Ciência Florestal

ISSN 1980-5098
Open access

Ci. Fl., Santa Maria, v. 32, n. 2, p. 523-547, Apr./June 2022 • https://doi.org/10.5902/1980509832690
Submitted: 20th/05/2018 • Approved: 7th/09/2021 • Published: 24th/06/2022

Artigos

Influence of the climate on productivity and the eucalyptus drought response and a proposal for maximizing wood productivity in function of soil attributes in Brazil

Influência do clima na produtividade e resposta à seca do eucalipto e uma proposta de maximização da produtividade de madeira em função dos atributos do solo no Brasil

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ABSTRACT

The genetic gains from eucalyptus breeding programs have decreased, compared to the previous decades, while the productivity has declined in recent years. This drop is mainly attributed to climate change, which, according to studies, has limited the productivity and altered the adaptation of forest species. In addition to this, it is considered that the soil is one of the components of the forest production that acts directly on the dynamics of water and nutrients for trees, and it is intended to evaluate the attributes of soils that maximize the productivity of wood to assist forestry companies in the indication of soils with better productive capacity to produce wood. Thus, the aim of the present study was to evaluate the influence of climate and soil attributes on the productivity of the eucalyptus forest and on the response to drought in Brazil (tropical and subtropical) in places with three types of climate: sub-humid, humid and super-humid. In addition, we sought to calculate a proposal for optimal values of stable soil attributes over a forest cycle/rotation to maximize *Eucalyptus* productivity. To do so, 24 experiments were installed in Brazil with 4 common clones in all the experiments to obtain strong edaphoclimatic contrasts, and, thus, to measure the productivity and the response to drought and to describe its relationship with the attributes of the soils. Three climatic groups were evaluated: Sub-humid (precipitation rate: evapotranspiration between 0.5 to 1.0, Wet (precipitation rate: evapotranspiration between 1.0 to 2.5), Super-humid (precipitation rate: evapotranspiration between 2.5 to 5.0). Wood productivity varied among *Eucalyptus* clones, with an average of 1.86 being the variation range. The genotype versus environment interaction (G X E) was strongly noted, and it was observed that some clones are more affected by the climate in relation to others. The optimal values of Sand, Clay, Silt, CEC, O.M to maximize the wood productivity were: 54.68 %, 18.94 %, 7.02 %, 31.49 $mmol_c/dm^3$, 27.17 g/cm^3.

Keywords: Climate; Edaphoclimatic groups; Tolerance to forest aridity; Soil quality

RESUMO

Os ganhos genéticos dos programas de melhoramento do eucalipto diminuíram em comparação com as décadas anteriores, enquanto a produtividade reduziu nos últimos anos. Essa queda é atribuída principalmente às mudanças climáticas, que, segundo estudos, têm limitado a produtividade e alterado a adaptação das espécies florestais. Além disso, considera-se que o solo é um dos componentes-chave da produção florestal e que atua diretamente na dinâmica da água e dos nutrientes para as árvores. Pretende-se avaliar, neste trabalho, os atributos dos solos que maximizam a produtividade da madeira para auxiliar as empresas silvicultoras na indicação de solos com melhor capacidade produtiva para produção de madeira. Assim, o objetivo do presente estudo foi avaliar a influência dos atributos do clima e do solo na produtividade da floresta de eucalipto e na resposta à seca no Brasil (tropical e subtropical) em locais com três tipos de clima: Subúmido, Úmido e Superúmido. Além disso, buscou-se calcular uma proposta de valores ótimos de atributos estáveis do solo ao longo de um ciclo/rotação da floresta para maximizar a produtividade do eucalipto. Para isso, foram instalados no Brasil 24 experimentos com 4 clones comuns em todos os experimentos para obter fortes contrastes edafoclimáticos, e, assim, medir a produtividade e a resposta à seca e descrever sua relação com os atributos dos solos. Três grupos climáticos foram avaliados: Subúmido (taxa de precipitação: evapotranspiração entre 0,5 e 1,0, Úmido (taxa de precipitação: evapotranspiração entre 1,0 e 2,5), Superúmido (taxa de precipitação: evapotranspiração entre 2,5 e 5,0). A produtividade de madeira variou entre os clones, com uma média de 1,86 sendo a faixa de variação. A interação genótipo *versus* ambiente (G X A) foi fortemente observada, e foi constatado que alguns clones são mais afetados pelo clima em relação a outros. Silte, CEC, MO para maximizar a produtividade da madeira foram: 54,68 %, 18,94%, 7,02%, 31,49 $mmol_c$ / dm³, 27,17 g / cm³.

Palavras-chave: Clima; Grupos edafoclimáticos; Tolerância à aridez da floresta; Qualidade do solo

1 INTRODUCTION

The rapid expansion of Brazilian forestry brings the need to have greater area demands as well as to guarantee high levels of productivity. The difficulties in obtaining land in large quantities for forestry as well as the high prices of rapid land inflation pressured by food production and livestock (INDÚSTRIA BRAILEIRA DE ÁRVORES, 2015; SILVA; HERNANDEZ, 2015) are notorious.

Thus, Brazil is no longer the most competitive country in terms of the cost of wood production, losing to countries such as Russia, Indonesia and the United States. Due to the emerging intrinsic inflation of the sector; due to the prices of the land, inputs and labor in recent years (INDÚSTRIA BRAILEIRA DE ÁRVORES, 2015), as well as migrating plantations to marginal areas, where knowledge on soils and forest productivity in these environments is still very limited (FERRAZ; LIMA; RODRIGUES, 2013). For this, due to the fact that Brazil underwent a process of stagnation of the productivity increase (BINKLEY *et al*., 2017) in the last decade. That is, if the increase in productivity does not accompany the increase of the intrinsic inflation of the sector (NICKELL, 1995), and the sector/country loses competitiveness in relation to the main players in the world market (FIGUEIREDO, 2008).

In this way, one of the efficient ways to reduce the cost of wood is to increase forest productivity, and one of the strategies to achieve this goal is to know the main environmental stresses to *Eucalyptus* that are factors that reduce the productivity. Among these, two stand out due to their association with the new forest frontiers, namely: i) Water stress, mainly in the central-west, north, northeast and part of southeastern Brazil; and ii) Thermal stress related to high temperatures (above 36°C) in tropical Brazil, or at low temperatures (below 5°C) in southern Brazil. Thus, the cooperative program on Tolerance of *Eucalyptus* Clones to Water and Thermal Stresses (TECHS) was proposed through a very robust experimental network installed in Brazil and Uruguay.

As forest managers often come up with questions about which are the best sites for *Eucalyptus* plantation, and often this information is not explicit, and in some way equated, there is a need to target where the best areas for plantations are. In this paper, we consider the productivity of wood, as well as considering the hypothesis that the climate is changing (BLAUM *et al*., 2016; SCREEN, 2017), thus searching for the best areas for *Eucalyptus* plantations, maintenance of the forest productivity of Brazilian forestry companies.

In the context of this work, TECHS discuss the climatic factors (BINKLEY *et al*., 2017). However, the sensitivity of the productivity of the clones to the different soil characteristics in the respective climatic conditions has not yet been considered in this experiment. That is, knowing the physical-chemical characteristics of the soils makes it possible to understand some soil-climate relations for different clones (SILVA *et al*., 2020b).

Thus, the aim of the present study was to evaluate the influence of climate and soil attributes on the productivity of the eucalyptus forest and on the response to drought in Brazil (tropical and subtropical) in places with three types of climate: sub-humid, humid and super-humid. In addition, we sought to calculate a proposal for optimal values of stable soil attributes over a forest cycle/rotation to maximize the *Eucalyptus* productivity.

2 MATERIAL AND METHODS

2.1 Characterization of clones

A group of breeders to be deployed at all TECHS sites defined a group of 18 *Eucalyptus* clones. These clones represented the different genetic materials in use in Brazil today, but with different species characteristics, susceptibility to water and thermal stresses. Diversity of ecophysiological behaviors within appropriate levels of productivity was sought here. All measurements and information from these clones were shared among the companies participating in TECHS to define the pool of clones to be used in TECHS.

Due to the great climatic amplitude of Brazil, the clones were divided into 4 groups: a) Tropical Clones and of Humid regions (Type U); b) Tropical clones and Drier regions (Type S); c) Clones from colder subtropical regions (Type F); and d) Intermediate clones and more Plastics (Type P). In this work, only 4 plastic clones planted in the TECHS were used and were indicated for the experiment because they are clones which are widely operationally planted by the forest companies in Brazil, namely: A1, C3, K2 and Q8. This is because only these clones were planted in a common way in all experiments. The main genetic characteristics and some climatic parameters of the clones used in these studies are presented, according to data reported by Flores *et al*. (2016) and Binkley *et al*. (2017) in Table 1.

Table 1 – The four genotypes of *Eucalyptus* in the network of TECHS experiments, climate of origin in which each clone was developed during the breeding programs and where they were selected

Clones	Genotype	Average Annual Temperature (ºC)	Rainfall (mm)	Climate	Natural Occurrence	Climate in which the clone was selected
A1	*Eucalyptus urophylla*	16-27	1000-2000	Tropical and Subtropical	Predominantly Aw, and to a lesser extent in climates Af, Am, Cwa and Cwb	Cwa
C3[1]	*Eucalyptus grandis x Eucalyptus camaldulensis*	15-22 e 16-27	800-2000 and 500-1500	Tropical and Subtropical	*Eucalyptus grandis* - Predominantly Cfa, and to a lesser extent in climates Cwa, Cwb and Cfb. *Eucalyptus camaldulensis* - predominantly Aw, to a lesser extent As, Cwa, Cwb	As
K2	*Eucalyptus saligna*	13-18	900-1400	Subtropical	Predominantly Cfb, Cfa, Cwb	Cfb
Q8	*Eucalyptus grandis*	15-22	800-2000	Subtropical	Predominantly Cfa, and to a lesser extent in climates Cwa, Cwb and Cfb.	Af

Source: Authors (2018)

In where: A1, C3, K2, Q8 = commercially planted *Eucalyptus* clones in Brazil; [1] Clone C3 is a hybrid of *Eucalyptus grandis* x *Eucalyptus camaldulensis*, and thus the climatic parameters of the two species have been described.

2.2 Characterization of previous land use

The plantations were carried out in areas of reforestation (*Eucalyptus* sp. and *Pinus* sp.), grass, as well as in areas of Native Brazilian Savanna (Table 2). The number of rotations ranged from 1st to 5th forest rotation, and the average forest rotation duration was between 6-7 years. The soil preparation was the operational one of the Brazilian forest companies, which on average ranged from 40 to 50 cm deep, and lateral squatting of 70 cm, using the subsoiler/scarifier for soil preparation. This information will be important to justify the soil attribute contents, as well as the yield and drought response results presented in this study.

Table 2 – History of land use and occupation before the installation of TECHS

TECHS	Town	State	Order of soil	Species/Vegetation Previous to Experiment	Years of Soil Occupation
2	Arapoti	PR	Ferralsol	*Pinus* sp.	40 years
4	Belo Oriente	MG	Ferralsol	*Eucalyptus* sp.	40 years
5	Guanhães	MG	Ferralsol	*Eucalyptus* sp.	30 years
6	Eldorado do Sul	RS	Nitisol	*Eucalyptus* sp.	14 years
7	Rio Verde	GO	Arenosol	*Eucalyptus* sp.	20 years
9	Estrela do Sul	MG	Ferralsol	*Pinus* sp.	35 years
10	Botucatu	SP	Ferralsol	*Eucalyptus* sp.	-
11	Chapadão do Sul	MS	Ferralsol	Grass	-
12	Aracruz	ES	Ferralsol	*Eucalyptus* sp.	20 years
13	Três Lagoas	MS	Ferralsol	Grass	-
14	Inocência	MS	Arenosol	Grass	-
15	Brejinho do Nazaré	TO	Arenosol	Brazilian Savanna	-
17	Três Marias	MG	Ferralsol	*Eucalyptus* sp.	40 years
19	Peixe	TO	Ferralsol	Grass	5 years
20	Mogi-Guaçu	SP	Ferralsol	*Eucalyptus* sp.	45 years
22	Telemaco Borba	PR	Ferralsol	*Eucalyptus* sp.	8 years
23	Otacílio Costa	SC	Cambisols	*Pinus* sp.	16 years
24	Borebi	SP	Arenosols	*Eucalyptus* sp.	14 years
26	Coração de Jesus	MG	Ferralsol	Brazilian Savanna	-
27	Antônio Olinto	PR	Nitisol	*Pinus* sp.	16 years
28	Três Barras	SC	Ferralsol	*Eucalyptus* sp.	12 years
29	Urbano Santos	MA	Arenosol	Brazilian Savanna	-
30	Bocaiúva	MG	Ferralsol	*Eucalyptus* sp.	20 years
33	Buri	SP	Ferralsol	*Eucalyptus* sp.	20 years

Source: Authors (2018)

In where: TECHS = number of the techs site that identifies where it was planted; MG = state of Minas Gerais; PR = state do Paraná; RS = state of Rio Grande do Sul; GO = state of Goiás; SP = state of São Paulo; MS = state of Mato Grosso do Sul; TO = state of Tocantins; SC = state of Santa Catarina; MA = state of Maranhão.

Additionally, in the history of soil use and occupation prior to the TECHS experiment, it was observed that the areas of plantations in Brazil range from very new areas to areas with 45 years of *Eucalyptus* plantations. These data portray well the reality of Brazil between traditional planting areas with extensive knowledge of forestry as well as high technological level used in wood production (e.g. TECHS 20 as a traditional site for forestry areas), to silvicultural frontier areas with limited knowledge in terms of soil and climatic conditions (e.g. TECHS 13 as a forestry frontier site).

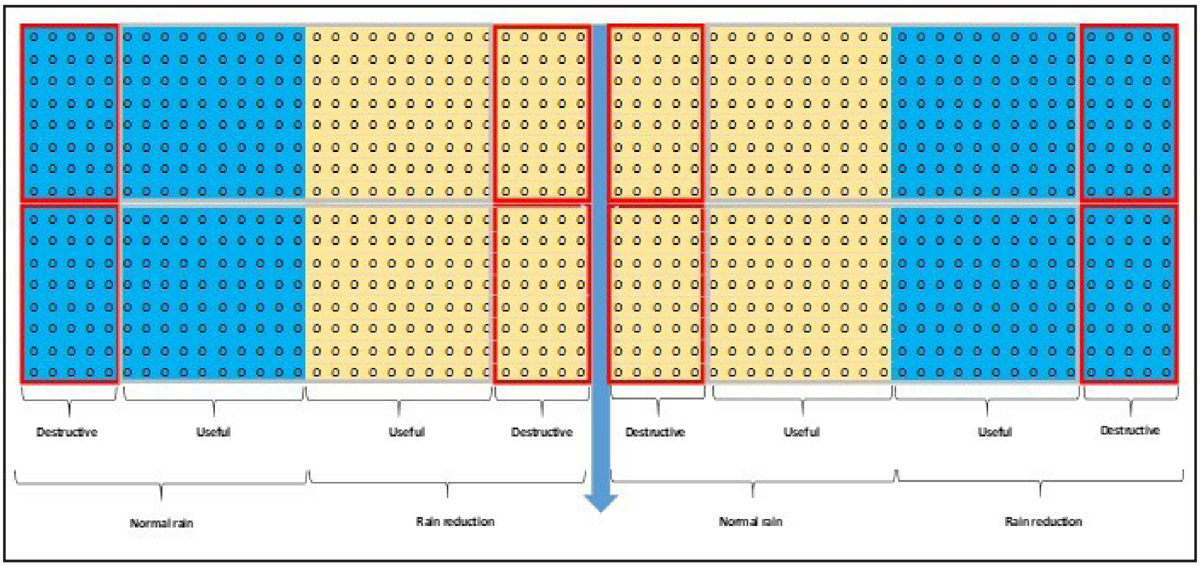
2.3 Experimental information

The fertilizations used previously were the same as those used in forestry companies, usually composed of NPK + S and micronutrients in the fertilization of planting, liming in total area without incorporation, and one or two cover fertilizations, ending the cover fertilization up to a maximum of 18 months after planting.

Each clone was planted in a single plot, with 8 Lines × 30 trees (plot size 24 m × 90 m - 2160 m^2), with trees at a square spacing of 3 m × 3 m (1111 ha^{-1} trees). One edge of each plot had 5 rows (each one with 8 trees) available for destructive sampling throughout the project.

The diameter at breast height (DBH) and the total height of the 80 central trees of the plots with rainfall and rainfall exclusion (70% of the total rainfall) were measured, as shown in Figure 1.

Figure 1 – Sketch of a complete replication of the TECHS water stress test with the 4 clones



Source: Authors (2018)

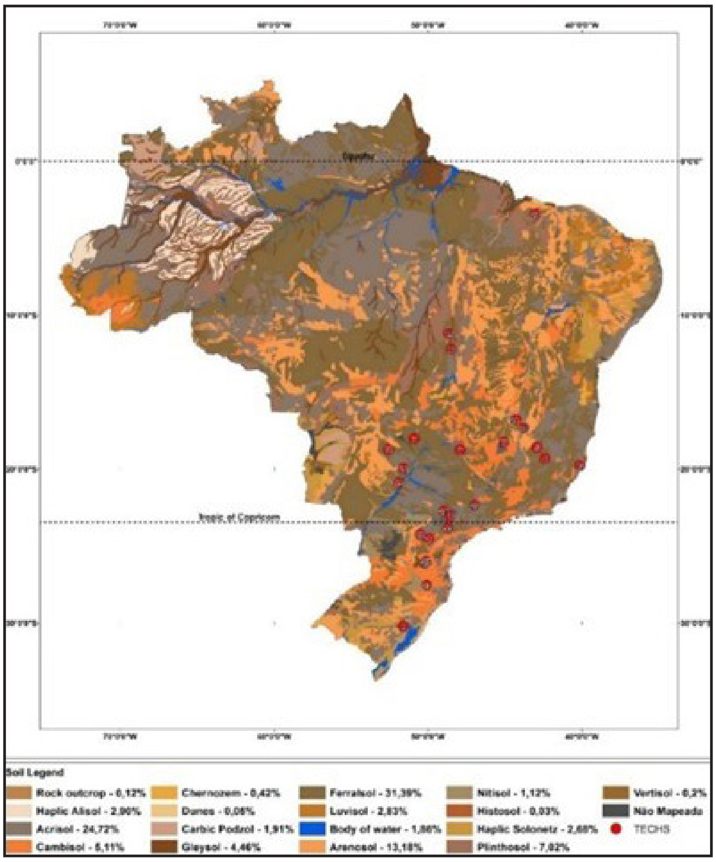
In where: *Note the central drainage line. Dimensions of 144 m x 180 m (12 lines per 60 plants, 3 m x 3 m)

For the manipulation of water availability, the “rainfall exclusion” was used in the four clones/plots studied. The technique is based on a cover made between the planting lines covering 30% of the plot surface area, thus estimating a reduction of rainfall reaching the soil to 70% of the total precipitation (Figure 2). The cover was made one year after planting the trees, with *Eucalyptus* poles and plastic tarps, with a slope that takes water out of the plot.

2.4 Edaphoclimatic characterization

The order of soil with the highest occurrence among the experiments was Ferralsol (67%), followed by Arenosol (21%), Nitisol (8%), and Cambisol (4%). According to the most up-to-date mapping of soils in Brazil (SANTOS *et al*., 2011), Ferralsols occur in approximately 31% of the Brazilian territory, and this shows that forest areas are generally shifted to marginal areas with the lowest natural fertility and highly weathered but deep soils, which is the case with Ferralsols (Figure 2).

Figure 2 – Map and location of the TECHS sites in Brazil



Source: Authors (2018)

The sites presented a variation in mean annual temperature of about 10°C (17.1 - 27.5 °C) between the coldest and hottest sites (Table 3). The mean annual rainfall ranged from 609 to 1525 mm. Likewise, climatic types ranged from the tropical climate with dry summer and driest month with rainfall less than 60mm, to Cwb climate with subtropical climate with mild summer temperature and rainfall above 40mm in the driest month (ALVARES *et al*., 2013).

Table 3 – Climatic description for 24 of the TECHS sites for the growth period (0-48 months) presented in this article

TECHS	Lat	Long	Alt	Town	State	Tavr °C	P (mm)	ETP (mm)	ETR (mm)	DEF (mm)	Class	Köppen Climate Classification	Aridity Index
2	-24.5	-50.0	770	Arapoti	PR	18.4	1436	569	562	7	Subtropical	Cwb	Super humid
4	-19.3	-42.4	243	Belo Oriente	MG	23.0	1065	1002	828	174	Tropical	Aw	Humid
5	-18.6	-42.9	873	Guanhães	MG	21.0	1013	796	704	92	Tropical	As	Humid
6	-30.2	-51.6	150	Eldorado do Sul	RS	20.6	1446	742	734	8	Subtropical	Cfa	Humid
7	-18.0	-50.9	681	Rio Verde	GO	23.2	1319	1036	724	312	Tropical	Aw	Humid
9	-18.7	-47.9	969	Estrela do Sul	MG	23.5	1334	1067	928	139	Tropical	Aw	Humid
10	-23.0	-48.5	869	Botucatu	SP	21.4	1332	842	783	58	Tropical	Aw	Humid
11	-18.7	-52.6	783	Chapadão do Sul	MS	22.8	1154	983	780	203	Tropical	Aw	Humid
12	-19.8	-40.1	36	Aracruz	ES	24.8	830	1218	728	490	Tropical	Aw	Sub-humid
13	-20.9	-51.9	361	Três Lagoas	MS	25.3	1123	1325	1027	298	Tropical	Aw	Sub-humid
14	-20.0	-51.6	480	Inocência	MS	24.3	1026	1188	916	272	Tropical	Aw	Sub-humid
15	-11.2	-48.6	255	Brejinho do Nazaré	TO	26.2	1189	1415	849	566	Tropical	Aw	Sub-humid
17	-18.3	-45.1	806	Três Marias	MG	22.4	921	941	652	289	Tropical	As	Sub-humid
19	-12.2	-48.5	255	Peixe	TO	26.7	987	1495	820	675	Tropical	As	Sub-humid
20	-22.4	-47.0	633	Mogi Guaçu	SP	22.3	1255	942	867	75	Tropical	Aw	Humid
22	-24.2	-50.5	888	Telêmaco Borba	PR	17.8	1436	569	561	7	Subtropical	Cwb	Super humid
23	-27.5	-50.1	870	Otacílio Costa	SC	17.1	1525	481	476	5	Subtropical	Cfa	Super humid
24	-22.7	-49.0	656	Borebi	SP	22.0	1116	908	800	109	Tropical	Aw	Humid

To be continued ...

Table 3 – Conclusion

TECHS	Lat	Long	Alt	Town	State	Tavr °C	P (mm)	ETP (mm)	ETR (mm)	DEF (mm)	Class	Köppen Climate Classification	Aridity Index
26	-16.8	-44.3	926	Coração de Jesus	MG	24.4	609	1179	496	683	Tropical	As	Sub-humid
27	-26.0	-50.1	916	Antônio Olinto	PR	17.8	1506	538	537	1	Subtropical	Cfa	Super humid
28	-26.1	-50.2	812	Três Barras	SC	17.6	993	518	470	48	Subtropical	Cfa	Humid
29	-3.4	-43.1	81	Urbano Santos	MA	27.5	878	1492	656	836	Tropical	Aw	Sub-humid
30	-17.3	-43.8	848	Bocaiuva	MG	24.4	609	1179	570	609	Tropical	As	Sub-humid
33	-23.9	-48.7	695	Buri	SP	20.0	1196	662	645	17	Subtropical	Cwb	Humid

Source: Authors (2018)

In where: TECHS = number of the techs site that identifies where it was planted; Lat = site geographic latitude; Long = site geographic longitude; Alt = altitude in relation to sea level; Tavr °C = average annual temperature, P (mm) = annual average rainfall, ETP (mm) = average annual potential evapotranspiration calculated by the Penman-Monteith method using the storage capacity of soil water at the specific site, ETR (mm) = annual average real evapotranspiration, DEF (mm) = average annual water deficit using the storage capacity of water in the soil of the specific site; Class = Tropical sites (T), Subtropical sites (ST).

The altitude varied from 36 to 926 meters in relation to the sea level, presenting an average of 619 meters (e.g. TECHS 12 as a lower altitude site, near the Brazilian coast, e.g. TECHS 26 as higher altitude site).

In this way, a wide variation of climates, altitudes, temperature, and orders of soils can be perceived (Table 3 and Figure 2). This may lead to confounding between different climates and soils, for example, to compare soils and productivity in an extremely water restrictive environment (e.g. TECHS 26 in Table 3) with climates with water surpluses and consequently there is higher productivity (e.g. TECHS 22 in Table 3). Thus, the grouping of the sites according to the climatic classification proposed by Köppen (KOPPEN, 1936) and the Aridity Index was performed to avoid comparisons of soils of climatically very different sites, which would not make sense.

Soil collections occurred prior to the installation of the experiments between the years 2011 and the beginning of 2012 prior to the preparation of soil and to generate the fertilization recommendation for the experiments. Generally, Brazilian forest companies close the cover fertilization two years after planting, and thus, the collection of soils occurred generally at 4 years to 5 years after the last fertilization, which reveals that little probability of residual effect of the cover fertilizations resulting of soil analysis. TECHS considered that nutrition was not the limiting factor, so it was used as a reference, the fertilizers that the companies usually use plus a "plus" that guaranteed that there was no lack of nutrition for the plantations.

Two composite samples were collected for each site, with layers 0-20 and 20-40 cm depth. Each composite sample represented 20 simple soil samples collected systematically in a zigzag path throughout the entire experimental area. Soil pH was determined in water (pH), in a ratio of 1: 2.5 (soil: water). Organic matter (O.M.) determined by the sodium bichromate digestion method (RAIJ; QUAGGIO; CANTARELLA, 1987). Ca, Mg and Al extracted with 1 mol L^{-1} KCl and analyzed by titulometry analysis (CLAESSEN, 1997). P and K available by means of an anion exchange resin extractor and determined, respectively, by colorimetry and flame photometry. The potential acidity (H + Al) was determined indirectly through SMP solution and quantified in potentiometer (QUAGGIO; RAIJ; MALAVOLTA, 1985). The saturation by bases (V) and by aluminum (m), Cation Exchange Capacity (CEC), Base Sum (BS) were determined indirectly from the values of potential acidity, exchangeable bases and exchangeable aluminum, as described by Ribeiro, Guimarães and Venegas (1999). Soil micronutrients Cu, Zn, Mn, Fe, extracted by Mehlich-1; boron (B) by weighing 20 g of soil with 40 ml of deionized water, heated to boiling under reflux for five minutes and, after cooling the solution, three drops of 0.1 mol L^{-1} $CaCl_2$ and filtered the material for the boron determinations (SILVA; FERREIRA, 1998). In relation to the physical analysis, a granulometric analysis was performed by the densimeter method (CLAESSEN, 1997), and the samples were dispersed with sodium hexametaphosphate, and the clay, silt and sand granulometry were considered. All soil attribute results presented in this work refer to the mean of the layers 0-20 and 20-40 cm.

It is understood as opportune to publish all attributes of soils raised during the initial collection of TECHS soils, but how some chemical attributes of soils, such as, P, K, Ca, Mg, vary according to the management, and for the selection of attributes considered stable in soils (ROSSET; SCHIAVOAND; ATANÁZIO, 2014), such as O.M., CEC, Clay, Silt, and Sand (Table 4). According to the criteria established by Raij *et al*. (1996) and Ribeiro, Guimarães and Venegas (1999), the mean values of soil attributes varied from very high (CEC, Fe), high (Ca, S), medium (O.M., K, Mg, Al, Cu, Mn, H+Al), low (m, Zn, B), very low (pH, P, SB, V).

Table 4 – Chemical characterization of the soils of the evaluated TECHS sites

Attribute	**pH - $CaCl_2$**	**P (mg dm^{-3})**	**K (mmol. dm^{-3})**	**Ca ($mmol_c$ dm^{-3})**	**Mg ($mmol_c$ dm^{-3})**	**Al ($mmol_c$ dm^{-3})**	**H + Al ($mmol_c$ dm^{-3})**	**SB ($mmol_c$ dm^{-3})**	**O.M. (g dm^{-3})**	**V (%)**
Average	4.06	1.98	2.59	22.08	5.65	14.23	81.27	30.84	28.9	28.58
Attribute	**m (%)**	**S (mg dm^{-3})**	**Cu (mg dm^{-3})**	**Zn (mg dm^{-3})**	**Mn (mg dm^{-3})**	**Fe (mg dm^{-3})**	**B (mg dm^{-3})**	**Clay (%)**	**Silt (%)**	**Sand (%)**
Average	39.77	11.50	0.78	0.35	3.65	59.88	0.13	33.89	12.32	53.8

Source: Authors (2018)

In where: O.M. = organic matter, P = phosphorus in soil, K = potassium in soil, Ca = calcium in soil ($mmol_c$ dm^{-3}), Mg = magnesium in soil, Al = aluminum, H+Al = potential acidity, SB = Exchangeable base sum; CEC = cation exchange capacity; V = base saturation; m = saturation by aluminum; S = sulfur content in soil; Cu = copper in the soil; Zn = zinc in soil; Mn = manganese in soil; Fe = iron in the soil; B = boron in soil; Clay = clay texture; Silt = silt texture; Sand= sand texture.

According to the criteria established by Embrapa (2006), the texture of the soils of TECHS was classified as average texture (340 g kg^{-1} clay, 120 g kg^{-1} silt, 540 g kg^{-1} sand). However, the texture varied from sandy to very clayey, silt texture was the only texture class not observed.

Holloway and Stork (1991), suggest that ideal soil attributes to study cause-effect relationships with productivity should provide immediate and accurate responses to soil fertility, several attributes are desirable to ensure good interpretations. As well as having ecological relevance, and are sensitive to long-term variations, but on the other hand, resistant to short-term variations such as changes in the atmospheric conditions and also in the evolution of culture in question. Among all the attributes presented, it was chosen to study the relationships between soil productivity and soil variables only influenced by management and fertilization after planting: organic matter (O.M.), Cation Exchange Capacity (CEC) and granulometry (Clay, Silt and Sand), because they are important attributes for soil quality (HOLLOWAY; STORK, 1991).

2.5 Tree Measurements

The standards measures include growth in DBH and Height of 80 trees for each plot, measured every 6 months after the first year of planting. Each company was responsible for these measurements after the standardization training through of the measurement protocol. For the calculation of commercial volume with bark (CVWB), volumetric models were used based on generic and widely used volume equations in Brazil calibrated for *Eucalyptus* sp. for the same planting density in TECHS. All evaluations of this work occurred in the measurement performed on the 4th-year old birthdays of the experiments, but the ages ranged from 46 to 53 months old, with a mean of 50.3 months of age.

From the volumetric data, the Dry Response (DR) was calculated for each clone in each experiment considering the Equation (1) below:

$$DR=\frac{CVWBw.\ -CVWBw\ out.}{CVWBw.out.}*100 \quad (1)$$

In where: DR = dry response (%); CVWB w. out. = commercial volume with bark without rain exclusion; CVWB w. = commercial volume with bark excluding rain.

2.6 Statistical analysis

The statistics was carried out using SigmaPlot 6® (SYSTAT, 2000). The data were subjected to compared using analysis of variance (ANOVA) based on. Significant differences between mean values were determined using the Scott-Knott test with P < 0.05. For meeting the assumptions of residual normality and homoscedasticity.

In order to visualize the results, the values of the attributes of soil as O.M., CEC, Clay, Silt and Sand (independent variables) were plotted as a function of productivity response variable) for all TECHS sites. From these graphs, the upper and middle border lines were obtained through the selection of sites with the aid of the Boundary Fit application (WALWORTH; LETZSCH; SUMNER, 1986; SHATAR; MCBRATNEY, 2004; WADT *et al*., 2013; ALMEIDA *et al*., 2016). Then, by using the Excel 2013 ® application, the quadratic models were adjusted, relating the values of the independent variables to the productivity, considering the sites (limit) of greater efficiency / productivity and the average ones. From the equations generated for the highest productivity sites, the critical levels for each soil attribute were calculated by means of the first derivative equations for each soil attribute, where it was possible to observe the sites with the highest probability of productivity optimization (GAZZIERO *et al*., 1998).

3 RESULTS AND DISCUSSION

3.1 Consequences of climate and clones on productivity

Table 5 shows the heterogeneity of productivity among the *Eucalyptus* clones (F = 5.66; p = 0.001012; DF = 3). The average productivity of CVWB was 149.1 m^{-3} ha^{-1}, ranging from 125.5 to 178.3 m^3 ha^{-1} among the most and least productive clones, these values being close to the national average of forest productivity (INDÚSTRIA BRAILEIRA DE ÁRVORES, 2015). Sustaining or increasing the high rates of Eucalyptus growth depend on a variety of changes in the future. Annual variations in precipitation can alter gross primary production and wood production by one-third to one-half, and any regional changes in climate would likely result in regional changes in production (STAPE; BINKLEY; RYAN, 2008).

Table 5 – Descriptive statistics of plant attributes and physical-chemical attributes (depth 0-40 cm) of the soils of the sites evaluated in TECHS

Attribute	Descriptive Statistics Measures								
	Value				Coefficient			Normality test	
	Average	Median	Minimum	Maximum	Variation	Kurtosys	Asymmetry	p-valor	Class
Plant Attributes									
CVWB A1	178.3	175.0	67.5	292.9	34%	-0.60	0.05	0.07	NO
CVWB C3	145.0	118.2	41.6	301.1	51%	-0.56	0.38	0.03	TN
CVWB K2	125.5	141.7	54.5	254.2	46%	-0.34	0.58	0.00	IN
CVWB Q8	147.8	119.0	37.7	298.3	49%	-0.40	0.66	0.03	TN
DR A1	-10.9	-10.4	-27.3	0.6	75%	-0.61	-0.40	0.10	NO
DR C3	-8.2	-8.1	-14.2	0.6	55%	-0.16	0.48	0.08	NO
DR K2	-13.9	-16.6	-24.9	1.1	58%	-0.93	0.29	0.06	NO
DR Q8	-13.9	-14.1	-25.9	-1.1	64%	-1.31	0.04	0.21	NO
Sub-Humid	100.5	88.0	60.2	170.4	37%	-1.22	0.69	0.17	NO
Humid	172.8	171.8	111.3	281.4	29%	0.58	0.94	0.20	NO
Super Humid	185.4	184.8	99.0	273.1	38%	-1.34	0.04	0.96	NO

Source: Authors (2018)

In where: CVWB = Commercial Volume With Bark of Clones (A1, C3, K2, Q8) in $m^3\ ha^{-1}$; DR = Dry Response (%); NO = normal data distribution; TN = tending to the normal distribution; IN = distribution of data Undetermined.

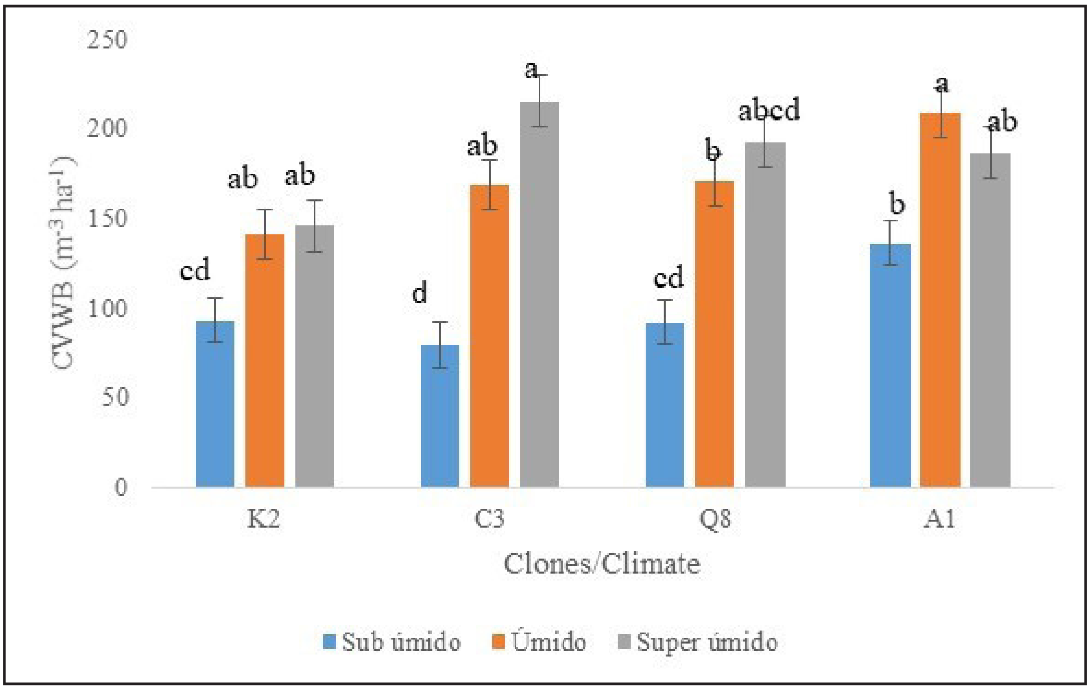
The reduction of 30% of the rainfall, reduce the CVWB or the DR between -8.2 and -13.9% of CVWB (Table 4), and is therefore not proportional to the relation between rainfall reduction and productivity of *Eucalyptus*. Stape *et al*. (2010) reports that irrigation increased *Eucalyptus* growth by about 30% and that water is a major limiting factor for productivity in Brazil (productivity from 46 $m^{-3}\ ha^{-1}\ year^{-1}$ to 62 $m^{-3}\ ha^{-1}\ year^{-1}$). Araujo (2010), reported that irrigated *Eucalyptus* in the Aquidauana region (MS state) had productivity above the rainfall conditions in 41%, and that to make irrigation an irrigation system feasible, productivity should be higher than the rainfall conditions. Obviously, the goal of TECHS was to evaluate or simulate a drought situation, and it can be observed that trees have very efficient ecophysiological mechanisms in which even water being the predominant factor for growth (STAPE *et al*., 2010), it is not the only factor, and the integration of factors of production is more important.

Still in this context, and abstracting the reasoning for physiological questions, it has been that the growth occurs basically by the interaction or the ability of the plants/trees to use the growth factor water, light and nutrients, especially for the *Eucalyptus* crop, the factor water is dominant (STAPE *et al*., 2010). Therefore, the main organs of the plant responsible for growth would be the roots of the *Eucalyptus*, responsible for water absorption; and the stomata, which are responsible for osmotic regulation and CO_2 inputs, for use in photosynthesis (RAVEN; EVERT; EICHHORN, 2001; TAIZ; ZEIGER, 2004). Many hypotheses for mechanisms causing disability mortality are currently discussed, among which cavitation and carbon formation have been the focus of several research, although additional mechanisms of carbon immobilization and transport failure may also occur (SALA *et al*., 2010; MCDOWELL, 2011). These data are in agreement with those obtained by Zeppel, Adams and Anderegg (2011) where mortality probably occurs due to reductions in precipitation and increases in temperatures and vapor pressure deficits (VPD) leading to greater soil moisture deficiencies and/or increased atmospheric water demand (MCDOWELL, 2011) in the most arid regions of forest plantations.

Table 4 also clearly shows the effect of the climatic gradient (sub-humid to super-humid), producing an effect on the productivity gradient of *Eucalyptus* wood ($F = 41.39$; $p = 0.000$; $DF = 2$). The wood productivity almost doubled along the climate gradient (sub-humid to super-humid) (1.86 times). Campoe *et al*. (2020) observed that productivity doubled between a climatic gradient (4 sites and 5 clones) throughout Brazil. The same authors report that patterns between sites are more strongly related to air temperature than to water stress.

It can be seen in Figure 3 that the effect of the climate does not have the same impact on wood productivity in the different clones, with some clones being more affected by the climate. There are clones with high adaptability to specific locations (e.g. productivity of clone C3 in the super-humid climate with high contrast of productivity in relation to the sub-humid climate), while others have good stability (e.g. clone A1 with high productivity in all climates). These results are in agreement with those found by Araujo *et al*. (2019), that results grouped the sites into three mega-environments according to a latitude gradient, over time.

Figure 3 – Volume of wood with bark (CVWB) as a function of the different climates and clones evaluated in the TECHS experiment



Source: Authors (2018)

The TECHS Project demonstrated that even with intensive forestry, wood production varies more than twice through environmental gradients, and the growth of highly selected clones differs more than twice within a location (CAMPOE *et al*., 2020). We saw this clearly for clone C3, in which the wood productivity varied 2.7 times from the sub-humid climate to the super-humid climate. The wood productivity of clone A1 varied only 1.5 times for sub-humid to humid climates. The wood production is responsible for less than half of the photosynthesis of a forest, and in this sense clones allocate carbon to other growth structures, such as roots or carbon biomass in the leaves (HAKAMADA *et al*., 2017).

3.2 Approximation of soil attributes for maximum *Eucalyptus* productivity

The "more is better" standardization curve has a positive slope (S) and is used to standardize indicators in which the highest values improve productivity, such as CEC, V (%); the "maximum value" has a positive slope up to the maximum value and is used for indicators that have a positive effect on soil quality up to a certain value, from which its influence is detrimental or negative, such as macroporosity, pH and hydraulic conductivity in saturated soil. Standardization curves of the "less is better" type have negative slope and standardize indicators such as soil density, resistance to penetration and saturation by Al^{+3} (MELO FILHO; SOUZA; SOUZA, 2007).

As the TECHS sites covered a great variability of climates and genotypes (clones), there was a great opportunity in this work to adjust which values of the attributes that maximize *Eucalyptus* productivity for the Brazilian conditions, and thus, are shown the equations obtained by means of the upper boundary lines and their respective maximum values (Table 6).

Table 6 – Equations generated by the populations with the highest productivities

Attribute	Equation	R²	Unit	Optimal value	C.V. (%)
Sand	$CVWB = -0.518x^2 + 5.6658x + 75.543$	0.22	%	54.68	61
Clay	$CVWB = -0.3407x^2 + 12.911x + 107.94$	0.45	%	18.94	56
Silt	$CVWB = -18.047x^2 + 253.46x - 595.67$	0.29	%	7.02	36
CEC	$CVWB = 0.0169x^2 - 1.0645x + 178.97$	0.64	$mmol_c\ dm^{-3}$	31.49	65
O.M.	$CVWB = -0.1651x^2 + 8.9741x + 100.74$	0.40	$g\ dm^{-3}$	27.17	52

Source: Authors (2018)

In where: Sand= sand texture (%); Clay = clay texture (%); Silt = silt texture (%); CEC = cation exchange capacity ($mmol_c\ dm^{-3}$); O.M. = organic matter ($g\ dm^{-3}$); CVWB = Commercial Volume With Bark of Clones (A1, C3, K2, Q8) in $m^3\ ha^{-1}$; R^2 = determination coefficient; Optimal value = optimal values calculated by the boundary curve; C.V. (%) = coefficient of variation.

It is observed in Table 5 that all attributes presented wide variability, shown by the high standard deviation/coefficient of variation, except for silt, which presented low coefficient of variation (PIMENTEL-GOMES; GARCIA, 2002). Soil granulometry has often been cited as one of the indicators of soil fertility, and hence its productive capacity (SPARLING; SHEPHED; KETTLES, 1992), along with other attributes such as microbial biomass, organic matter of the soil, etc. Thus, it is noted that in terms of textural class of soil, this was classified as an average according to Embrapa (2006) and are in agreement with data presented by Tu, Ristaino and Hu (2006), who reported that soils suitable for forest plantations would have a medium texture to optimize productivity (150 to 350 g kg^{-1} of clay), while for pastures they would be more sandy, and for most crops ranging from sandy to clayey (SILVA *et al*., 2020a).

In the view of the above, very sandy soils may not be ideal to maximize productivity due to their low water and nutrient retention capacity (GONÇALVES *et al*., 2012); while, on the other hand, heavier or more clayey soils with above-average texture, have problems of lower aeration, lower porosity, and indirectly of higher apparent density (CORRÊA *et al*., 2015), than for the roots of *Eucalyptus* that develops in comparison to other cultures (LACLAU *et al*., 2013). In Brazil, similarly to Australia, most *Eucalyptus* species show high growth when planted in medium fertility soils. It can be inferred that the acceptable level of fertility is lower than that required for agriculture and higher than that required for *Pinus* spp. (ORGANIZAÇÃO DAS NAÇÕES UNIDAS PARA A ALIMENTAÇÃO E A AGRICULTURA, 1981).

For O.M., the optimal contents are considered as average according to the criteria described by Raij *et al*. (1996) and Ribeiro, Guimarães and Venegas (1999), revealing that the critical levels are extremely related to different crops, that is, agricultural crops are much more demanding than *Eucalyptus* in relation to soil fertility, saved to biomass proportions. Thus, the contents of O.M. smaller than 27 g dm^{-3} are not sufficient to supply and retain water and nutrients for *Eucalyptus* and, on the other hand, contents higher than the critical level can make nutrients available to *Eucalyptus* and behave like hydrophobic agents in relation to water, and the *Eucalyptus* root system (BREEMEN; BUURMAN, 1998), and directly from the CEC, which is indirectly related to O.M.

4 CONCLUSIONS

The results allow a clear view of the dynamics of the different performance of *Eucalyptus* clones in three climates in Brazil (sub-humid, humid, super-humid). It is also possible to perceive an interaction of the clones with the climate (G X E interaction), some of which are more affected by the climate than the others.

The 30% reduction in the transformation reduces the CVWB or the DR between -8.2 and -13.9% of the average CVWB of -11.7%, not being proportional to the reduction in rainfall with productivity.

For the clones evaluated, the soil with the most favorable attributes to maximize the yield had medium texture and average fertility.

ACKNOWLEGEMENTS

The TECHS Project relied on contributions from more than 150 people from 26 companies, and we thank everyone for their contributions to the Project. The project was financed by 26 companies with a principal researcher: Anglo American (Andre Machado), Arauco (Rodrigo Coutinho), Arborgen (Gabriela Bassa), ArcelorMittal (Roosevelt Almado), Cenibra (Fernando Leite), CMPC (Elias Araujo), Comigo (Ubirajara Oliveira), Copener (Jacyr Alves), Duratex (Raul Chaves), Eldorado (Vinicius Silva), Fazenda Campo Bom (Jacqueline Pirez), Fibria (Rodolfo Loos), Florestal Itaquari (Admir Mora), Forestal Oriental (Ricardo Methol), Gerdau (Francisco Gomes), GMR (Paulo Leite), International Paper (Cristiane Lemos), Jari (Katia Silva), Klabin (James Stahl), Lwarcel (Marcela Capoani), Montes del Plata (Alejandro Gonzalez), Plantar (David Fernandes), Rigesa (Ricardo Paim), Suzano (Luiz Fabiano), Vallourec (Helder Andrade) and Veracel (Helton Lourenço). Fundamental assistance was provided to various aspects of the project by Luiz Barrichelo, Dario Grattaplagia, Mike Ryan, Eduardo Mattos, Robert Hubbard, Rodrigo Hakamada, Aurelio Aguiar, Leandro de Siqueira, Gleison dos Santos and João Flavio Silva. The project also received support from these universities and institutes: University of São Paulo - Brazil, State University of São Paulo - Brazil, Federal University of Lavras - Brazil, Federal University of Rio Grande do Norte - Brazil, Colorado State University - USA, North Carolina State University - USA, USDA Forest Service, CNPq - Brazil and Fapesp - Brazil.

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Contribution: Conceptualization, Resources, Writing – review & editing

How to quote this article

Silva, V. E.; Buzzetti, S.; Montanari, R.; Panosso, A. R.; Moreira, S. C. D.; Silva, J. F. Influence of the climate on productivity and the eucalyptus drought response and a proposal for maximizing wood productivity in function of soil attributes in Brazil. Ciência Florestal, Santa Maria, v. 32, n. 2, p. 523-547, 2022. DOI 10.5902/1980509832690. Available from: https://doi.org/10.5902/1980509832690.