

SEEDLING DENSITY ON THE MORPHOLOGICAL QUALITY OF *Toona ciliata* M. Roem. (MELIACEAE)

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Received for publication: 07/09/2024 – Accepted for publication: 30/09/2025

Resumo

Efeito da densidade de plântulas na qualidade morfológica de Toona ciliata M. Roem. (meliaceae). O sucesso do plantio florestal depende da qualidade das mudas produzidas, visando aumentar a produtividade do povoamento por meio do aprimoramento das técnicas utilizadas. Pesquisadores têm buscado definir as melhores metodologias para a produção de mudas florestais que apresentem altas taxas de sobrevivência e bom desempenho após o plantio. O presente estudo teve como objetivo avaliar a influência de diferentes densidades de mudas na bandeja sobre a qualidade morfológica de *Toona ciliata* ao longo do tempo. O experimento foi conduzido em casa de vegetação, em delineamento inteiramente casualizado. As mudas foram submetidas a tratamentos de alta e média densidade na bandeja, representando 494 e 247 plantas m⁻², respectivamente, até 210 dias após a emergência. Foram avaliadas as características morfológicas: altura, diâmetro do coleto, área foliar, massa seca de raiz, massa seca de caule, massa seca de folhas, massa seca total e o índice de qualidade de Dickson. A alta densidade na bandeja proporcionou maiores valores nas variáveis morfológicas de altura e área foliar das mudas de *Toona ciliata* em casa de vegetação. Para a densidade média, os maiores valores foram observados no diâmetro do coleto, massa seca de raiz e no índice de qualidade de Dickson. O sistema radicular das mudas tende a crescer ao longo do tempo, reduzindo a proporção da parte aérea. As variáveis morfológicas apresentaram alta correlação entre si de forma diretamente proporcional, sendo a massa seca total e o índice de qualidade de Dickson as que mostraram as maiores correlações.

Palavras-chave: Cedro-australiano; fitomassa; muda; índice de qualidade de Dickson.

Abstract

The success of forest planting depends on the quality of the seedlings produced, aiming to increase stand productivity by refining the techniques used. Researchers have sought to define the best methodologies for producing forest seedlings with high survival rates and strong performance after planting. The present study aimed to evaluate the influence of different seedling densities in the tray on the morphological quality of *Toona ciliata* over time. The experiment was conducted in a greenhouse, in a completely randomized design. The seedlings were subjected to high- and medium-density treatments in trays, corresponding to 494 and 247 plants m⁻², respectively, until 210 days after emergence. Morphological characteristics, height, stem diameter, leaf area, root dry weight, stem dry weight, leaf dry weight, total dry weight, and Dickson quality index were evaluated. Tray high-density provided higher values for the morphological variables height and leaf area in *Toona ciliata* seedlings in a greenhouse. For medium-density, the highest values were stem diameter, root dry weight, and Dickson quality index. The root system of the seedlings tends to grow over time, reducing the shoot proportion. The morphological variables are highly correlated with each other in a direct, proportional manner, with total dry weight and the Dickson quality index showing the highest correlations.

Keywords: Australian red cedar; phytomass; seedling; Dickson quality index

INTRODUCTION

Brazilian silviculture studies have basically focused on fast-growing species, such as *Eucalyptus* and *Pinus* (IBÁ, 2024). However, other alternatives should be studied to achieve greater diversity in forestry production. One of them is *Toona ciliata* M. Roem var. *australis* (Australian red cedar), which has been a standout over the years (STEFANO *et al.*, 2015).

Originally from the tropical regions of Australia, *T. ciliata* is an exotic species belonging to the Meliaceae family and has adapted well to its development in Brazil (SCHWERZ *et al.*, 2019). In general, it shows rapid growth, reaching up to 40 m in height and 3 m in diameter, providing a good financial return in a short time compared to native cedars and other forest essences.

As a result, this species of wood has been gaining ground in the market, with its primary purpose focused on the furniture industry, as it provides quality material for sawmills, with good durability, easy drying, and unfolding, in addition to being considerably resistant to xylophagous organisms (ANDRADE *et al.*, 2020).

However, to guarantee specific characteristics, *T. ciliata* cutting for marketing must occur around 12 years of age, depending on site conditions, management, and the intended use of the wood (SILVA *et al.*, 2021).

According to Souza *et al.* (2010), mean productivity at 10 years of age is approximately 150 m³ ha⁻¹, with thinning carried out for lumber production. Therefore, this species can become an attractive option in the search for a quality planted forest with good productivity. However, it is essential to adopt good practices to achieve this objective, from the greenhouse development to the procedures carried out in the field and at harvest (FERREIRA *et al.*, 2020).

The production of high-quality seedlings is a strategic, crucial investment in silviculture that results in the establishment of more productive, healthy, and sustainable forests. It is the first stage of the production chain in silviculture, being fundamental for establishing commercial forests and for environmental recovery. Quality seedlings, with good root development and health, guarantee more efficient planting and a higher survival rate, optimizing resource and labor use and directly impacting the productivity and success of the forestry enterprise (ELOY *et al.*, 2013).

The quality of the produced seedlings is essential to a successful planting; that is, specimens that demonstrate good physiological characteristics typically have better adaptation and initial growth, which can guarantee the plantation stability. Thus, one way to determine the quality index of seedlings is through morphological parameter assessment, which provides greater ease in evaluating and visualizing nursery conditions (MATOS *et al.*, 2022).

However, several factors can influence these characteristics, such as the number of seedlings per tray and its relationship with the degree of competition for growth space, the capacity to capture light, and the capacity to capture water and assimilate nutrients (NARDINI *et al.*, 2020). This density can affect plant development, which tends to exhibit different patterns depending on the species and on the genetic materials within the same species, in response to the different spacing applied in the nursery.

In this study, we hypothesize that seedling density affects the growth and development of *Toona ciliata* seedlings in the greenhouse, and the interception of photosynthetically active radiation, allowing forest managers to accelerate the production of seedlings with better qualities. Therefore, the present study aimed to evaluate the different densities of seedlings in trays on the morphological quality of *Toona ciliata* over time.

MATERIALS AND METHODS

Study area and experimental design

The experiment was conducted in a greenhouse at the Federal University of Santa Maria, campus Frederico Westphalen, under geographic coordinates 27°23'26" S; 53°25'43" W, 461 m above sea level, in the municipality of Frederico Westphalen – RS. According to the Köppen climate classification, the region's climate is humid subtropical (Cfa), with temperatures ranging from 36.3°C to 2.3°C and an annual average of 19.4°C (CARON *et al.*, 2024).

For the study, *T. ciliata* seeds were purchased from Arbocenter Comércio de Sementes, located in Birigui - SP. Sowing was carried out on April 20th in commercial conical polypropylene tubes with open bottoms, with a volume of 90 cm³, arranged in plastic trays containing 96 tubes, positioned 1.0 m above the ground. The tubes were filled with a commercial substrate (Tecnomax®), composed of expanded vermiculite, pine bark, eucalyptus bark, rice husk, and coconut fiber, and supplemented with Basacote® fertilizer (16-8-12) at a rate of 10 g/L of substrate, with a release time of 6 months.

After 20 days, the seedlings were thinned to eliminate surplus in each container, leaving only the most. During the experiment, the water regime in the greenhouse (covered with 150 µm thick plastic film) was systematized into three daily irrigations of 10 minutes using sprinkler nozzles, with a water depth of 12 mm/day.

The experimental design was completely randomized, with the forest species evaluated at two levels of plant density on a tray: 100% (high density) and 50% (medium density), corresponding to 494 and 247 plants m⁻², respectively. Fifteen plant collections were carried out at different periods over time; the first was carried out 30

days after emergence, and the last at 210 days, indicating a 15-day interval between determinations. Double borders were used, with six plants evaluated in each of the fifteen periods, in each treatment.

Description of the assessments conducted

During the experiment assessment period, morphological characteristics, height, stem diameter, leaf area, root dry weight, stem dry weight, leaf dry weight, total dry weight, and Dickson quality index were determined.

To determine seedling height, the distance from the plant crown to the apex was measured with a ruler graduated in millimeters. The stem diameter was measured at the substrate level, using a digital caliper with millimeter precision (0,01mm). The measurements of total dry weight, root dry weight, and leaf dry weight were carried out by separating the plant shoot and root parts, followed by oven-drying at 65°C under forced ventilation until constant weight. The weighing was conducted with an electronic scale with milligram precision (0,001g). Total dry weight was obtained by summing the dry weights of the root, stem, and leaf.

The leaf area was calculated using the LI-3000C leaf area meter. The Dickson quality index was determined using the equation proposed by Dickson; Leaf; Hosner (1960), given by the following equation (1):

$$DQI = \frac{TDW}{\frac{H \cdot LDW}{SD \cdot RDW}} \quad (1)$$

Where: DQI = Dickson quality index; TDW = total dry weight (g); LDW = leaf dry weight (g); RDW = root dry weight (g); H = height of the shoot (cm); SD = stem diameter (mm).

To verify the seedling density in the tray that provided the best use of solar radiation, an evaluation of the conversion efficiency of photosynthetically active radiation was carried out. Radiation measurements were carried out using a pyranometer (LI200X, LICOR). The model proposed by Monteith (1977) was used to estimate total dry weight production, which is a function of the amount of photosynthetically active radiation intercepted multiplied by the efficiency of converting this radiation into dry phytomass. Thus, the radiation-use efficiency can be calculated through the relationship between the production of total dry weight and the intercepted photosynthetically active radiation involved in the production of phytomass, given by the following equation (2):

$$TDW = \varepsilon b * PAR_i \quad (2)$$

Where: TDW = production of dry biomass (g m⁻²); εb = conversion efficiency of PAR_i radiation into dry phytomass produced (g MJ⁻¹); PAR_i = intercepted photosynthetically active solar radiation (MJ m⁻²).

The radiation-use efficiency value, given by the angular coefficient, represents the amount of phytomass accumulated for each unit of energy intercepted. The photosynthetically active radiation intercepted was determined based on the model proposed by Varlet-Grancher *et al.* (1989), given by the following equation (3):

$$PAR_i = 0,95 * (PAR_{inc}) * (\ln^{-k * LAI}) \quad (3)$$

Where: PAR_i = photosynthetically active radiation intercepted (MJ m⁻²); PAR_{inc} = incident photosynthetically active radiation (MJ m⁻²); k = extinction coefficient (the average value of k obtained in the present study was used, which was 0.18 and 0.13 for HD and DM, respectively); LAI = leaf area index.

Leaf area index was determined from the leaf area of each plant and the tray area explored by it, given by the following equation (4):

$$LAI = \frac{LA}{AES} \quad (4)$$

Where: LAI = leaf area index; LA = total leaf area of the plant (m²); AES = tray area explored by the plant (m²).

The extinction coefficient was obtained from the optical properties of the leaves and the geometry of the plant canopy, and was calculated for each plant density, given by the following equation (5):

$$k = -\ln \left(\frac{R_{inf}}{R_{sup}} \right) / LAI \quad (5)$$

Where: k = extinction coefficient; R_{inf} = solar radiation measured under the seedling canopy (MJ m⁻²); R_{sup} = solar radiation measured over the seedling canopy (MJ m⁻²); LAI = leaf area index.

Data analysis

The data were analyzed using the Statistical Analysis System (SAS Institute, 2003) in a completely randomized design, with two factors, plant density and periods over the evaluation time, with six replications. They were subjected to analysis of variance (F-test), the Shapiro-Wilk test for normality, and the Bartlett test for homoscedasticity of variances, which indicated that the data were normally distributed. In the case of significant variance, multiple comparisons of means were performed using the Tukey test at 5% probability of error, and regression analysis was performed. These analyzes were carried out to identify similarities and divergences in the morphological variables in *T. ciliata* seedlings, which are essential to discuss the influence of the two densities on the growth and development of the seedlings analyses were carried out to identify similarities and differences in morphological variables in *T. ciliata* seedlings, which are essential for discussing the influence of the two densities on seedling growth and development.

The functional relationship between seedling densities in the tray and morphological variables was evaluated using Pearson's correlation test, with all analyzed values included. These relationships allow us to evaluate whether variations in seedling density in the tray influence morphological variables.

RESULTS

From the analysis of variance, significant differences are observed across days after emergence for all variables studied. Likewise, the parameters height, stem diameter, leaf area, and Dickson quality index also showed differences in relation to seedling density in the tray. The interaction of days after emergence with planting density was significant for the variables height, leaf area, and Dickson quality index.

From the test of means, we observed that the highest mean values for height were 18.50 cm at 180 days in the treatment with high density of seedlings in the tray, while the variable leaf area presented the highest mean value height was 18.50 cm at 180 days for the treatment with high seedling density in the tray, while the variable leaf area showed the highest mean at 210 days for the same treatment. For the variables stem diameter, root dry weight, and Dickson quality index, the highest results were observed at 210 days in the medium-density treatment. The variables measuring dry weight did not show differences among seedling density treatments in the tray across the evaluation periods.

When analyzing the regression equations for all morphological variables across the different seedling densities in the trays, we observed a systematic positive relationship with days after emergence; that is, in longer periods, the highest values were observed. Likewise, height and leaf area were higher in the high-density treatment. At the same time, diameter, root dry weight, and Dickson quality index were higher in the medium-density treatment, producing better-quality seedlings, according to the variables studied. Overall, both treatments promoted seedling development (Figure 1).

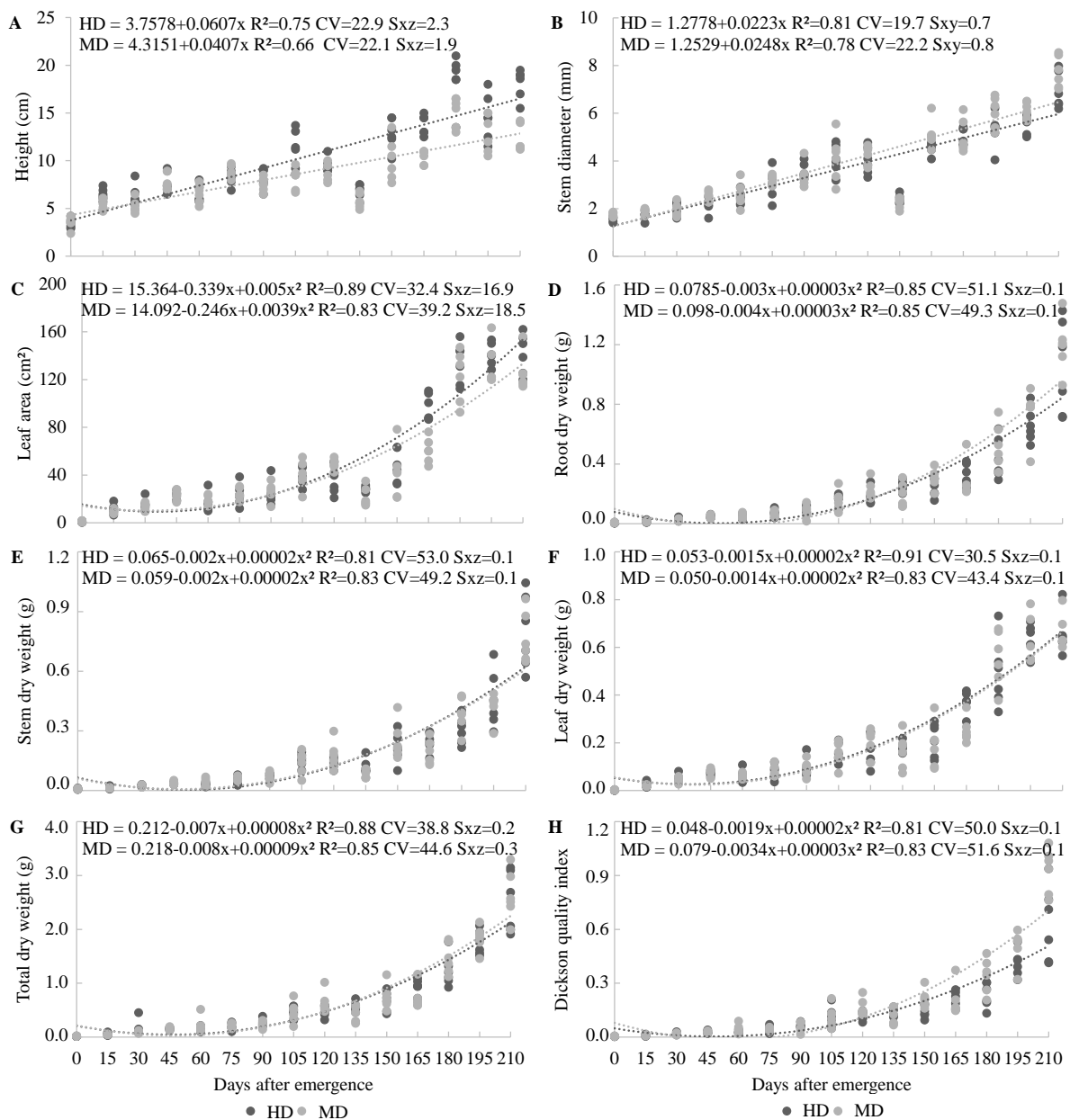


Figure 1. Regression equations for morphological variables over time, arranged in high-density (HD) and medium-density (MD) seedlings in the tray over time, in *Toona ciliata* seedlings

Figura 1. Equações de regressão para variáveis morfológicas ao longo do tempo dispostas em mudas de alta densidade (HD) e média densidade (MD) na bandeja ao longo do tempo, em mudas de *Toona ciliata*

The analysis of root, stem, and leaf biomass partitioning for the two treatments tested revealed a tendency for the root system to increase over time across the two seedling densities in the trays. On the other hand, a reduction in the shoot was observed, both in the proportion of stem and leaf. This characteristic was better observed in the treatment with medium density, due to lower plant competition, resulting in greater accumulation of dry root weight (Figure 2).

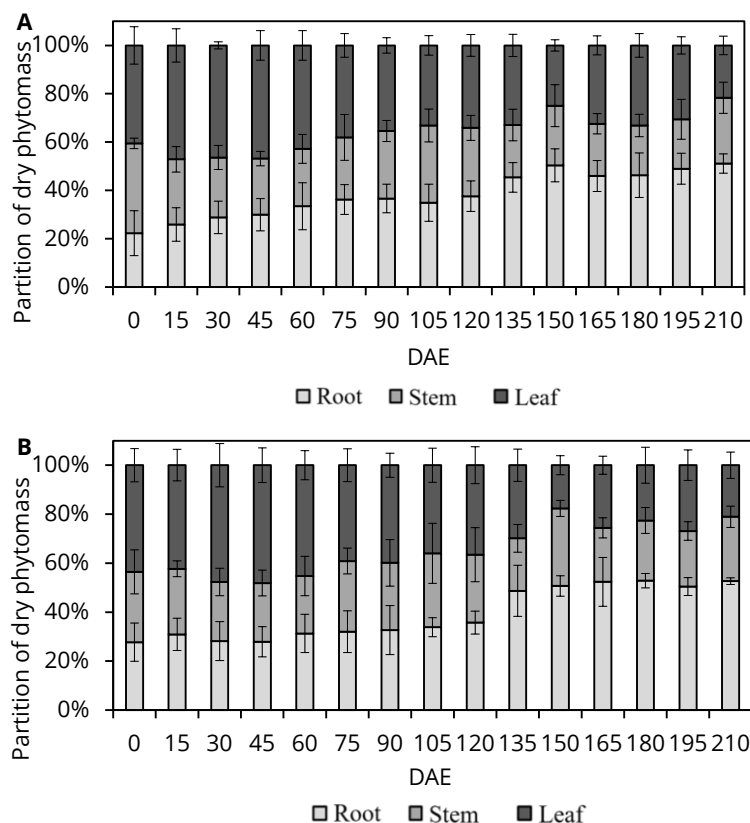


Figure 2. Partition of dry phytomass of *Toona ciliata* seedlings in the condition of high-density (A) and medium-density (B) seedlings in the tray, on different days after emergence (DAE), with their respective standard deviation bars.

Figura 2. Partição da fitomassa seca de mudas de *Toona ciliata* na condição de alta densidade (A) e média densidade (B) de mudas na bandeja, em diferentes dias após a emergência (DAE), com suas respectivas barras de desvio padrão.

Pearson's correlation analysis demonstrated that all variables studied, across both tray density treatments, showed high, directly proportional correlation coefficients. For some variables, these results were already expected, such as the correlations between height and stem diameter, days after emergence, and the relationships between dry weights. In general, the Dickson quality index and total dry weight showed the highest correlations, particularly with days after emergence and dry weight variables (Table 1).

Table 1. Pearson's correlation coefficient between morphological variables arranged in different seedling densities in the tray over time, in *Toona ciliata* seedlings.

Tabela 1. Coeficiente de correlação de Pearson entre variáveis morfológicas dispostas em diferentes densidades de mudas na bandeja ao longo do tempo, em mudas de *Toona ciliata*.

PD	DAE	H	SD	LA	RDW	SDW	LDW	TDW
HD	DQI	0.97*	0.84*	0.93*	0.94*	0.99*	0.97*	0.98*
	DAE		0.87*	0.91*	0.93*	0.98*	0.97*	0.95*
	H			0.89*	0.89*	0.86*	0.90*	0.87*
	SD				0.92*	0.91*	0.94*	0.90*
	LA					0.94*	0.95*	0.98*
	RDW						0.97*	0.96*
	SDW							0.97*
	LDW							

PD	DAE	H	SD	LA	RDW	SDW	LDW	TDW	
MD	DQI	0.96*	0.83*	0.93*	0.91*	0.99*	0.97*	0.94*	0.99*
	DAE		0.83*	0.90*	0.89*	0.97*	0.95*	0.94*	0.96*
	H			0.91*	0.91*	0.84*	0.88*	0.86*	0.86*
	SD				0.93*	0.91*	0.95*	0.90*	0.93*
	LA					0.91*	0.93*	0.95*	0.94*
	RDW						0.97*	0.94*	0.98*
	SDW							0.95*	0.98*
	LDW								0.97*

Where: DAE = days after emergence; H = height; SD = stem diameter; LA = leaf area; RDW = root dry weight; SDW = stem dry weight; LDW = leaf dry weight; TDW = total dry weight; DQI = Dickson quality index; PD = planting densities; HD = high density; MD = medium density; *Pearson correlation coefficients significant at 5% error probability.

The total dry weight increase showed a positive linear relationship with accumulated intercepted photosynthetically active radiation, with high coefficients of determination and a response dependent on seedling density (Figure 3). This same characteristic was observed for leaf area index: when analyzing the angular coefficients, we found that increasing seedling density increased leaf area index and, consequently, the plants were more efficient at converting solar radiation into phytomass. The efficiency of radiation use in total dry weight of seedlings, relative to the amount of intercepted photosynthetically active radiation accumulated, was 1.42 g MJ⁻¹ in the high-density treatment and 1.11 g MJ⁻¹ in the medium-density treatment (Figure 3).

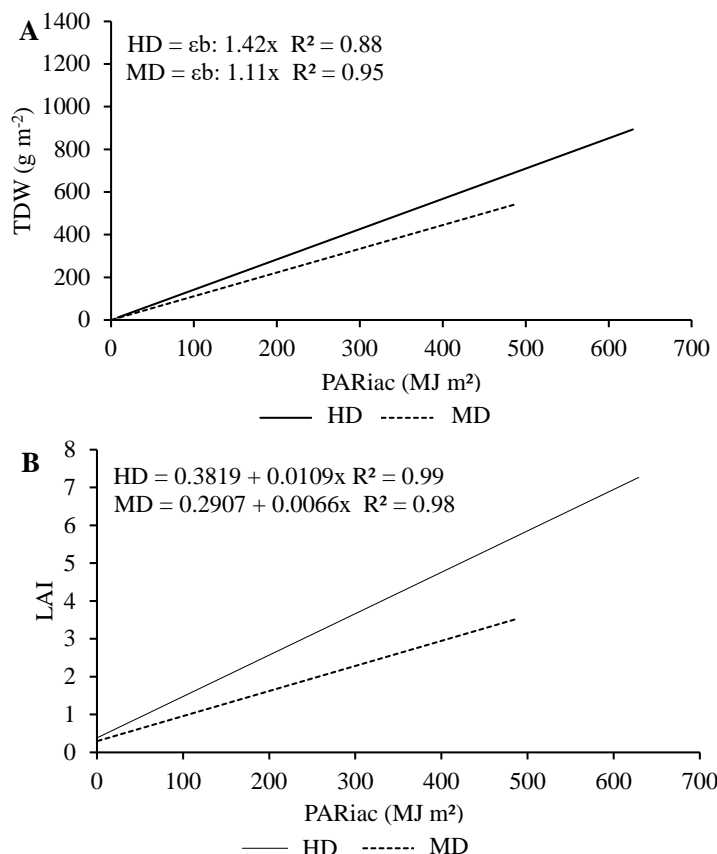


Figure 3 - Relationship between intercepted accumulated photosynthetically active radiation (PARiac) with total dry weight production (TDW) (a) and leaf area index (LAI) (b) for high-density (HD) and medium-density (MD) of *Toona ciliata* seedlings.

Figura 3 - Relação entre radiação fotossinteticamente ativa acumulada interceptada (PARiac) com produção total de peso seco (TDW) (a) e índice de área foliar (LAI) (b) para alta densidade (HD) e média densidade (MD) de mudas de *Toona ciliata*.

DISCUSSION

By analyzing the results, we observe that seedling density in the tray has influenced growth, especially height. According to Eloy *et al.* (2013), shoot height is widely used as a criterion for classifying seedlings because it is easy to measure and does not require plant destruction.

Regarding the values observed for this variable in the present study, we note that they are consistent with those reported by Massad *et al.* (2023), who evaluated the performance of *Peltophorum dubium* (Spreng.) Taub. seedlings at different densities in trays and concluded that the higher density presented better performance in height, and this characteristic can be attributed to the greater competition for light and space.

The seedling diameter also stands out as a relevant variable that best predicts post-planting performance (CARGNELUTTI FILHO *et al.*, 2012). High values of this characteristic are usually associated with a well-formed root system, which benefits plant establishment and development under weed-competition conditions. Both variables are important as parameters for seedling qualification.

Regarding density, Eloy *et al.* (2013) reported that decreasing the number of seedlings per tray reduces growth in height but increases diameter, corroborating the results of this study (Figure 1). This reduction in the number of individuals improves air circulation, thereby reducing the intensity of contamination by pathogenic fungi. In addition, it also allows for more efficient irrigation, helps with the proper application of fertilizers, and provides better sun exposure to the seedlings. Given these characteristics, associated with the growth variables studied, it is recommended to use a medium seedling density in the tray, as this produces better-quality seedlings.

Likewise, Gonçalves *et al.* (2019) highlighted that greater stem diameter development is desirable relative to shoot height. For the same author, this occurs because seedlings with greater heights and reduced diameters indicate etiolation and are easily damaged in the field, or even unable to survive in adverse conditions. Therefore, with a larger diameter, seedlings have a higher survival rate in the field, greater formation ability, and greater ability to form new roots.

Plant density influenced the increase in leaf area index by affecting the distribution of plants in the canopy and, mainly, the leaf area index. This was observed in the greater accumulation of dry matter resulting from intercepted and accumulated photosynthetically active radiation, and it is closely linked to leaf area index (Figure 3). Thus, as it increases, the amount of intercepted photosynthetically active radiation increases and, as a consequence, so does the accumulation in phytomass. This characteristic was also observed by Caron *et al.* (2012) in *Eucalyptus grandis* W. Hill ex Maiden seedlings and by Eloy *et al.* (2018) in *Acacia mearnsii* De Wild seedlings, both studying the conversion efficiency of photosynthetically active radiation into biomass.

These results corroborate those cited by Maggioni *et al.* (2014) when working with the species *Ocimum basilicum* L., where they observed that the growth of seedlings depends on the amount of photosynthetically active radiation intercepted, the efficiency of using this energy in the photosynthesis process, the density of plants per tray, and the environment of cultivation.

These situations show that plant arrangement is a critical management practice, given its interaction with solar radiation interception, which is one of the main determining factors in the growth and development of a given crop. In seedling cultivation, the supply of water and nutrients is generally not a limiting factor because they can be controlled. In this context, solar radiation, in interaction with water and nutrient availability, becomes the main determinant of biomass production, as observed by Nardini *et al.* (2022). Therefore, the growth of *T. ciliata* seedlings will depend on the amount of photosynthetically active radiation intercepted and the efficiency with which this energy is used in the photosynthetic process for phytomass production, as well as on plant density in the tray.

From the Pearson correlation analysis (Table 1), we observed that all morphological parameter coefficients across the different treatments were significant. The height variable showed, for most relationships, the lowest correlation estimates, demonstrating that, despite being an easy-to-measure variable, it is risky to use it in isolation as an indicator of seedling quality.

However, the characteristics related to dry weight showed the highest correlation values, with total dry weight, in general, standing out as the highest for both seedling density treatments, thus highlighting that it can be considered a good quality indicator (Table 2). This result corroborates those obtained by Eloy *et al.* (2013) with *Eucalyptus grandis* W. Hill ex Maiden, who reported high Pearson correlation coefficients for total dry weight.

According to Fonseca *et al.* (2002), the Dickson quality index is a good indicator, as it considers parameters such as robustness and the balance of biomass distribution in the seedling, and uses results from several significant parameters to assess quality. In contrast, Gomes *et al.* (2019) explain that this index is a variable characteristic and can be influenced by species, nursery management of seedlings, the type and proportion of the substrate, container volume, and, mainly, seedling age. Therefore, the higher its value, the higher the quality of the seedling.

Similarly, Elli *et al.* (2016) studied the *Acacia mearnsii* De Wild. Seedlings and found an increasing trend in the Dickson quality index throughout the period of seedling evaluation in the air-conditioned greenhouse, under the influence of different volumes of tubes. In this study, dry matter production was considered one of the best parameters for characterizing seedling quality. However, they highlighted that determining this variable may not be feasible in many forest nurseries, as it requires complete destruction of seedlings, equipment to measure weight, and the use of high-temperature drying ovens.

From the regression analysis of the analyzed variables (Figure 1), we observed that all variables showed increasing trends, especially in later periods. Similar results were reported by Eloy *et al.* (2013), who showed that *Eucalyptus grandis* W. Hill ex Maiden seedlings also showed an increasing trend in the Dickson quality index throughout the analyzed period across all treatments.

Regarding the results for the dry phytomass partition variable (Figure 2), it is worth noting that they are consistent with the work by Schwerz *et al.* (2017), who also found a higher percentage of roots, followed by leaves and stems. The relationship of assimilation in seedlings is mainly directed toward root and leaf formation, indicating that the proportions of biomass compartments vary with plant age. Therefore, seedlings with higher root biomass tend to perform better after planting, due to a larger root area and greater efficiency in absorbing water and nutrients.

CONCLUSION

- Seedling density in the tray influences the morphological variables of *Toona ciliata* seedlings in a greenhouse.
- High density provides greater height and leaf area values. The medium density, in turn, showed the highest values for stem diameter, root dry weight, and Dickson quality index at 210 days after seedling emergence.
- There is a tendency for the root system proportion to increase over time, reducing that of the shoot, from the stem and leaf.
- The morphological variables are highly correlated with each other in a directly proportional way, and, in general, the total dry weight and the Dickson quality index present the highest correlations.
- To produce seedlings from the *Toona ciliata* species in a nursery, it is recommended to use a medium density of seedlings in the tray, as it produces better quality seedlings, according to the variables studied, in particular the Dickson quality index.

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