Evaluación de modelos espacio-temporales y herramientas de sensoramiento remoto para mejorar la eficiencia experimental en sistemas forestales

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Maestría en Ciencias Agrarias

Opción Bioestadística

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Resumen

El área forestal en Uruguay ha crecido significativamente en los últimos 30 años. Al presentar ciclos de 8 a 25 años, se genera variabilidad temporal y espacial y se plantean desafíos para el estudio de experimentos. Este trabajo comparó estrategias para modelar datos espacio-temporales y evaluó el uso de imágenes satelitales en el fenotipado. Se analizaron dos experimentos: Los Moros, con *Eucalyptus grandis* plantado en 2003 y 16 tratamientos (manejo silvícola y material genético), y Quebrachal, con *Eucalyptus grandis* y *Pinus taeda* combinados con *switchgrass* en la entrefila plantados en 2008 que evalúan 9 tratamientos (distanciamiento entre filas y control de malezas). En Los Moros, se incorporó el tiempo como covariable en modelos mixtos. Asimismo, a través de algoritmos de Aprendizaje Automatico (Rrandom Forest y Support Vector Regression), se estimó el volúmen por hectárea de las parcelas a través de imágenes satelitales y se comparó con los datos obtenidos a campo. En Quebrachal, se evaluaron modelos mixtos con estructuras de varianza-covarianzas temporales, espaciales y espacio-temporales para predecir volumen de madera y área basal; con el mejor modelo seleccionado a través de BIC se compararon los tratamientos y su interacción. En Los Moros y Quebrachal, tratamientos más densos dieron como resultado árboles más chicos y mayor productividad de madera por hectárea. El uso de imágenes satelitales muestra resultados promisorios en el desarrollo de modelos de predicción en condiciones experimentales. En Quebrachal, la integración de estructuras espacio-temporales en los modelos mejoró la precisión de las estimaciones. Este trabajo aporta evidencias de mejoras al momento de adoptar estrategias de análisis que incorporen información espacio-temporal. Sumado a la adopción de herramientas de sensoramiento remoto en condiciones experimentales, muestra que es posible generar mejoras sustanciales en los sistemas de producción forestales, impulsando optimizaciones en diversos factores que contribuyen positivamente en la sostenibilidad económica y ambiental de estos.

Palabras clave: forestación, modelos espacio-temporales, espaciamiento, control de malezas, imágenes satelitales

Evaluation of spatio-temporal models and remote sensing tools to improve experimental efficiency in forestry systems

Summary

The forest área in Uruguay has significantly increased over the last 30 years. With cycles ranging from 8 to 25, temporal and spatial variability is generated, psoing challenges for the study of experiments. This work compared strategies for modeling spatio-temporal data and evaluated the use of satellite imagery in phenotyping. Two experiments were analyzed: Los Moros, with *Eucalytpus grandis* planted in 2003 and 16 treatments (silvicultura management and genetic material), and Quebrachal, with *Eucalytpus grandis* and *Pinus taeda* combined with switchgrass in the inter-row planted in 2008 evaluating 9 treatments (row spacing and weed control). In Los Moros, time was incorporated as a covariate in mixed models. Likewise, through ML algorithms (RF and SVR), the volume per hectare of the plots was estimated through satellite images and compared with field data. In Quebrachal, mixed models with temporal, spatial and spatio-temporal variace-covariance structures were evaluated to predict wood volumen and basal area; with the best model selected through BIC, treatments and their interaction were compared. In Los Moros and Quebrachal, denser treatments resulted in smaller trees and higher wood productivity per hectare. The use of satellite imagery shows promising results in the development of prediction structures in the models improving the accuracy of the estimates. This work provides evidence of improvements when adopting analysis strategies that incorporate spatio-temporal information. In addition to the adoption of remote sensing tools under experimental conditions, it shows that substantial improvements can be generated in forest production systems, promoting optimization in various factors that contribute positively to their economic and environmental sustainability.

Keywords: forestry, spatio-temporal models, weed control, satellite imagery

1. Introducción

El área destinada a la forestación en el país ha experimentado un aumento significativo en los últimos cuarenta años, pasando de 6,575 hectáreas a 1,1 millones de hectáreas en 2022 (MGAP, 2021). Este notable desarrollo del sector forestal ha resultado en la utilización de suelos con aptitud forestal a lo largo del territorio nacional (Califra et al., 2007; Durán et al., 2005) y subraya la necesidad de adquirir un conocimiento más profundo sobre el crecimiento de rodales productivos, así como del diseño y análisis de ensayos para comparar tratamientos en contextos experimentales, que a menudo perduran muchos años en el campo. Los ciclos de forestación comunes varían entre ocho y veinticinco años, dependiendo del propósito de producción, ya sea para la producción de pulpa de celulosa, madera de elaboración mecánica o doble propósito.

En este contexto toma importancia la investigación en el sector forestal y la generación de experimentos que permitan comparar prácticas silvícolas. Los ensayos de evaluación forestal se caracterizan por tener parcelas de gran tamaño, lo que frecuentemente resulta en estimaciones imprecisas de los efectos de los tratamientos debido a la considerable variabilidad en el tipo de suelo y relieve dentro de cada parcela (Dutkowski et al., 2002). Este factor, a menudo, no es debidamente considerado por los investigadores, lo que conduce a un problema comercial significativo: la implementación de prácticas estándar o inapropiadas en extensas áreas, lo cual afecta de manera desigual a zonas que requieren manejos específicos.

El control de la variabilidad local y la búsqueda de independencia y uniformidad dentro de las unidades experimentales y las superficies comparadas, ha sido un tema de interés constante en la investigación agrícola (Fisher, 1935). El desarrollo y la aplicación de bloques y otras técnicas de diseño experimental han avanzado significativamente, inclusive se ha abordado la heterogeneidad intrínseca en algunos estudios. No obstante, en escenarios de gran variabilidad, se han desarrollado metodologías avanzadas como los diseños de bloques incompletos (Yates, 1939), los diseños en látices (Cochran y Cox, 1957) y los diseños hilera-columna (Williams y John, 1989), que han mejorado la eficiencia en comparación con los modelos de análisis derivados de diseños en bloques completos al azar (Patterson y Hunter, 1983; Yau, 1997).

Por otra parte, en los ensayos forestales —que se extienden durante largos períodos—, la consideración de la variabilidad espacio-temporal es crucial. Limitarse a analizar los resultados finales puede llevar a la pérdida de información valiosa y reducir la aplicabilidad de los resultados para el desarrollo de estrategias de manejo efectivas (González Barrios et al., 2020). Por ello, se han propuesto estrategias dentro de los modelos mixtos para capturar la variabilidad entre años en las mediciones y así mejorar la precisión de los modelos utilizados para comparar tratamientos. La variabilidad del suelo en grandes superficies, como las empleadas en ensayos forestales, es ampliamente reconocida como un factor significativo que afecta la comparación entre tratamientos en experimentos de campo (López y Arrué, 1995). La modelización de correlaciones espaciales mejora la eficacia de los modelos de crecimiento y la estimación de las medias de los tratamientos en experimentos forestales (González Barrios et al., 2015; Lee y Wong, 2001; Liu y Ashton, 1999). Los enfoques espacio-temporales han emergido como herramientas fundamentales, representando una mejora considerable en la estimación de efectos, lo que subraya la importancia de modelos que integren estructuras espaciales y temporales para una evaluación precisa de tratamientos en ensayos forestales (Brownie et al., 2004; Gregoire et al., 1995; O´Rourke y Kelly, 2015).

Una de las alternativas que presenta la forestación es que se pueden instalar cultivos entre filas y, de esta manera, obtener productos intermedios. Sistemas de *intercropping* tales como *switchgrass*-pinos/eucaliptos consisten en incorporar plantas en el área que hay entre las filas de los árboles en un sistema agroforestal (Albaugh et al., 2012; Kimura et al., 2018; Minick et al., 2014; Tian et al., 2017;). Muchos trabajos sugieren el *intercropping* como una alternativa productiva de gran potencial como de fuente de bioenergía porque podría mejorar la eficiencia en el uso del suelo (ciclo de nitrógeno, secuestro de carbón, etc.), tiene retornos económicos tempranos y con menos riesgo por la diversificación de productos (Albaugh et al., 2012; Blazier et al., 2012; Kimura et al., 2018), manteniendo los beneficios económicos y medioambientales de un sistema de forestación (Albaugh et al., 2014; Blazier et al., 2012; Cacho et al., 2015; Muwamba et al., 2015). Además, se aprovecha el espacio entre filas en la etapa inicial mientras la canopia de los árboles aún no está tupida del todo, lo cual ocurre durante los primeros dos años de crecimiento (Tian et al., 2017). Incluso se encontró mayor crecimiento del *switchgrass* durante este período en un sistema de *intercropping* que en uno de monocultivo; esto puede deberse a la reducción del estrés calórico y a que se dan interacciones complejas debajo y por encima de la tierra que pueden beneficiar a las especies del sotobosque (Tian et al., 2017). En la actualidad, es escasa la información disponible sobre el establecimiento, manejo y sostenibilidad de sistemas de *intercropping* que combinen especies forestales como eucalipto y pino con *switchgrass* (Albaugh et al., 2014; Fang et al., 2000; Kimura et al., 2018; Minick et al., 2014; Tian et al., 2017).

En sistemas forestales que utilizan especies como el pino y el eucalipto, evaluar el espaciamiento y el material genético es esencial para optimizar la productividad y sostenibilidad de las plantaciones. Varios trabajos han mostrado que el espaciamiento adecuado influye significativamente en las características de la madera, siendo cruciales para determinar la calidad y el tipo de producto final (Forrester et al., 2013; West y Smith, 2019). Por ejemplo, en sistemas forestales como los utilizados en Uruguay, densidades de plantación más altas se utilizan comúnmente para la producción de pulpa de celulosa, mientras que las densidades más bajas son destinadas a la producción de madera sólida (Resquin et al., 2018). En ese sentido, la selección del tipo de material genético juega un papel importante en la productividad de las plantaciones, donde diferentes materiales, como clones puros e híbridos de eucaliptus o plantas provenientes de semilla, muestran variaciones en el crecimiento, la productividad y la adaptación al ambiente para los fines específicos de producción, ya sea para pulpa o madera sólida (Ferraz Filho et al., 2018; Griffin, 2014). Estos factores, combinados con prácticas silviculturales adecuadas, como el espaciamiento, la fertilización y el raleo, son fundamentales para mejorar tanto el rendimiento cuantitativo como cualitativo de las plantaciones (Cassidy et al., 2012; Forrester, 2013). Por tanto, la integración de enfoques experimentales que consideren tanto el espaciamiento como el material genético es vital para una gestión forestal eficiente, permitiendo un manejo optimizado que se alinea con los objetivos productivos y ambientales de las plantaciones.

En el contexto del desarrollo de actividades de forestación de precisión, que busca optimizar la productividad y sostenibilidad de las plantaciones, el uso de imágenes satelitales se ha vuelto cada vez más relevante. Esta tecnología proporciona datos continuos y de alta precisión a un costo razonable, esencial para la gestión eficiente de los recursos. En particular, las imágenes de alta resolución obtenidas de sensores remotos han demostrado ser cruciales para estimar variables clave como el volumen de madera y la biomasa en plantaciones de eucaliptus y así facilitar el análisis en extensas áreas forestales (Liu et al., 2022; Tinkham et al., 2018). Los índices de vegetación derivados de estas imágenes, como el (Índice de vegetación de diferencia normalizada) NDVI y el (Índice de razón simple) SRI , entre otros, han mostrado correlaciones positivas con diversas variables productivas, lo que permite una evaluación precisa y más económica que los métodos tradicionales de inventario a campo (Hirigoyen et al., 2021; Le Maire et al., 2012). Por otro lado, el procesamiento y análisis de datos de teledetección se ha mejorado mediante el uso de algoritmos de *machine learning*, como *random forest* y *support vector regression*, proporcionando herramientas avanzadas para el mapeo y la estimación de atributos productivos (Dos Reis et al., 2019; Liu et al., 2022). Este enfoque integrado no solo mejora la eficiencia de la gestión, sino que también apoya la toma de decisiones informadas en el manejo de plantaciones, particularmente en contextos experimentales donde se comparan diferentes tratamientos silvícolas. Por lo tanto, la combinación de teledetección y estrategias de análisis avanzados representa un avance significativo en sistemas de producción forestales, proporcionando una base sólida para la investigación y práctica sostenible.

El objetivo de este proyecto fue evaluar estrategias de modelación espacio-temporal (ST) y utilización de información de imágenes satelitales para mejorar la eficiencia de experimentos agroforestales. Para ellos se trabajó con dos experimentos independientes para abordar diferentes objetivos específicos: i) comparar estrategias de modelación incorporando información de correlaciones ST que mejoren la eficiencia de diseños experimentales; ii) evaluar el efecto del distanciamiento o arreglo espacial sobre variables de producción de madera con destino a elaboración mecánica y pulpa de celulosa y iii) generar estrategias de relevamiento de información de variables productivas de árboles mediante el uso de imágenes satelitales. Los experimentos utilizados fueron ensayos en pino y eucalipto de largo plazo con evaluación de tratamientos de distanciamiento y control de malezas con fajas de *intercropping* y un experimento de eucalipto de largo plazo evaluando diferentes arreglos espaciales y material genético. Se evaluaron diferentes estrategias para incorporar información espacio-temporal basadas en indicadores de eficiencia y ajuste del modelo. Por otro lado, índices de vegetación y diferentes estrategias de *machine learning* fueron evaluados en términos de correlaciones entre predichos por el modelo versus mediciones manuales con el objetivo de determinar estrategias óptimas en el uso de imágenes satelitales. Se espera que este proyecto genere un aporte sustancial a la mejora de las herramientas de análisis en sistemas forestales y mejore el entendimiento y la toma de decisiones tanto en el ámbito experimental como comercial en Uruguay.

1.1. Objetivos

1.1.1. Hipótesis general

Existen herramientas de análisis modernas que permiten hacer mejores estimaciones que las que se están realizando en experimentos de evaluación forestal para medir y predecir variables productivas en plantaciones de eucaliptus y pino en experimentos de largo plazo y bajo condiciones de gran variabilidad espacial interparcelaria.

1.1.2. Objetivo general

Evaluar y comparar diferentes metodologías de análisis de datos y sistemas de medición en experimentos forestales con medidas repetidas en el tiempo y gran variabilidad espacial.

1.1.3. Hipótesis específicas

a) La variabilidad temporal y espacial existente en los experimentos puede ser incorporada en los modelos mixtos utilizados para predecir el rendimiento de experimentos forestales a través del uso de estructuras de correlación en la matriz de varianza-covarianza y mejorar su ajuste y precisión.

b) La densidad de plantación y el material genético son factores que afectan la productividad y la mortalidad en rodales de eucaliptus tanto para producción de pulpa como para elaboración mecánica.

c) La distancia entre filas y el control de malezas incide en los niveles de productividad de madera de pinos y eucaliptos en condiciones de largo plazo y afectan el desempeño de *switchgrass* como cultivo de intersiembra.

d) El uso de imágenes satelitales a través de algoritmos de *machine learning* permite obtener buenas predicciones de productividad de madera en condiciones parcelarias experimentales.

1.1.4. Objetivos específicos

a) Evaluar el desempeño, en términos de ajuste, de modelos que incorporan estructuras de correlación dentro de la matriz de varianza y covarianza de modelos mixtos en relación con modelos clásicos de análisis de datos en el estudio de experimentos forestales.

b) Comparar manejos silvícolas y materiales genéticos en un experimento de largo plazo con eucaliptus en términos de productividad de madera y mortalidad.

c) Comparar y evaluar la productividad de madera y rendimiento individual en árboles de pino y eucaliptus y biomasa de *switchgrass* —como cultivo de intersiembra— con diferentes distanciamientos y franjas de control de malezas.

d) Determinar la mejor estrategia de *machine learning* utilizando información de las bandas espectrales e índices de vegetación provenientes de imágenes satelitales para predecir volumen de madera por hectárea en el contexto de experimentos forestales.

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

Siri, P.; Bruno, C., Balzarini, M.; Fedrigo, J.K.; Benitez, V.; Hirigoyen, A.; Posse, J.P.; Ingaramo, L.; González Barrios, P.

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2.1 Resumen

El impacto de las prácticas forestales fue evaluado en las variables de crecimiento y dinámica de mortalidad de eucalipto. Se realizó un experimento en el norte de Uruguay durante dieciséis años, comparando dieciséis tratamientos de espaciamiento y raleo según el material genético y el objetivo productivo. La altura de los árboles y el diámetro a la altura del pecho fueron evaluados anualmente por árbol. Todas las variables fueron analizadas utilizando modelos mixtos lineales. Se utilizó análisis de supervivencia de Kaplan-Meier y la prueba de Log Rank para comparar la supervivencia de los árboles. 460 árboles ha^{-1} de material de semilla resultaron en el área basal individual más alta (0,023 m^{2}), mientras que los tratamientos con 2000 árboles ha^{-1}, sin raleo, generaron un mayor rendimiento por hectárea (1147 m^{3} ha^{-1}). Se detectaron variaciones en la mortalidad en tratamientos de mayor densidad (por encima de 800 árboles ha^{-1}). Este estudio subraya la importancia crítica de gestionar el espaciamiento, el material genético y las prácticas de raleo para optimizar el crecimiento del eucalipto y la sostenibilidad de sistemas forestales.

Palabras clave: manejo forestal, densidad del rodal, tasa de supervivencia, raleo

2.2. Summary

The impact of forestry practices was evaluated on *Eucalyptus's* growth variables and mortality dynamics. An experiment was conducted in the northern of 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 on a per-tree basis. 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 (1147 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 and sustainability of forestry systems.

Keywords: Forest management · stand density · survival rate · thinning

2.3. INTRODUCTION AND OBJECTIVES

In the past few decades, forestry has emerged as a globally significant field, critically influencing both economic and ecological dynamics worldwide. Notably, *Eucalyptus,* one of the most widely planted hardwood species, covers over 25 million hectares worldwide (Elli et al., 2020), with more than ten million hectares in South America (Martins et al., 2022). In Uruguay, driven by evolving regulatory policies, there has been a remarkable expansion of areas designated for fast-growing species, particularly *Eucalyptus*, which now dominates 70% of the country's planted 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 such as high-quality wood, mechanical transformation products, bioenergy, and cellulose pulp (Resquin et al., 2019). The productivity potential of forest systems is primarily influenced by management practices, such as genetic selection, soil preparation, initial stand density (SD), weed and pest control, and thinning, rather than environmental variations (Binkley and Fisher, 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). Evaluating these aspects within experimental conditions is not frequent, leading to a general lack of detailed information.

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 and 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 planting density 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 and 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 et al., 2017; Lie & Xue, 2019) There is a pressing need for further research efforts to address the impacts of competition on productivity, with a specific focus on solid wood production. 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). This gap highlights the need for multifaceted applications and benefits of such research in sustainable forestry management. Therefore, this study aims to evaluate the effect of tree spacing, genetic material (*E. grandis* grown by seed or clones, pure or hybrid E. *grandis* × E. *camaldulensis*), and thinning practices on stand growth, considering two different end uses: cellulose pulp or solid wood.

2.4. MATERIALS AND METHODS

2.4.1. 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, which is evenly distributed throughout the year. The average temperature is around 18 ºC, with the highest mean temperature occurring in January (22 ºC), and the lowest in June (10 ºC). The region exhibits frequent and significant temperature fluctuations throughout the year. The predominant soils in the area 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).

2.4.2. Experimental design and data collection

In this study, we analyzed an *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.

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 of dataset C 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 of plantation, 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 (plots) were of fixed dimensions, measuring 900 square meters (30 m × 30 m).

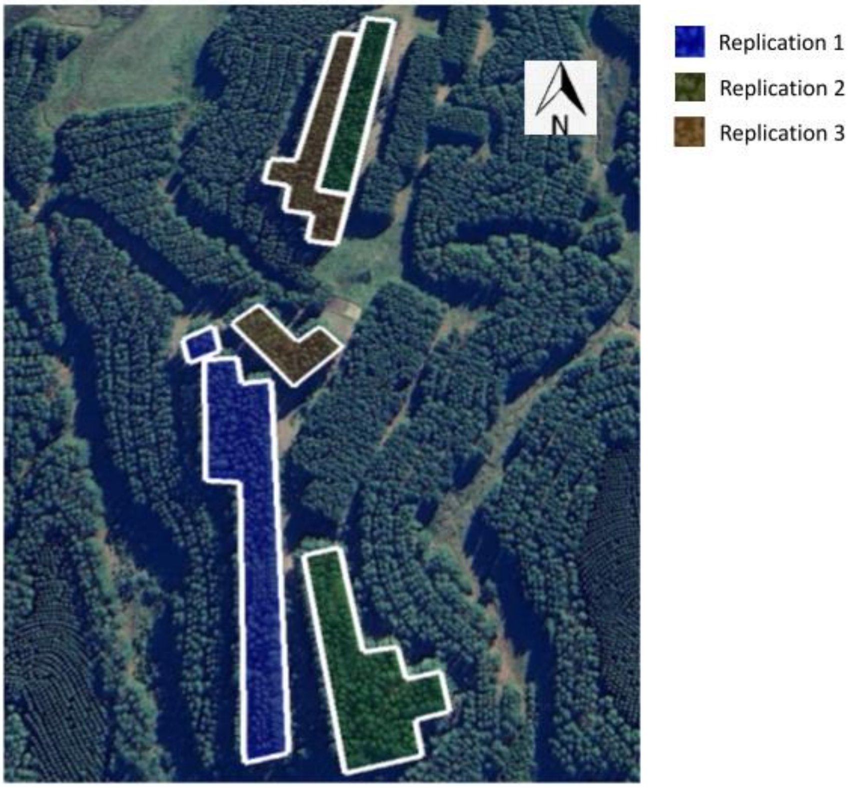

Figure 1. Satellite image of the experimental site, where replications are differentiated by color, and treatments from each dataset are distributed in each replication. Each experimental unit is a square of 30 meters by 30 meters

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

Data	Treatment code	Genetic material	Initial density (trees ha^{-1})	Thinnig*	Final density (trees ha^{-1})	Distance among trees (m x m)
A	400_400_C1	*E. Grandis*	400	-	400	5 x 5
A	500_350_C1	*E. Grandis*	500	8	350	4.5 x 4.5
A	622_444_C1	*E. Grandis*	622	8	444	4 x 4
A	622_622_C1	*E. Grandis*	622	-	622	4 x 4
A	800_333_C1	*E. Grandis*	800	2 / 8	333	3.5 x 3.5
A	800_800_C1	*E. Grandis*	800	-	800	3.5 x 3.5
A	800_333_S	*E. Grandis*	800	2 / 8	333	3.5 x 3.5
A	800_800_S	*E. Grandis*	800	-	800	3.5 x 3.5
B	400_400_C2	*E. Grandis* x *E. camandulensis*	400	-	400	13 x 5
B	500_350_C2	*E. Grandis* x *E. camandulensis*	500	8	350	6 x 5
B	622_350_C2	*E. Grandis* x *E. camandulensis*	622	8	444	4.5 x 4.5
B	622_622_C2	*E. Grandis* x *E. camandulensis*	622	-	622	4 x 5
B	800_333_C2	*E. Grandis* x *E. camandulensis*	800	2 / 8	333	4 x 5
B	800_800_C2	*E. Grandis* x *E. camandulensis*	800	-	800	3.5 x 3.55
C	1111_460_S	Seed	1111	2 / 8	460	3.5 x 3.5
C	1111_1111_S	Seed	1111	-	1111	3 x 3
C	1600_1033_S	Seed	1600	2 / 8	1033	3 x 3
C	1600_640_S	Seed	1600	8	640	2.5 x 2.5
C	2000_2000_S	Seed	2000	-	2000	2.5 x 2.5

[*] Years after planting

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 planting densities, a varying number of observational trees per experimental unit were observed. In dataset C, individual tree volumes were calculated for each treatment using the taper functions described by Hirigoyen et al. (2021a). 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.

2.4.3. 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 either BA (m^2) or individual/total tree volume (m^3 ha^{-1}), μ is the overall mean, τ_i: is the effect of the *i-th* SD, δ_j is the effect of *j-th* replication, x is a covariate: the year in a linear and quadratic relationship with the response variable and β_1 and β_1, the associated coefficients, $\tau\delta^{ij}$ is the SD by replication interaction effect, τx_{ik} is the interactión between the covariate and treatment effect, 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 a grouping criterion or subject. This approach was chosen due to the non-continuous nature of the measurements over the years.

For each variable, an analysis of variance was conducted, followed by a post hoc Tukey test (α= 0.05) to determine significant differences. To compare the survival rate of *Eucalyptus* among treatments, Kaplan-Meier survival analysis and Log Rank test (α = 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, which was at age 8 for the thinning treatment. 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).

2.5. RESULTS

2.5.1. 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. 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, by the age of sixteen years, the 400_400_C2 exhibited a greater BA compared to 800_800_C2, this probably has to do with the fact that, being hybrid clones, competition has not yet started to affect the growth of the trees. The remaining treatments were grouped without significant differences (Dataset C). 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 years. Nevertheless, at the age of sixteen years, 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.

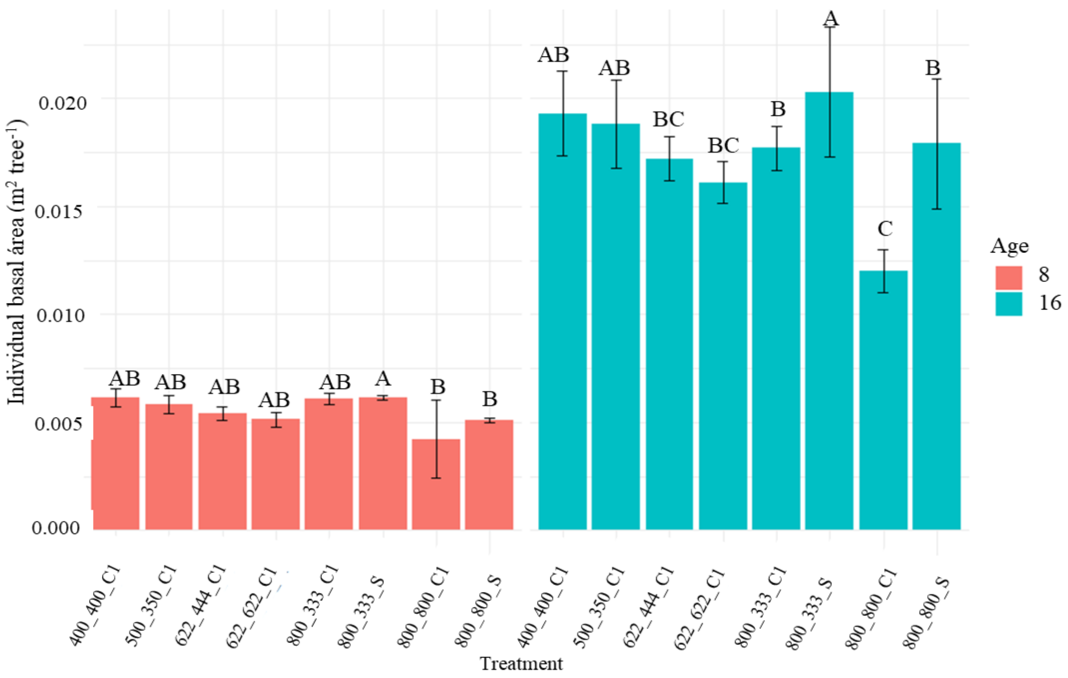

Figure 2. Adjusted means and standard error for individual basal area (m^2 tree-[1]) for each treatment evaluated in data A at ages 8 at ages 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$)

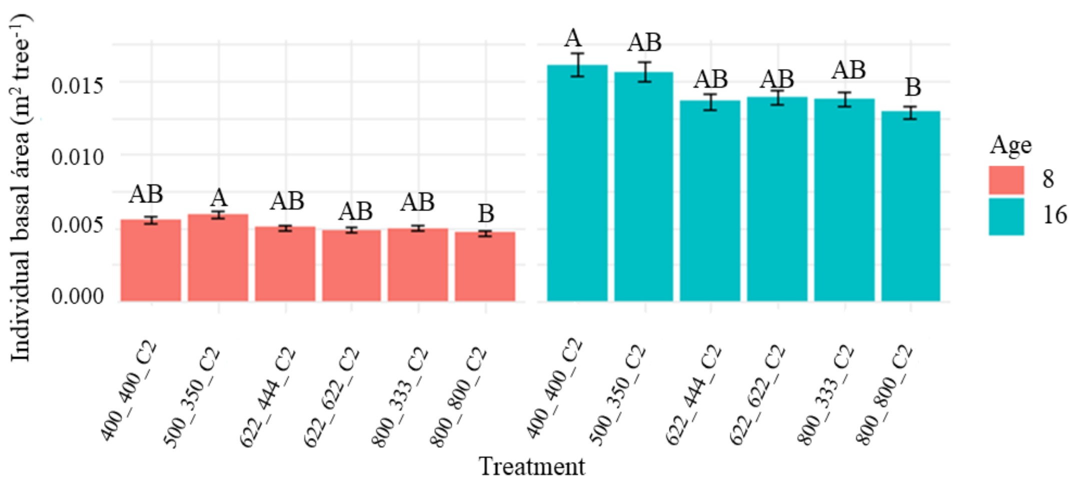

Figure 3. Adjusted means and standard error for individual BA (m^2 tree−1) for each treatment evaluated in dataset B at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$)

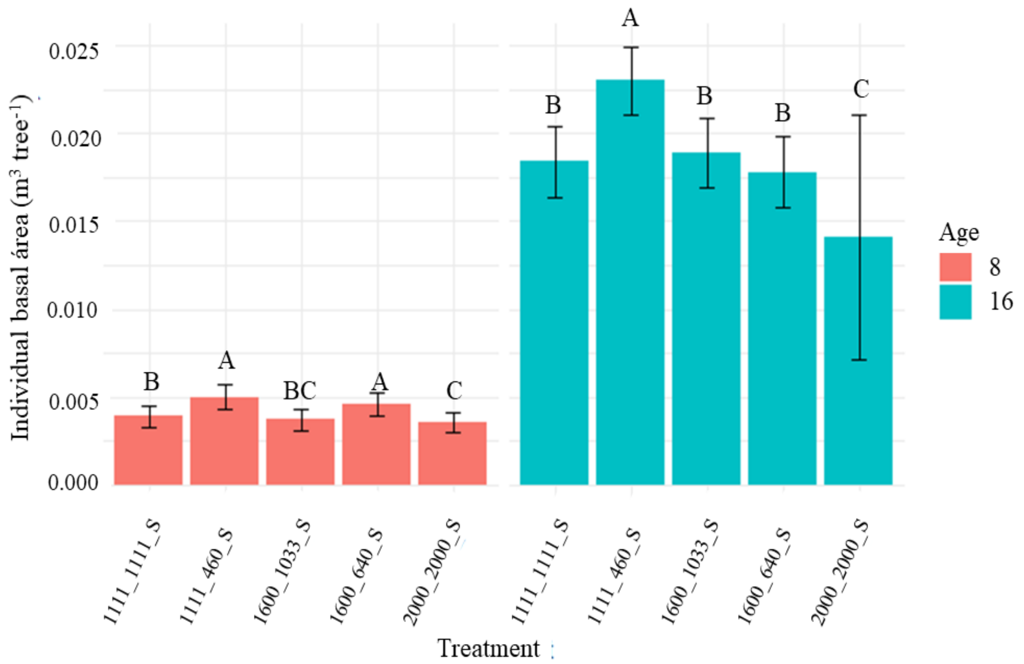

Figure 4. Adjusted means and standard error for individual basal area (m^2 tree−1) for each treatment evaluated in dataset C at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$)

2.5.2. 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 the age of sixteen, 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.

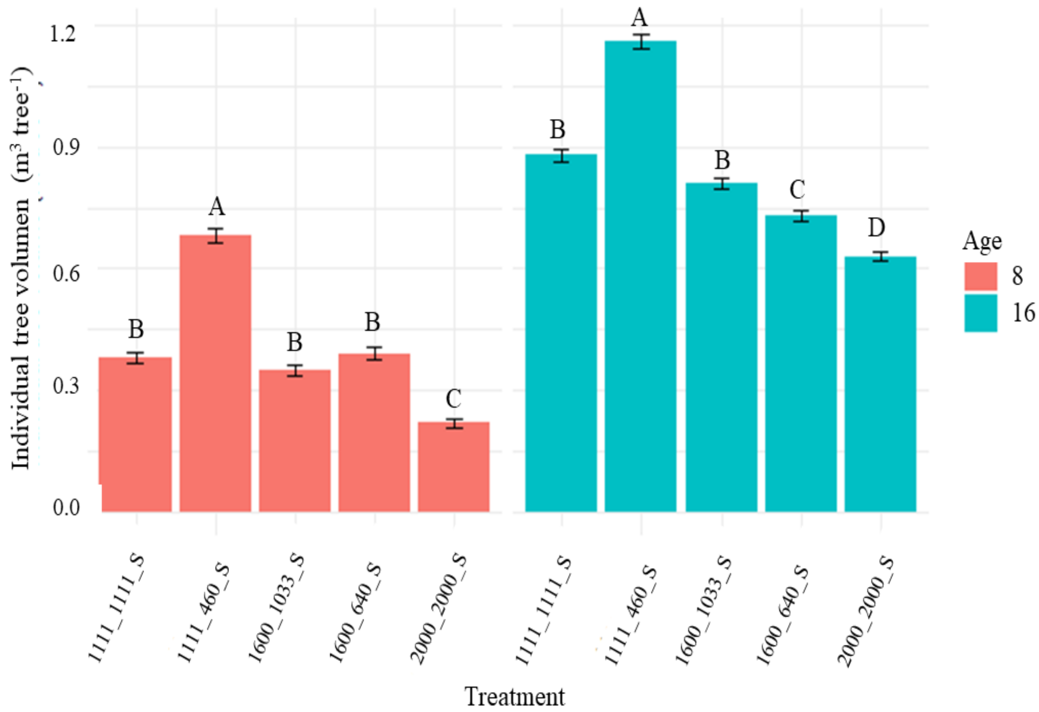

Figure 5. Adjusted means and standard error for individual tree volume (m^3 tree−1) for each treatment evaluated in dataset C at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$)

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 such as 1111_1111_S and 2000_2000_S exhibit higher volumes per hectare at ages 8 and 16, respectively. As the years progress, fewer differences become apparent, and changes in ranking emerge. 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.

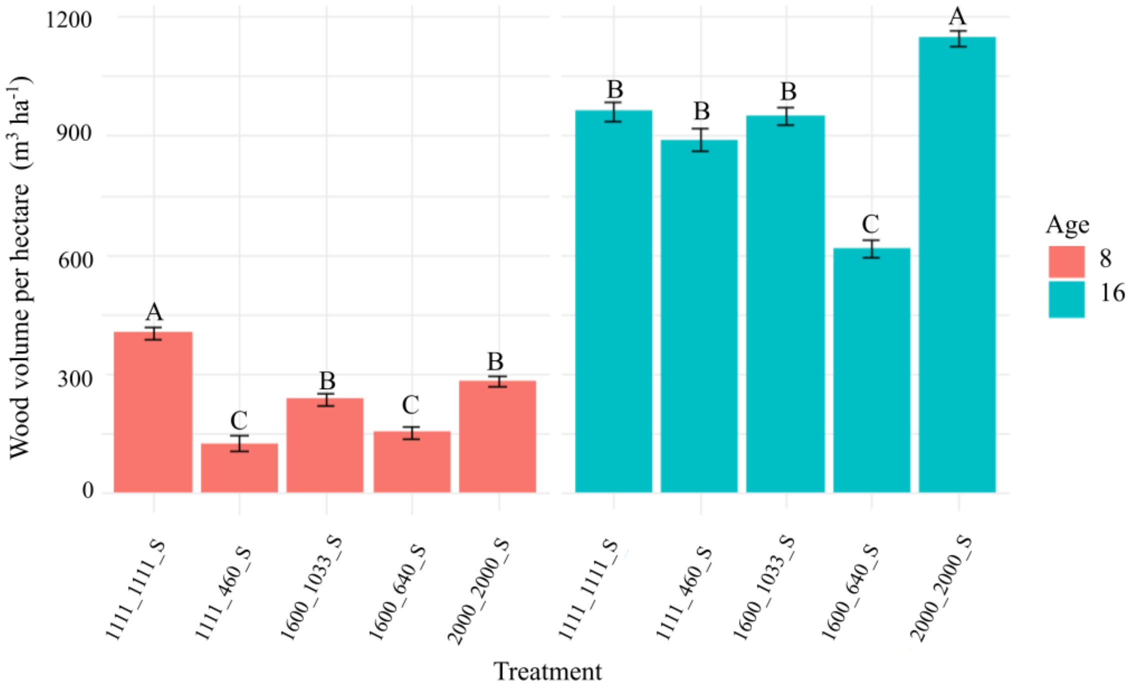

Figure 6. Adjusted means and standard error for wood volume per hectare (m^3 ha^{-1}) for each treatment evaluated in dataset C, at ages 8 and 16 years after planting. Means with common letters are not significantly different ($p \leq 0.05$)

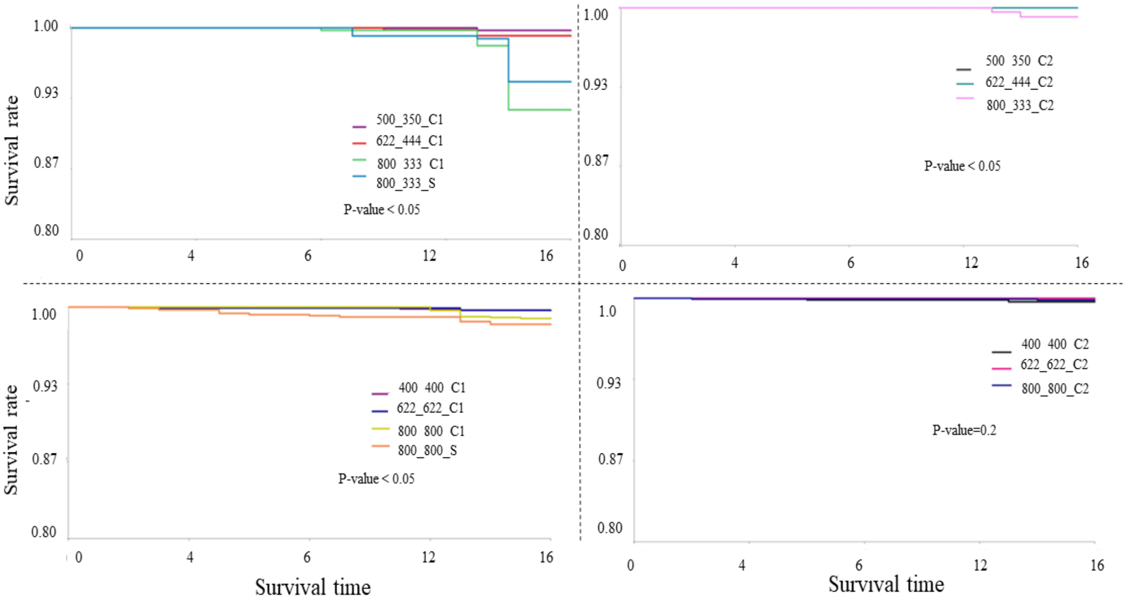

Figure 7. Tree survival rate for dataset A (left panels) and B (right panels), with thinning (lower panels) without thinning (upper panels, time 0 is eight years after planting when the final density was reached) evaluated from the time that final SD was reached antil age 16. Means with common letters are not significantly different ($p \leq 0.05$)

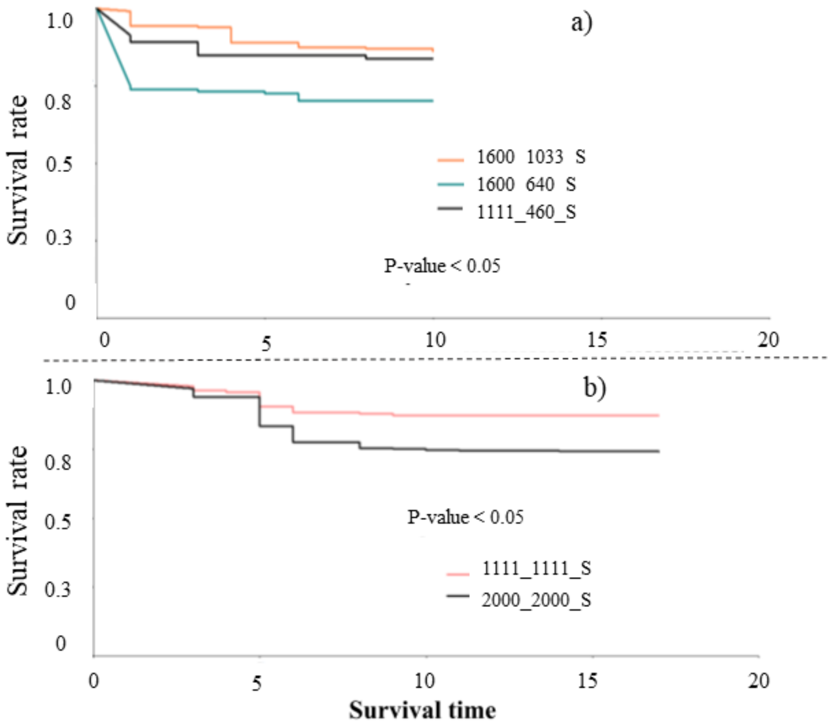

Figure 8. Tree survival rate for data C was evaluated from the latest thinning practice (final SD) until age 16 by treatment. The analysis was performed separately depending on silvicultural practices with (upper panel, time 0 is eight years after planting when the final density was reached) and without thinning (lower panel. Means with common letters are not significantly different ($p \leq 0.05$)

2.5.3. 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. 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.

2.6. DISCUSSION

2.6.1. 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 in 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.

2.6.2. 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 pulp due to larger trees at final time with the trees not being too uniform, 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 great 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 density, especially in hybrid clones (Dataset B), where initial density plays a significant role. Additionally, thinning effects are more pronounced in treatments that start with high SDs and undergo substantial reductions in individual numbers by the end of the period. This is linked to initial SDs of fewer than 800 trees per hectare and thinnings of less than 50% of individuals.

In Dataset B, the majority of treatments did not show significant differences, as depicted in 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 is not only attributable to C2, but was also observed in C1 and seed material. It's important to emphasize that all treatments in this dataset employed a hybrid clone as the genetic material. 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 basal area values at sixteen years, suggesting the viability of dual-purpose stands where larger trees caused the average individual BAs to be higher. 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 the 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 (1120 m^3 ha^{-1}) compared to 1111_460_S (885 m^3 ha^{-1}) and 1600_640_S (620 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.

2. 6. 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 yet. This demonstrates that the impact of competition is contingent on specific genetic and environmental circumstances.

In Dataset C, which evaluated seed-type treatments with higher stand densities, 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 (2019). 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 and the development of refined management strategies tailored to local stands.

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.

2.7. CONCLUSIONS

Our research after sixteen 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 planting densities were particularly effective in enhancing individual tree growth, whereas higher densities, 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.

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3. Spatio-temporal mixed models strategies to increase experimental precision in large agroforestry experiments

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3.1. Resumen

El crecimiento de la forestación genera la necesidad de mejorar prácticas forestales y la demanda de estrategias de analisis más efectivas. Sistemas integrados, que combinan la silvicultura con cultivos, ofrecen soluciones sostenibles, contribuyendo a la biodiversidad y la salud del ecosistema. Esta investigación explora los efectos a largo plazo del control de malezas y el espaciamiento en *Eucalyptus grandis* y *Pinus taeda*, intercalados con *switchgrass*, en un experimento parcelario. Utilizando modelos mixtos espacio-temporales, se buscó incrementar la precisión experimental y comprender la dinámica del crecimiento de los árboles y el manejo forestal. utilizando el modelo con mayor ajuste, se encontraron efectos significativos del espaciamiento y control de malezas en el volumen de madera y el área basal. Los resultados óptimos se alcanzaron con un espaciamiento de filas de 7 m para ambas especies para volumen de madera por hectárea, mientras que un espaciamiento de 12 m fue preferible para el volume individual. Con nivel medio y bajo de control de malezas se encontró el mayor volumen de madera individual y por hectarea. La productividad del *switchgrass* difirió notablemente entre niveles de franja libre de malezas alto y bajo, siendo más productivos los niveles bajos. Se resalta el valor del análisis espacio-temporal en experimentos agroforestales. Los resultados son un aporte positivo a la mejora de la productividad y sostenibilidad de los sistemas agroforestales, particularmente para sistemas con características ambientales similares.

Palabras clave: distancia entre filas, control de malezas, eucalipto, pino, volumen de madera

3.2. Abstract

The global rise in afforestation highlights the need of improved forestry practices like tree spacing, underscoring the demand for better management strategies. Integrated systems such as agroforestry systems, merging forestry with crops or pastures, offer sustainable solutions, contributing to biodiversity and ecosystem health. This research explores the long-term effects of weed control and row spacing on *Eucalyptus grandis* and *Pinus taeda*, intercropped with switchgrass, in an experimental context. Using spatiotemporal mixed models, we aimed to increase experimental accuracy and understand the dynamics between tree growth and agroforestry management. The study evaluated various spatiotemporal variance and covariance structures, finding significant impacts of spacing and weed control on wood volume and basal area. Optimal results were achieved with a 7 m row spacing for both species for wood volume per hectare, while a 12 m spacing was preferable for individual tree sizes. Effective weed control was linked to medium and low levels, affecting both per tree and per hectare wood volume. Switchgrass productivity differed notably between high and low management levels, with lower levels proving more productive. This study illustrates the value of spatiotemporal analysis in agroforestry, aiding in the development of superior forest management approaches. Although centered on production, future economic evaluations are advised for a holistic understanding of these systems. Our findings notably enhance the productivity and sustainability of agroforestry systems, relevant to regions with comparable environmental characteristics.

Keywords: row distance · weed control · Pine · Eucalyptus · wood volume

3.3. Introduction

Forestry systems are sustainable systems that produce energy, with social and environmental benefits, providing an extended variety of products (Silva et al. 2019; Heidari et al. 2021). Eucalyptus is the most planted species in the world, covering more than nineteenth million hectares (Heidari et al. 2021). On the other hand, pine is the most planted species in the southern United States and one of the most widely produced worldwide (Samuelson et al. 2004). In many parts of the world, there is rapid growth and development in the forestry and cellulose production sector (López 2010; Cardoso et al. 2013; Heidari et al. 2021). Particularly in Uruguay, eucalyptus (mainly *E. grandis*) is planted for pulp or timber production, while pine (*P. taeda*) is planted solely for sawn timber. The product's destination has an impact on the management carried out and the potential environmental impact it may have (Hernandez et al. 2015). Due to the diversity of management strategies and extractable products, strengthening experimentation and analysis of this type of experiment at the global and regional levels becomes essential (Cardoso et al. 2013; Condés et al. 2013).

Planting spacing plays a crucial role in the growth and development of trees, and it is a key factor that must be studied and related to the thinning operations carried out during the production cycle (Ferrere et al. 2005; Cardoso et al. 2013; West and Smith 2019). Spacing significantly impacts productive traits, health and other factors affecting tree productivity, both in their individual and in the per unit area characteristics. This impact varies throughout the extensive production cycle; moreover, these factors have differential repercussions depending on the species (Cardoso et al. 2013; Resquin et al. 2019; Spencer et al. 2021). Numerous studies on eucalyptus (West and Smith 2019; Stape et al. 2022) and pine (Dos Santos et al. 2020) have demonstrated the relevance of optimizing spacing for a comprehensive understanding and effective management of forest systems (West et al. 2021; Kunstler et al. 2016; Reid 2006). For example, Resquin et al. (2019) found that different planting densities had contrasting effects on the dynamics of aboveground biomass and wood density of *Eucalyptus benthamii*, *E. dunnii* and *E. grandis* grown for bioenergy in Uruguay. West and Smith (2019) found that initial spacing influenced competitive processes among trees during early growth in an experimental plantation of *Eucalyptus pilularis*. Additionally, André et al. (2021) reported that different spacings significantly affected the wood volume production of eucalyptus clones grown in the Brazilian Cerrado region.

The presence of weeds can compromise tree growth as they compete for water, nutrients and other factors, reducing the qualitative and quantitative benefits of individuals and interfering with the development of forest species (Wagner et al. 2018). Effective weed management and control are essential for the establishment of commercial forest species (Amaral et al. 2020). There is a significant influence on the silvicultural management that is carried out, which includes weed management and the clear zone left around the trees to manage competition (Samuelson et al. 2004; Coll et al. 2019). Understanding the influence of weed competition is crucial to achieving maximum productivity, considering that these plantations are complex and remain in the field for a long time with their competition dynamic, along with its consequences (Gabbard and Fowler 2021; Zeller et al. 2022).

Agroforestry systems often employ intercropping strategies to enhance production diversification and efficient land utilization. Switchgrass (*Panicum virgatum* L.), a perennial C4 grass from North America, is recognized as a model bioenergy crop due to its high yield potential and environmental benefits, notably in carbon sequestration and greenhouse gas mitigation (Larnaudie et al. 2022). Intercropping has been suggested as an efficient, productive alternative offering enhanced land use (e.g., improved nitrogen cycle, carbon sequestration) and earlier economic returns with lower risk through diversification (Albaugh et al. 2012; Blazier et al. 2012; Kimura et al. 2018), while sustaining the economic and environmental benefits associated with forestation (Albaugh et al. 2014; Cacho et al. 2015; Muwamba et al. 2015). Introducing switchgrass in agroforestry systems by intercropping between tree rows could enhance both economic and ecological sustainability by diversifying production and improving land-use efficiency (Albaugh et al. 2012; Blazier et al. 2012; Kimura et al. 2018). Initial growth benefits of switchgrass under less dense canopies indicate the potential for reduced heat stress and beneficial below- and above-ground interactions (Tian et al. 2017). However, research on the establishment, management and long-term sustainability of switchgrass-forestry intercropping systems, especially in Uruguay, is limited and necessitates further investigation.

Modeling growth variables in long-term experiments, such as those in forest research, poses challenges due to temporal and spatial variability (López and Arrué 1995; Skovsgaard and Vanclay 2013). Employing strategies that address spatial and/or temporal correlations significantly enhances the efficiency of large-scale experimental analysis (Van Laar 1996; Richter et al. 2012; Piepho et al. 2014). Recent applications of linear mixed models in forestry research underscore their utility: Guillemot et al. (2015) investigated the effects of thinning intensity and tree size on the growth response to climate in *Cedrus atlantica* using a mixed modeling approach, highlighting temporal variability. In contrast, Pretzsch and Biber (2016) focused on tree species mixing to increase stand density, addressing spatial correlations. Similarly, González Barrios et al. (2015) explored spatial soil variability in *Eucalyptus grandis* growth, while their subsequent study (2020) extended this to spatio-temporal modeling, revealing significant impacts on early growth dynamics. These studies illustrate the benefits of integrating spatial and temporal dimensions to generate more reliable conclusions in forest trials, essential for assessing treatment effects and guiding sustainable management practices.

This study aims to evaluate the long-term growth responses of *Eucalyptus grandis* and *Pinus taeda* under varying weed control intensities, row spacings and their interactions. We examined different strategies through the evaluation of two separate experiments, one for each species. Both experiments were conducted using a strip plot design with three replications, focusing on the primary treatments of row spacing and weed control effects in conjunction with the growth traits of switchgrass and trees. The objectives included assessing several linear mixed models approaches that account for spatio-temporal correlations and identifying the optimal combinations of row spacing and weed control for production variables, utilizing the most effective strategy.

3.4. Materials and methods

3.3.1. Experimental design and site description

The experiment was installed in the department of Cerro Largo, Uruguay, at coordinates 32º62´S and 54º45´W (1446.2 masl). 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 occurring in January (22 ºC) and the lowest in June (10 ºC). The region exhibits frequent and significant temperature fluctuations throughout the year. The predominant soils are umbric-ochric Luvisols Typical sandy to rhodic sandy loam (classified as CONEAT 2.14 in the Uruguayan System of Soil Aptitude). Additionally, there are Melanic Subeutric Lithosols, gravelly sand, sometimes stony and very shallow (CONEAT 2.11b).

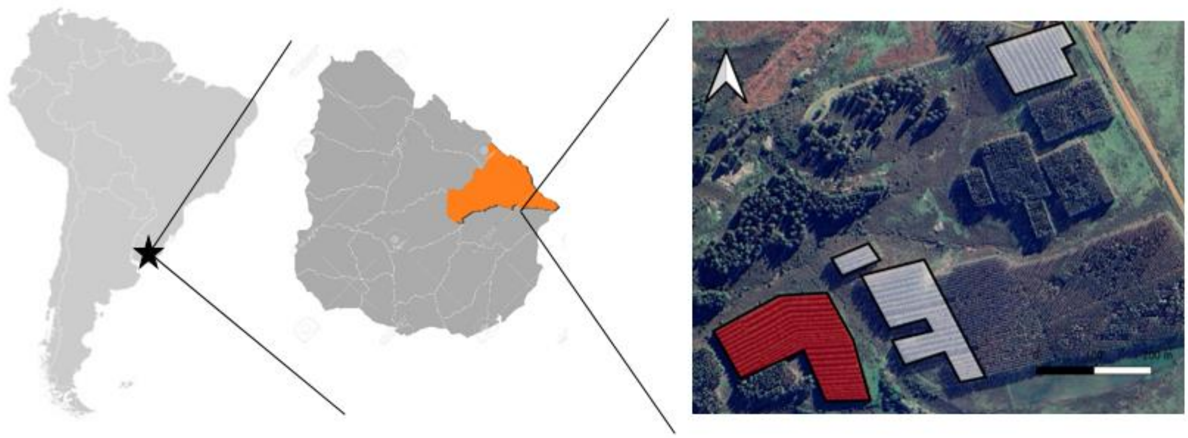

Figure 1. Location and scheme of the study area Quebrachal with both trials with eucalyptus (white) and pine (red), located in Cerro Largo department (Uruguay)

A long-term field study (intercropping study with switchgrass and forestry) was established in the northeast of Uruguay to determine weed control and row distance effects on the site productivity within the context of intensive forest management for the production of solid wood. For this, switchgrass was planted in the inter-row and kept for four years. Between the planted switchgrass and trees, weed control was applied in strips of different widths and this conformed the treatments together with the distance between rows. As this multifunctional intercropped production system has the potential to be broadly applicable, we evaluated the long-term effect that the different treatments have on wood production and its consequences.

The trial was planted in 2005 to assess intercropping and its interaction with spacing and weed control strategies. Switchgrass (*Panicum virgatum*) was planted in the inter-row to evaluate its performance under the different site conditions. This switchgrass trial continued for four years before the focus shifted solely to the trees. During this initial phase, standard nitrogen fertilization was applied. By the fourth year, two separate trials were initiated for *Eucalyptus grandis* and *Pinus taeda* to study the influence of row spacing, weed control strips and their interaction on multiple productive variables such as wood volume, diameter at breast height and height over the years.

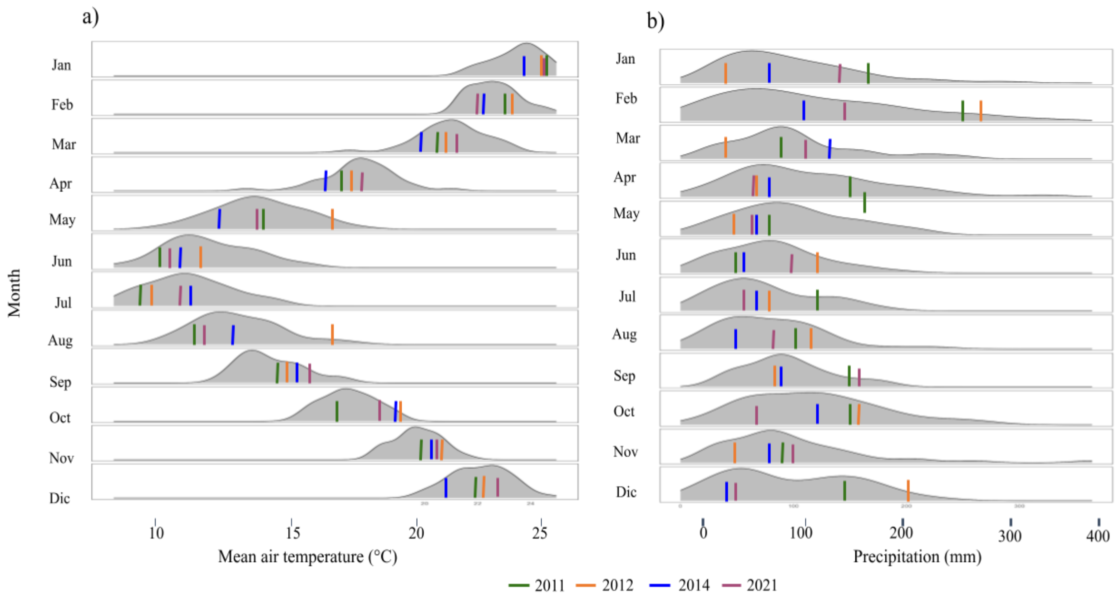

Figure 2. Distribution of mean air temperature (°C) (left panel) and cumulative monthly rainfall (right panel) in Cerro Largo for the period 1978-2021 (density plots) and averages for the period 1978-2021, and for the years 2011, 2012, 2014 and 2021 (indicated by different symbols). The experiments were planted on October 2003 and the last measurement date was on October 2021

The experimental design was strip plot with nine treatments that are a combination of three row distances (RD) and three weed control strips (Figure 3) with three replications. The planting spacing was 7, 9 and 12.5 m by 3.40 m, depending on the treatment, while the weed control strips were 2.75, (high control), 1.5 (medium control) and 0.9 m (low control). There were three experimental units for each treatment with three levels and nine small plots in total for studying the interactions. Each tree was georeferenced with the UTM coordinate system and then a relative georeferencing was carried out within perimeter of the trial marking a point 0.0. We used the spatial information for each tree and included it as realizations of a random variable in each tree in the mixed models. This experiment was established by Lumin Forest Products, LLC.

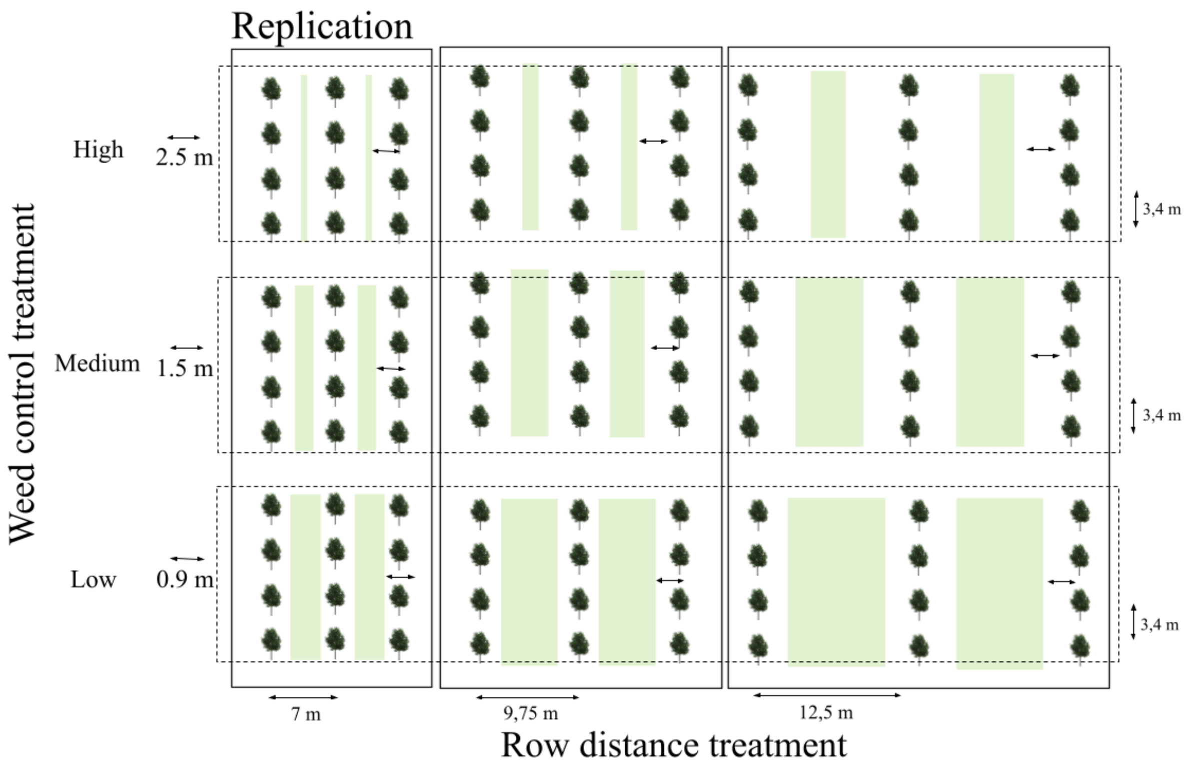

Figure 3. Trial sketch showing the randomization for row distance and weed control treatments for one of the three replications of the trials. The green rectangles between tree rows represent the switchgrass bands present in the first four years of the trial

Plant height (h) and diameter at breast height (DBH) were measured for each tree in both eucalyptus and pine trials at three, four, six and thirteen years after planting. Additionally, in the thirteenth year, each tree was georeferenced. This data was subsequently utilized to assess the performance of models with different spatiotemporal structures for predicting yield per treatment and conducting relevant comparisons. Equations derived from Hirigoyen (2021) were employed to estimate individual tree volume. The total wood volume per hectare (m^3 ha^{-1}) was then calculated for each tree by multiplying its volume by the number of live trees in each plot for each measurement date and subsequently scaling it by the plot area to obtain the volume per hectare.

3.4.2. Statistical analysis

Different strategies were used for both trials to address the spatial and temporal variability of the productive variables for *Pinus taeda* and *Eucalyptus grandis* (Table 1); this allowed for modeling intra-plot (i.e. among trees) and temporal (i.e. repeated measurements in the same tree) correlations. Linear mixed models were used with different temporal, spatial and spatio-temporal correlation structures, modeled in the G matrix (spatial correlation) and the R matrix (temporal correlation). The basic model with the same structure for fixed effect for all cases follows Plaia (2015):

$$Y_{ijklt} = \mu + \gamma_t + \underline{Rep_k} + \underline{(\gamma Rep)}_{tk} + RD_i + (RD\gamma)_{it} + \underline{(RDRep\gamma)}_{ikt} + WC_j + \underline{(WCRep)}_{jk} + (WC\gamma)_{jt} + (RDWC)_{ij} + \underline{(WCRDRep)}_{ijk} + \underline{\varepsilon}_{ijklt}$$

Were Y_{ijkl} is the response variable (either BA or wood volumen individually or per hectare) of the *l-th* tree in the *i-th* row distance treatment, j-th weed control treatment, and the *k-th* replication, μ is the overall mean, γ_t is the year effect, Rep_k is the replication random effect iid ~ N (0; σ^2_{rep}), RD_i is the row distance effect, WC_j is the weed control strip effect, ε_{ijklt} is the residual error with ε_{ijklt} ~ (0, $\sigma^2_e\mathbf{\Sigma}$). Treatment means were compared by a Tukey test at 95% confidence level.

First, a null model was used that assumes that ∑s and ∑t matrices are identity matrices, assuming no correlation among plots or trees. Secondly, temporal modeling was carried out considering only the temporal relation between measures on the same tree. The ∑t matrix was modeled with several correlation structures, i.e. compound symmetry (CS) that assumes homogeneous variances among times, autoregressive of order 1 (AR1), heterogeneous autoregressive of order 1 (ARH1) and heterogeneous compound symmetry (CHS). Furthermore, spatial structures were modeled in matrix G, where four spatial correlation models were compared ($\sum$s): Gaussian (GAU), exponential (EXP), power (POW) and spherical (SPH); spatial structure across all measurement times for each tree and plot. Finally, combined models considering simultaneously the temporal and spatial correlation structures were compared.

Models were compared by Bayesian information criterion (BIC) and a likelihood ratio test (LRT) between the best spatial, temporal and spatio-temporal versus the null model. All models used maximum likelihood to estimate variance components and the Kenward-Roger method was included to correct the degrees of freedom. Once the best ST structure was selected for each variable, models were run to evaluate the tree's performance in wood volume and BA, individually and per hectare. All analyses were performed with SAS using PROC MIXED (Version 9.2) (SAS Institute 2011).

Table 1. Description of the modeling strategies evaluated for the three productive variables

Strategy	**Description**	
Null	No correlation among trees or measurements times	
Temporal modeling	Considers temporal correlation between measures on the same tree	Homogeneous: CS, CSH, UN, ARH, FA(1), ANTE(1)
Spatial modeling	Considers spatial correlation correlation among average yield among tree	GAU, SPH, POW, EXP
Spatio-temporal modeling	Combination of both strategies	

The switchgrass yield performance was evaluated under the different treatments as well and a linear mixed model (2) was used to evaluate total yield at final time in response to the row distance and the weed control treatments:

$$Y_{ijkl} = \mu + RD_i + SW_j + (RDSW)_{ij} + Rep_k + (RepRD)_{ik} + (RepSW)_{jk} + (RDSWRep)_{ijk} + \varepsilon_{ijkl} \quad (1)$$

Where Y_{ijkl} is the response variable (biomass productivity, ton ha^{-1}) in the *ijk-th* experimental unit, RD_i is the row distance effect, WC_j is the weed control effect, Rep_k is the random effect of the replications and ε_{ijkl} is the residual effect. All models used residual maximum likelihood to estimate variance components. The Kenward-Roger method to correct the degrees of freedom was used. Models were compared based on the BIC. All analyses were performed with SAS (version 9.2) (SAS Institute 2011).

3.5. Results

3.5.1. Model comparison

To compare the performance among different structures in linear mixed models for both pine and eucalyptus, we report the BIC and LRT (Tables 2, 3, 4 and 5). For eucalyptus wood volume, the best temporal model used a CSH variance-covariance structure, for spatial model an EXP structure was selected, and for the ST strategies the optimal combination was between CSH and EXP (Table 2). Regarding BA, the best models were UN, POW and ARH combined with SPH structure, for temporal, spatial and ST strategies respectively (Table 2). For pine wood volumen (Table 4), the selected temporal model used an ARH structure, the best spatial model used POW and the optimal combination for the ST strategy was UN with EXP (Table 4). In terms of BA, the best structures were ANTE, POW and the combination of UN and SPH for temporal, spatial and ST strategies, respectively (Table 4). For BA in pine, all combinations with unstructured temporal structure had the same BIC value; however, the combination with exponential was considered the best model based on parsimonious criteria.

In all instances, the combination of both temporal and spatial structures yielded superior results compared to either structure alone (Table 3 and 5), as evidenced when compared to the null model. The incorporation of any form of structure that accounts for variance among observations significantly enhances model fit, particularly in the context of long-term experiments (Tables 3 and 5), as indicated by the significant LRT in all cases. The best model, determined through comparison among different structures for both species and characteristics (Tables 2, 3, 4 and 5), was subsequently utilized for comparing treatments and interactions.

Table 2. Model fit (BIC) and likelihood for the variables basal area and wood volume for *Eucalyptus grandis* for individual tree height, individual tree volume and stand volume per hectare to compare modeling strategies.

Modeling strategy	Wood volume			Modeling strategy	Basal area		
	Structure	**-logLik**	**BIC**		**Structure**	**-logLik**	**BIC**
Null	Identity	3709	3753	**Null**	Null	-3000	-2944
Temporal	CS	3330	3376	**Temporal**	CS	-3696	-3651
	CSH	3304	*3352*		CSH	-	-
	ARH	-	-		ARH	-	-
	ANTE	3411	3462		ANTE	-	-
	UN	3714	3768		UN	-3961	*-3907*
	FA(1)	-	-		FA(1)	-3700	-3654
Spatial	EXP	3316	*3363*	**Spatial**	EXP	-3681	-3634
	SPH	3354	3702		SPH	-	-
	PWR	3319	3365		PWR	-3600	*-3654*
	GAU	-	-		GAU	-	-
Best spatio temporal	ARH / SPH	1923	1971	**Best spatio temporal**	ARH(1) / EXP	-4200	-4149
	ARH / EXP	2225	2274		ARH(1) / SPH	-4319	*-4269*
	CSH / EXP	1898	*1948*		CSH / EXP	-4175	-4124
	CSH /PWR	1904	1954		FA(1) / PWR	-4186	-4133

CS compound symmetry, CSH compound symmetry heterogeneous ANTE antedependence, FA(1) factor analytic order 1, ARH autoregresive heterogenoeus, UN unstructure, POW: power, EXP: exponential, SPH: spherical, GAU: Gaussian.

Table 3. Likelihood ratio test results for *Eucalyptus grandis* for basal area and wood volume per hectare

Basal area				**Wood volume**			
Modeling strategy		**Chi-square**	**p-value**	**Modeling strategy**		**Chi-square**	**p-value**
Null	-3000			**Null**	3709		
Temporal - UN	-3961	961	<0.05	**Temporal - CSH**	3304	405	<0.05
Spatial - EXP	-3681	681	<0.05	**Spatial - EXP**	3316	393	<0.05
ST - ARH / SPH	-4319	1319	<0.05	**ST - CSH / EXP**	1898	1157	<0.05

UN: unstructure, EXP: exponential, CSH compound symmetry heterogeneous, EXP exponential, ARH/SPH: autoregressive heterogeneous and spherical combined, and CSH/EXP: combination of compound symmetry heterogeneous and exponential.

Table 4. Model fit (BIC) and likelihood for the variables basal area and wood volume for *Pinus taeda* for individual tree height, individual tree volume and stand volume per hectare to compare modeling strategies

Modeling strategy	**Wood volume**			**Modeling strategy**	**Basal area**		
	Structure	**-logLik**	**BIC**		**Structure**	**-logLik**	**BIC**
Null	Identity	1617	1662	**Null**	Null	1578	1623
Temporal	CS	1398	1444	**Temporal**	CS	1101	1146
	CSH	553	601		CSH	926	974
	ARH	479	*<u>527</u>*		ARH	-	-
	ANTE	-	-		ANTE	645	*<u>697</u>*
	UN	-	-		UN	-	-
	FA(1)	-	-		FA(1)	120	1255
Spatial	EXP	1483	1529	**Spatial**	EXP	-	-
	SPH	1618	1665		SPH	1574	1620
	PWR	1528	*<u>1573</u>*		PWR	1362	*<u>1407</u>*
	GAU	-	-		GAU	-	-
Best spatio temporal	UN / EXP	313	*<u>367</u>*	**Best spatio temporal**	ARH(1) / EXP	897	946
	UN / GAU	313	*<u>367</u>*		ARH(1) / SPH	708	664
	UN / PWR	313	*<u>367</u>*		CSH / EXP	606	*<u>662</u>*
	UN / SPH	313	*<u>367</u>*		FA(1) / PWR	605	*<u>662</u>*

CS: compound symmetry, ANTE: interdependence, FA(1): factor analytic, ARH: autoregressive heterogenoeus, UN: unstructure, POW: power, EXP: exponential, SPH: spherical, GAU: gaussian, UN/EXP: unstructured and exponential combined, UN/GAU: unstructured and GAU combined, UN /POW: unstructured and power combined, UN/SPH: unstructured and spherical combined. The model with the smallest BIC is shown in italic and underlined for each modeling strategy.

Table 5. Likelihood test results for *Pinus taeda* for basal area and wood volume per hectare

Basal area				Wood volume			
Modeling strategy		**Chi-square**	**p-value**	**Modeling strategy**		**Chi - square**	**p-value**
Null	1617			**Null**	1578		
Temporal - UN	479	1138	<0.05	**Temporal - CSH**	645	933	<0.05
Spatial - EXP	1483	134	<0.05	**Spatial - EXP**	1362	216	<0.05
ST - ARH / SPH	313	1304	<0.05	**ST - CSH / EXP**	605	973	<0.05

UN: unstructure, EXP: exponential, ARH/SPH: autoregressive heterogeneous and spherical combined, CSH: compound simmetry heterogeneous, EXP: exponential, CSH/EXP compound simmetry heterogeneous and exponential combined n. α = 0.05.

3.5.2. Stand volume and basal area

For both BA and wood volume across the two species, the models chosen based on the BIC and LTR were utilized to assess yield differences among treatments. Significant interactions were observed among levels of the two factors for both species and traits. In the case of eucalyptus, the productivity of wood volume per hectare ranged from 202.7 to 286.5 m^3 ha^{-1} (Figure 4), the peak value was achieved at a 7 m row distance, irrespective of the weed control intensity. At a 9.75 m row distance, a significant variance was noted between high and low weed control levels. Conversely, for the BA, fewer significant differences were detected. The optimal treatment for both BA and volume was identified at a 7 m row distance across all weed control levels, with no significant differences found in their interaction.

For pine, there was a significant interaction effect for volume per hectare. The higher value was obtained with 7 m of RD with medium WC level (420.3 m^3 ha^{-1}), which was significantly different from low control and medium. Within 9.75 m RD significant differences were found between low and medium WC, being high control the best level with 9.75 m. For 12.5 m of RD there were no significant differences between high and medium, but the lowest volume was obtained with low WC. On the other hand, for BA, lower effect of interaction was found, the best RD was 7 m regardless of the WC level and the lower BA values per hectare were found at 12.5 m of RD.

For both species, opposite trends were found in individual tree volume in comparison when the productivity per hectare results. For pine, higher values were found at 12.5 m of RD in low and medium WC and had significant differences with high and low WC at 7 m of RD. Whereas, for eucalyptus, more differences were found among treatments. The highest individual volume was obtained at high control and 9.75 m of RD (1.1 m^3 $tree^{-1}$) and significant differences were found with 12.5 m with low control and with all combinations at 7 m of RD.

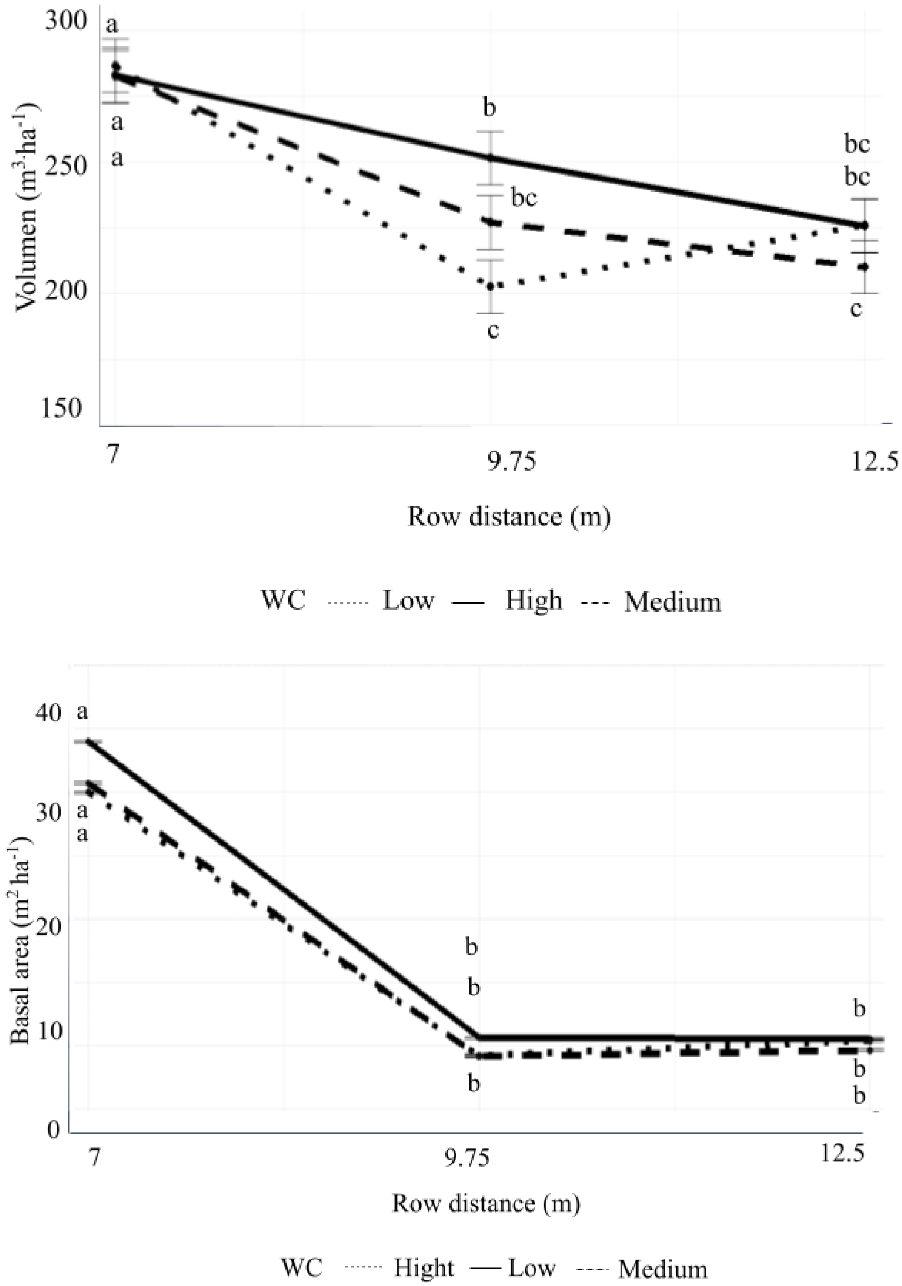

Figure 4. Wood volume (m^3 ha^{-1}) (upper panel) and basal area (m^2) (lower panel) results for *Eucalytpus grandis* at year 18 for the different levels of row distance (RD), weed control (WC) and its interaction

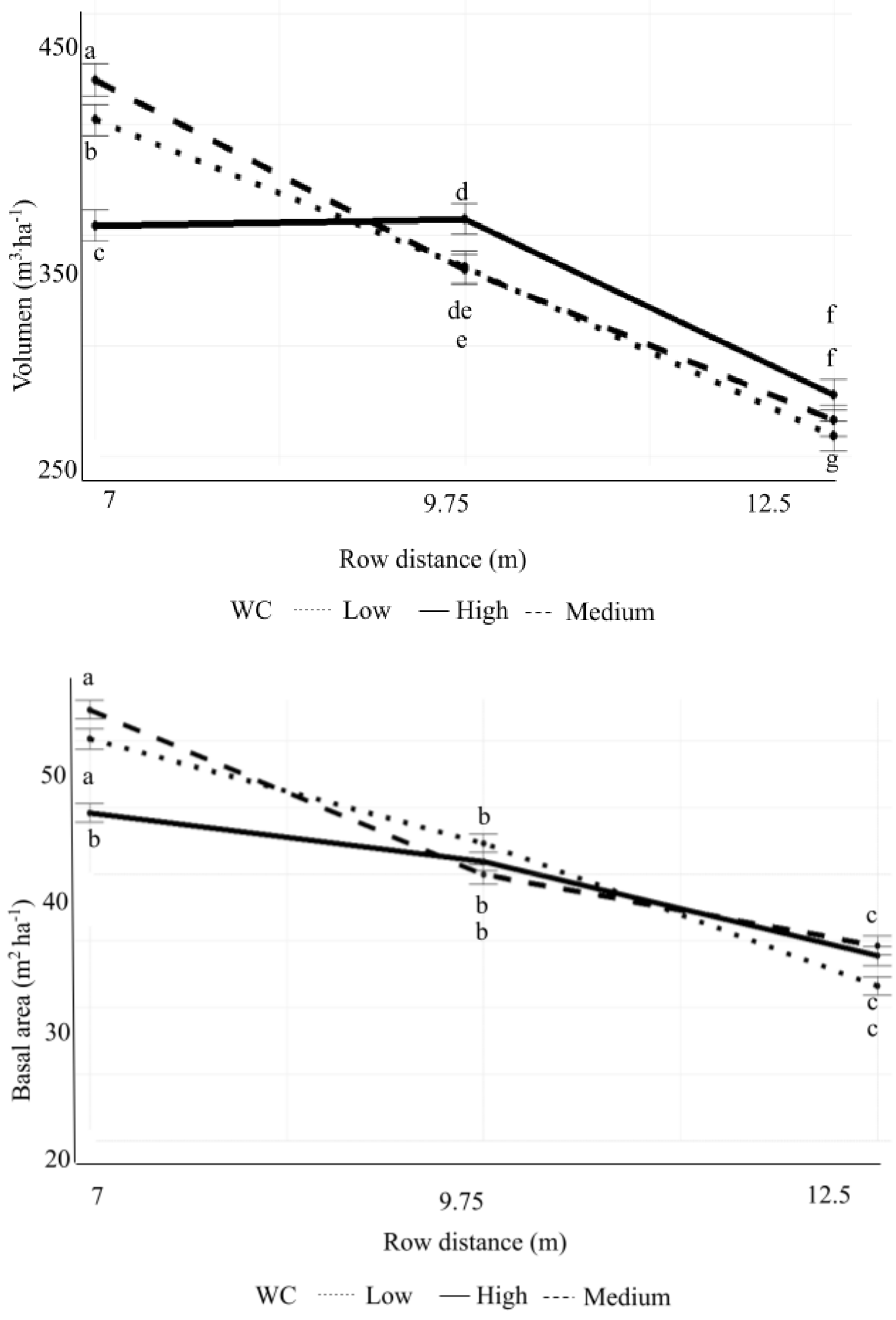

Figure 5. Wood volume (m^3 ha^{-1}) (upper panel) and basal area (m^2) (lower panel) results for *Pinus taeda* at final year 18 for the different levels of row distance (RD), weed control (WC) and its interaction

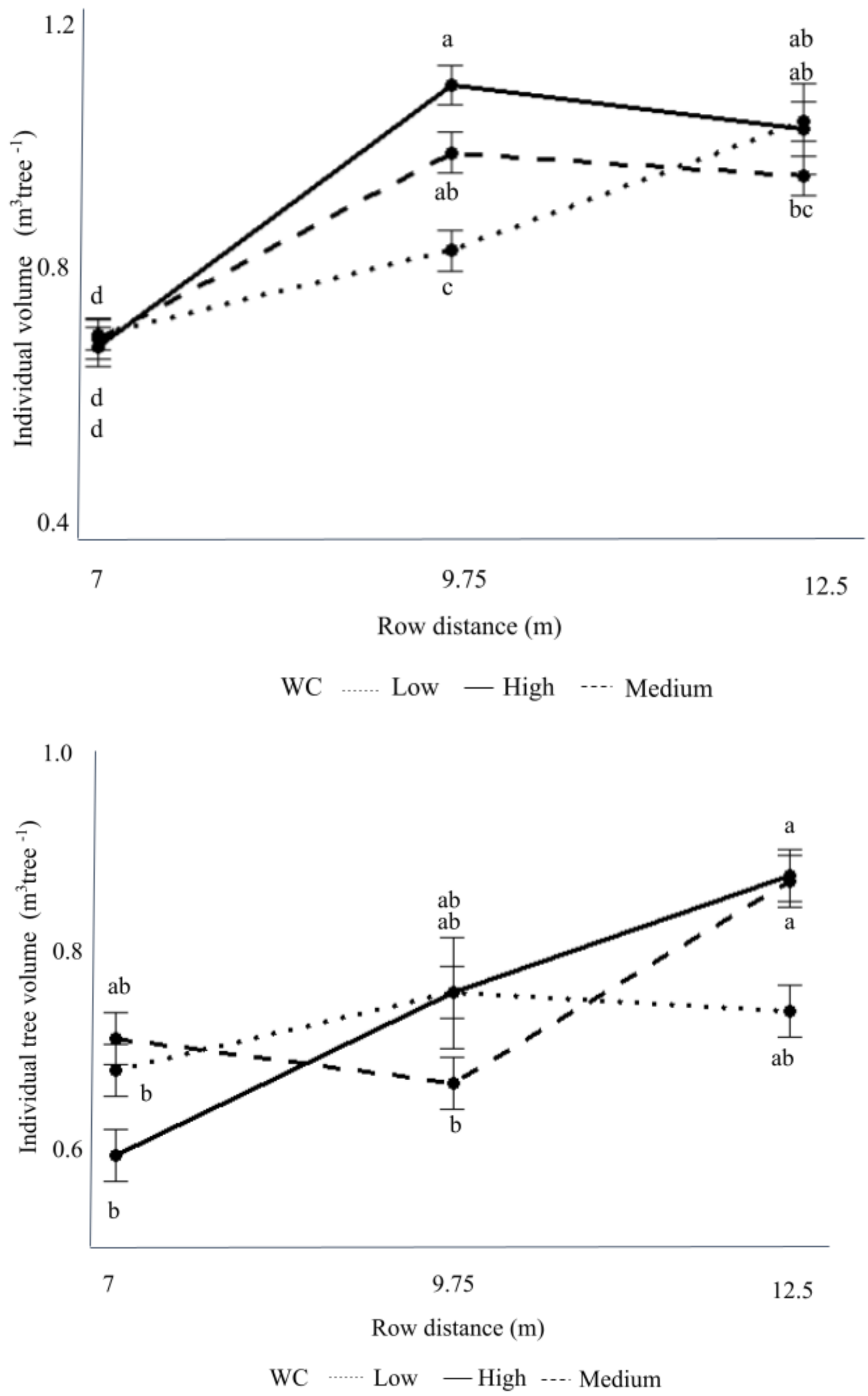

Figure 6. Individual tree volume for *Eucalyptus grandis* (upper panel) and *Pinus taeda* (lower panel) at final year 18 for the different levels of row distance (RD), weed control (WC) and its interaction

3.5.3. Switchgrass

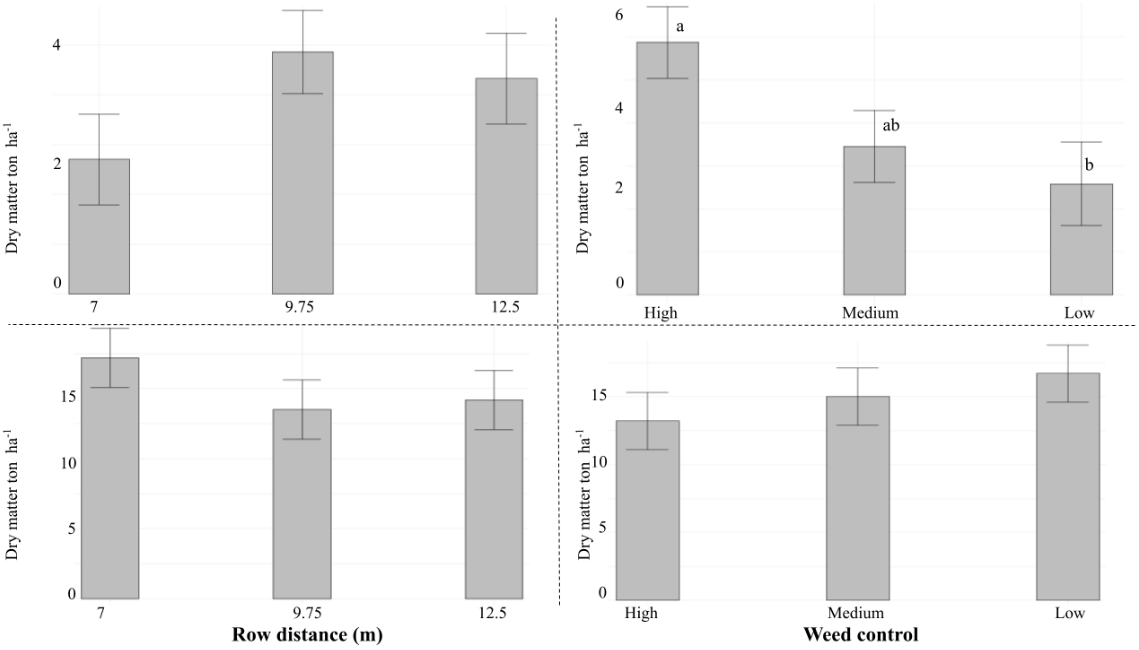

Figure 7. Switchgrass yield (dry matter biomass) at final time (fourth year of the trial) for eucalyptus (lower panels) and pine (upper panels) in tons ha^{-1}

No significant effect of interaction was observed, so results were analyzed separately. The only significant difference found was in pine between high and low WC (6 ton ha^{-1} vs 2 ton ha^{-1}). For eucalyptus, no significant differences were observed among treatments and yield values were between 10 ton ha^{-1} and 20 ton ha^{-1}.

3.6. Discussion

Forestry systems, characterized by their inherent complexity and spread over large areas for extended periods, require experimental designs that effectively capture many interactions and changes over time. The incorporation of spatio-temporal structures into the model matrix represents a significant advancement in this regard, markedly improving the model fit for eucalyptus volume by combining CSH and EXP, and for BA with ARH and SPH compared to the null model (González Barrios et al. 2020). This approach proved equally effective for pine wood volume, where combining UN and SPH, as well as for BA with UN and EXP, indicated substantial improvement. The effectiveness of more complex structures for model fitting and treatment comparison underscores the importance of addressing both spatial and temporal variability in agroforestry studies (Skovsgaard and Vanclay 2013; Pretzsch and Biber 2016).

In Uruguay, the exploration of long-term experiments that include individual measurements over the years and the georeferencing of each tree is limited. Integrating this spatio-temporal information into the model analysis was crucial for deciphering the variability observed in the experiment, highlighting the critical importance of these approaches in experimental forest design. Through this study, we demonstrate how the adoption of spatio-temporal structures can provide deeper and more accurate insights into forest growth dynamics and the interaction between different management practices, thus supporting the development of more informed and sustainable forest management strategies (Guillemot et al. 2015; González Barrios et al. 2020).

No mortality effect was observed, primarily attributed to control management practices implemented during the experiment. For this reason, this factor was not considered in subsequent analyses. Notably, shorter row distances yielded superior results for both basal area and volume across the species studied. This outcome underscores the importance of tailored management strategies based on the intended final use of the forest product. Interestingly, a compensatory effect was observed, leading to smaller individual tree sizes but increased overall yield per hectare. This phenomenon aligns with findings by Gonçalves et al. (2008) and André et al. (2021), highlighting how spacing critically influences forest species development across diverse ecosystems, including Uruguay's plantations, where typical practices involve clear-cutting at six years, prompting inter-tree competition. However, in our study, competition dynamics were carefully controlled, allowing us to explore alternative impacts such as tree size and canopy architecture, with trees harvested at 18 years for lumber, suggesting that managed plantations can achieve industrially viable volumes and sizes.

Lower row distances were associated with smaller tree diameters, reducing individual tree volumes, consistent with observations by Hakamada et al. (2020) and André et al. (2021). Yet, this reduction was offset by the increased number of trees per hectare, enhancing total BA and wood volume. The trade-off between individual tree volume and stand density did not always benefit the latter, particularly for eucalyptus and pine, pointing to the need for a nuanced understanding of spacing's role in optimizing wood production for biomass and solid wood objectives. Our findings also indicate the necessity of evaluating wood's technological properties, as initial spacing and competition with intercropped switchgrass could influence wood density and quality, an aspect not hindered by nutrient or water deficits due to the experiment's controlled conditions.

Planting spacing emerges as a pivotal management factor for pine, affecting tree morphology, growth patterns and even maintenance requirements (do Santos et al. 2021). Low-density spacing fosters the growth of fewer but larger trees, preferable for solid wood outputs, whereas high-density planting produces smaller trees, aligning with the demands of the pulp and paper sector (Lima et al. 2013). This study's observations underscore the significant implications of spacing on product outcomes, reinforcing literature claims (Lima et al. 2013) regarding the balance between stand density, tree size and overall yield. Our experiment suggests a 9.75 m RD as optimal, balancing individual volume and yield, thereby offering a strategic guideline for managing forestry plantations with long-term, solid wood production goals in mind.

The observed positive correlation between secondary growth and an increased allocation of space per tree is consistent with findings across various forest species (Ferreira et al. 2014; Silva et al. 2019: André et al. 2021), reaffirming the importance of RD in promoting tree development. Specifically, treatments involving wider RDs led to the emergence of larger trees, exhibiting both greater BA and volume. This can be attributed to the enhanced availability of natural resources, such as light, water and nutrients, which are crucial for tree growth, particularly in terms of diameter and BA (Binkley et al. 2017; André et al. 2021). In denser plantations, particularly as trees age, competition for these resources intensifies, typically resulting in reduced diameter growth. Consequently, the observed increase in volume per hectare in such settings is due to a combination of higher tree density and the presence of taller trees, leveraging eucalyptus competitive dynamics to produce greater variability and ultimately higher volumes per hectare despite lower individual BAs or volumes.

However, the response patterns in pine differed notably from those observed in eucalyptus. The variations in individual tree volume and the overall wood volume per hectare at the final measurement were less pronounced across different RDs for pine, indicating a distinct growth dynamic compared to eucalyptus. Moreover, the interaction between RD and WC exhibited a markedly different impact on pine growth, suggesting species-specific responses to spatial management and competition. These findings underscore the complexity of forest ecosystems and the need for management practices tailored not only for the species but also for the specific environmental conditions and the intended production outcomes. Future research should delve deeper into these dynamics, exploring the optimal balance between tree density and resource allocation to maximize both individual and per-hectare productivity in forest plantations.

The intercropping strategy, where two different crops coexist within the same field, introduces both complexity and opportunity in forest management, especially in areas with limited research on such practices, like Uruguay. Integrating switchgrass, known for its bioenergy potential, with traditional forestry species such as eucalyptus and pine highlights important questions about symbiotic relationships and competitive dynamics in agroforestry systems (Vargas et al. 2018). Our research shows that switchgrass yields under the optimal conditions for both eucalyptus and pine are comparable to those in monoculture, demonstrating the viability and efficiency of intercropping for increasing biomass production without negatively impacting tree growth (Blazier et al. 2012; Albaugh et al. 2014; Kimura et al. 2018).

This approach also brings substantial benefits beyond productivity. Intercropping acts as a versatile strategy, offering immediate income through the short-term harvest of one crop while ensuring the growth and yield of the long-term forest products. The cooperative existence of tree species and switchgrass in this shared space promotes ecological synergies, potentially improving soil quality, biodiversity and ecosystem resilience (Fedrigo et al. 2018). While the initial four years of growing trees alongside switchgrass lay the groundwork for understanding their mutual effects, the consequences of such interactions throughout the trees' productive cycle warrant further investigation. Continuing to study these intercropping systems could reveal deeper insights into their long-term ecological effects, guiding sustainable practices that enhance both economic and environmental outcomes.

Understanding the long-term behavior of trees and their interaction within intercropping systems is essential for advancing agroforestry, particularly in regions like Uruguay where such practices are still emerging. This research contributes valuable insights into tree growth dynamics within strip plot-designed intercropping systems, examining both final outcomes and intermediate stages of development. Identifying the most effective strategies for analyzing extensive, multi-decadal trials is crucial for the forestry industry to adopt best management practices. Moreover, the incorporation of spatio-temporal variability into our analyses significantly enhances the precision of our predictions and the efficacy of treatment comparisons (Wolfinger 1996; Piepho et al. 2014; González Barrios et al. 2020), reinforcing the necessity of nuanced, context-specific forestry strategies.

Reduced row distances yield higher wood volume per area, attributed to a higher count of smaller trees. This increase in tree numbers elevates both planting and harvesting costs, due to the need for more seedlings and the complexities of processing smaller-diameter trees (Gonçalves et al. 2008; André et al. 2021). Furthermore, a denser tree population demands more nutrients, potentially raising fertilization needs and overall production expenses. Consequently, there is a pressing need for further research to determine the optimal spacing that balances productivity with cost-efficiency across different areas. As forestry continues to develop as a critical component of Uruguay's agricultural landscape, our study underscores the importance of adopting integrated, scientifically backed approaches to agroforestry. Future investigations should aim to refine our understanding of intercropping systems' long-term ecological and economic impacts, guiding the evolution of sustainable and profitable forestry practices.

3.7. Conclusions

In assessing the long-term growth responses of *Eucalyptus grandis* and *Pinus taeda*, our study underscores the critical impact of row spacing and weed control on both species' productivity. Specifically, optimal wood volume per hectare for eucalyptus was achieved with a 7 m row distance, demonstrating the significant role of spacing in maximizing yield. Interestingly, while the same row distance favored hectare productivity, tree-level outcomes revealed larger sizes at a 12 m distance, indicating a nuanced interaction between growth metrics and management practices. Moreover, the study highlighted the importance of moderate to low weed control levels in achieving enhanced wood volume, both at individual and hectare scales. The differential responses of eucalyptus and pines to these management strategies underscore the necessity of tailored approaches for each species. For pine, a distinct interaction effect was noted for volume per hectare, with the highest value observed at 7 m of row distance under medium weed control, illustrating the intricate dynamics of forest management practices. Our findings advocate for the integration of spatiotemporal analysis in agroforestry research, emphasizing the value of precise management in improving forest productivity and sustainability. Future research should further explore these interactions, especially considering the economic aspects of forestry operations to ensure a comprehensive understanding of agroforestry systems' efficiency.

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4. Use of satellite imagery to estimate eucalyptus wood productivity under experimental conditions in forest spacing trials

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4.1. Resumen

La creciente demanda mundial de forestación exige estrategias silvícolas innovadoras, especialmente del espaciamiento. Este estudio aborda esta necesidad mediante el análisis de un experimento a largo plazo con 39 parcelas de *Eucalyptus grandis*, estructurado en un diseño de bloques completos al azar con tres repeticiones. Se recopiló información de crecimiento a tráves de datos anuales de trece tratamientos de espaciamiento y materiales genéticos. Se evaluó la productividad a los trece y dieciocho años posplantación. Se utilizaron imágenes satelitales de alta resolución (10m x 10m en 2016 y 3m x 3m en 2021) para predecir el volumen de madera. Para comtemplar problemas de no normalidad, clasificamos el volumen de madera por hectárea en tres o cuatro niveles de productividad. Utilizando algoritmos de *machine learning* (*random forest* y *support vector regression)*, ejecutamos doscientas iteraciones con 70/30 para entrenamiento y prueba. Este enfoque logró altas precisiones de clasificación al cabo de trece años (0,90 para RF y 0,98 para SVR), que disminuyeron ligeramente en el año 13 (0,88 para RF y 0,78 para SVR), ilustrando las complejidades en la predicción de la productividad a largo plazo. Nuestros hallazgos resaltan la eficacia de combinar imágenes satelitales con métodos estadísticos para mejorar la precisión y eficiencia en las evaluaciones de productividad forestal, presentando una alternativa rentable a los relevamientos de campo tradicionales. Se ofrece un avance en la experimentación forestal, sugiriendo caminos para evolucionar hacia prácticas de manejo forestal más sostenibles y a partir de datos de calidad.

Palabras clave: volumen, *machine learning*, forestación de precisión

4.2. Abstract

The increasing global demand for forest plantations calls for innovative silvicultural strategies, especially in spacing management. Our study addresses this need through an analysis of a long-term experiment with 39 large *Eucalyptus grandis* plots, structured in a randomized complete block design with three replications. We annually collected data from thirteen treatments that varied in spacing and genetic materials, providing comprehensive insights into the growth dynamics of these plantations. Our research focused on productivity between thirteen and eighteen years after planting. Moving beyond traditional methods, we employed high-resolution satellite imagery (10 m x 10 m in 2016 and 3 m x 3 m in 2021) to predict wood volume. To overcome issues of non-normality and fit, we classified the wood volume per hectare into three or four productivity levels. Utilizing machine learning algorithms, specifically random forest and support vector regression, we executed 200 iterations with a 70/30 split for training and testing. This approach achieved high classification accuracies at the thirteen-year mark (0.90 for RF and 0.98 for SVR), which slightly decreased by the eighteenth year (0.88 for RF and 0.78 for SVR), illustrating the complexities in predicting long-term productivity. Our findings highlight the effectiveness of combining satellite imagery with statistical methods to improve the accuracy and efficiency of forest productivity assessments, presenting a cost-effective alternative to traditional field surveys. Therefore, our study offers a modest step forward in experimental forestry, suggesting pathways for evolving towards more sustainable, data-driven forest management practices.

Key words: volume · forestry precisión · machine learning

4.3. Introduction

The growing development of the forestry sector globally presents constant challenges to silvicultural systems in their efforts to make more efficient use of natural resources (Martins et al. 2022). In particular, eucalyptus stands out as one of the most relevant fast-growing species, contributing over a third of the world's timber production (Liu et al. 2022). Forest biomass destined for cellulose production, along with timber forest products, contribute to employment and income diversification in a sustainable, low-carbon economy. In Uruguay, the forestry sector has experienced steady growth for over two decades (Resquin et al. 2019), driven by the productive performance of species such as pine and eucalyptus, as well as the promotion of new plants aimed at industrialization (Hirigoyen et al. 2021b). Currently, these forest plantations cover over one million hectares in Uruguay (MGAP-DIEA 2019). Innovation in forest management tools and optimization in the use of natural resources are key components in promoting the sustainability of these production systems (Çatal and Carus 2017), especially in long-term projections as those seen in Uruguay.

Wood stock volume is a key parameter for assessing eucalyptus plantations. In Uruguay, given the unique characteristics of forest plantations that remain in the field for extended periods (8 to 20 years) and cover large areas, inventories are conducted frequently, leading to high demands on time, human and economic resources. Accordingly, obtaining data from forest inventories that can project the spatial and temporal availability of timber and non-timber resources poses a significant challenge for the productive sector (Tinkham et al. 2018). Traditional characterization of stands and plots for management involves field sampling, which allows the sizing of a forest inventory with an acceptable level of error and uncertainty (Cruz-Leyva et al. 2010). Collecting quality information requires considerable time and costs, which in many cases account for a large portion of a company's overall budget (Liu et al. 2022). In this context, reducing costs and time without compromising the quality of results in this process is one of the main improvement goals in forest management.

Wood volume is a crucial trait in forestry, impacting decisions such as harvest timing and production allocation. This trait's significance in forest management is well-documented in studies like Moskalik et al. (2022), who discuss the importance of accurate wood volume determination for economic and logistical aspects of the wood trade. Myroniuk et al. (2023) also emphasize the importance of accurately estimating merchantable wood volume through stem taper equations for effective forest management. Transitioning into remote sensing, or the use of remote sensors, involves techniques for acquiring and processing data from the Earth's surface using various platforms at a distance from the measured object (Hirigoyen et al. 2021c). To date, numerous forest parameters have been mapped using a variety of optical remote sensing images with different sensors and bands (Dos Reis et al. 2019; Liu et al. 2022). This tool streamlines the use of time, material resources, and covers large areas, including those difficult to access for traditional inventories.

While the acquisition and processing of data from remote sensors do not eliminate the need for field measurements, they reduce their volume and the time spent collecting them. This continuous spatial and temporal information provision underscores the efficiency of remote sensing as a tool, highlighting its importance in gathering data for the analysis of forest stands and experiments. The detailed study of the relationship between volume (and other productive traits, such as canopy characteristics) and spectral variables continues to pose challenges in improving the accuracy of volume estimates in eucalyptus plantations. These challenges are particularly pronounced in experimental settings, where plot sizes are relatively small, limiting the ability to obtain information at the appropriate resolution.

There is a wide range of remote sensing images that provide information about forest ecosystems (Nelson 2013; Zald et al. 2016). The relationship between growth characteristics (volume, biomass) and the information provided by multispectral images is generally linked through vegetation indices (VI) (Hirigoyen et al. 2021c). The advantage is that it allows obtaining relatively good quality information with shorter times, resources and costs than traditional inventories and reduces uncertainties associated with the inference and estimation of large heterogeneous areas (Franklin and Ahmed 2017). The VIs that can be obtained from satellite images and are most frequently used are the NDVI (normalized difference vegetation index) and the SR (simple ratio) (Hirigoyen 2021b). However, this often depends on the species, site-specific conditions and stand management.

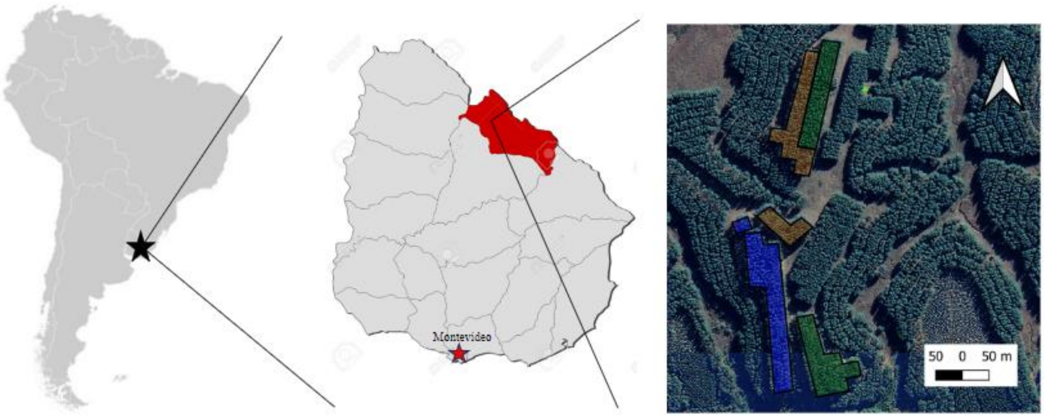
Currently, both parametric and non-parametric models are widely used to map forest structural characteristics (Hirigoyen 2021a). Parametric models are useful for establishing regression equations between remote sensing variables and forest structure parameters. However, in complex forest environments, these relationships can be non-linear, or there might be correlations among the remote sensing variables (Lary et al. 2016). In contrast, non-parametric models, such as random forest (RF), can capture the non-linear relationships between remote sensing variables and forest structure parameters and disregard the covariation among remote sensing variables (Dos Reis et al. 2019). Therefore, non-parametric models are often considered more capable of quantifying forest parameters in relation to variables obtained through remote sensing (Liu et al. 2022). Field inventory data and information derived from IV form the foundation for developing and refining estimation models which, once validated, can be utilized to estimate relevant forest variables by extrapolating the values obtained from image processing to larger areas of interest.

The use of satellite imagery to enhance forest inventories has shown significant progress in production settings but is less explored in experimental settings with specific spatial arrangements for treatment comparisons (Hirigoyen et al. 2021c; Dos Reis et al. 2019). This study aims to validate spatial arrangements in the experimental context of *Eucalyptus grandis* in Uruguay, to enhance the accuracy and applicability of high-resolution multispectral data for specific forest objectives. The primary goals are (i) to evaluate the use of ML models to improve volume estimation and (ii) to compare the outcomes obtained with different ML models and several predictor variables.

4.4. Materials and methods

4.4.1. Description of the experimental site

The "Los Moros" experiment was installed in the department of Rivera, Uruguay, at coordinates 30°54'S and 50°33'W (152 meters above sea level) (Figure 1). The average annual precipitation is 1500 mm, which is evenly distributed throughout the year. The average temperature is around 18 °C, with the highest average temperature in January (22 °C) and the lowest in June (10 °C). The region experiences frequent and significant temperature fluctuations throughout the year. The predominant soils in the area are moderately deep Melanic/Umbreptic Inceptisols with a sandy loam-to-loam texture, characterized by low fertility and good drainage (classified as CONEAT 7.2 in the Uruguayan Soil Aptitude System). Additionally, there are also Dystric Ochric Umbreptic Planosols with a deep sandy loam texture and imperfect drainage (CONEAT G03.21).



The three blocks of the experiment are identified with different colors. Taken from Siri et al. 2024

Figure 1. Location and schematic of the experimental site Los Moros in the department of Rivera, Uruguay

In this study, information from a long-term eucalyptus trial involving various tree spacing treatments, genetic materials and production objectives was utilized. The trial was established in 2003 and annual measurements of diameter at breast height (DBH) and tree height were taken individually from year 2 post-planting to year 18. The experimental design was a randomized complete block design with three replications and thirteen treatments (for details, see chapter 1), with fixed-size plots (30 m × 30 m). Edge trees of each experimental unit were excluded from this study. Since fixed-size plots were used and treatments were associated with different planting densities, a variable number of trees per experimental unit was observed.

Individual tree volumes for each treatment were calculated using taper equations described in Hirigoyen et al. (2021a). Volumes per hectare were obtained by multiplying individual volumes by survival rates and the final density of each treatment. Basal area (BA) was determined for each tree using formula (1). Due to measurement issues in three evaluation years, averages between the previous and following years were used for those missing years. Corner positions of the blocks were recorded using sub-meter post-processed global positioning system (GPS) with a resolution of 0.5 meters.

$$BA = \pi * (DBH)^2 / 4 \qquad (1)$$

4.4.2. Acquisition of Satellite Images

Planet Labs offers daily high-resolution multispectral imagery (3 to 4 meters), featuring red, green, blue (RGB) and near-infrared (NIR) band data. We used the PlanetScope Ortho Tile products (Planet Labs 2018). The satellite images (level 3B) undergo rigorous geometric correction (Frazier and Hemingway 2021). The analytical process involved 4 of the 8 bands provided by the images (RGB, NIR), with an orthorectified spatial resolution of 3.125, and daily review. Images of this type were specifically obtained for years 13 and 18, with average approximate resolutions of 10 and 3 meters, respectively. Six spectral indices were calculated using the band information from these images (Table 2). The processing was carried out using QGIS (QGIS Development Team 2009) and R software (R Core Development Team 2013).

Table 1. Vegetation indices used to estimate wood volume for eucalyptus experimental plots at Los Moros site.

Vegetation index	Formulation	Reference
Enhaced vegetation index	$EVI = 2.5\,\frac{\rho_{NIR} - \rho_{Red}}{1 + \rho_{NIR} + 6\rho_{Red} - 7.5\rho_{Blue}}$	(Huete and Van Leeuwen 1999)
Green normalized difference vegetation index	$GNDVI = \frac{\rho_{NIR} - \rho_{Green}}{\rho_{NIR} + \rho_{Green}}$	(Gitelson and Mezlyak 1998)
Normalized difference vegetation index	$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$	(Rouse Jr et al. 1973)
Simple ratio index	$SRI = \frac{\rho_{NIR}}{\rho_{Red}}$	(Jordan 1969)
Greenness index	$GI = \frac{\rho_{green}}{\rho_{Red}}$	(Xue and Su 2017)
Soil adjusted vegetation index	$SAVI = \frac{\rho_{NIR} - \rho_{Red}}{(\rho_{NIR} + \rho_{Red} + L^{*}) \times (1+L)}$	(Norman 1977)

* A value of L = 0.2 was used for the SAVI

4.4.3. Variable selection

After gathering band data for each pixel and subsequently calculating vegetation indices for each plot, the mean, maximum, minimum and standard deviations for each indicator were computed. Additionally, BA and wood volume for each plot were estimated, leading to the projection of wood productivity per hectare. For model predictor variable selection, Spearman correlations among all variables were computed, discarding those with correlations above 0.9 to reduce multicollinearity effects. Then, the variance inflation factor (VIF) was calculated for the least correlated variables and those with a VIF exceeding 10 were removed from the analysis to be incorporated into the ML models. This strategy was suitable for assessing wood productivity at 13 years. However, for the 13-year assessment, using lower resolution image data, variable selection differed as no correlations above 0.9 were found between variables. Therefore, all predictive variables were included in the random forest strategy and the most significant predictors were chosen based on the minimal depth criterion for evaluating wood volume productivity per hectare.

4.4.4. Machine learning algorithms

With the previously selected variables, ML algorithms were assessed as tools for determining the predictive potential of field-measured productive variables (wood volume) using predictive variables obtained from satellite images. Specifically, two of the most common methods in ML prediction were used: random forest (RF, Liaw and Wiener 2022) and support vector regression (SVR, Meyer et al. 2022). The original goal was to predict wood productivity as a quantitative variable (m^3 ha), but, due to the low predictive capacity achieved, it was decided to construct ordinal variables as labels to divide the dataset into different productivity levels. Accordingly, the dataset was first divided into 3 or 4 groups (terciles or quartiles) and were also grouped using cluster analysis (k-means) into three or four groups (cluster_3 and cluster_4). Moreover, for calibrating the ML models, two subsets are needed: a training subset and a testing subset (Lary et al. 2016). In this case, the total data set (39 plots) was randomly divided into two: test data (70% of the data) and validation data (30%), and this procedure was repeated two hundred times to average the accuracy results and, thus, obtain the best method for predicting volume per hectare. The accuracy in each iteration was defined as the number of correctly classified plots relative to the total number of plots being evaluated.

4.5. Results

Once the satellite images for each time period (year 13 and year 18) were downloaded, tables of information per plot were created, which were then processed with ML models. Figure 2 shows the type of image that was downloaded and the experimental unit that was worked with (marked in red).

Figure 2. Satellital image from Planet Labs features pixels in varying colors, each representing spectral band values used for calculating vegetation indices. The red square indicates a plot, serving as the experimental unit for evaluating machine learning models (with a total of 39 plots)

4.5.1. Estimation of productivity at 13 years after plantation

A descriptive analysis of the data was performed, utilizing information from each tree within the plots. Tertiles and quartiles were established to show which treatments fell into each category. Figure 3 illustrates the distribution of treatments across quartiles and tertiles. It was observed that treatments with a lower final stand density had lower productivity per hectare. In contrast, treatments with higher density were placed in tertiles 2 and 3 and quartiles 3 or 4, irrespective of the genetic material used. In this regard, the average per treatments had a minimum of 240 m^3 per hectare, a maximum of 649 m^3 per hectare and an average of 430 m^3 per hectare approximately (Figure 3).

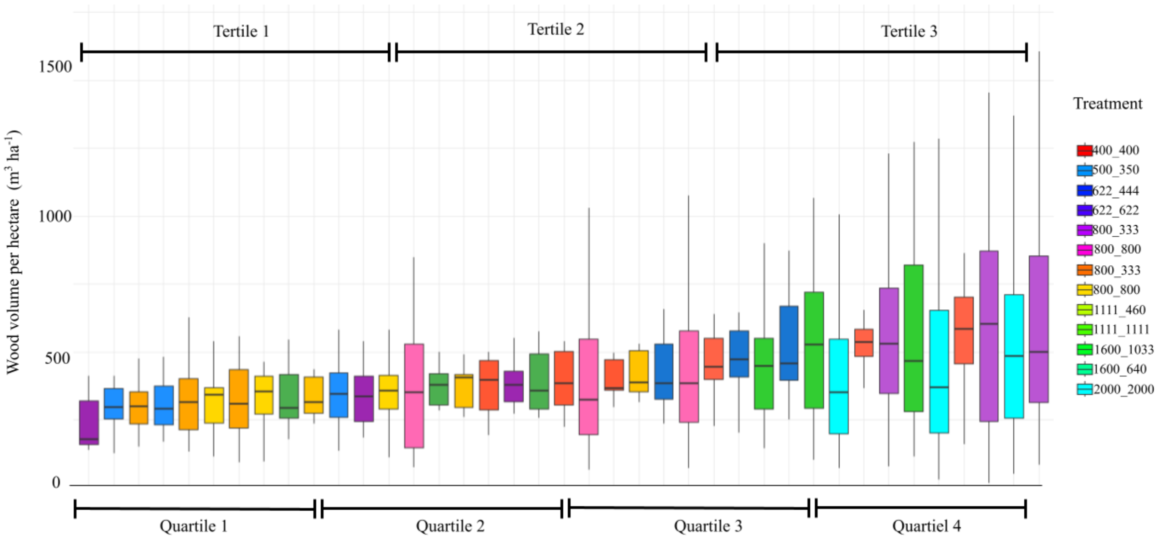


Figure 3. Boxplot of wood volume per hectare for each experimental plot at 13 years post-plantation, differentiated by treatment type (initial and final stand density). The plots were classified into 3 (tertile) or 4 (quartile) groups based on an ascending order of wood volume

Using preliminary data obtained through RF at 13 years post-planting, the selected variables for evaluating the ML models were standard deviation of EVI, standard deviation of BLUE, minimum of EVI, minimum of GI, maximum of GI and maximum of EVI (Figure 4). When assessing the RF and SVR models for predicting wood volume per hectare using these important variables, the highest accuracy achieved was 0.98 for predicting cluster_3 for SVR (Table 3). This was followed by the tertile grouping, which showed an accuracy of 0.90 in the case of RF strategy. These results indicate that the ML models, particularly when applied to the selected spectral variables, can effectively predict the productivity of eucalyptus plantations, with certain clustering approaches yielding more precise outcomes than others.

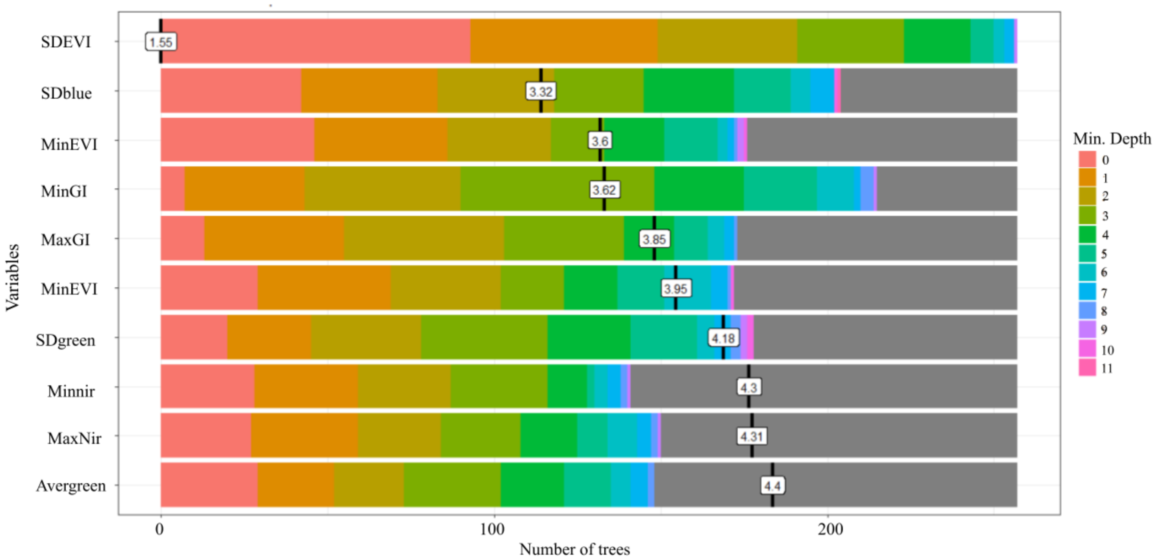


Figure 4. Relative importance (minimal depth) of explanatory variables in the random forest approach for prediction of wood volume per hectare at 13 years post-planting

Tabla 2. Accuracy values obtained for each model (RF and SVR) at 13 years post-plantation for each response variable. The accuracy presented is the average of the 200 times the procedure was repeated using 70% of the data for training and 30% for testing

Model	**Type of clustering**	**Accuracy**
Random forest	*Tertile*	*0.9*
	Quartile	0.37
	Cluster_3	0.83
	Cluster_4	0.71
Support vector regression	Tertile	0.74
	Quartile	0.74
	Cluster_3	*0.98*
	Cluster_4	0.84

4.5.2. Estimation of productivity at 18 years of growth

At 18 years, when the average of wood volumen per hectare of the experimental units its observed, the minimum was 80 m^3 ha, while the maximum was 910 m^3 ha and the average was 480 m^3 ha. There was greater variability in productivity per hectare compared to the values obtained at 13 years. In this case, with higher quality information available from higher resolution images, it was possible to preselect predictor using Spearman´s correlation information between spectral band variables and IVs (Figure 4).

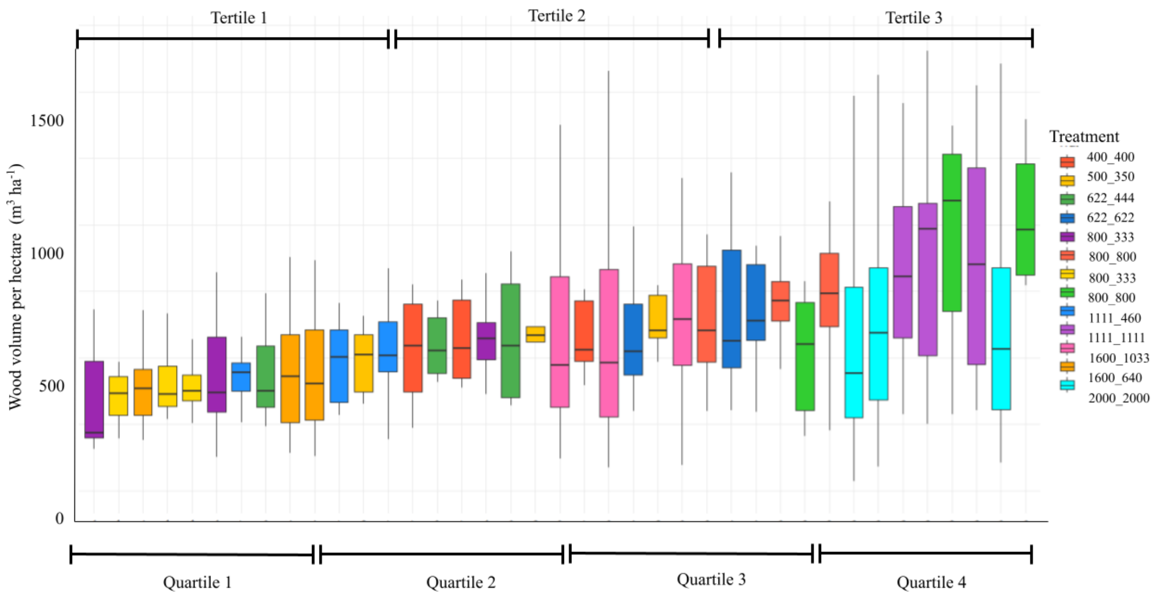


Figure 5. Boxplot of wood volume per hectare for each experimental plot at 18 years post-plantation, differentiated by treatment type (initial and final stand density). The plots were classified into 3 (tertile) or 4 (quartile) groups based on an ascending order of wood volume productivity

In the 18th year post-plantation, the accuracy values for each model, RF and SVR, were assessed for different response variables. This analysis was based on an average of 200 repetitions of the modeling process, using 70% of the data for training and 30% for testing. For RF, the highest average accuracy was observed for the tertile group at 0.88, followed by cluster_3 at 0.8, cluster_4 at 0.71, and the lowest for quartile at 0.35. In the case of SVR, the cluster_3 group showed an average accuracy of 0.78, with tercil close behind at 0.77, cluster_4 at 0.67 and cuartil at 0.46.

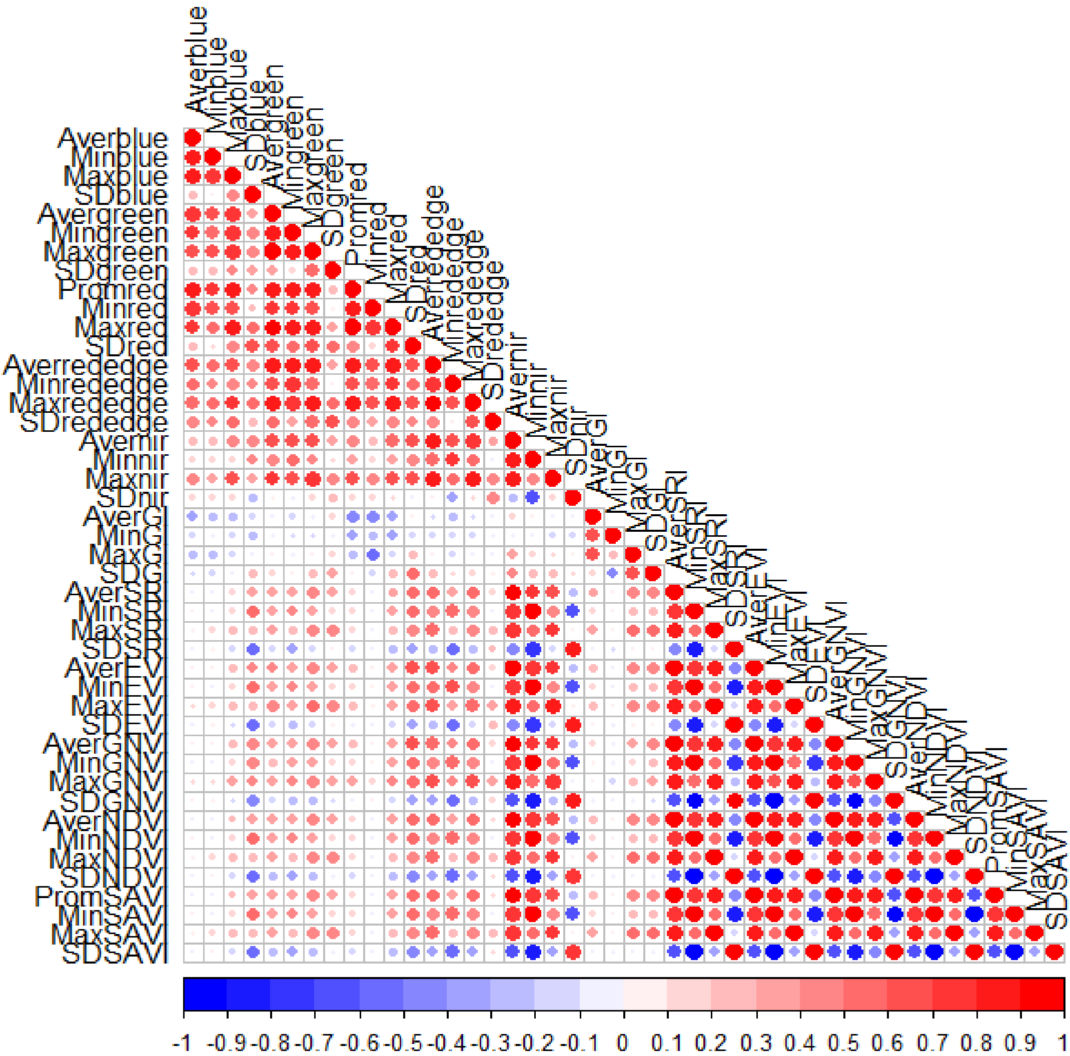


Figure 6. Spearman correlations between all calculated predictor variables, spectral bands and vegetation indices were derived from data at 18 years post-plantation. Higher positive values are represented by intense red colors and larger circles, whereas higher negative values are depicted by intense blue colors and larger circles

Table 3. Predictor variables selected based on two criteria for year 18: variables with Spearman correlation coefficients less than 0.9 and variables with VIF less than 10

Variables cor < 0.9	**Variables VIF < 10**
Min. blue	Min. rededge
Max. blue	SD rededge
SD blue	Max. NIR
Min. green	SD NIR
SD green	Average GI
SD green	Min. GI
Min. red	Max. NIR
Min. rededge	SD NIR
SD rededge	Max. GNDVI
Max. NIR	
SD NIR	
Average GI	
Min. GI	
Max. GI	
SD GI	
Max. GNDVI	

Table 5. Accuracy values obtained for each model (RF and SVR) at 18 years post-plantation for each response variable. The accuracy presented is the average of the 200 times the procedure was repeated using 70% of the data for training and 30% for testing

Model	**Response variable**	**Average accuracy**
Random Forest	Cluster_3	0.8
	Cluster_4	0.71
	Tertile	*0.88*
	Quartile	0.35
Support vector regression	Cluster_3	*0.78*
	Cluster_4	0.67
	Tertile	0.77
	Quartile	0.46

Table 6. Accuracy of all evaluated models and all categorical response variables using only the calculated vegetation indices as independent variables. The highest accuracy values are in italics

Response variable	GI	SRI	EVI	GDNVI	NDVI	SAVI
			RF			
Quartile	0.29	0.3	*0.34*	0.24	0.32	0.32
Tertile	0.28	0.24	0.28	0.23	0.25	0.25
Cluster_3	0.27	0.28	0.31	0.24	0.29	0.29
Cluster_4	0.17	0.21	0.28	0.26	0.23	0.23
			SVR			
Quartile	0.28	0.22	0.23	0.2	0.21	0.21
Tertile	0.29	0.2	0.19	0.18	0.19	0.19
Cluster_3	*0.41*	0.36	0.36	0.36	0.35	0.37
Cluster_4	0.37	0.26	0.27	0.26	0.27	0.27

Table 6 presents the accuracy of evaluated models for all categorical response variables, using solely calculated vegetation indices as independent variables. The results highlight that, for the RF model, the highest accuracies were achieved with the EVI index in the cuartil response variable, at 0.34. In contrast, the SVR model showed its best performance in the cluster_3, notably with the GI index, achieving an accuracy of 0.41. Generally, these accuracies are lower compared to those obtained when combining all spectral bands and selected variables, as shown in Table 5. This indicates that while individual vegetation indices can provide significant insights, the combination of multiple bands and variables tends to enhance model accuracy for predicting forest productivity.

4.6. Discussion

The use of remote sensing to estimate volume and aerial biomass in eucalyptus has been evaluated by several authors (Gama et al. 2010; Ismail et al. 2015; Dube et al. 2015), but the combination of multispectral data modeled by machine learning, specifically RF and SVR, has still been little explored (dos Reis et al. 2019; Souza et al. 2019). Precisely, in this work, we analyzed the levels of wood volume prediction - in terms of productivity categories- per hectare of *Eucalyptus grandis* through the use of satellite images under conditions of experimental plots, differing from the majority of works that are done in the context of productive stands (Yuan et al. 2017; Hirigoyen et al. 2021c). Our results reaffirm findings by other authors related to the possibility of obtaining good predictions of wood volume through the pixel information provided by the images and the vegetation indices constructed with them (Shen et al. 2018; Domingues et al. 2023), achieved both at year 13 and year 18 post-plantation. In this particular case, the validation was performed with information gathered individually in each of the experimental plots, which positively contributes to the precision of the data against which the predictions obtained with the ML models are contrasted. Particularly in Uruguay, efforts made to predict productive variables have been focused mainly on leaf area index (Hirigoyen et al. 2021c), but there is a certain lack of information on wood volume that is important to address.

In this particular case, discrete response variables were used, generated from the continuous variable of volume per hectare (tertiles, quartiles, cluster_3 and cluster_4). Initially, there was an intention to evaluate and predict numerical values (m^3 ha^{-1}), but the results were not satisfactory, possibly due to the relative low number of datapoints available (experimental units). Furthermore, in 2016, where information from satellite images with 10 m by 10 m pixels was used, this could have been a factor that contributed to not achieving acceptable levels of prediction. For this reason, and to begin evaluating these remote sensing tools under experimental conditions, it was decided to generate different discrete variables, with groups more similar to each other and less similar to others, to assess the prediction levels of treatment groups (Table 3 and 5).

Remote sensing data is often highly correlated and the resulting multicollinearity can induce singularities in analyses typically employed in ML contexts (Dos Reis et al. 2019; Hirigoyen 2021b). Therefore, to predict volume in both year 13 and year 18, the most relevant and least correlated variables were identified, and they varied between the two time points. For year 13, the relevant variables included the standard deviation of EVI, standard deviation of BLUE, minimum of EVI, minimum of GI, maximum of GI and maximum of EVI. In contrast, the year 18 required a more diverse set of variables (Table 4). This variation often means that information derived from spectral bands carries different values depending on the time of assessment, due to changes in image quality and shifts in stand structure, consequently affecting tree mortality and competitive dynamics. It's crucial to note that under experimental conditions, like our case, where different spacing treatments and genetic materials are evaluated, additional factors may arise that can confound effects, thereby limiting the predictive potential of ML models.

The assessment of the ML models demonstrated relatively high accuracy levels, particularly for year 13, with the highest being 0.98 (Table 3) when using cluster_3 as the response variable. Conversely, for year 18, the maximum model accuracy reached was 0.88, predicting volume tertiles per hectare with RF. Considering that tree forms vary from one period to another and assuming that thinning practices were conducted prior to both image assessments, it is expected that the number of remaining trees in both cases would be similar, as there were no significant mortality reductions between 13 and 18 years post-plantation. This might be one of the factors explaining the slight decrease in predictive power when comparing both time points. The growth dynamics of the canopy, especially under conditions of low competition post-thinning, may lead to increased coverage and overlap, potentially affecting the estimation of wood volume using satellite imagery (Liu et al. 2022). This could also be supported by the idea that these species exhibit a rapid growth rate, which may significantly alter the form of the trees (Dos Reis et al. 2019).

When the results for individual VIs were analyzed using both RF and SVR models, the highest accuracy values were obtained with SVR using VIs such as GI and SAVI (0.41 and 0.37, respectively; Table 6), contrary to expectations since NDVI and GNDVI are generally the most commonly used VIs (Xue and Su 2017). Although these two indices did not show low accuracy values, they were consistently lower than in models where all the previously selected predictive variables were used, whether they were VIs or spectral bands.

As noted in previous studies (Hirigoyen et al. 2021c), pixel information from satellite images has proven to be a valuable tool for studying and estimating the productive variables of eucalyptus stands in Uruguay. Additionally, discrepancies between model estimates and observed volumes per hectare may stem from differences in the timing of image capture and in situ data collection (Zhao and Popescu 2009;

Hirigoyen et al. 2021c), which in our case was approximately a month for both evaluation periods. There are potential limitations in this study, including the already mentioned temporal interval and the spatial mismatch between field measurements and pixels highlighted in other publications (Hirigoyen et al. 2021c). Moreover, temporal changes in image resolution due to technological improvements also affect the resolution and quality of information that can be obtained from spectral bands. This was more evident in the first evaluation period, which worked with a pixel resolution of 10 m, substantially less than the 3 m resolution obtained at 18 years. In summary, while there are several aspects to improve to enhance the potential of remote sensing tools in forestry systems, there is increasing evidence that it is possible to obtain higher quality information and models that can provide reliable predictions in both productive and experimental plot contexts.

4.7. Conclusion

Our sixteen-year investigation into eucalyptus treatments for dual purposes has shown that double-purpose eucalyptus treatments can generate basal areas comparable to those intended solely for solid wood production. This highlights the adaptability and potential of various genetic materials in response to spacing treatments, emphasizing the utility of seed-type materials, particularly when applied at lower spacing densities correlated with an increase in basal area and tree volume. Furthermore, our analysis of spacing, genetic selection and thinning practices emphasizes the impact of each factor on precision forestry management. Higher planting densities, even without thinning, resulted in increased overall hectare productivity. Yet, this boost comes with higher mortality rates in denser plantations, suggesting a balanced approach is needed in plantation management. These findings inform our recommendations for enhancing the sustainability and productivity of eucalyptus and pine stands under varying environmental conditions.

Moreover, machine learning models were applied and adjusted to predict the wood volume per hectare of eucalyptus in an experimental context in Uruguay using satellite imagery. An accuracy of 0.98 was achieved evaluating support vector regression (SVR) and estimating three clusters through preselected spectral bands and vegetation indices. Although NDVI and GNDVI are highly utilized vegetation indices, GI and SAVI stood out for estimating volume per hectare using SVR as the machine learning model. This study provides valuable information and tools that contribute to the understanding and research of forestry experiments in Uruguay. The images were instrumental in accurately predicting wood volume per hectare, with ample room for improvement in quantitative predictions expected. The future integration of more advanced tools such as in-situ drones and higher-resolution satellite images is anticipated to positively impact the enhancement of forestry evaluation systems, reducing operational costs and enabling a greater volume of information for designing more sustainable long-term management strategies.

Modeling spatio-temporal variability is critical for improving treatment comparisons in agroforestry experiments. More complex structures resulted in increased precision and fit in treatment comparisons for both species (pine and eucalyptus) and the productive characteristics studied. Moreover, higher densities lead to smaller tree sizes but higher productivity per area; thus, studying and planning spacing according to the final product is crucial. Intercropping cultivation was beneficial in all cases (for pine and eucalyptus), not affecting tree growth, and productivity of switchgrass was comparable whether planted separately (as a monocrop) or in this case.

Further research is needed to address these interactions in Uruguay, particularly in long-term experiments planted over large areas. Especially, studies that include economic analyses, cost-productivity balances per unit area and total establishment are necessary. Detailed study of forestry experiments is essential to achieve ideal management that generates the highest profits while being environmentally beneficial, and, in this case, having data individualized per tree and over many years contributes to advancing the understanding of these plantations and their interaction with the Uruguayan environment.

Competing interests: there are no conflicts of interests among the authors.

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5. Discusión general

5.1. Variabilidad espacio-temporal en los modelos utilizados para comparar el crecimiento forestal

Se destaca la importancia del seguimiento individual de los árboles a lo largo del tiempo particularmente en ensayos de manejo forestal. Este enfoque permite captar las correlaciones temporales y espaciales entre las observaciones, lo que resulta crucial para entender la dinámica de crecimiento en eucalipto y pino. La incorporación del tiempo como covariable, así como la adaptación de estructuras de varianzas y covarianzas en los modelos mixtos, ha mejorado significativamente el ajuste de los modelos (González Barrios et al., 2020; Wolfinger, 1996). Mientras la literatura ha profundizado en el análisis de correlaciones temporales, la integración de la variabilidad espacial ha sido menos frecuente, pero es fundamental para reflejar la heterogeneidad inherente de los ecosistemas forestales (González Barrios et al., 2015).

Las estrategias para modelar datos correlacionados en el tiempo y el espacio, utilizando estructuras como ANTE(1), ARH(1), CSH o UN, que admiten varianzas heterogéneas y correlaciones dependientes del intervalo temporal entre mediciones, han probado ser las más adecuadas (Davidian y Giltinan, 2003; Skovsgaard y Vanclay, 2013). Esta capacidad de modelado es vital en las etapas tempranas de crecimiento, donde la variabilidad entre observaciones tiende a incrementarse. Además, la variabilidad espacial en suelos afecta significativamente el crecimiento de los árboles, lo que subraya la necesidad de incorporar esta dimensión en los modelos de crecimiento para tomar decisiones informadas sobre espaciamiento, material genético, prácticas de laboreo, etc. (Dutilleul, 1993; Moral et al., 2010).

El uso de diseños experimentales que reflejen la variabilidad espacial interparcelaria es crucial para mejorar la eficiencia estadística en la estimación de medias de tratamientos porque permiten detectar diferencias significativas y guiar decisiones silviculturales (Zas, 2006). La adopción de modelos lineales mixtos y otras técnicas ha mostrado cómo la inclusión de información espacial y temporal mejora el ajuste de los modelos y facilita una interpretación más precisa de los datos experimentales (Dutkoski et al., 2006; González Barrios et al., 2020; Liang et al., 2020).

En este trabajo pudo demostrarse que la integración de análisis espacio-temporales en los modelos de crecimiento forestal proporciona una comprensión más detallada y precisa de los patrones de crecimiento y mejora significativamente la capacidad de detectar diferencias significativas en tratamientos; particularmente en experimentos sobre manejo y pensados para producción de madera solida. Este avance metodológico resalta la pérdida de precisión al utilizar datos promedio parcelarios y observaciones tratadas como independientes, subrayando la importancia de adaptar nuestras estrategias de modelado a la complejidad real de los sistemas forestales para una gestión más sostenible y efectiva.

5.2 Efectos del distanciamiento y material genético sobre variables productivas y sobrevivencia de árboles en eucalipto (Los Moros)

La investigación enfocada en la relación entre el tamaño del árbol, la producción y la densidad de plantación es fundamental para optimizar las prácticas silviculturales. Se ha encontrado que, con el aumento de la densidad de plantación, el volumen individual de los árboles disminuye, mientras que el volumen total por hectárea tiende a incrementarse, en concordancia con los hallazgos de Binkley et al. (2010) y Forrester et al. (2013), entre otros autores. Además, la influencia del material genético en los resultados productivos es relevante, evidenciando que los mismos tratamientos de distanciamiento afectan de manera distinta a los diversos materiales genéticos. Por ejemplo, los materiales de semilla presentan generalmente mayor área basal y volumen individual y se adaptan mejor a condiciones específicas del sitio, aunque con una mayor variabilidad dentro de tratamientos lo cual levanta los promedios pero no necesariamente hace que sea lo mejor si es un experimento para elaboración mecánica (Caniza et al., 2018; Stape et al., 2022).

El origen del material genético como el de semillas muestra un mejor rendimiento en contextos de bajo potencial en comparación con los clones, que, debido a su mayor uniformidad, son preferidos para la producción de madera sólida (Binkley et al., 2017). Sin embargo, la adaptabilidad y la consistencia en la selección de árboles para diferentes propósitos son cruciales, destacando la necesidad de considerar tanto el material genético como los factores ambientales en la gestión forestal, especialmente en Uruguay para plantaciones con múltiples propósitos.

Menores distanciamientos promueven un crecimiento más rápido de los árboles. Esto incrementa la competencia por la luz y otros recursos, lo que resulta en árboles más pequeños (Forrester et al., 2013; Rocha et al., 2019). Estos efectos son consistentes con los estudios de Resquin et al. (2018), que han demostrado cómo las densidades más altas intensifican la competencia y afectan la supervivencia y el crecimiento, particularmente en tratamientos de semillas, reafirmando la necesidad de un manejo adecuado de la densidad para optimizar el rendimiento y la supervivencia. Estos aspectos no necesariamente se manifiestan en rodales con clones híbridos, donde solamente los tratamientos extremos (400_400_C2 y 800_800_C2) dieron diferencias significativas por lo que la competencia no parece haberse manifestado aún.

En resumen, la interacción entre el distanciamiento y el material genético juega un papel crucial en la determinación de la productividad y la supervivencia de los árboles en ensayos forestales particularmenta para madera sólida dado que cuando es para pulpa o biomasa, se plantan mayores densidades y se precisa mayor volúmen sin ser tan relevante el tamaño de los árboles individuales. La competencia inducida por la densidad de plantación, que varía con la edad, el material genético y las condiciones del sitio, subraya la complejidad de la gestión forestal (Dwyer et al., 2010; Fernandes et al., 2023; Schneider et al., 2015). Los resultados de esta tesis destacan la importancia de una planificación forestal que integre consideraciones sobre distanciamiento y material genético, para informar prácticas de manejo que maximicen la productividad forestal y la sostenibilidad.

5.3. Efecto del distanciamiento y control de malezas sobre variables de crecimiento en pino y eucalipto (Quebrachal)

Con respecto al pino, el efecto del distanciamiento fue similar a lo observado en eucalipto, donde mayores densidades resultaron en árboles más pequeños y un menor rendimiento por hectárea. El espaciamiento es un factor determinante en el crecimiento y comportamiento de los pinos porque influencia directamente la forma, el volumen, la tasa de crecimiento (Dos Santos et al., 2021). Un menor distanciamiento tiende a producir pocos árboles más grandes, lo cual es preferible para madera con destino a transformación mecánica, mientras que densidades más altas generan árboles más pequeños, pero aumentan la productividad por unidad de área, adecuado para la industria celulósica (Lima et al., 2013). Los ensayos en Quebrachal y Los Moros indicaron que densidades mayores de árboles por hectárea resultaron en árboles más pequeños, pero con mayores productividades por hectárea.

A pesar de que muchos estudios han explorado el crecimiento inicial de los árboles y su respuesta al control de malezas, hay poca información sobre el comportamiento de cultivos en intersiembra en Uruguay. Es importante generar conocimiento en esta área, especialmente cuando cultivos como el *switchgrass*, utilizados como fuente de biocombustibles, muestran una productividad similar creciendo bajo diferentes distanciamiento entre filas. En la entrefila de pino, a diferencia de eucalipto, hubo diferencias significativas cuando se comparan distintas franjas de control de malezas entre el control alto y el bajo (Blazier et al., 2012; Kimura et al., 2018). Los sistemas agroforestales que incorporan múltiples cultivos desarrollan interacciones beneficiosas para el medioambiente y aportan a la sostenibilidad de estos tanto desde el punto de vista económico como ambiental (Fedrigo et al., 2018).

Mientras estos trabajos se han centrado en evaluar aspectos productivos, la dinámica de manejo forestal subraya la importancia del análisis económico. Las decisiones sobre distanciamiento, material genético y manejo pueden influir significativamente en la economía de los sistemas forestales. Futuras investigaciones deberían enfocarse en aspectos económicos para optimizar las estrategias de manejo forestal, teniendo en cuenta la necesidad de equilibrar la productividad con los costos de implantación y manejo. La silvicultura en Uruguay, siendo un sistema productivo relativamente nuevo, presenta el desafío de desarrollar estrategias eficientes que maximicen la productividad y la sostenibilidad económica de las plantaciones forestales.

5.4. Uso de imágenes satelitales para la estimación de volumen de madera en parcelas experimentales de eucalipto

El uso de teledetección para estimar el volumen y otras características productivas en eucalipto ha sido evaluado extensamente, pero la aplicación de datos multiespectrales modelados por *machine learning*, en particular *random forest* (RF) y *support vector regression* (SVR), ha sido menos explorada. Nuestro estudio avanzó en esta dirección, analizando la predicción del volumen de madera en términos de categorías de productividad por hectárea en condiciones experimentales. Confirmamos parte de la hipótesis de que el volumen puede predecirse efectivamente utilizando la información por píxel proporcionada por las imágenes satelitales, con índices vegetativos siendo herramientas útiles para capturar atributos biofísicos de la producción forestal (Domingues et al., 2023; Shen et al., 2018). Se lograron predecir etiquetas de volumen en el año 13 y 18 del ciclo productivo. Particularmente, utilizamos variables de respuesta discretas generadas a partir del volumen por hectárea, como cuartiles, terciles y *clusters*. Aunque inicialmente se consideró evaluar y predecir valores numéricos de volumen, la complejidad de la escala de imagen satelital y la saturación de ciertos índices vegetativos (como el NDVI) llevó a la decisión de trabajar con categorías discretas.

La colinealidad de las variables de imagen satelital presentó un desafío, y se seleccionaron las variables más relevantes y menos correlacionadas para predecir el volumen en los años 13 y 18. Estas variables resultaron ser distintas para cada momento, reflejando la evolución de las características forestales a lo largo del ciclo productivo. Se obtuvieron altas exactitudes (encima de 0,9) en las predicciones, particularmente para el año 13, mientras que en el año 18 la exactitud máxima fue de 0,88 utilizando RF para predecir terciles de volumen. Esto puede ser posiblemente explicado por cambios en la forma y densidad de las copas de los árboles a lo largo del tiempo, lo cual afecta la interpretación de las imágenes y la estimación del tamaño de los árboles (Liu et al., 2022). En este sentido, la predicción de volúmen puede ser una herramienta eficiente en etapas más tempranas del crecimiento de los árboles cuando no se saturaron las imágenes aún y se distinguen los árboles entre sí.

Este estudio enfrenta complejidades que se intentaron corregir al máximo, como el intervalo temporal entre las mediciones de campo y las imágenes satelitales, y el desajuste espacial entre las mediciones de campo y los píxeles. A los trece años, la resolución de los píxeles era menor (10 m), lo que podría haber contribuido a una subestimación de la heterogeneidad espacial y a una representación homogénea de los rodales en las imágenes satelitales. A pesar de estas limitaciones, el estudio ha demostrado que las imágenes satelitales son una herramienta valiosa para trabajar con etiquetas de volumen a etapas avanzadas del ciclo de crecimiento de experimentos forestales, aunque enfrentan desafíos para determinar parámetros estructurales precisos de los árboles, como la altura o el diámetro a la altura del pecho.

Este trabajo demuestra la potencialidad de las imágenes satelitales y de las técnicas de *machine learning* para predecir la productividad forestal, abriendo caminos para la integración de tecnologías avanzadas como los drones y aportando a la interpretación de las imágenes satelitales. Estos avances prometen optimizar los sistemas de evaluación e inventario forestal, reducir los costos operativos y mejorar la toma de decisiones en el manejo forestal en Uruguay particularmente en etapas tempranas del ciclo productivo y tratandose de etiquetas, puede ser una herramienta eficiente en ensayos muy grandes para clasificar parcelas. Para obtener información detallada y valiosa en experimentos forestales de manejo no serían una herramienta recomendada como fue trabajada en esta tesis, pero es un desafío encontrar estrategias para poder determinar volumen como variable numérica.

6. Conclusiones generales

Los experimentos forestales parcelarios de largo plazo son fundamentales para adquirir información local y de calidad, impactando directamente en la efectividad al momento de diseñar nuevos sistemas agroforestales. Esta investigación subraya la importancia de estos estudios para entender la dinámica de crecimiento en eucalipto y pino bajo diversas condiciones de manejo y tratamientos silviculturales en Uruguay.

El empleo de estrategias de modelación espacio-temporal en el contexto de modelos lineales mixtos ha demostrado ser una herramienta valiosa y ofrece flexibilidad para abordar distintos tipos de bases de datos y experimentos. Este enfoque mejora la capacidad para capturar las complejidades inherentes al crecimiento forestal y proporciona un marco más robusto para la evaluación de tratamientos y la interpretación de interacciones dinámicas en los sistemas forestales.

En cuanto a los efectos del espaciamiento, se observó que densidades menores favorecen un incremento en el área basal y el volumen de los árboles, mientras que densidades más altas, aunque aumentan la productividad total por hectárea y elevan las tasas de mortalidad, generan árboles de menor tamaño. Estos resultados resaltan la necesidad de considerar el equilibrio entre el espaciamiento y el material genético para optimizar tanto la producción de madera como la sostenibilidad de las plantaciones particularmente en ensayos para madera sólida.

La productividad del *switchgrass* intercalado en un sistema agroforestal demostró ser poco afectada en relación con su crecimiento creciendo bajo cualquier distancia entre filas tanto con pino como con eucalipto, lo que sugiere que el desarrollo de sistemas agroforestales que integren cultivos entre líneas de árboles podría ser una estrategia viable para incrementar la eficiencia de las plantaciones forestales en Uruguay, además de permitir la obtención de productos intermedios previo a la cosecha de los árboles.

Finalmente, el uso de imágenes satelitales y el análisis mediante modelos de *machine learning*, como *support vector regression* y *random forest*, han probado ser efectivos para predecir la productividad forestal en términos de volumen de madera por hectárea como variable categórica. Este estudio revela que la teledetección puede ser una herramienta crucial para monitorear y gestionar los recursos forestales en etapas tempranas de crecimiento y para clasificar parcelas en ensayos de gran tamaño, aunque es necesario continuar explorando y mejorando las metodologías para lograr predicciones más precisas y cuantitativas.

En resumen, la integración de enfoques de modelación espacio-temporal, la consideración cuidadosa del espaciamiento y material genético en el diseño de los tratamientos, junto con el aprovechamiento de tecnologías avanzadas como la teledetección, proporcionan una base sólida para avanzar en la investigación forestal y mejorar la gestión de los recursos forestales en Uruguay.

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