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Impact of paclobutrazol on the initial growth of *Tectona grandis* clones under different water availability regimes

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ABSTRACT

Plantations continually confront climatic challenges that may impede their initial establishment in the field, thereby adversely affecting their overall productivity. In order to establish protocols for forest plantations that address potential challenges arising from global climate variations, growth regulators play a significant role. The use of plant growth regulators in early forest species' growth and establishment stages is limited. The present study assessed the morphophysiology of *Tectona grandis* clones in response to different water regimes and paclobutrazol concentrations applied to the soil. The experiment followed a randomized block design with four blocks and a 5x3 factorial scheme. This scheme included five concentrations of PBZ: 0.0 (control), 1.0, 2.0, 4.0, and 8.0 mg plant^{-1}, and three levels of water availability: 40%, 70%, and 100% of field capacity. There was no interaction between PBZ concentration and water regime factors. Based on the analysis applied to each treatment, plants' morphological and physiological variables did not respond to the use of different PBZ concentrations, although significant differences were observed in some morphological and physiological traits. The higher water availability provided by 100% field capacity led to the highest increase in stem diameter, root and total dry mass values. *Tectona grandis* clones presented increased carboxylation efficiency and water-use efficiency at 40% field capacity.

Keywords: drought tolerance, field capacity, morphological changes, PBZ.

Impacto do paclobutrazol no crescimento inicial de clones de *Tectona grandis* sob diferentes disponibilidades hídricas

RESUMO

As plantações enfrentam continuamente desafios climáticos que podem impedir seu estabelecimento inicial no campo, afetando adversamente sua produtividade geral. Em um esforço para estabelecer protocolos para plantações florestais que abordem desafios potenciais decorrentes de variações climáticas globais, os reguladores de crescimento desempenham um papel significativo. O uso de reguladores de crescimento vegetal nos estágios iniciais de crescimento e estabelecimento de espécies florestais é limitado, o objetivo do presente estudo foi avaliar a morfofisiologia de clones de *Tectona grandis* em resposta a diferentes regimes hídricos e concentrações de paclobutrazol aplicadas ao solo. O experimento seguiu um delineamento de blocos casualizados com quatro blocos e um esquema fatorial 5x3. Este esquema incluiu cinco concentrações de PBZ: 0,0 (controle), 1,0, 2,0, 4,0 e 8,0 mg planta^{-1}, e três níveis de disponibilidade de água: 40%, 70% e 100% da capacidade de campo. Não houve interação entre a concentração de PBZ e os fatores do regime hídrico. Com base na análise aplicada a cada tratamento, as variáveis morfológicas e fisiológicas das plantas não responderam ao uso de diferentes concentrações de PBZ. No entanto, diferenças significativas foram observadas em algumas características morfológicas e fisiológicas. A maior disponibilidade hídrica proporcionada por 100% da capacidade de campo levou ao maior aumento nos valores de diâmetro do caule, raiz e massa seca total. Os clones de *Tectona grandis* apresentaram aumento na eficiência de carboxilação e eficiência no uso da água a 40% da capacidade de campo.

Palavras-chave: capacidade de campo, mudanças morfológicas, PBZ, tolerância à seca.

1. INTRODUCTION

In the current environmental context, plantations face constant exposure to climatic challenges that can restrict their initial establishment in the field, negatively impacting their productive potential (Assad *et al.*, 2021). Factors such as intense solar radiation, soil salinity, temperature fluctuations, and seasonal rainfall patterns are the primary constraints affecting this process (Hatfield and Prueger, 2015). Limited water availability has the potential to bring about significant alterations in plant metabolism and plasticity, leading to morphological and physiological changes, including leaf senescence, reduced mass, heightened stomatal resistance, and diminished photosynthetic capacity (Chen *et al.*, 2022).

Commercial plantations often use fast-growing species highly adaptable to varying edaphoclimatic conditions, and these traits are typically observed in exotic species. This profile increases interest in these species in order to help maximizing timber production and sustaining its industry while preserving native flora (Rocha *et al.*, 2015).

The bulk of investments in planted forests are focused on various species within the *Eucalyptus* and *Pinus* genera due to their extensively documented characteristics. However, one species gaining ground in these plantations is teak (*Tectona grandis*), known for its highly durable wood and market value addition (Ibá, 2021). The amalgamation of improved silvicultural practices, such as spacing adjustments and pre-planned thinning, coupled with Brazil's edaphoclimatic conditions, has significantly reduced its cutting cycle from 80 to 20 years, compared to its original region, showcasing promise for timber production (Rocha *et al.*, 2015). Data indicates that teak plantations occupy larger proportions than *Eucalyptus* in the states of Mato Grosso and Rondônia, and the species is steadily intensifying in the state of Pará (Ibá, 2021).

In an attempt to devise protocols for forest plantations that mitigate potential issues caused by planetary climate variations, growth regulators come into play. These organic compounds possess the ability to inhibit or induce plant growth and development, allowing alterations in their morphophysiological processes, potentially rendering species more resilient to abiotic stresses (Ribeiro *et al.*, 2017).

The plant growth regulator paclobutrazol (PBZ) has been employed in agricultural and tree species, resulting in more compact plants with expanded roots at the expense of the aboveground parts (Brito *et al.*, 2016). PBZ is employed for commercial purposes to regulate vegetative growth by altering the dry mass distribution in seedling production processes. It facilitates a higher allocation of biomass to the root system compared to the plant area (Benett *et al.*, 2014; Binotti *et al.*, 2019). Additionally, PBZ has been shown to enhance leaf chlorophyll content, increase the photosynthetic rate, and boost the production of antioxidants, while simultaneously reducing the plant's transpiration rate (Xia *et al.*, 2018). Collectively, these effects can contribute to improving the water status in plants and, consequently, enhance their tolerance to water deficit (Maheshwari *et al.*, 2022).

PBZ belongs to the triazole chemical group; it presents Class III toxicological classification (little toxic) and inhibits gibberellins biosynthesis (Oliveira *et al.* 2020; Desta and Amare, 2021). This substance acts by reducing the activity of enzymes found in the endoplasmic reticulum, which accounts for oxidizing ent-kaurene. It is the precursor of GA12, which, in turn, is the first gibberellin formed in all plants (Taiz *et al.* 2017; Tesfahum and Yildiz, 2018). In addition to the negative impact on gas synthesis, this regulator can also affect the synthesis of hormones, such as abscisic acid (ABA), cytokinin and ethylene (Desta and Amare, 2021). Although it is a fungicide with high persistence in the soil, it shows low mobility and risk of contamination due to leaching; moreover, it can be applied on plant leaves or directly in the soil (Brito *et al.*, 2016). Its application on leaves can lead to uneven plant size if it is not properly performed, whereas soil application is more efficient due to high stability of this product on soil surface, a fact that makes it available to be absorbed by plants for longer periods of time (Desta and Amare, 2021).

Given the limited studies in the literature on the use of plant growth regulators in forest species, this study hypothesizes that the application of different paclobutrazol concentrations to the soil, in combination with varying water regimes, will significantly influence the morphophysiology of *Tectona grandis* clones during their early stages of growth and establishment.

2. MATERIAL AND METHODS

The experiment was conducted in a greenhouse setting at the experimental garden of the Rio Branco campus of the Federal University of Acre (UFAC), which is located at BR 364, km 4, Industrial District, Rio Branco, Acre, Brazil (latitude 9°57'34" S, longitude 67°52'13" W and altitude 150 m). According to Köppen’s classification, climate in the region is of the Am type (hot and humid equatorial climate); its mean annual temperature reaches 25.5ºC, and its mean annual rainfall rates range from approximately 1,700 to 2,400 mm (Barbosa *et al.*, 2022; Bento *et al.*, 2021).

Young plants of *Tectona grandis*, clone PROTECA A3, approximately 120 days old, suitable for planting, were obtained through a donation from Grupo Proteca, a company located in Cuiabá, Mato Grosso. The aforementioned clones were transplanted, separately, to 11-L pots filled with homogeneous mix comprising soil (Plinthic Argisol or Ultisol) and commercial substrate, at 4:1 ratio. Transplanted plants were arranged on suspended benches andmanually irrigated every other day with a watering can for 14 days to enable acclimation. Manual weeding was carried out whenever necessary to avoid competition and compromising plant development.

Water availability regimes were initiated following the completion of the acclimation period. The determination of field capacity (FC) was carried out through the gravimetric method, utilizing three pots filled entirely with a soil-commercial substrate mix. These pots were saturated with moisture and left to undergo free drainage for 7 days. The water content retained by the dry substrate after saturation and subsequent excess water drainage was defined as 100% FC (Taiz *et al.*, 2017). The other water treatments (40% and 70% FC) were established by calculating the respective water weight rates at 100% field capacity. Maintenance of water treatments involved regularly weighing the pots using a digital electronic scale and manually replenishing the transpired water volume as needed with the assistance of a watering can.

The experiment followed a randomized block design, with four blocks and a 5x3 factorial scheme. This scheme included five concentrations of PBZ: 0.0 (control), 1.0, 2.0, 4.0, and 8.0 mg plant^{-1} (Maheshwari *et al.*, 2022), and three levels of water availability: 40%, 70%, and 100% of field capacity. The experimental plots comprised pots with one plant each, totaling 60 plants.

The commercial product used in the experiment was Paclobutrazol PESTANAL® Analytical Standard (250 mg). PBZ concentrations were applied in a single dose of 100 mL (to facilitate the application of PBZ) per plant, 27 days after planting and 14 days after implementing the water availability regimes.

Morphological assessments were based on plant height, diameter, biomass and leaf area. Plant height (H) was obtained by measuring the basal part to the cauline apex. Collar diameter (D) was measured at 3 cm from the ground. Leaf area (LA) was determined through the random selection of five plants, which had their leaves extracted and arranged on a flat surface that had a measuring tape graduated in centimeters attached to its side. Leaves were photographed and images were digitized and processed in Image Pro Plus® software; spatial measurement was calibrated based on using the metric tape in the images to determine LA (cm^2/leaf), and on equation ($y = 108.22\ x – 128.65$; $R^2 = 0.9112$). Based on the leaf dry mass of each plant, it was possible to infer the LA per plant. Plants were cut at collar height and divided into root, stem and leaf to measure root dry mass (RDM) and shoot dry mass (ShDM), which comprised leaf (LDM) and stem (StDM) dry mass; it was done for dry matter production analysis purposes. Plant tissues were placed, separately, in paper bags, labeled and taken to an air circulation oven at 105°C, until they reached constant weight. Then, they were weighed on analytical balance. Total dry mass (TDM) was calculated by adding shoot and root dry mass, whereas shoot:root ratio (S:R) was calculated by dividing ShDM by RDM.

Photosynthesis and gas exchange were assessed using portable closed-system photosynthesis equipment, Infrared Gas Analyzer (IRGA), Model Li-6400XT, by LI-COR Inc. CA, USA. Readings were performed in the middle part of the first fully expanded leaf, from 7:00 am to 10:00 am. Each measurement procedure comprised net photosynthesis (A, in µmol m^{-2}s^{-1}), stomatal conductance (gs, in mol m^{-2}s^{-1}), leaf transpiration (E, in mmol m^{-2}s^{-1}) and partial pressure of carbon dioxide (Ci, µmol CO_2 mol^{-1} air). Chamber temperature was maintained at 30°C, external CO_2 concentration (reference) was maintained at 400 ppm and photosynthetically active photon flux density (PPFD) in the leaf was maintained at 1,200 µmol photons m^{-2}.s^{-1} for these measurements. Carboxylation efficiency (A/Ci) was determined based on collected data; it was calculated based on the A:Ci ratio (µmol m^{-2}s^{-1}) = net photosynthesis/partial CO_2 pressure. Water-use efficiency (WUE) was calculated based on the A:E ratio (µmol CO_2 mmol^{-1}H_2O^{-1}) = net photosynthesis/transpiration.

At the end of the experiment, 68 days after the application of the growth regulator and 91 days after the water regime implementation, all 60 plants survived and were evaluated by morphological assessments. Regarding physiological evaluation, in total, 36 plants were used for assessments focused on investigating the effects of PBZ concentrations (0.0, 2.0 and 8.0 mg plant^{-1}) by comparing the second lowest and the highest dose of it to the control treatment.

The results of the treatments underwent analyses for variance homogeneity (Cochran, $p<0.05$) and error normality (Shapiro-Wilk, $p<0.05$). Once these assumptions were satisfied, analysis of variance (ANOVA, $F<0.05$) was conducted using a double factorial design within randomized blocks. Mean tests (Tukey, $p<0.05$) were applied to compare recorded mean values for factors A (concentration of PBZ) and B (water availability) in cases where significant differences were observed between treatments. All these statistical analyses, including mean tests, variance homogeneity, error normality, and analysis of variance, were carried out using

IBM SPSS software.

3. RESULTS AND DISCUSSION

3.1. Paclobutrazol (PBZ)

There was no interaction between PBZ concentration and water regime factors. Variables were analyzed under the influence of each treatment, in separate. Based on the analysis applied to each treatment, plants' physiological (Table 1) and morphological (Table 2) variables did not respond to the use of different PBZ concentrations ($p>0.05$).

Table 1. Physiological characteristics (average values) of *Tectona grandis* clones subjected to PBZ application (mg plant^{-1}): photosynthesis rate (A, µmol CO_2 $m^{-2}s^{-1}$), transpiration rate (E, mmol H_2O $m^{-2}s^{-1}$), partial pressure of CO_2 (Ci, µmol CO_2 mol^{-1}), stomatal conductance (gs, mmol H_2O $m^{-2}s^{-1}$), carboxylation rates (A/Ci, µmol $m^{-2}s^{-1}$) and water-use efficiency (WUE, µmol CO_2 mmol H_2O^{-1}).

PBZ	A	E	Ci	Gs	A/Ci	WUE
0	13.64	3.67	21.82	0.15	0.64	3.79
2	12.68	4.17	23.90	0.19	0.56	3.34
8	13.22	3.56	21.16	0.15	0.63	3.87

Table 2. Morphological characteristics (average values) of *Tectona grandis* clones subjected to PBZ application (mg plant^{-1}): total height (H, cm), basal diameter (D, mm), leaf dry mass (LDM, g), stem dry mass (StDM, g), root dry mass (RDM, g), shoot dry mass (ShDM, g), total dry mass (TDM, g), shoot/root ratio (S/R) and leaf area (LA, cm^2).

PBZ	H	D	LDM	StDM	RDM	ShDM	TDM	S/R	LA (x10^3)
0	77.3	17.0	45.0	31.7	33.8	76.7	110.4	2.6	4741
1	72.8	15.7	41.3	28.3	30.0	69.8	99.6	2.8	4516
2	78.8	17.5	50.4	32.9	32.5	83.3	115.8	2.9	5327
4	74.3	15.8	43.3	31.3	28.3	74.6	102.9	2.9	4561
8	71.0	15.8	47.1	29.2	31.3	76.3	107.5	2.6	4967

Plants' physiological variables, such as photosynthesis, transpiration, partial CO_2 pressure, stomatal conductance, carboxylation efficiency and water-use efficiency recorded mean values equal to 13.2 µmol CO_2 $m^{-2}s^{-1}$, 3.8 mmol H_2O $m^{-2}s^{-1}$, 22.3 µmol CO_2 mol^{-1}, 0.2 mmol H_2O $m^{-2}s^{-1}$, 0.6 µmol $m^{-2}s^{-1}$ and 3.7 µmol CO_2 mmol H_2O^{-1}, respectively (Table 1).

Mean values observed for plant height, diameter, root dry mass, shoot dry mass, total mass, shoot:root dry mass ratio, and leaf area reached 74.8 cm, 16.4 mm, 31.2 g, 76.1 g, 107.2 g, 2.8 (dimensionless) and 4822 cm^2, respectively, at different PBZ concentrations (Table 2). Overall, the highest values recorded for the aforementioned variables were observed after 2 ppm of PBZ were applied to plants, although this concentration did not have a significant effect on them ($p>0.05$).

PBZ concentrations did not have any effect on the herein investigated morphophysiological variables ($p>0.05$) (Table 1 and 2). PBZ often reduces cell elongation and division by lowering biologically active gibberellin levels (Desta and Amare, 2021). This effect can result in shorter internodes and, later on, in reduced plant height (Rademacher, 2016). Although the current findings may be linked to regulator's action duration, its slow absorption after its application to the soil allows it to remain relatively stable for up to 60 post-application days, without affecting plant growth and development processes (Maganhotto *et al.*, 2003; Oliveira *et al.*, 2012). Moreover, the PBZ molecule can show limited mobility within plant tissues. Consequently, plant growth returns to normal levels as new tissues, which are not affected by regulator's effects, develop at the stem apex (Espindula *et al.*, 2010; Pricinotto and Zucareli, 2014).

The specific focus of plant physiology analyses may have reduced PBZ impact on teak clones. This factor can be attributed to strong association between gas exchange and environmental factors. Moreover, leaf morphology and anatomy adaptability can be an effective method to adjust plants' hydraulic conductivity and stomatal conductance in response to varying environmental conditions (D'arêde *et al.*, 2017; Rodrigues *et al.*, 2016). Previous observations have evidenced lower PBZ influence on leaf gas exchange, as opposed to its impact on photoassimilates' distribution and accumulation. This factor was noticed in several *Toona ciliata* clones subjected to PBZ application through substrate immersion (Rodrigues *et al.,* 2016). Differences in expression levels, as well as the temporary duration of gibberellin inhibitors' impact on leaf gas exchange, were linked to transportation and breakdown rate in tissues (Harmath *et al.*, 2014).

According to Moraes *et al.* (2013), changes in *Hymenaea courbaril* seedlings' shoot due to the application of this regulator through substrate irrigation were only noticeable after 90 days. These results are in compliance with observations in the current study.

Findings about the investigated clones are in compliance with previous reports, according to which, PBZ either did not influence nor had minimal impact on secondary growth accounting for increasing plant diameter due to vascular cambium and phellogen activity (Meena *et al.*, 2018; Santos *et al.*, 2018). Lack of PBZ's effect on plant stem was similarly noticed in 6-year-old *Syzygium cumini* trees grown in soil subjected to growth regulator applications (Hegde *et al.*, 2018). According to the aforementioned authors, PBZ played a limited or negligible role in cell division processes and did not change plant stem circumference (Hegde *et al.*, 2018).

PBZ application may have had a delayed effect on plants, since it was absorbed slowly after its application straight to the soil, besides having lingering impact on both plant height and shoot structure (Juárez-Rodríguez *et al.*, 2021; Villa *et al.*, 2012). Furthermore, PBZ can interact with plants' surrounding environment, a fact that can potentially influence its absorption by, and persistence in, the soil, depending on its composition, on microorganisms' presence in it, and on climatic factors (Villa *et al.*, 2012).

3.2. Water availability

Significant differences ($p<0.05$) were observed in some physiological (Table 3) and morphological traits (Table 4) based on the analysis applied to the water-availability effect on plant development.

Table 3. Physiological characteristics (average values) of *Tectona grandis* clones subjected to water regimes (Field capacity, FC%): photosynthesis rate (A, µmol CO_2 $m^{-2}s^{-1}$), transpiration rate (E, mmol H_2O $m^{-2}s^{-1}$), partial pressure of CO_2 (Ci, µmol CO_2 mol^{-1}), stomatal conductance (gs, mmol H_2O $m^{-2}s^{-1}$), carboxylation rates (A/Ci, µmol $m^{-2}s^{-1}$) and water-use efficiency (WUE, µmol CO_2 mmol H_2O^{-1}).

CC	A	E	Ci	gs	A/Ci		WUE	
40	14.23	3.75	20.97	0.27	0.70	**a**	3.98	**a**
70	13.65	3.87	21.78	0.31	0.65	**ab**	3.79	**ab**
100	11.66	3.79	24.13	0.35	0.49	**b**	3.28	**b**

Different letters indicate significant differences between the treatments (Tukey's test; $p < 0.05$).

Table 4. Morphological characteristics (average values) of *Tectona grandis* clones subjected to water regimes (Field capacity, FC%): total height (H, cm), basal diameter (D, mm), leaf dry mass (LDM, g), stem dry mass (StDM, g), root dry mass (RDM, g), shoot dry mass (ShDM, g), total dry mass (TDM, g), shoot/root ratio (S/R) and leaf area (LA, cm^2).

CC	H	D		LDM		StDM	RDM		ShDM	TDM		S/R		LA ($x10^3$)
40	71.1	15.3	**b**	39.3	**b**	27.5	27.8	**b**	66.8	94.5	**b**	2.8	**ab**	4281
70	78.4	15.5	**b**	46.0	**ab**	31.3	24.3	**b**	77.3	101.5	**b**	3.3	**a**	4795
100	75.0	18.2	**a**	51.0	**a**	33.3	41.5	**a**	84.3	125.7	**a**	2.2	**b**	5390

Different letters indicate significant differences between the treatments (Tukey's test; $p < 0.05$).

Significant water-availability effect on plant carboxylation efficiency and water-use efficiency ($p<0.05$) was observed (Table 3). The highest mean values recorded for these variables were observed for plants subjected to the treatment with the highest water restriction (40% FC), whereas the lowest mean values were observed for plants grown in soils with higher water availability (100% FC).

Instantaneous carboxylation efficiency (A/Ci) increased under lower water-availability levels ($p<0.05$). This result is primarily explained by internal carbon dioxide concentration and increased CO_2 assimilation rate, besides environmental variations, such as the weather on the measurement day. Reduced carboxylation efficiency may take place due to intercellular CO_2 accumulation in plants subjected to water shortage. This is because lower CE is associated with reduced water availability to plants (Santos *et al.*, 2021).

Likewise, water-use efficiency (WUE) was higher in plants grown under 40% field capacity ($p<0.05$). This variable tends to present higher values under water-shortage conditions. It represents the photosynthesis:transpiration ratio (A:E), whose value is associated with the number of CO_2 molecules fixed by plants per lost water molecule (Ferraz *et al.*, 2012).

Plants grown under some stress type overall reduce their stomatal conductance and transpiration rates, whereas their water use efficiency increases (Taiz *et al.*, 2017). Reduced WUE, as herein observed for 70% and 100% FC, indicated lack of water restriction signs. It happened because WUE under favorable water availability conditions is lower than that observed under water shortage conditions, since plants can activate water-saving mechanisms to reduce transpiration rates (Dias *et al.*, 2019).

Higher water availability (100% FC) had a significant effect ($p<0.05$) on plant development in comparison to that of higher water restriction (40% FC), since it increased plants' diameter, as well as leaf, root and total dry mass (Table 4).

Shoot:root dry mass ratio (S:R ratio) in plants subjected to the 100% FC treatment was statistically lower than that observed for plants subjected to the 70% FC treatment. This finding has indicated better balance in plant biomass distribution in soil presenting high water availability (Table 4).

With respect to the herein assessed water-availability levels, plants exposed to control field capacity (100% FC) recorded increased ($p<0.05$) diameter, leaf, root and total dry mass (Table 4), as well as reduced ($p<0.05$) S:R ratio (Table 4), carboxylation rates and water-use efficiency (Table 3). Water stress caused by lack, or excess, of water can affect plant growth and total biomass, besides impairing photosynthesis and oxidative respiratory processes (Reinelt *et al.*, 2023).

Cell growth stands out as one of the physiological processes highly responsive to water shortage, which often results in reduced biomass (Ribeiro *et al.*, 2017). Restricting leaf development can be one of plants' initial responses to decreased water availability (Taiz *et al.*, 2017; Tatagiba *et al.*, 2015). Leaf area reduction is primarily influenced by cell turgor pressure, which, in its turn, is determined by water content in plants (Yang *et al.*, 2021). Consequently, decreased leaf dry matter can stem from leaf shedding, since decreasing leaf counting is a physiological mechanism used by plants to survive under water-deprived conditions by effectively reducing their tissues' transpiration area (Ilyas *et al.*, 2021). Nonetheless, this reduction notably affects plants' photosynthetic ability by lowering biomass accumulation in them (Beltramin *et al.*, 2022; Guirra *et al.*, 2022).

Literature findings support the current results. Matos *et al.* (2018) investigated teak plants' growth under water shortage conditions and reported that plants subjected to high water shortage (25% and 50% FC) remained alive and presented reduced vegetative growth due to an efficient stomatal closure mechanism resulting from high stomatal sensitivity. A study focused on investigating *Myracroduon urundeuva* plants subjected to three different field capacities (25%, 50% and 75% FC) has shown that plants exposed to higher water availability recorded higher development rates (Figueroa *et al.*, 2004). According to a study focused on assessing *Guazuma ulmifolia* seedlings grown under different water regimes (12.5%, 25%, 50% and 100% FC), the control treatment (100% FC) recorded the highest values for plant height, diameter, leaf area, shoot and root dry masses, in comparison to the other treatments.

Although values observed for some parameters have decreased, teak plants may have triggered mechanisms to induce drought resistance, since none of the adopted water regimes affected plant height increase, shoot dry mass and leaf area, or resulted in plant death.

This growth capacity, even under water shortage conditions, is an indicator of tolerance to drought and it may be closely linked to higher water-use efficiency of teak plants, since the 40% field capacity has increased its WUE ($p<0.05$) (Table 3). WUE increase is an important property that contributes to genotypes' resilience and growth under drought conditions, and that can indicate plants' mechanism to cope with water-limited environments (Freitas and Silva, 2018; Müller *et al.*, 2020; Tardieu, 2013).

Water availability at 100% FC has favored biomass growth and accumulation in plants. However, the lowest soil water availability level (40% FC) was not enough for plants to fully maintain continuous transpiration flow for days, or at times, presenting high atmospheric demand. In addition, it contributed to reducing biometric variables and dry matter production.

The results encourage further investigations into the possibility of evaluating new growth regulators to promote greater adaptability and resistance of tree species to soils with water deficits, as well as exploring the behavior of other forest species with PBZ and other regulators under water-deficit conditions.

4. CONCLUSIONS

PBZ concentrations used in the current study did not affect *Tectona grandis* morphological and physiological traits.

Higher water availability, provided by 100% field capacity, resulted in the greatest increase in stem diameter, as well as in leaf, root, and total dry mass. Conversely, *Tectona grandis* clones exhibited improved carboxylation efficiency and water-use efficiency at 40% field capacity.

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6. REFERENCES

ASSAD, E. D.; ZANATTA, J. A.; RACHWAL, M. F. G.; PUGLIERO, V. S.; ZANETTI, M. R.; PAVÃO, E. de M. et al. **Impactos de mudanças do clima em plantios de eucalipto no Sul do Brasil.** Colombo: Embrapa Florestas, 2021. 83p. (Documentos, 349).

BARBOSA, V. H. R.; MARQUES, M. E. S.; GUIMARÃES, A. C. R.; BAIA, M. V. M.; ALMEIDA, D. J. Avaliação do Potencial expansivo de solos da Formação Solimões no Estado do Acre para uso em Pavimentação. **Revista Matéria**, v. 27, n. 2, p. 1-11, 2022. https://dx.doi.org/10.1590/S1517-707620220002.137

BELTRAMIN, F. A.; SILVA, W. C.; SANTOS, C. C.; SCALON, S. P. Q.; VIEIRA, M. C. Water-retaining polymer mitigates the water deficit in *Schinus terebinthifolia*: photosynthetic metabolism and initial growth. **Engenharia Agrícola**, v. 40, n.6, p. 684–691, 2022. https://doi.org/10.1590/1809-4430-Eng.Agric.v40n6p684-691/2020

BENETT, K. S. S.; FARIA JUNIOR, M. J. A.; BENNET, C. G. S.; SELEGUINI, A.; LEMOS, O. L. Utilização de paclobutrazol na produção de mudas de tomateiro. **Comunicata Scientiae**, v. 5, n. 2, p. 164-169, 2014.

BENTO, V.; JUCÁ, E. V. L.; MENEZES, R. S.; LIMA, B. C.; VERAS, N. M.; MOURA, S. S. Interpretando a diversidade climática do Acre através da leitura de climogramas. **UÁQUIRI - Revista do Programa de Pós-Graduação em Geografia da Universidade Federal do Acre**, v. 3, n. 2, p. 96-111, 2021. https://doi.org/10.29327/268458.3.2-6

BINOTTI, E. D. C.; BINOTTI, F. F. S.; LUCHETI, B. Z.; COSTA, E.; PINTO, A. H. Shading levels and plant growth regulator for formation of *Schizolobium amazonicum* compact seedlings. **Engenharia Agrícola**, v. 39, n. 5, p. 586-591, 2019. https://doi.org/10.1590/1809-4430-Eng.Agric.v39n5p586-591/2019

BRITO, C. L. L.; MATSUMOTO, S. N.; SANTOS, J. L.; GONÇALVES, D. N.; RIBEIRO, A. F. F. Efeito do paclobutrazol no desenvolvimento de plantas de girassol ornamental. **Revista de Ciências Agrárias**, v. 39, n. 1, p. 153-160, 2016. https://doi.org/10.19084/RCA15044

CHEN, J. J.; SUN, Y.; KOPP, K.; OKI, L.; JONES, S. B. Effects of Water Availability on Leaf Trichome Density and Plant Growth and Development of *Shepherdia xutahensis*. **Frontiers in Plant Science**, v. 13, p. 1-14, 2022. https://doi.org/10.3389/fpls.2022.855858 .

D'ARÊDE, L. O.; MATSUMOTO, S. N.; SANTOS, J. L.; VIANA, A. E. S.; RAMOS, P. A. S. Initial vegetative growth of coffee plants submitted to foliar spraying of Paclobutrazol. **Coffee Science**, v. 12, n. 4, p. 451-462, 2017. https://doi.org/10.25186/CS.V12I4.1311

DESTA, B.; AMARE, G. Paclobutrazol as a plant growth regulator. **Chemical and Biological Technologies in Agriculture**, v. 8, n. 1, p. 1-15, 2021. https://doi.org/10.1186/s40538-020-00199-z

DIAS, M. S.; REIS, L. S.; LIMA, I. R. V.; OLIVEIRA, A. W.; SANTOS, R. H. S.; ALMEIDA, C. A. C. et al. Eficiência do uso da água pela cultura do amendoim sob diferentes lâminas de irrigação e adubação. **Colloquium Agrariae**, v. 15, n. 2, p. 72-83, 2019. https://doi.org/10.5747/ca.2019.v15.n1.a286

ESPINDULA, M. C.; ROCHA, V. S.; SOUZA, L. T.; SOUZA, M. A.; GROSSI, J. A. S. Efeitos de reguladores de crescimento na elongação do colmo de trigo. **Acta Scientiarum**, v. 32, n. 1, p. 109-116, 2010. https://doi.org/10.4025/actasciagron.v32i1.943

FERRAZ, R. L. S.; MELO, A. S.; SUASSUNA, J. F.; BRITO, M. E. B.; FERNANDES, P. D.; NUNES JÚNIOR, E. S. Trocas gasosas e eficiência fotossintética em ecótipos de feijoeiro cultivados no semiárido. **Pesquisa Agropecuária Tropical**, v. 42, p. 181-188, 2012. https://doi.org/10.1590/S1983-40632012000200010

FIGUEIRÔA, J. M.; BARBOSA, D. C. A.; SIMABUKURO, E. A. Crescimento inicial de plantas jovens de *Myracrodruon urundeuva* Allemão (Anacardiaceae) sob diferentes regimes hídricos. **Acta Botânica Brasílica**, v. 18, n. 3, p. 573-580, 2004.

FREITAS, R. S.; SILVA, E. C. Respostas fisiológicas de mudas de *Aspidosperma pyrifollium* (Apocynaceae) a ciclos de suspensão de rega. **Scientia Plena**, v. 14, n. 5, p. 1-12, 2018. https://doi.org/10.14808/sci.plena.2018.051201

GUIRRA, B. S.; SILVA, J. A.; LEAL, C. C. P.; TORRES, S. B.; SILVA, J. E. S. B.; GUIRRA, K. S. et al. Crescimento e metabolismo de mudas de *Pityrocarpa moniliformis* Benth. sob déficit hídrico. **Ciência Florestal**, v. 32, n. 2, p. 923-938, 2022. https://doi.org/10.5902/1980509863444

HARMATH, J.; SCHMIDT, G.; FORRAI, M.; SZABÓ, V. Influence of some growth retardants on growth, transpiration rate and CO_2 fixation of *Caryopteris incana* 'Heavenly Blue'. **Folia Oecologica**, v. 41, n. 1, p. 24-33, 2014.

HATFIELD, J. L.; PRUEGER, J. H. Temperature extremes: Effect on plant growth and development. **Weather and Climate Extremes**, v. 10, p. 4-10, 2015. https://doi.org/10.1016/j.wace.2015.08.001

HEGDE, S.; DINAKARAN, A. J.; HONNABYRAIAH, M. K.; GURUPRASAD, T. R.; SHIVANNA, M.; HALES, G. K. Influence of Paclobutrazol on Growth and Yield of Jamun cv. Chintamani. **International Journal of Current Microbiology and Applied Sciences (IJCMAS)**, v. 7, n. 1, p. 1590-1599, 2018. https://doi.org/10.20546/ijcmas.2018.701.193

ILYAS, M.; NISAR, M.; KHAN, N.; HAZRAT, A.; KHAN, A. H.; HAYAT, K. *et al.* Drought Tolerance Strategies in Plants: A Mechanistic Approach. **Journal of Plant Growth Regulation**, v. 40, p. 926–944, 2021. https://doi.org/10.1007/s00344-020-10174-5

IBÁ. **Relatório IBÁ 2021 relativo a 2020**. São Paulo, 2021.

JUÁREZ-RODRÍGUEZ, L.; PÉREZ-GRAJALES, M.; CASTRO-BRINDIS, R.; SEGURA-MIRANDA, A.; MAGAÑA-LIRA, N.; MAGDALENO-VILLAR, J. J. Evaluation of doses, application periods and residuality of paclobutrazol in tomato. **Bioagro**, v. 34, n. 1, p. 63-74, 2021. https://doi.org/10.51372/bioagro341.6

MAGANHOTTO, C. M. S. S.; FAY, E. F.; VIEIRA, R. F. Degradação do paclobutrazol em solos tropicais. **Pesquisa Agropecuária Brasileira**, v. 38, n. 10, p. 1223-1227, 2003. https://doi.org/10.1590/S0100-204X2003001000012

MAHESHWARI, C.; GARG, N. K.; HASAN, M.; PRATHAP, V.; MEENA, N. L.; SINGH, A.; TYAGI, A. Insight of PBZ mediated drought amelioration in crop plants. **Frontiers in Plant Science**, v. 13, p. 1-15, 2022. https://doi.org/10.3389/fpls.2022.1008993

MATOS, F. S.; FREITAS, I. A. S.; SOUZA, B. R.; LOPES, V. de A.; ROSA, V. do R. Crescimento de plantas de *Tectona grandis* sob restrição hídrica. **Agrarian**, v. 11, n. 39, p. 14-21, 2018.

MEENA, R. K.; SAROJ, P. L.; ADIGA, J. D.; NAYAK, M. G.; MEENA, H. R. Effect of Paclobutrazol on Flowering, Fruiting and Yield of Cashew (*Anacardium occidentale* L.) in West Coast Region of Karnataka. **International Journal of Current Microbiology and Applied Sciences**, v. 7, n. 10, p. 380-391, 2018. https://doi.org/10.20546/ijcmas.2018.710.041

MORAES, C. B.; UESUGI, G.; ONO, E. O.; RODRIGUES, J. D.; GUERRINI, I. A.; MORI, E. S. Influência do uso de biorreguladores no crescimento de *Hymenaea courbaril*. **Revista do Instituto Florestal**, v. 25, n. 2, p. 223–229, 2013. https://doi.org/10.24278/2178-5031.2013252413

MÜLLER, C.; HODECKER, B. E. R.; BARROS, N. F.; MERCHANT, A. A physiological approach for pre-selection of Eucalyptus clones resistant to drought. **iForest**, v. 13, p. 16-23, 2020. https://doi.org/10.3832/ifor3185-012

OLIVEIRA, A. F.; CRUZ, M. C. M.; OLIVEIRA, D. L.; MESQUITA, H. A. Paclobutrazol em oliveira submetida a diferentes regimes hídricos. **Semina: Ciências Agrárias**, v. 33, n. 6, p. 2137-2148, 2012. https://doi.org/10.5433/1679-0359.2012v33n6p2137

OLIVEIRA, M. B.; FIGUEIREDO, M. G. F.; PEREIRA, M. C. T.; MOUCO, M. A. C.; RIBEIRO, L. M.; SIMÕES, M. O. M. Structural and cytological aspects of mango floral induction using paclobutrazol. **Scientia Horticulturae**, 2020. https://doi.org/10.1016/j.scienta.2019.109057

PRICINOTTO, L. F.; ZUCARELI, C. Paclobutrazol no crescimento e desempenho produtivo da soja sob diferentes densidades de semeadura. **Revista Caatinga**, v. 27, n. 4, p. 65–74, 2014.

RADEMACHER, W. Chemical regulators of gibberellin status and their application in plant production. *In*: HEDDEN, P.; THOMAS, S. G. (eds.). **The Gibberellins**. Oxford: Wiley-Blackwell, 2016.

REINELT, L.; WHITAKER, J.; KAZAKOU, E.; BONNAL, L.; BASTIANELLI, D.; BULLOCK, J. M. et al. Drought effects on root and shoot traits and their decomposability. **Functional Ecology**, v. 37, p. 1044–1054, 2023. https://doi.org/10.1111/1365-2435.14261

RIBEIRO, A. F. F.; MATSUMOTO, S. N.; RAMOS, P. A. C.; SANTOS, J. L. D.; TEIXEIRA, E. C.; D’ARÊDE, L. O. et al. Paclobutrazol e restrição hídrica no crescimento e desenvolvimento de plantas de café. **Coffee Science**, v. 12, n. 4, p. 534-543, 2017. https://doi.org/10.25186/cs.v12i4.1361

ROCHA, H. F.; LEONARDO, F. V. S.; OLIVEIRA, A. C. Commercial plantations of *Tectona grandis* L.f. in Brazil. **Multitemas**, n. 48, p. 9-28, 2015.

RODRIGUES, L. C.; CASTRO, E. M.; PEREIRA, F. J.; MALULEQUE, I. F.; BARBOSA, J. P.; ROSADO, S. C. Effects of paclobutrazol on leaf anatomy and gas exchange of *Toona ciliata* clones. **Australian Forestry**, v. 79, p. 241-247, 2016. https://doi.org/10.1080/00049158.2016.1235476

SANTOS, J. A.; MATSUMOTO, S. N.; TRAZZI, P. A.; RAMOS, P. A. S.; OLIVEIRA, L. S.; CAMPOE, O. C. Morphophysiological changes by mepiquat chloride application in *Eucalyptus* clones. **Trees**, v. 35, p. 189–198, 2021.

SANTOS, S. M. S.; MATSUMOTO, S. N.; SILVA, R. A.; OLIVEIRA, L. S.; VIANA, A. E. S. V. Modulation of the initial growth of *Eucalyptus* clones using paclobutrazol: when smaller is better. **Australian Journal of Crop Science**, v. 12, n. 4, p. 610-616, 2018. https://doi.org/10.21475/ajcs.18.12.04.pne894

TAIZ, L.; ZEIGER, E.; MØLLER, I. A.; MURPHY, A. **Fisiologia e desenvolvimento vegetal.** Porto Alegre: Artmed, 2017. 888 p.

TARDIEU, F. Plant response to environmental conditions: assessing potential production, water demand, and negative effects of water deficit. **Frontiers in Physiology**, v. 4, n. 17, p. 1-11, 2013. https://doi.org/10.3389/fphys.2013.00017

TATAGIBA, S. D.; XAVIER, T. M. T.; TORRES, H.; PEZZOPANE, J. E. M.; CECÍLIO, R. A.; ZANETTI, S. S. Determinação da máxima capacidade de retenção de água no substrato para produção de mudas de eucalipto em viveiro. **Floresta**, v. 45, n. 4, p. 745-754, 2015. https://doi.org/10.5380/rf.v45i4.38334

TESFAHUM, W.; YILDIZ, F. A review on: Response of crops to paclobutrazol application. **Cogent Food & Agriculture**, v. 4, p. 1-9, 2018. https://doi.org/10.1080/23311932.2018.1525169

VILLA, F.; OLIVEIRA, A. F.; VIEIRA NETO, J.; SILVA, L. F. O. Déficit hídrico e paclobutrazol no crescimento inicial de plantas jovens de oliveira. **Cultivando o Saber**, v. 5, n. 4, p. 30-51, 2012.

XIA, X.; TANG, Y.; WEI, M.; ZHAO, D. Effect of Paclobutrazol Application on Plant Photosynthetic Performance and Leaf Greenness of Herbaceous Peony. **Horticulturae**, v. 4, n. 5, p. 1-12, 2018. https://doi.org/10.3390/horticulturae4010005

YANG, X.; LU, M.; WANG, Y.; WANG, Y.; LIU, Z.; CHEN, S. Response Mechanism of Plants to Drought Stress. **Horticulturae**, v. 7, n. 3, p. 1-36, 2021. https://doi.org/10.3390/horticulturae7030050