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Prediction of *Eucalyptus* productivity and basic wood density using a novel water-availability-sensitive proxy

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Water availability is a key driver of Eucalyptus productivity in tropical environments, yet traditional climatic indices often fail to adequately capture hydrological variability under humid conditions. This study evaluated how water availability, interacting with soil and management factors, influences productivity and basic wood density across contrasting tropical environments. Data from commercial Eucalyptus plantations across São Paulo, Bahia, and Maranhão were analyzed using multivariate regression models integrating climatic indices and a novel water-availability proxy (Log_{10}(AWAI)).

Results: The models showed high predictive performance (adjusted $R^2 > 99\%$), with the proposed proxy exhibiting greater explanatory power in São Paulo and Maranhão. Basic wood density emerged as an integrative trait linking growth and environmental conditions: under humid climates, higher density was associated with increased biomass accumulation, whereas under drier conditions it reflected conservative strategies related to hydraulic safety. Additionally, clone HGU-1 demonstrated high ecophysiological plasticity and productive stability across contrasting environments.

Conclusion: The proposed proxy improves the representation of water availability in tropical conditions and supports more accurate water zoning, genetic material selection, and management strategies. These findings highlight the role of basic wood density as a functional indicator of the growth–safety trade-off in Eucalyptus plantations.

Keywords: Adaptive plasticity; forest ecophysiology; forest productivity; genotype–environment interaction; multivariate modeling.

HIGHLIGHTS

New water-availability proxy captures climatic control on productivity.
Water availability drives volumetric and biomass productivity.
Basic wood density indicates efficiency–safety trade-offs.
G×E interactions shape productivity under tropical climates.

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INTRODUCTION

The genus *Eucalyptus* exhibits remarkable adaptive plasticity to the edaphoclimatic conditions of Australia and Southeast Asia, promoting the diversification of physiological strategies capable of sustaining growth across a wide range of water and thermal regimes (Myburg et al., 2014). This functional diversity underpins its silvicultural success in Brazil, where the combination of genetic improvement and intensive management have enabled high growth rates in hybrids such as *Eucalyptus grandis* × *E. urophylla* (Stape et al., 2010). However, plantation productivity results from a complex interaction between genetic factors, management decisions, such as spacing and environmental variables. Although water availability is the primary constraint in tropical regions, its influence is critically modulated by soil water-holding capacity and atmospheric evaporative demand (Stape et al., 2010; Almeida et al., 2007).

The scientific challenge lies in the fact that soil physical or chemical limitations can restrict root systems, reducing effective water availability and exacerbating water deficits more severely than isolated rainfall indices suggest. Despite this, conventional climatic indices often fail to capture this soil-plant-atmosphere interaction with enough sensitivity to be integrated into models that already account for age and spacing. Consequently, a significant gap remains in identifying metrics that refine the simultaneous prediction of productivity (volumetric and mass) and basic wood density, which represents the functional trade-off between hydraulic efficiency and structural safety.

In this study, we question whether including a more hydrologically sensitive proxy can enhance the precision of multifactorial models. Our central hypothesis is that volumetric productivity, mass productivity, and basic density are governed by a hierarchy of factors where spacing and effective water availability, represented by the [Log10(AWAI)] proxy, act as determining modulators, outperforming traditional metrics in explaining biological variations across contrasting environments. Accordingly, the objectives of this study were to: (i) quantify the relative contribution of edaphoclimatic variables, age, and spacing to the volumetric and mass productivity of Eucalyptus; (ii) validate the effectiveness of the [Log10(AWAI)] proxy in predicting mass productivity and basic wood density; and (iii) identify the determinants of productive stability to support water zoning and the recommendation of resilient genetic materials.

MATERIALS AND METHODS

Characterization of the study region and genetic materials

The study was conducted in 63 Production Units (Pus) of Suzano S.A., distributed across the states of São Paulo (SP), Bahia (BA), and Maranhão (MA), encompassing a broad edaphoclimatic gradient under tropical and subtropical conditions. Sixteen commercial clones were evaluated, belonging to the species *E. grandis*, *E. urophylla*, *E. platyphylla*, *E. brassiana*, and *E. tereticornis*, as well as interspecific hybrids widely used in commercial plantations in Brazil. One of these hybrids was present in all three regions, enabling comparisons under contrasting environmental conditions.

Climatic classification of the regions and subregions was performed according to Köppen (1936) and its update for the Brazilian territory proposed by Alvares et al. (2013). Six climatic subtypes were identified: in São Paulo, Cfa (humid subtropical, no dry season) and Cwa (subtropical with dry winter and hot summer); in Bahia, Af (humid tropical rainforest) and Aw (tropical savanna with a dry winter); and in Maranhão, Am (tropical monsoon with a short dry season) and As (tropical with dry summer).

These subtypes were organized from the most humid to the driest, forming a continuous climatic gradient across the three evaluated regions. The spatial distribution of these climatic units, as well as their soil and physiographic characteristics, is illustrated in Figure 1. Regional differences include variations in altitude (50–800 m), soil texture and depth, and landforms, ranging from high hills to plains and plateaus.

The climatic data used refer to the period from 2012 to 2018 and were obtained through Suzano S.A.'s Climate Fingerprint (CF) system, which integrates regional meteorological records with local measurements of mean temperature (T) and precipitation (P). These data were validated and complemented with historical series from the Brazilian National Institute of Meteorology (INMET).

Potential evapotranspiration (PET) was estimated using the empirical method of Thornthwaite (1948), which relates mean monthly temperature and latitude to the potential water loss from a vegetated surface. The thermal index (I) and adjustment factor (α) were calculated following the original methodology, allowing PET to be corrected for site-specific conditions. Monthly PET estimates, expressed in millimeters, were subsequently used to calculate water availability indices (AWAI and MCMI), which supported the regional analysis of productivity.

Aridity and Water Availability Indices

Climate characterization for the six environmental units was based on indices derived from the relationship between precipitation (P) and potential evapotranspiration (PET). We utilized the Modified Climatic Moisture Index (MCMI) proposed by Willmott and Feddema (1992) and the UNEP Aridity Index (AI-UNEP) (Middleton and Thomas, 1992). To enhance analytical sensitivity in humid environments, we proposed the Annual Water Availability Index (AWAI), defined by Equation 1:

$$AWAI = \frac{\sum_{Jan}^{Dec}\left(P / PET\right)}{12} + \sum_{Jan}^{Dec} MCMI \qquad (1)$$

The ecophysiology of the Eucalyptus genus justifies the choice of an annual integrative indicator. Unlike short-cycle annual crops, perennial forest species exhibit greater resilience and the capacity to integrate variations in water availability throughout the annual growth cycle. Although extreme aridity may occur at monthly scales (where IAM may drop below -0.5), the 12-month summation buffers these fluctuations, providing a more accurate reflection of the water balance available for forest productivity.

For statistical analysis and correlation with wood productivity and basic density, the IDHA was converted into a climatic proxy using a decimal logarithm transformation (Equation 2):

$$\left[Log_{10}\left(AWAI\right)\right] = log_{10}\left(AWAI + 6\right) \quad (2)$$

The constant offset (+6) was adopted based on the historical range of the integrated multi-year averages (2012–2018). As summarized in Table 1, while extreme annual anomalies were recorded, most notably during the 2015/16 El Niño event in the Maranhão Cerrado, where the AWAI reached -6.59, these fluctuations were buffered within the overall seven-year study period. For all six environmental units, the 7-year mean AWAI remained above -5.2 (Table 1), ensuring that the value 6 was the smallest integer capable of providing positive arguments for the logarithmic function when applied to the integrated climatic series. Sensitivity tests confirmed that this specific offset preserves data variance and maximizes model linearity, directly contributing to the high coefficients of determination (R^2) observed in correlations with wood productivity and basic density.

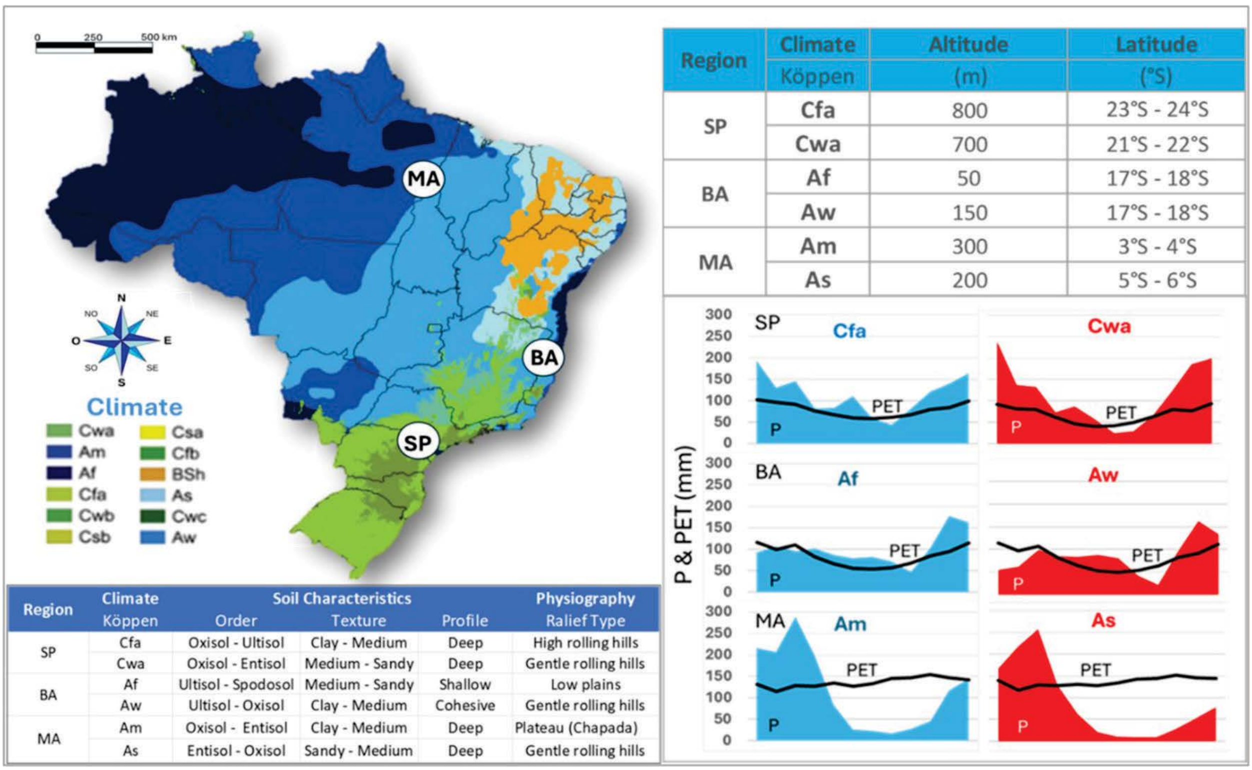
Table 1 presents the average variables used in the calculation of AWAI (2012–2018), highlighting the reduction observed during the 2015–2016 El Niño event, which significantly affected water availability in the evaluated regions.

To position the growth period of the clones (assessment period) within regional hydroclimatic cycles, historical precipitation series (1986–2024) from the São Paulo, Bahia, and Maranhão regions were analyzed, sourced from INMET and Suzano S.A.'s Climate Fingerprint. The series were smoothed using a seven-year moving average (MM7), as proposed by Girardi and Girardi (2001), in order to identify long-term rainfall oscillations.

Interannual and multidecadal climatic phenomena widely recognized in the literature, such as El Niño–Southern Oscillation (ENSO), La Niña, the Atlantic Dipole, and the South Atlantic Convergence Zone (SACZ) (Andreoli and Kayano, 2007; Grimm and Zilli, 2009), which influence regional precipitation patterns, were considered. Figure 2 shows the smoothed series and the temporal location of the assessment period within these cycles.

Numerical characterization of the sampled environments

The numerical characterization of the sampled environments was performed by consolidating edaphoclimatic and productivity variables from the six climatic units defined in Section 2.1. For each unit, soil, climate, and growth information were compiled from Suzano S.A.'s corporate database and its edaphoclimatic maps. The selection of environments was



Region	Climate Köppen	Altitude (m)	Latitude (°S)
SP	Cfa	800	23°S - 24°S
	Cwa	700	21°S - 22°S
BA	Af	50	17°S - 18°S
	Aw	150	17°S - 18°S
MA	Am	300	3°S - 4°S
	As	200	5°S - 6°S

Region	Climate	Soil Characteristics			Physiography
	Köppen	Order	Texture	Profile	Ralief Type
SP	Cfa	Oxisol - Ultisol	Clay - Medium	Deep	High rolling hills
	Cwa	Oxisol - Entisol	Medium - Sandy	Deep	Gentle rolling hills
BA	Af	Ultisol - Spodosol	Medium - Sandy	Shallow	Low plains
	Aw	Ultisol - Oxisol	Clay - Medium	Cohesive	Gentle rolling hills
MA	Am	Oxisol - Entisol	Clay - Medium	Deep	Plateau (Chapada)
	As	Entisol - Oxisol	Sandy - Medium	Deep	Gentle rolling hills

Figure 1: Characterization of the study regions according to Köppen's climate classification, adapted from Alvares et al. (2013).

based on three main axes: (i) volumetric productivity, expressed as mean annual increment (MAI); (ii) water availability derived from climatic indices (Log_{10}(AWAI)/AWAI); and (iii) edaphic characteristics, including soil texture and depth, due to their influence on water retention and soil water dynamics.

From the full set of evaluated genetic materials, clones were selected based on extremes of productivity and basic wood density at seven years (BD_7), allowing the representation of contrasting physiological strategies within *Eucalyptus* species and hybrids. *Eucalyptus grandis* clones were used as a reference for high productivity and low wood density, whereas *E. urophylla* × *E. tereticornis* and *E. grandis* × *E. brassiana* hybrids represented materials with contrasting growth and density patterns.

Table 2 presents the numerical characterization used in the analyses, including mean age, spacing, soil texture, altitude, potential evapotranspiration (PET), climatic index (Log_{10}(AWAI), and mean annual increment (MAI), which served as the basis for environmental classification and subsequent statistical modeling.

Measurement and correction of volumetric productivity

Mean Annual Increment (MAI, m^3/ha/yr) was estimated based on rigorous stem scaling of representative trees in each sampled stand. Trees were sectioned into segments of known length (L), and diameters with and without bark were

Table 1: Variables used to calculate the Annual Water Availability Index (AWAI) between 2012 and 2018, highlighting the El Niño 2015–2016 event.

	Köppen	P (mm)	PET (mm)	P/PET	MCMI	AWAI	Log_{10}(AWAI)
Impact of Mean Climatic Variables on WAIs (2012- 2018)	Cfa	1359	947	1.55	2.03	3.58	0.981
	Cwa	1346	798	1.69	1.32	3.00	0.954
	Af	1206	1005	1.26	0.51	1.77	0.890
	Aw	1007	971	1.07	-0.82	0.25	0.796
	Am	1397	1673	0.83	-3.39	-2.56	0.482
	As	1035	1698	0.61	-5.68	-5.07	0.145
Effect of El Niño on WAIs (2015 – 2016)	Cfa	1502	876	1.72	2.74	4.46	1.019
	Cwa	1509	795	1.90	2.07	3.96	0.998
	Af	1052	1176	1.19	-1.78	-0.59	0.734
	Aw	712	1130	0.63	-4.39	-3.76	0.351
	Am	984	1725	0.57	-5.40	-4.83	0.067
	As	775	1735	0.45	-7.03	-6.59	< 0*

Köppen: Climate classification; P (mm): Precipitation in millimeters; PET (mm): Potential evapotranspiration in millimeters; P/PET: Ratio between precipitation and potential evapotranspiration; MCMI: Accumulated Modified Aridity Index; AWAI: Annual Water Availability Index; Log_{10}(AWAI): Base-10 logarithm of the Annual Water Availability Index. <0*: undefined logarithmic.

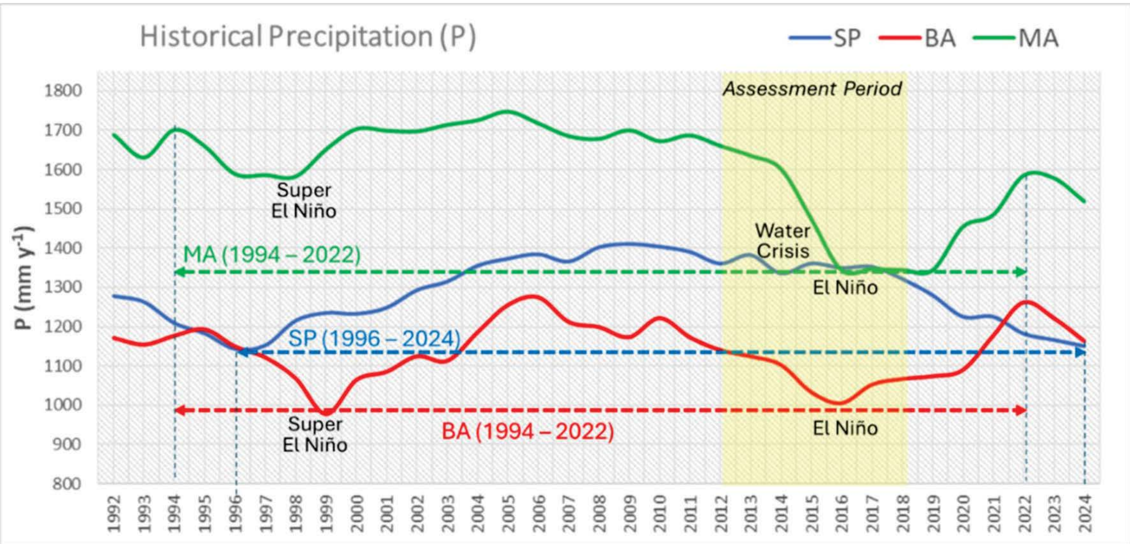


Figure 2: Hydroclimatic cycles (1986–2024) for São Paulo, Bahia, and Maranhão, showing wet and dry phases and the assessment period of the sampled stands.

measured at both ends of each segment. The cross-sectional areas A_i and A_{i+1} (m^2) were calculated from these diameters, allowing individual tree volume to be estimated using Smalian's method (Equation 3) (Brito et al., 2021).

Total volume per hectare was obtained based on the average planting spacing. Dividing this value by stand age (years) yielded the observed MAI (MAI_x):

$$V = \sum_{i=1}^{n} \frac{\left(A_i + A_{i+1}\right)}{2} \times L \qquad (3)$$

$$MAI = \frac{V}{years} \qquad (4)$$

The Mean Annual Increment at age seven (MAI_7) was estimated to normalize productivity across different stand ages (X) and initial spacings (Equation 5). An adjustment factor (Factor) was calculated using a second-degree polynomial equation (Equation 6), where the coefficients (βi) were selected based on the planting spacing (Table 3). These coefficients were derived from a large-scale operational database (over 1,0 MM hectares), ensuring that the growth trajectory reflects local competition and site quality. The standardized (MAI_7) then served as the input for the wood density correction.

$$IMA_7 = \frac{IMA_x}{Fator} \qquad (5)$$

$$Fator = \beta_2 X^2 + \beta_1 X + \beta_0 \qquad (6)$$

This standardization enabled comparisons among clones and regions on a common age and structural basis, isolating effects associated with temporal development and tree spatial arrangement.

Sampling and determination of basic wood density

Destructive sampling comprised 260 representative trees from 16 commercial *Eucalyptus* clones, in addition to one extra clone used as a technical reference (HGU-1), evaluated across three regions (SP, BA, and MA). In each stand, three to five trees were selected based on criteria of diameter uniformity, absence of visible defects, and genotypic representativeness within each climatic unit.

From each tree, 1.0 m-long logs were collected between 2 and 7 m along the commercial stem (Figure 3). This height range was chosen because it represents the portion of the trunk with greater anatomical and densitometric homogeneity, avoiding the basal region, influenced by root–stem transition, and the upper region near crown transition, which exhibit higher structural and anatomical variability.

The logs were debarked and sectioned to obtain samples for basic wood density (BD) analysis. The material was processed into homogeneous chips according to SCAN-CM 43:95, which specifies the water displacement method (Archimedes' principle) for determining saturated volume.

Sample preparation and processing followed the guidelines of SCAN 40:94, adapted to the analytical routine of the study, and comprised the following steps: (i) selection of representative stands and trees; (ii) felling and sectioning into logs; (iii) debarking and transport to the laboratory; (iv) chipping and pre-selection of wood chips; (v) controlled drying and sample identification; and (vi) determination of basic wood density as the ratio between oven-dry mass and saturated volume.

Table 2: Environmental and genetic characterization of the sampled sites and clones, including variables used in the productivity models (MAI).

Region	Clim.	Species*	Age (years)	Spacing (m²/tree)	Text. (%)	Alt.	PET	Log_{10}(AWAI)	MAI (m³/ha/yr)
SP n =19 6 clones	Cfa	EGR / HGU	6.6	6.3	36	810	876	0.981	62.0
	Cwa	EGR / HGU	6.6	7.1	23	730	845	0.954	49.2
BA n = 17 5 clones	Af	HGU / EUR	5.6	8.6	33	53	1.011	0.890	47.5
	Aw	HGU / EUR	5.9	9.5	42	124	1.069	0.805	31.8
MA n = 27 8 clones	Am	HGU e EUR / HGB e EPL	5.8	9.7	29	252	1.693	0.480	35.1
	As	HGU e EUR / HGB e HUT	5.9	10.1	24	245	1.698	0.149	21.0

Clim.: Climate; Text.: Texture; Alt.: Altitude; PET: Potential evapotranspiration; Log_{10}(AWAI): Base-10 logarithm of the Annual Water Availability Index; MAI: Mean Annual Increment. *Sampled species and hybrids: HGU = *E. grandis* × *E. urophylla* hybrid; EGR = *E. grandis*; EUR = *E. urophylla*; HGB = *E. grandis* × *E. brassiana* hybrid; EPL = *E. platyphylla*; HUT = *E. urophylla* × *E. tereticornis* hybrid.

Table 3: Polynomial coefficients and adjustment factors used to standardize the Mean Annual Increment to age seven (MAI_7) based on initial planting spacing.

Spacing (m²/pl)	Age (years)	Factor MAI_7				MAI_7 (m³/ha/yr)
		β_2	β_1	β_0	Factor	
5.1	5.4	-0.02	0.16	0.71	1.09	63.4
6.3	5.7	-0.02	0.16	0.60	1.04	69.5
7.7	5.3	-0.01	0.17	0.49	1.00	52.6
8.0	8.2	-0.01	0.17	0.47	0.95	35.6
9.0	6.2	-0.01	0.18	0.41	1.00	43.5
10.1	5.2	-0.01	0.18	0.36	0.96	40.0

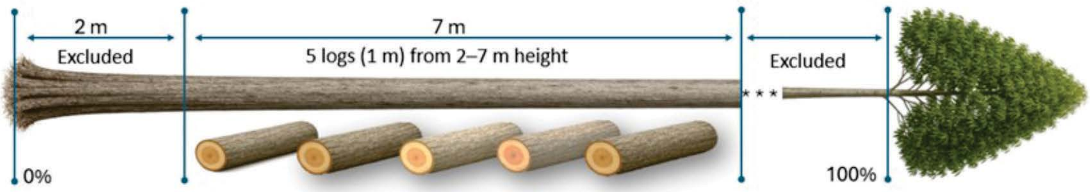


Figure 3: Schematic representation of destructive sampling showing the position of the 1.0 m logs collected along the commercial stem (from 2 to 7 m above ground level).

Correction of basic wood density values for comparative purposes

To enable a direct and unbiased comparison among clones and environments of different ages and growth rates, all productivity and wood quality metrics were standardized to a reference age of seven years (MAI_7 and BD_7). After MAI_7 estimation, a dual-correction methodology was applied to standardize basic wood density (BD). First, the observed density(BD_{obs}) was adjusted for the environmental effect (BD_{ca}) by calculating the difference between the observed MAI (MAI_y) and the reference MAI (MAI_{ref}) specific to each index (Equation 7). This step compensates for the influence of growth rate on wood densification (Lima et al., 2007). Second, BD_{ca} was normalized to age seven (BD_7) using an age-related factor (Equation 8), following the biological logarithmic pattern of wood densification (Trugilho et al., 1996; Vidaurre et al., 2020).

$$BD_{ca} = BD_{obs} + BD_{obs} \times \frac{\left(-0.2305 \times MAI_y\right) + \left(0.2305 \times MAI_{ref}\right)}{100} \quad (7)$$

$$BD_7 = BD_{ca} + BD_{ca} \times \left(-0.174 ln\left(x\right) + 0.3386\right) \quad (8)$$

The coefficients for correction were fitted using a robust wood quality database covering approximately 200,000 hectares, with systematic monitoring starting at age three. To ensure the transparency and reproducibility of these procedures, the coefficients and a representative sample of the calculation steps are provided in Table 4.

Genotypic and ecophysiological characterization of genetic materials by climate

The genotypic and ecophysiological characterization of the *Eucalyptus* genetic materials evaluated across the three study regions, São Paulo (SP), Bahia (BA), and Maranhão (MA), was based on corporate information from the partner company and historical records of clonal operational performance.

For each clone and species, mean ranges of basic wood density standardized to seven years (BD_7), volumetric mean annual increment (MAI_7), and a climate-based drought tolerance level (DTL-C) were compiled. The DTL-C parameter was used as a comparative indicator of physiological resilience and was assigned based on the relative performance of genotypes under different water-availability regimes within each climatic type.

DTL-C classification was structured into five categories, VL (very low), L (low), M (moderate), H (high), and VH (very high), allowing the representation of climate-conditioned tolerance gradients. This approach enables the integration of anatomical (BD_7), climatic (Log_{10}(AWAI) and AWAI), and productive (MAI_7) variables in subsequent multivariate analyses.

Table 5 summarizes the genotypic characterization by climate, including species and hybrids, BD_7 ranges, mean productivity (MAI_7), and the assigned drought tolerance level (DTL-C) for each climatic subtype.

Statistical analyses

Statistical analyses were conducted to identify patterns and quantify relationships among climatic, edaphic, and management variables. To ensure model reliability and address potential collinearity, the Variance Inflation Factor (VIF) was calculated for all predictors (AWAI, spacing, age, soil texture, and altitude), with a threshold of VIF < 5 adopted to exclude redundant variables. The Annual Water Availability Index (AWAI) was developed as a step-by-step derived variable to capture intra-annual seasonality, with a logarithmic transformation [Log_{10}(AWAI+6)] applied to ensure normality.

Model performance was assessed using the adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), and 10-fold cross-validation. The 10-fold CV was implemented to confirm the stability of the regression coefficients and the absence of overfitting across the different environmental 'blocks' (SP, BA, and MA). All analyses were performed using Minitab® (v. 21.2) at a 5% significance level (α = 0.05).

RESULTS

Analysis of climatic aspects

The Annual Water Availability Index (AWAI) enabled an integrated characterization of the relationship between precipitation (P) and potential evapotranspiration (PET) across the three evaluated regions. After logarithmic transformation [Log_{10}(AWAI + 6)], a well-defined climatic gradient was observed among Köppen climate types, with higher values in humid climates (Cfa, Cwa, and Af) and progressively lower values in drier environments (Aw, Am, and As).

Figure 4A shows mean Log_{10}(AWAI) values for the 2012–2018 period. In São Paulo, Cfa and Cwa climates exhibited the highest average water availability, whereas in

Table 4: Representative dataset of the dual-correction process for basic wood density (BD_7), illustrating the standardization based on age and site-specific water availability.

AWAI (Index)	MAI_7 (m³/ha/yr)	MAI_{ref} AWAI (m³/ha/yr)	BD_{obs} (kg/m³)	ajca (%)	BD_{ca} (kg/m³)	ajid (%)	BD_7 (kg/m³)
3.58	63.43	56.36	424	1.6%	430	3.5%	446
3.48	52.66	57.26	421	-1.1%	417	0.4%	418
3.00	35.65	45.64	506	-2.3%	495	-3.8%	476
1.77	42.94	50.09	432	-1.6%	425	4.9%	445
0.59	43.31	32.03	407	2.6%	418	2.6%	429
-3.74	37.77	25.54	492	2.8%	506	3.8%	526

Note: AWAI: Available Water Adequacy Index; MAI_7: Mean Annual Increment standardized to age seven; AWAI: Reference productivity generated by the hydrological models developed in this study; BD_{obs} : Observed basic wood density; Ajca: Environmental adjustment factor (Eq. 7); BD_{ca}: Density corrected by growth rate; Ajid: Age-related adjustment factor (Eq. 8); BD_7: Final standardized basic density at seven years.

Table 5: Genotypic and ecophysiological characterization of Eucalyptus clones and species evaluated under different Köppen climate types in São Paulo (SP), Bahia (BA), and Maranhão (MA).

Region	Climate Köppen	Eucalyptus		BD_7 Kg/m³ (7 yr)	MAI_7 m³/ha/yr	DTL-C Climate Level
		Clones	Species			
SP	Cfa	EGR	E. grandis	406 – 414	47 – 75	M
		HGU	EGR x EUR	421 – 429	44 – 72	H
	Cwa	EGR	E. grandis	420 – 430	41 – 67	L
		HGU	EGR x EUR	435 – 445	38 – 64	M
BA	Af	HGU	EGR x EUR	439 – 452	33 – 58	M
		EUR	E. urophylla	454 – 467	29 – 54	H
	Aw	HGU	EGR x EUR	458 – 473	30 – 48	L
		EUR	E. urophylla	473 – 488	26 – 44	M
MA	Am	HGU	EGR x EUR	451 – 469	30 – 45	L
		EUR	E. urophylla	466 – 484	28 – 43	L
		EPL	E. platyphylla	480 – 500	29 – 41	H
		HGB	EGR x E. brassiana	490 – 510	26 – 38	H
	As	HGU	EGR x EUR	474 – 496	22 – 32	VL
		EUR	E. urophylla	479 – 501	20 – 30	L
		HUT	EUR x E. tereticornis	549 – 572	17 – 25	VH
		HGB	EGR x E. brassiana	504 – 527	20 – 28	M

BD_7: basic wood density at seven years; MAI_7: Mean annual increment at seven years; DTL-C: climate-based drought tolerance level; Tolerance levels: VL (very low), L (low), M (moderate), H (high), and VH (very high); tolerance is climate-dependent, meaning the same clone may show different levels under distinct climatic conditions (e.g., a clone rated M in Cfa may be rated L in Cwa).

Bahia, the Af climate maintained higher indices than Aw. In Maranhão, the lowest values of the study were observed, particularly under the As climate, which represented the most restrictive water-availability condition among all regions.

Interannual variation in precipitation (Figure 4B) highlighted pronounced climatic anomalies. In São Paulo, a strong reduction in rainfall was observed during the 2014 Water Crisis, while in Bahia and Maranhão the most severe decrease occurred in 2015–2016, associated with the El Niño event. These oscillations coincided with reductions in annual AWAI values, reflecting periods of increased water deficit throughout the assessment period.

These results confirm the existence of a consistent hydrological gradient among regions and climatic subtypes and demonstrate the sensitivity of the index in capturing interannual variability relevant to *Eucalyptus* growth and productivity.

Volumetric and biomass productivity – MAI and MAIb

Variables influencing volumetric productivity (MAI) across the three regions

Multivariate regression models fitted for each region revealed strong relationships between climatic, edaphic, and management variables and the volumetric mean annual increment (MAI) of *Eucalyptus* clones. The models showed high explanatory power (R^2_adj > 99%) and low predictive uncertainty (RMSE < 0.5%), indicating strong statistical consistency and model stability (Table 6).

The annual water availability index [Log_{10}(AWAI)] was the variable with the greatest contribution to productivity in São Paulo (43%) and Maranhão (50%), reinforcing the central role of water availability in determining plantation

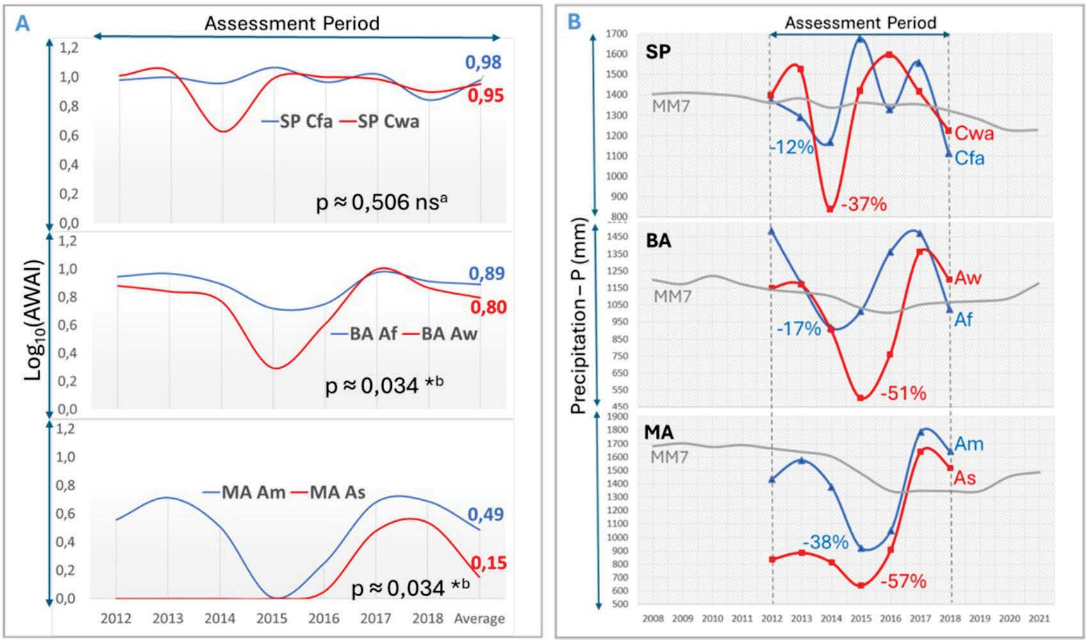


Figure 4: A: Comparison of mean annual water availability [Log_{10}(AWAI)] among different Köppen climate types across the three study regions (SP, BA, and MA). B: Interannual precipitation anomalies relative to the 7-year moving average in São Paulo, Bahia, and Maranhão, highlighting the 2014 Water Crisis and the 2015–2016 El Niño event. *ns[a] = not significant (p > 0.05); *b = significant (p < 0.05).

Table 6: Multivariate regression models for volumetric productivity (MAI) of *Eucalyptus* clones across three regions (SP, BA, and MA), showing model robustness and the relative contribution of explanatory variables.

Multivariate Regression Models	Explained variability	Model robustness β0		Variable contribuition		SP	BA	MA
				Intercept	(-)	(+)	(+)	
	R^2 (adj)	R^2 (CV 10-fold)	RMSE	β1	Log (AWAI)	43%	26%	50%
				β2	Altitude	19%	*	26%
MAI SP	99.70%	99.65%	0.47%	β3	Age	-29%	*	-19%
MAI BA	99.47%	99.37%	0.38%	β4	Spacing	9%	-37%	5%
MAI MA	99.90%	99.85%	0.28%	β5	Texture	*	-37%	*

Note: (+) indicates positive correlation; (–) indicates negative correlation; * denotes non-significant effect (p > 0.05). R^2(adj): adjusted coefficient of determination; R^2 (CV 10-fold): predictive coefficient from 10-fold cross-validation; RMSE: root mean square error.

productivity. In Bahia, soil texture and planting spacing were the main determinants of MAI, each accounting for 37% of the explained variability, indicating a stronger influence of edaphic attributes and stand structure in this region.

Coefficient directions showed consistent patterns across regions. In general, increases in water availability and altitude were associated with higher MAI values, whereas stand age showed a negative relationship with productivity. Reductions in spacing also resulted in lower MAI, reflecting increased intraspecific competition for resources.

These results demonstrate that climatic factors are predominant in regions with greater hydrological variability (SP and MA), whereas edaphic and structural plantation attributes play a more prominent role in humid tropical environments with higher soil heterogeneity, such as Bahia.

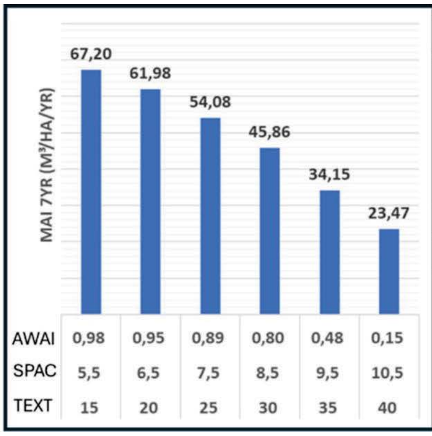
Figure 5 presents the multivariate regression model fitted for Clone 1 – HGU (*E. grandis* × *E. urophylla*), highlighting the contribution of climatic, edaphic, and management variables to mean annual increment (MAI). The model showed an excellent fit (R^2_adj = 99.37%) and low predictive uncertainty (RMSE = 0.14%), indicating high statistical robustness.

Among the explanatory variables, the annual water availability index [Log_{10}(AWAI)], soil texture, and planting spacing were significant ($p < 0.05$), contributing 13%, 40%, and 47% of the explained variability, respectively. The volumetric response estimated by the model (Figure 5) indicates that productivity is particularly sensitive to edaphoclimatic variation and planting management, with an additional effect of water availability.

Variables influencing biomass productivity (MAIb) across the three regions

The multivariate regression models fitted for the three regions showed high explanatory power for mean annual biomass productivity (MAIb), with adjusted R^2 values above 99% and low RMSE values (< 0.2%), indicating high statistical stability (Table 7).

The annual water availability index [Log_{10}(AWAI)] was the main explanatory variable in São Paulo (66.8%) and Maranhão (65.9%), demonstrating a strong dependence of biomass productivity on the regional water balance. In Bahia,



MAI Clone 1 = 94,03 + 10,453 LAWAI - 0,7907 Text - 3,9917 Spac

Multivariate Regression Models	Predictor's Explained Variability	Model Robustness	
	R^2(adj)	R^2 (CV 10-fold)	RMSE
MAI Clone 1	99,37%	99,31%	0,14%

Model	Variable		Coefficient	Contribuition
MAI Clone 1	β_0	Intercept	94,03	*
	β_1	Log (AWAI)	10,453	13%
	β_2	Texture	-0,791	(-) 40%
	β_3	Spacing	-3,992	(-) 47%

Figure 5: Multivariate regression model and volumetric response of Clone 1 – HGU (*E. grandis* × *E. urophylla*) to climatic, edaphic, and management variables under tropical conditions in Brazil.

Note: (+) positive correlation; (–) negative correlation; * non-significant ($p > 0.05$); R^2(adj): adjusted coefficient of determination; R^2 (CV 10-fold): coefficient from 10-fold cross-validation; RMSE: root mean square error; MAIb: mean annual biomass increment; LAWAI: Log_{10}(AWAI) – Base-10 logarithm of the Annual Water Availability Index; Text: Texture; Spac: Spacing.

Table 7: Multivariate regression models and contribution of climatic, edaphic, and management variables to mean annual biomass productivity (MAIb) of *Eucalyptus* clones across the three study regions (SP, BA, and MA).

Multivariate Regression Models	Explained variability	Model robustness β0		Variable contribuition		SP	BA	MA
				Intercept	(-)	(-)	(-)	
	R^2 (adj)	R^2 (CV 10-fold)	RMSE	β1	Log (AWAI)	67%	25%	66%
				β2	Altitude	*	*	*
MAI SP	99.88%	99.87%	0.15%	β3	BD_7	31%	8%	6%
MAI BA	99.91%	99.90%	0.14%	β4	Spacing	-3%	-25%	28%
MAI MA	99.96%	99.95%	0.10%	β5	Texture	*	-43%	*

Notes: R^2adj: adjusted coefficient of determination; R^2 (10-fold CV): cross-validated coefficient of determination; RMSE: root mean square error; BD_7: basic wood density at seven years; [Log_{10}(AWAI)]: log-transformed annual water availability index; "(–)" indicates inverse correlation; "*" denotes non-significant variables ($p > 0.05$).

soil texture and planting spacing were the most influential factors, contributing 42.9% and 24.9%, respectively.

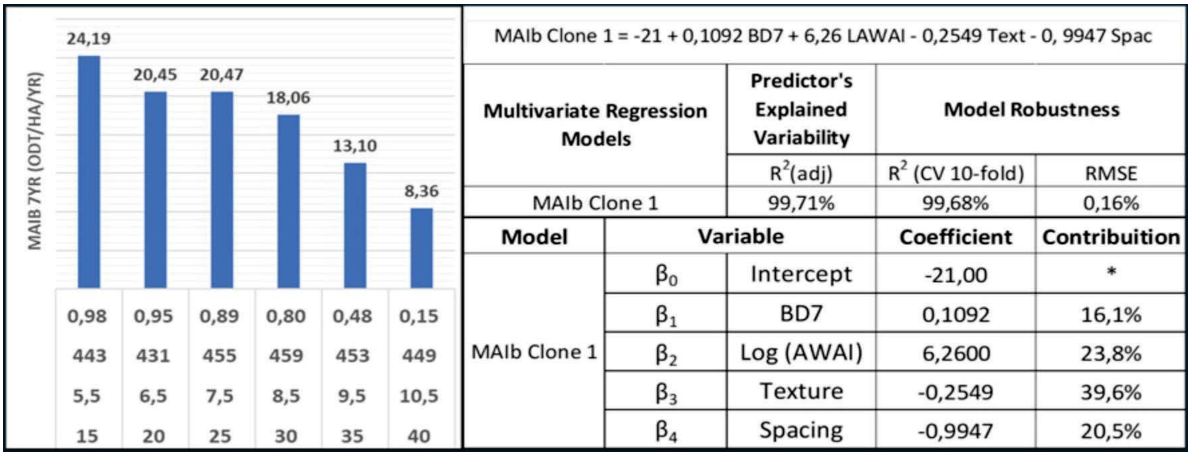
Basic wood density at seven years (BD_7) showed a consistent effect, although of lower relative magnitude, explaining between 6.0% (MA) and 30.5% (SP) of the variability in MAIb. Altitude did not show a significant effect in any of the regions ($p > 0.05$).

The multivariate regression models for both volumetric (MAI) and biomass (MAIb) productivity exhibited exceptionally high coefficients of determination ($R^2 > 0.99$) and minimal errors (RMSE < 0.5%). This high precision is attributed to the intentional experimental design, which utilizes extreme genetic and environmental contrasts to maximize the response signal. The near-perfect alignment between R^2adj and R^2cv (with differences as low as 0.01%) confirms the absence of overfitting and the high predictive stability of the models across different regions. Notably, the shift in variable contributions, such as the increased importance of soil texture in the Bahia (BA) models, demonstrates that the models successfully integrated regional edaphoclimatic specificities into the productivity estimates.

Figure 6 presents the multivariate model fitted specifically for clone HGU-1 (*E. grandis* × *E. urophylla*). The model describes the MAIb response to the variables identified as most relevant in the regional models, [Log_{10}(AWAI)], BD_7, soil texture, and planting spacing, allowing visualization of biomass productivity patterns as a function of these drivers.

Finally, complementary analyses based on regional models were used to isolate the effect of basic wood density on volumetric (MAI) and biomass (MAIb) productivity, while holding management factors and annual water indices constant. This approach enabled quantification of the direct influence of BD_7 on clonal performance under different climatic and edaphic conditions.

Figure 7 presents the slope coefficients (β_1) associated with basic wood density in the models fitted for each Köppen climate across the three regions (SP, BA, and MA). These coefficients quantify changes in biomass productivity (MAIb) in response to increases in basic wood density (BD_7).



MAIb Clone 1 = -21 + 0,1092 BD7 + 6,26 LAWAI - 0,2549 Text - 0, 9947 Spac

Multivariate Regression Models	Predictor's Explained Variability	Model Robustness	
	R^2(adj)	R^2 (CV 10-fold)	RMSE
MAIb Clone 1	99,71%	99,68%	0,16%

Model	Variable		Coefficient	Contribuition
MAIb Clone 1	β_0	Intercept	-21,00	*
	β_1	BD7	0,1092	16,1%
	β_2	Log (AWAI)	6,2600	23,8%
	β_3	Texture	-0,2549	39,6%
	β_4	Spacing	-0,9947	20,5%

Figure 6: Multivariate regression model and biomass productivity response of clone HGU-1 (*E. grandis* × *E. urophylla*) to climatic, edaphic, and management variation under tropical conditions in Brazil.
R^2(adj): adjusted coefficient of determination; R^2(CV 10-fold): cross-validated coefficient of determination; RMSE: root mean square error; BD_7: basic wood density at seven years; [Log_{10}(AWAI)]: annual water availability index (log-transformed); "(–)" indicates inverse correlation; "*" denotes non-significant variable ($p > 0.05$). MAIb: mean annual biomass increment; LAWAI: Log_{10}(AWAI) – Base-10 logarithm of the Annual Water Availability Index; Text: Texture; Spac: Spacing.

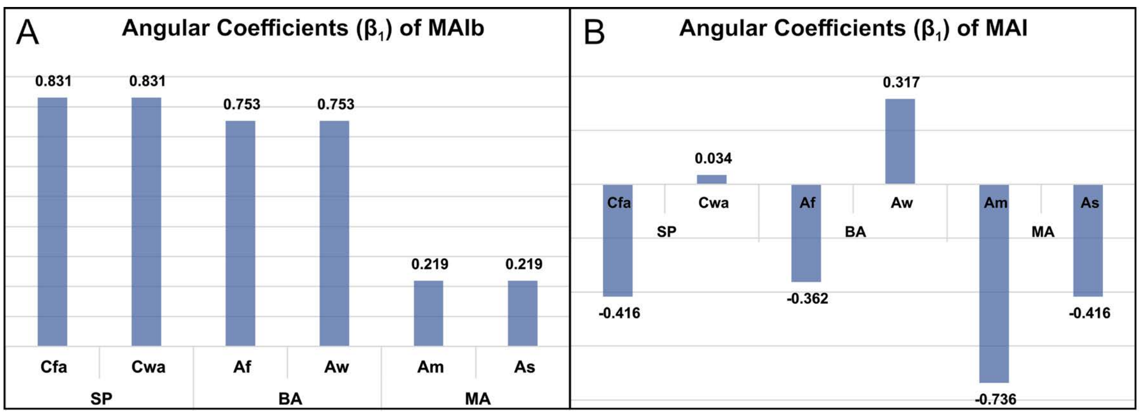


Figure 7: Impact of increasing basic wood density (BD_7) on slope coefficients (β_1) of volumetric (MAI) and biomass (MAIb) productivity models across Köppen climate types in the three study regions (SP, BA, and MA).

The results show that, under more humid climates, β_1 coefficients tend to assume positive values, indicating that increases in basic wood density are associated with gains in MAIb. In contrast, under drier climates, coefficients of lower magnitude or negative values are observed, reflecting reductions in MAIb as wood density increases.

These patterns demonstrate the existence of distinct climate-dependent responses of biomass productivity, indicating that the effect of basic wood density on MAIb varies according to the prevailing water regime of each climatic unit.

Integration of genetic, edaphic, and climatic factors in Eucalyptus productivity

Integration of the results obtained from the multivariate models allowed the synthesis, for each Köppen climate type, of the combination of genetic, edaphic, and management attributes associated with the observed productivity patterns. Table 8 summarizes the main evaluated species and hybrids, together with edaphic characteristics (soil texture and water availability), management attributes (spacing), and genetic background (species and hybrids), as well as the corresponding mean values of basic wood density (BD_7), volumetric productivity (MAI), and biomass productivity (MAIb).

From this synthesis, consistent differences among climatic zones were observed, both in predominant genetic composition and in average density and productivity levels. Under more humid climates (Cfa and Cwa), clones such as HGU (*E. grandis* × *E. urophylla*) and EGR (*E. grandis*) expressed high volumetric and biomass productivity (MAI ≈ 20 m^3/ha/yr; MAIb ≈ 55-57 t/ha/yr), combined with lower basic wood density (400-420 kg/m^3) and high water availability (Log_{10}(AWAI) ≈ 0.95-0.98).

In contrast, in drier environments (Aw, Am, and As), a transition toward more conservative strategies was observed, characterized by increased basic wood density (460-520 kg/m^3) and reduced Log_{10}(AWAI) values (< 0.80). In these climates, hybrids such as *E. urophylla* × *E. tereticornis*, *E. grandis* × *E. brassiana*, and *E. platyphylla* predominated. These patterns reflect the combined variation of genetic traits and environmental conditions across the evaluated regions.

DISCUSSION

Analysis of climatic aspects

Analysis of precipitation recorded between 2012 and 2018 (Figure 4) revealed significant climatic oscillations among the different climate types across the three evaluated regions (SP, BA, and MA), reflecting distinct regional patterns that were nonetheless synchronized in terms of water-deficit anomalies. These events were modulated by large-scale atmospheric phenomena, including the El Niño–Southern Oscillation (ENSO), subtropical atmospheric blocking, and thermal anomalies in the Atlantic and Pacific oceans (Marengo et al., 2015).

Table 8: *Eucalyptus* species and hybrids evaluated under each Köppen climate type, with their respective edaphic, management, and productivity variables, including volumetric (MAI) and biomass increment (MAIb) mean annual increment at seven years of age.

Region	Clim.	Species	Text.	Spac.	BD_{7yr}	Log_{10} (AWAI)	$MAIb_{7yr}$	MAI_{7yr}	MAI_{7c}	ΔMAI_7
			(% clay)	(m^2/pl.)	(kg/m^3)	(Index)	(odt/ha/yr)	(m^3/ha/yr)	(m^3/ha/yr)	(%)
SP	Cfa	HGU	31	5.5	420	0.981	21.14	56.88	57.65	1.3
		EGR	31	5.5	400	0.981	20.31	57.38	57.65	0.5
	Cwa	HGU	21	6.9	440	0.964	19.39	49.81	48.38	-3.0
		EGR	21	6.9	420	0.964	18.56	49.94	48.38	-3.2
BA	Af	HGU	20	8.1	440	0.890	21.73	55.81	55.05	-1.4
		EUR	20	8.1	460	0.890	22.48	55.23	55.05	-0.3
	Aw	HGU	35	8.5	450	0.825	16.26	40.82	39.80	-2.6
		EUR	35	8.5	470	0.825	17.01	40.89	39.80	-2.7
MA	Am	HGU	32	9.5	460	0.520	14.60	35.87	36.41	1.5
		EUR	32	9.5	480	0.520	14.82	34.89	36.41	4.2
		EPL	32	9.5	500	0.520	15.04	33.99	36.41	6.6
		HGB	32	9.5	510	0.520	15.15	33.57	36.41	7.8
	As	HGU	30	10.5	470	0.279	12.74	30.62	25.93	-18.1
		EUR	30	10.5	490	0.279	12.96	29.88	25.93	-15.2
		HUT	30	10.5	580	0.279	13.95	27.17	25.93	-4.8
		HGB	30	10.5	520	0.279	13.29	28.87	25.93	-11.3

Notes: BD_7: basic wood density at seven years; Log_{10}(AWAI): annual water availability index; $MAIb_{7yr}$: mean annual biomass increment; MAI_7: mean annual increment at seven years; MAI_{7c}: mean annual increment adjusted at seven years; ΔMAI_7: percentage difference between MAI_7 values obtained from volumetric- and mass-based models.

In São Paulo, the 2014 Water Crisis caused precipitation reductions of up to −37% under the Cwa climate, associated with the persistence of dry air masses and inhibition of the South Atlantic Convergence Zone (SACZ) (Nobre et al., 2016). This event resulted in prolonged water deficits and sharp declines in river discharge across southeastern Brazil (Freitas et al., 2020), directly affecting forest growth. In Bahia, the largest reductions occurred between 2014 and 2016, coinciding with the 2015–2016 Super El Niño, which displaced the Intertropical Convergence Zone (ITCZ) toward the Northern Hemisphere and reduced moisture transport to northeastern Brazil (Freire, Lima and Cavalcanti, 2011). The Aw climate exhibited the most severe reduction (−51%), demonstrating heightened sensitivity to oceanic variability. In Maranhão, the strongest impacts were observed among the regions, with reductions ranging from −38% to −57% under the Am and As climates, consistent with the strong dependence of the monsoonal regime on equatorial Pacific anomalies (Marengo et al., 2020). The rapid rainfall recovery observed in 2017–2018 coincided with the onset of La Niña, which enhanced Amazonian moisture transport.

Analysis of the [Log_{10}(AWAI)] proxy confirmed this regional hydrological gradient, with decreasing values from south to northeast to north: 0.98–0.95 in São Paulo (Cfa, Cwa), 0.89–0.80 in Bahia (Af, Aw), and 0.48–0.15 in Maranhão (Am, As). Significant differences between Af–Aw ($p \approx 0.034$) and Am–As ($p \approx 0.019$) highlight the strong hydrological seasonality of dry tropical environments, whereas the absence of significant contrasts in São Paulo ($p \approx 0.506$) indicates greater interannual stability. These results demonstrate the robustness of [Log_{10}(AWAI)] as an integrative indicator capable of discriminating zones of hydrological stability and vulnerability at the regional scale.

The coherence between this proxy and indices widely used in climatology and forest management, such as the UNEP Aridity Index and the Modified Climatic Moisture Index (Silva and Azevedo, 2020), further supports its potential as an ecophysiological diagnostic tool and as a support for forest zoning, particularly under scenarios of increasing climatic variability.

Volumetric and biomass productivity (MAI and MAIb)

Analysis of variables affecting volumetric productivity (MAI)

The multivariate models explained more than 99% of the variability in MAI across the three regions, demonstrating high statistical robustness and strong environmental and edaphic control over stand growth. Among the evaluated variables, the annual water availability index [Log_{10}(AWAI)] showed the greatest explanatory contribution, particularly in São Paulo (43%) and Maranhão (50%), reinforcing that water-use efficiency (WUE) is the primary growth-controlling factor under tropical conditions (Stape et al., 2010).

Altitude and soil texture also showed significant effects. Sites at higher altitudes and with sandier soils exhibited higher MAI, possibly due to improved drainage, lower vapor pressure deficit, and greater photosynthetic efficiency, in agreement with Laclau et al. (2022). Stand age showed a negative relationship with MAI, reflecting the physiological decline of current annual increment as the silvicultural cycle progresses (Binkley et al., 2004).

Planting spacing, in turn, exerted contrasting effects among regions. In São Paulo, narrower spacing favored increased light-use efficiency (LUE) through earlier canopy closure, whereas in Maranhão wider spacing reduced competition for water, increasing effective water availability per tree, as reported by Almeida et al. (2007) and Binkley et al. (2010). These patterns confirm that productivity results from the functional balance between WUE and LUE, modulated by edaphoclimatic conditions and management practices.

The specific analysis of clone HGU-1 (Figure 5) confirmed its high physiological plasticity and productive stability under contrasting edaphoclimatic conditions. The fitted model (R^2_adj = 99.37%; RMSE = 0.14%) reinforces that [Log_{10}(AWAI)], soil texture, and spacing are the main predictors of MAI. The positive relationship between [Log_{10}(AWAI)] and MAI indicates that clone productivity is strongly associated with WUE, consistent with the behavior reported for *E. grandis* × *E. urophylla* hybrids under moderate water deficit (Stape et al., 2010; Binkley et al., 2010). This dual physiological efficiency (LUE + WUE), combined with a deep and exploratory root system, confers remarkable productive stability to HGU-1 under hydroclimatic variability, in line with findings reported by Laclau et al. (2022).

Regional integration of the models indicates that [Log_{10}(AWAI)] was the main determinant of MAI, with elasticity varying among environments. In São Paulo, small oscillations in AWAI resulted in increases of up to +12 m^3/ha/yr, confirming the role of water availability in growth control (Stape et al., 2010); in Bahia, soil texture exerted greater influence; and in Maranhão, productivity gains were essentially hydraulic (+14 m^3/ha/yr), reflecting strong water limitation in dry tropical environments. These results demonstrate that volumetric productivity of *Eucalyptus* depends on fine ecophysiological adjustments to local edaphoclimatic conditions and management, as also discussed by Laclau et al. (2022).

From a genetic perspective, the observed patterns reinforce the need for matching genetic material to environmental conditions. *Eucalyptus grandis* clones showed higher productivity under humid climates (Cfa, Cwa) due to rapid growth and greater investment in conductive tissues (Stape et al., 2010), whereas hybrids involving E. urophylla, E. pellita, and E. tereticornis exhibited greater drought resilience and productive stability in dry tropical regions (Almeida et al., 2007).

Overall, these results confirm that *Eucalyptus* productivity emerges from the interaction among climatic (primarily water), edaphic, genetic, and management factors, supporting the use of integrated ecophysiological models and adaptive selection criteria in breeding programs and climatic zoning of *Eucalyptus* plantations in Brazil.

Analysis of variables affecting biomass productivity (MAIb) across the three regions

Biomass productivity of *Eucalyptus* clones, expressed as mean annual biomass increment (MAIb), reflects the balance between volumetric growth and the efficiency of carbon allocation to woody tissues. Analysis of the fitted models (Table 6) showed that annual water availability [Log_{10}(AWAI)] and basic wood density at seven years (BD_7) were the most determinant variables for biomass accumulation, both being highly significant ($p < 0.001$). Across the three evaluated regions, [Log_{10}(AWAI)] explained more than 60% of the variation, indicating that water-use efficiency (WUE) constitutes the primary physiological driver of biomass productivity under tropical conditions.

In São Paulo, BD_7 accounted for approximately 30% of the variability in MAIb, indicating that increases in wood density, associated with thicker cell walls and a lower proportion of vessels, favor carbon fixation per unit volume. Thus, biomass productivity emerges not solely from produced volume, but from the combined effects of density, water availability, and genotypic physiological efficiency.

Recent studies support this relationship between hydrological environment and wood structure. Elissetche et al. (2024) demonstrated that basic wood density increases under reduced water availability, reflecting greater investment in lignification and a balance between hydraulic resistance and conductive efficiency. Similar results were reported by Almeida et al. (2020) for *Eucalyptus urophylla*, who observed increased basic density and heartwood proportion under dry climates, evidencing anatomical and physiological plasticity as an adaptive response to water stress. Costa et al. (2020) confirmed the strong environmental dependence of basic wood density, proposing its use as a functional indicator of adaptive capacity. Brito et al. (2021) further showed that increased wood density in *Eucalyptus* clones is associated with anatomical adjustments that optimize water and light use, particularly in short rotations. Together, these findings reinforce that basic wood density acts as an ecophysiological variable, expressing the balance between hydraulic conductivity and resistance within the xylem.

Accordingly, MAIb does not depend solely on volumetric growth, but rather on a functional triad composed of light-use efficiency (LUE), water-use efficiency (WUE), and basic wood density (BD), all modulated by genotype × environment interactions under contrasting tropical regimes (Stape et al., 2010; Laclau et al., 2022).

The specific analysis of clone HGU-1 (*E. grandis* × *E. urophylla*) confirmed this interaction. The clone-specific model showed high precision (R^2_adj = 99.71%; RMSE = 0.16%), with [Log_{10}(AWAI)] (coefficient = 6.26; 33%) and BD_7 (coefficient = 0.1092; $p < 0.001$) standing out as key predictors. In environments with clay-rich soils, soil texture and spacing exerted negative effects, reflecting the clone's sensitivity to drainage and root aeration (Oliveira et al., 2023). Nevertheless, HGU-1 exhibited high ecophysiological plasticity: in humid regions (SP), it prioritized LUE and rapid canopy closure; in dry regions (MA), it shifted investment toward WUE, with deep root systems and strong stomatal control. This response confirms its physiological versatility and adaptation to tropical contrasts (Almeida et al., 2020; França et al., 2017).

Genotype × environment interaction and the LUE–WUE balance in biomass production

Integrated analysis of Figure 7 and Table 6 reveals that *Eucalyptus* biomass productivity is strongly modulated by genotype × environment interactions, reflecting the functional balance between light-use efficiency (LUE) and water-use efficiency (WUE) under different environmental regimes and wood density levels. Under humid climates (Cfa and Af), increases in basic wood density at seven years (BD_7) resulted in substantial gains in MAIb ($\beta_1 \approx 0.8$), whereas under dry climates (Am and As) this effect was much weaker ($\beta_1 \approx 0.2$). This contrast indicates that wood densification is advantageous when water is not limiting but becomes energetically costly under prolonged water stress, a condition in which metabolism prioritizes hydraulic safety over volumetric growth.

This behavior reflects an ecophysiological trade-off between efficiency and safety. In humid environments, rapid growth and high photosynthetic efficiency predominate. In contrast, in dry environments, stomatal control and higher wood density confer hydraulic safety and productive stability (Janssen et al., 2019; Hacke et al., 2000). Anatomical studies further support this pattern. Almeida et al. (2020), for example, reported fiber wall thickening and reduced vessel diameter in *E. urophylla* under water deficit—anatomical responses aimed at maintaining hydraulic function under stress. Trueba et al. (2016) and Barotto et al. (2018) also described the efficiency–safety trade-off, whereby wider vessels enhance water transport and volumetric growth (MAI) but reduce resistance to cavitation.

In clonal plantations, Laclau et al. (2022) demonstrated that productive stability is associated with the ability to maintain functional water flow throughout the rotation, with xylem anatomical arrangement, particularly the ratio between vessel area and wall thickness, being a key determinant of WUE. In this context, basic wood density should not be treated merely as a technological attribute, but rather as a functional indicator of anatomical plasticity and ecophysiological adaptation, integrating hydraulic architecture and biomass productivity.

Under humid environments (Cfa and Cwa), clones such as HGU (*E. grandis* × *E. urophylla*) and EGR (*E. grandis*) expressed high volumetric and biomass productivity, lower wood density, and high water availability. These results characterize materials physiologically oriented toward LUE, with rapid canopy closure and high photosynthetic capacity (Almeida et al., 2007; Stape et al., 2010).

Conversely, under dry environments (Aw, Am, and As), a transition toward more conservative strategies was observed, characterized by increased wood density and reduced Log_{10}(AWAI) values, with predominance of hybrids such as *E. urophylla* × *E. tereticornis*, *E. grandis* × *E. brassiana*, and *E. platyphylla*, which are better adapted to water scarcity and increased cavitation resistance (Janssen et al., 2019; Hacke, et al., 2000; Barotto et al., 2018; Costa et al., 2020). The variation in MAI (ΔMAI_7) indicated that low-density clones exhibited a higher risk of productivity overestimation in dry environments, particularly under extreme climatic events.

From an evolutionary perspective, species within the *Symphyomyrtus* section, including *E. grandis*, *E. urophylla*, *E. brassiana*, and *E. tereticornis*, exhibit a broad functional gradient between hydraulic efficiency and mechanical resistance (Grattapaglia et al., 2012), which explains their wide climatic adaptability and silvicultural versatility. Thus, the results of this study confirm the existence of an evolutionary–functional gradient between fast-growth strategies (low density, high MAI) and conservative strategies (high density, greater hydraulic stability), reflecting the adaptive essence of the genus *Eucalyptus*. These findings reinforce the importance of aligning genetic selection with regional water balance, climatic risk patterns, and management objectives, particularly under scenarios of increasing climatic variability in tropical regions.

Despite the robust predictive performance and high stability confirmed by cross-validation, some limitations of this study should be acknowledged. As an observational study, the identified relationships between water availability and productivity reflect strong correlations rather than definitive causality. The use of AWAI and Potential Evapotranspiration (PET) methods carries inherent uncertainties typical of simplified hydrological modeling. Furthermore, the results are specific to the genetic portfolio and management practices of the studied forest base. Additionally, future climate uncertainty poses a challenge, as increasing frequency of extreme weather events may shift the established eco-physiological thresholds, potentially affecting the long-term stationarity of these models. Therefore, while these models offer high regional accuracy, caution is advised when generalizing these findings to different genetic materials or rapidly changing climatic scenarios outside the original experimental scope.

CONCLUSION

This study, encompassing 63 environmental units across São Paulo, Bahia, and Maranhão, indicates that Eucalyptus volumetric and biomass productivity are closely associated with the interaction among climate, soil, management, and genetic material. The results suggest that annual water availability acts as a primary driver of growth, with the [log10 (AWAI)] proxy demonstrating high sensitivity in capturing interannual variability and climatic contrasts.

The high predictive stability confirmed by cross-validation (R^2cv) supports the model's reliability, explaining a substantial proportion of the variation in MAI and MAIb, while edaphic conditions and planting spacing appear to modulate the balance between light- and water-use efficiency across different climates.

Basic wood density (BD7) was identified as a potential integrative indicator of physiological performance, likely favoring biomass accumulation under humid conditions and potentially conferring hydraulic safety in drier environments. Accordingly, the studied clones exhibited ecophysiological plasticity by adjusting LUE- and WUE- oriented strategies in response to environmental constraints. From an applied perspective, these findings support the potential use of water zoning based on [log10 (AWAI)] to guide genetic allocation and planting density.

In summary, within the scope of this study, water availability is confirmed as a dominant determinant of productivity, and basic wood density stands out as a functional indicator of the efficiency–safety trade-off underlying the adaptive capacity of Eucalyptus clones under tropical climatic variability.

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AUTHORSHIP CONTRIBUTION

Project Idea: AJS; LS; JEMP; GBV

Funding: AJS; LS

Processing: AJS

Analysis: AJS

Writing: AJS

Review: RGCS; TCCN; GCVS; GBV

DATA AVAILABILITY

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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