial SD is associated with lower survival rates, as seen in treatments 1600_640_S and 2000_2000_S. In the non-thinned treatments, a decrease in survival was observed starting from year five, which can be attributed to a period of sustained and extreme water deficit (MGAP, 2008). Treatment 1600_640_S, which starts the production cycle with a high density, exhibits the highest mortality. Therefore, the thinning effect at age 8 does not significantly impact survival, as the majority of mortality occurs before thinning. Among the non-thinned treatments, treatment 2000_2000_S displays the highest mortality and significant differences compared to other treatments.

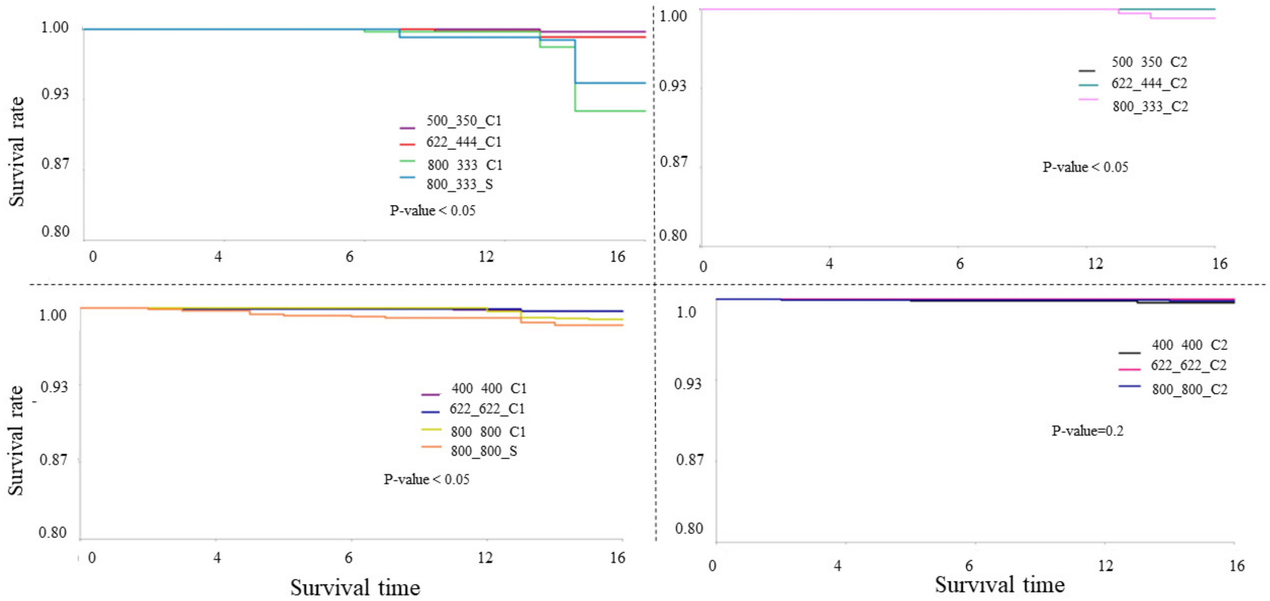

Figure 7. Tree survival rate for dataset A (left panels) and B (right panels), with thinning (lower panels) and without thinning (upper panels) evaluated from the time that final SD was reached until age 16. Means with common letters are not significantly different ($p \leq 0.05$).

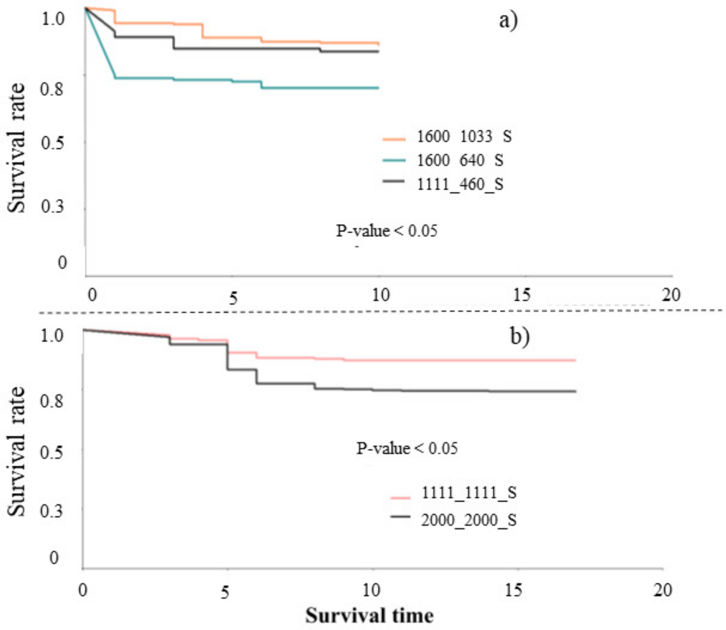

Figure 8. Tree survival rate for dataset C was evaluated from the latest thinning practice (final SD) until age 16 by treatment. The analysis was performed separately depending on silvicultural practices with (upper panel) and without thinning (lower panel). Means with common letters are not significantly different ($p \leq 0.05$).

4. DISCUSSION

4.1. Model selection

The significance of integrating temporal variability to enhance precision in estimating the mean effect of treatments in forestry experiments has been underscored (Loughin et al., 2007; González Barrios et al., 2020). The use of repeated measures analysis, highly recommended for its efficacy in reducing standard errors and narrowing confidence intervals, thereby increasing statistical power, is exemplified by Gezan & Carvalho (2018). Overlooking temporal correlations can raise the risk of Type 1 errors, leading to false detection of non-existent differences between treatments (Sherman, 2011). Consistent with these findings, our study affirms the effectiveness of models that consider temporal correlations among trees. This approach not only serves as a powerful tool for the design and optimization of silvicultural systems but also facilitates a detailed understanding of tree development and the interactions between treatments and their effects on productivity variables.

4.2. Basal area and wood volume

The investigation into the relationship between tree size and production related to planting density is crucial, as highlighted by Forrester et al. (2013). We observed that individual wood volume decreases, while overall stand volume increases at higher densities, aligning with findings from global spacing studies (Binkley et al., 2010; Forrester et al., 2013). Significant variations in BA at the final assessment indicated diverse genetic responses to treatments. Treatments using seed material, recommended for solid wood due to larger trees at final time, adapted better to local conditions, leading to higher BA and tree volume, yet exhibited more heterogeneity (Stape et al. 2022). This aligns with Caniza et al. (2018), noting seed materials excel in low-potential environments versus clones, which show greater uniformity and are preferred for solid wood production, especially C2 due to homogeneous productivity, despite requiring intensive silviculture and site preparation (Binkley et al. 2017). These findings underline the importance of considering genetic and environmental factors in forestry, particularly for Uruguay's dual-purpose wood and pulp production.

Higher SD leads to a rapid expansion of leaf area and biomass, ensuring quick site coverage. This phenomenon is well-documented in the literature (Forrester et al., 2013; Rocha et al., 2019). However, this growth also increases competition for light, leading to smaller tree sizes. Our study supports this, showing that denser treatments result in lower BA and individual volume, an important factor for pulp production, where achieving the right balance between quality and quantity per hectare is key. The impact of spacing on tree size becomes more evident with age, particularly in the first five years, which are the most competitive (Rocha et al., 2019). Following Malan and Hoon (1992), our findings underscore that managing stand density through initial spacing or thinning is vital for optimal tree growth. Stands that are widely spaced (i.e. 400_400) or thinned (i.e. 800_333) demonstrate quicker growth compared to denser ones (i.e. 800_800). Thinning also affects solid wood yield, tree dominance, mortality, and cessation of growth (Fernandes et al., 2023). Our extensive analysis indicates that differences in BA at the final assessment are more closely related to targeted rather than initial SD, especially in hybrid clones (Dataset B). Additionally, thinning effects are more pronounced in treatments with high initial SD and undergo substantial reductions in individual numbers at harvest. This is linked to initial SDs of fewer than 800 trees per hectare and thinning of less than 50% of individuals.

In Dataset B, most of treatments did not show significant differences (Figure 3). The only substantial distinction was observed between the two extreme treatments (800_800_C2 and 400_400_C2) at the final assessment. Over the years, the ranking of treatments in Dataset B demonstrated notable variability, which can be attributed to the interplay of site-specific conditions and SD. This pattern was also observed in C1 and seed material. It's important to emphasize that all treatments in this dataset employed a hybrid clone. The Kaplan-Meier analysis (Figure 7) revealed that mortality rates did not significantly influence production in treatments without thinning. As the study progressed, the variability among treatments became more pronounced, a dynamic influenced by the experimental area's size and the diversity of specific site conditions.

The comparison between seed and clone treatments shows greater variability in the former, affecting data spread and adjusted means (Figures 2 and 4), essential for dual-purpose seed material strategies. At the productive cycle's end, this variability allows for diverse production goals based on each tree's volume or BA. Thinned trees at age eight are aimed at pulp production, while seed-type genetic treatments exhibit higher BA at sixteen years, suggesting the viability of dual-purpose stands. Such stands offer outcomes comparable to single-purpose wood or pulp stands, allowing for an intermediate product. This underscores the potential of dual-purpose stands to optimize resource use and enhance productivity, which should be considered in forest management strategies.

In our study, a detailed analysis becomes evident when examining tree volumes, especially from the perspective of pulp production objectives. Similar to our observations in BA, the analysis of individual tree volumes in seedling treatments revealed a consistent trend: higher stand densities (2000_2000_S) correlate with lower individual tree volumes (0.64 $m^3.tree^{-1}$) (Figure 5). This trend underscores the intricate balance between tree density and individual growth in forestry management. However, a contrasting compensatory effect was noted in the volume per hectare metric, where treatments with higher densities exhibited increased volumes per hectare. This effect is particularly evident in seed materials with 2000_2000_S (1014 $m^3.ha^{-1}$) compared to 1111_460_S (620 $m^3.ha^{-1}$) and 1600_640_S (466 $m^3.ha^{-1}$) at year sixteen. These findings are critical for understanding the dynamics of wood production in high-density plantations and underscore the importance of considering both individual tree growth and overall stand productivity in developing effective forestry management strategies, particularly in Uruguay's environmental conditions.

4.3. *Survival analysis*

Research indicates that competition's relation to SD involves factors like age, growth, genetics, phenology, and site conditions (Dwyer et al., 2010; Fernandes et al., 2023). Our findings show intensified competition at higher densities in seed-type treatments (Figure 5), consistent with Uruguayan studies (Resquin et al., 2018). Yet, in Dataset B, competition was not a significant factor in stand growth. Notably, hybrid genetic materials, with crown structures distinct from pure *Eucalyptus grandis*, exhibit reduced competition. This demonstrates that the impact of competition is contingent on specific genetic and environmental circumstances.

In Dataset C, we observed significant differences in tree mortality for both thinned and unthinned treatments. These results support the hypothesis that increased competition among closely spaced trees leads to higher mortality rates over time (Harris, 2007; Schneider et al., 2015). Treatments with higher initial SD, notably 1111_460_S and 2000_2000_S, showed lower survival rates, aligning with the theory that dense populations undergo rapid early growth, a critical factor in stand establishment decision-making (Rocha et al., 2019). Early reduction of live trees, crucial during the initial competitive years (West and Smith, 2019), can mitigate competition's adverse effects on final yield (Akhtar et al., 2008; Resquin et al., 2018). The management of stocking levels, both during and post-thinning, significantly influences resource availability per tree, affecting both tree size and the stand's overall value at harvest (Cassidy et al., 2012). Our findings underscore the importance of timely thinning decisions: Delaying thinning, even with an optimal final SD, can lead to suboptimal growth and reduced stand performance due to the initial high density's effects (Binkley, 2004; Ferrere et al., 2005).

Significantly, our findings align with Resquin et al. (2018), who reported a positive correlation between wood volume and final SD. In our study, trees planted at narrower spacings exhibited lower BA and individual wood volume, yet resulted in higher wood volume per hectare. It is crucial to consider how management practices, including thinning, impact these outcomes, as suggested by Qu et al. (2022) and Forrester (2013). While our study accounted for the effects of thinning by calculating the post-thinning survival rate, the potential confounding impact of mortality on wood volume and growth patterns must be acknowledged.

The extensive literature on tree growth prediction models underscores their effectiveness and value in guiding productive decisions (Hirigoyen, 2018). In our study, we leveraged local models, which are instrumental in offering predictive insights based on current data and in unraveling the complex dynamics of tree growth and mortality across various treatments. These models are particularly beneficial for working with local stands, as they enable a thorough characterization of long-term trials, incorporating nearly annual measurements over sixteen years. Employing these models has allowed us to discern the specific growth patterns and mortality dynamics within the *Eucalyptus* plantations under study. They adeptly account for the unique characteristics and complexities of the local environment, enhancing the accuracy of our predictions and the efficacy of our forest management decisions. This research underscores the significance of using site-specific models to capture the nuanced aspects of tree growth and mortality, thereby contributing to more precise productivity assessments.

Our research highlights the complex dynamics of tree growth and production influenced by diverse environmental conditions and genetic compositions, particularly in an experimental context. The complex interplay between site-specific conditions, genetic materials, and treatment effects stands out as a crucial area for further research. Exploring these aspects in greater detail is essential for a more thorough understanding of forest ecosystems and advancing sustainable forestry practices. Future studies in this field will not only augment our knowledge but also pave the way for innovative, eco-friendly approaches in forestry management, both locally and globally.

5. CONCLUSIONS

Our research after 16 years demonstrates that dual-purpose *Eucalyptus* treatments can yield basal areas similar to those aimed solely at solid wood production. This highlights the adaptability and productivity potential of various genetic materials in response to spacing treatments. This underscores the utility of seed-type materials, particularly when applied to lower spacing densities, which have been correlated with an increase in individual tree basal area and volume.

Furthermore, our analysis of spacing, genetic selection, and thinning practices emphasizes their critical roles in forestry management. Lower SD were particularly effective in enhancing individual tree growth, whereas higher SD, even when unthinned, resulted in larger overall productivity per hectare. However, this increase comes with higher mortality rates in denser plantings, suggesting a need for a balanced approach in plantation management. These findings inform our recommendations for improving the sustainability and productivity of *Eucalyptus* plantations under varying environmental conditions.

SUBMISSION STATUS

Received: 26 Dec. 2023
Accepted: 25 Jun. 2024
Associate editor: Fernando Gomes

CORRESPONDENCE TO

Pablo González Barrios
Av. Garzón, 780, Montevideo, Uruguay
e-mail: pablog@fagro.edu.uy

AUTHORS' CONTRIBUTIONS

Paulina Siri: conceptualization (equal), data curation (lead), formal analysis (lead), investigation(equal), methodology (equal), software (equal), validation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal).

Cecilia Bruno: conceptualization (supporting), formal analysis(equal), methodology(equal), writing – original draft (supporting), writing – review & editing (supporting).

Mónica Balzarini: conceptualization (supporting), formal analysis (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Valentina Benitez: data curation (supporting), investigation (supporting), resources (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Andrés Hirigoyen: investigation (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Luciana Ingaramo: conceptualization (supporting), data curation (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Juan Pedro Posse: conceptualization (supporting), data curation (supporting), investigation (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Jean Kassio Fedrigo: investigation (supporting), supervision (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Pablo Gonzalez: conceptualization (lead), data curation (supporting), formal analysis (lead), funding acquisition (lead), investigation (lead), methodology (lead), project administration (lead), software(equal), supervision (lead), writing – original draft (lead), writing – review & editing (lead).

SUPPLEMENTARY MATERIAL

The following online material is available for this article:

Figure S1. Yearly predicted values for individual basal area (m^2 $tree^{-1}$) for each treatment evaluated in dataset A at ages 2 to 16 years after planting. Initial stand densities are separated by color.

Figure S2. Yearly predicted values for individual basal area (m^2 $tree^{-1}$) for each treatment evaluated in dataset B at ages 2 to 16 years after planting. Initial stand densities are separated by color.

Figure S3. Yearly predicted values for individual basal area (m^2 $tree^{-1}$) for each treatment evaluated in dataset C at ages 2 to 16 years after planting. Initial stand densities are separated by color.

Figure S4. Yearly predicted values for individual tree volume (m^3 $tree^{-1}$) for each treatment evaluated in dataset C at ages 2 to 16 years after planting. Initial stand densities are separated by color.

Figure S5. Yearly predicted values for wood volume per hectare (m^3 ha^{-1}) for each treatment evaluated in dataset C at ages 2 to 16 years after planting. Initial stand densities are separated by color.

REFERENCES

Akhtar J, Saqib ZA, Qureshi RH, Haq MA, Iqbal MS, Marcar NE. The effect of spacing on the growth of *Eucalyptus camaldulensis* on salt-affected soils of the Punjab, Pakistan. Canadian journal of forest research 2008; 38(9): 2434-2444.

André JL, Oliveira RDS, Sette Jr CR, Alfenas AC, Zauza EÂV, de Siqueira L. et al. Wood volume of *Eucalyptus* clones established under different spacings in the Brazilian Cerrado. Forest Science 2021; 67(4): 478-489.

Bentancor L, Hernández J, del Pino A, Califra Á, Resquín F, González-Barrios P. Evaluation of the biomass production, energy yield and nutrient removal of *Eucalyptus dunnii* Maiden grown in short rotation coppice under two initial planting densities and harvest systems. Biomass and Bioenergy 2019; 122: 165-174.

Bhandari SK, Veneklaas J, McCaw L, Mazanec R, Renton M. Investigating the effect of neighbor competition on individual tree growth in thinned and unthinned eucalypt forests. Forest Ecology and Management 2021; 499: 119637.

Binkley D. A hypothesis about the interaction of tree dominance and stand production through stand development. Forest Ecology and Management 2004; 190(2-3): 265-271.

Binkley D, Stape JL, Bauerle WL, Ryan MG. Explaining growth of individual trees: light interception and efficiency of light use by *Eucalyptus* at four sites in Brazil. Forest ecology and management 2010; 259(9): 1704-1713.

Binkley D, Campoe OC, Alvares C, Carneiro RL, Cegatta I, Stape JL. The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. Forest Ecology and Management 2017; 405: 271-283.

Binkley D, Fisher, RF. Ecology and management of forest soils. 5th ed. Chichester: John Wiley & Sons; 2019.

Caniza FJ, Garcia MDLA, Aparicio JL, De La Peña CA, Mastrandrea CA, Flores Palenzona M, et al. Avances del INTA en la silvicultura clonal de *Eucalyptus grandis* en la Mesopotamia argentina. 2018

Cassidy, M, Palmer G, Glencross K, Nichols JD, Smith RGB. Stocking and intensity of thinning affect log size and value in *Eucalyptus pilularis*. Forest Ecology and Management 2012; 264: 220-227.

DeBell DS, Keyes CR, Gartner BL. Wood density of *Eucalyptus saligna* grown in Hawaiian plantations: effects of silvicultural practices and relation to growth rate. Australian Forestry 2001; 64(2): 106-110.

Dieste A, Cabrera MN, Clavijo L, Cassella N. Analysis of wood products from an added value perspective: The Uruguayan forestry case. Maderas. Ciencia y tecnología 2019; 21(3): 305-316.

Di Rienzo J, Casanoves F, Balzarini M, Gonzalez L, Tablada M, Robledo C. 2022. InfoStat.

Dwyer JM, Fensham RJ, Fairfax RJ, Buckley YM. Neighbourhood effects influence drought-induced mortality of savanna trees in Australia. Journal of Vegetation Science 2010; 21(3): 573-585.

Elli EF, Sentelhas PC, Bender FD. Impacts and uncertainties of climate change projections on *Eucalyptus* plantations productivity across Brazil. For. Ecol. Manag. 2020; 474.

Fernandes GL, Casas GG, Fardin LP, Nogueira GS, Leite RV, Couto L et al. Effects of Spacing on Early Growth Rate and Yield of Hybrid *Eucalyptus* Stands. Pertanika Journal of Tropical Agricultural Science 2023; 46(2).

Ferraz Filho AC, Mola-Yudego B, Gonzalez-Olabarria J, Scolforo JRS. Thinning regimes and initial spacing for *Eucalyptus* plantations in Brazil. Anais da Academia Brasileira de Ciências 2018; 90: 255-265.

Ferrere P, Lopez GA, Boca RT, Galetti MA, Esparrach CA, Pathauer PS. Initial density effect on *Eucalyptus* globulus growth in a Nelder modified trial. Forest Systems 2005; 14(2): 174-184.

Forrester DI. Growth responses to thinning, pruning and fertilizer application in *Eucalyptus* plantations: a review of their production ecology and interactions. Forest ecology and management 2013; 310: 336-347.

Forrester DI, Wiedemann JC, Forrester RI, Baker TG. Effects of planting density and site quality on mean tree size and total stand growth of *Eucalyptus* globulus plantations. Canadian Journal of Forest Research 2013; 43(9): 846-851.

Forrester DI. Linking forest growth with stand structure: Tree size inequality, tree growth or resource partitioning and the asymmetry of competition. Forest Ecology and Management 2019; 447: 139-157.

Gezan SA, Carvalho M. Analysis of repeated measures for the biological and agricultural sciences. Appl. statistics Agric. Biol. Environ. Sci. 2018; 279–297.

González Barrios P, Borges A, Terra J, Pérez Bidegain M, Gutiérrez L. Spatio-Temporal Modeling and Competition Dynamics in Forest Tillage Experiments on Early Growth of *Eucalyptus grandis L*. Forest Science 2020; 66(5): 526-536.

Griffin AR. Clones or improved seedlings of *Eucalyptus*? Not a simple choice. International Forestry Review 2014; 16(2): 216-224.

Harris F. The effect of competition on stand, tree, and wood growth and structure in subtropical *Eucalyptus grandis* plantations [PhD Thesis] Lismore, Australia: Southern Cross University; 2007.

Hirigoyen A, Franco J, Diéguez U. Modelo dinámico de rodal para *Eucalyptus globulus* L. en Uruguay. Agrociencia (Uruguay) 2018: 22(1): 63-80.

Hirigoyen A, Navarro-Cerrillo R, Bagnara M, Franco J, Requin F, Rachid-Casnati C. Modelling taper and stem volume considering stand density in *Eucalyptus grandis* and *Eucalyptus dunnii*. iForest-Biogeosciences and Forestry 2021; 14(2), 127.

Lie Z, Xue L. Density effect and self-thinning in *Eucalyptus urophylla* stands. *J*ournal of Forestry Research 2019; 30(2): 529-535.

Lintz HE, Gray AN, Yost A, Sniezko R, Woodall C, Reilly M et al. Quantifying density-independent mortality of temperate tree species. Ecological indicators 2016; 66: 1-9.

Littel RC, Milliken GA, Stroup WW, Wolfinger RD, Schabenberger O. SAS for Mixed Models. 2nd ed. NC, USA.

Loughin TM, Roediger MP, Milliken GA, Schmidt JP. On the analysis of long-term experiments. Journal of the Royal Statistical Society Series A: Statistics in Society 2007; 170(1): 29-42.

Malan FS, Hoon, M. Effect of initial spacing and thinning on some wood properties of *Eucalyptus grandis*. South African Forestry Journal 1992; 163(1): 13-20.

Ministerio de Ganadería Agricultura y Pesca (2008). *Análisis de las condiciones hídricas hacia fines de 2008.* https://descargas.mgap.gub.uy/OPYPA/Anuarios/Anuario%202008/material/pdf/39.pdf

Pires EM, Zanuncio JC, Nogueira RM, Soares MA, de Oliveira MA. Dispersal of the zoophytophagous predator *Brontocoris tabidus* and *Podisus nigrispinus* (Heteroptera: Pentatomidae) in an *Eucalyptus* plantation. Florida Entomologist 2020; 103(2): 168-171.

Qu Y, Wang H, Dean TJ, Zhang J, Zhang X. Growth dominance and growth efficiency in response to thinning treatments in Chinese fir plantations with long-term spacing trials. Forest Ecology and Management 2022; 521: 120438.

R Development Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ray DK, Ramankutty N, Mueller ND, West PC, Foley J.A. Recent patterns of crop yield growth and stagnation. Nature communications 2012; 3(1): 1293.

Resquin F, Navarro-Cerrillo RM, Rachid-Casnati C, Hirigoyen A, Carrasco-Letelier L, Duque-Lazo J. Allometry, growth and survival of three *Eucalyptus* species (*Eucalyptus* benthamii Maiden and Cambage, *E. dunnii* Maiden and *E. grandis* Hill ex Maiden) in high-density plantations in Uruguay. Forests 2018; 9(12): 745.

Resquin F, Navarro-Cerrillo RM, Carrasco-Letelier L, Casnati CR. Influence of contrasting stocking densities on the dynamics of above-ground biomass and wood density of *Eucalyptus benthamii, Eucalyptus dunnii*, and *Eucalyptus grandis* for bioenergy in Uruguay. Forest Ecology and Management 2019; 438: 63-74.

Rocha MFV, Veiga TRLA, Soares BCD, Araújo ACCD, Carvalho AMM, Hein PRG. Do the growing conditions of trees influence the wood properties? Floresta e Ambiente 2019; vol 26.

SAS Institute 2011. SAS® Version 9.2. SAS Institute, Cary, NC.

Sherman M. Spatial statistics and spatio-temporal data. Texas: Wiley; 2011.

Schneider PR, Finger CAG, Schneider PSP, Fleig FD, Cunha TAD. Influência do espaçamento no autodesbaste de povoamento monoclonal de *Eucalyptus saligna* Smith. Ciência Florestal 2015; 25: 119-126.

Stape JL, Silva CR, Binkley D. Spacing and geometric layout effects on the productivity of clonal *Eucalyptus* plantations. Trees, Forest and People 2022; 8:100235.

West PW, Smith RGB. Inter-tree competitive processes during early growth of an experimental plantation of *Eucalyptus pilularis* in sub-tropical Australia. Forest Ecology and Management 2019; 451: 117450.