UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
Campus de Botucatu

FACULDADE DE CIÊNCIAS AGRONÔMICAS
UNESP | BOTUCATU

TÚLIO BARROSO QUEIROZ

AMPLITUDE DE TEMPERATURAS ÓTIMAS PARA O CRESCIMENTO DE CLONES DE *Eucalyptus* NO BRASIL E URUGUAI

Botucatu
2020

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Tese apresentada à Faculdade de Ciências Agronômicas da Unesp Câmpus de Botucatu, para obtenção do título de Doutor em Ciência Florestal.

Orientador: Otávio Camargo Campoe

Coorientador: Iraê Amaral Guerrini

Botucatu

2020

Q3a

Queiroz, Túlio Barroso
Amplitude de temperaturas ótimas para o crescimento de clones de Eucalyptus no Brasil e Uruguai / Túlio Barroso Queiroz. -- Botucatu, 2020
83 p.

Tese (doutorado) - Universidade Estadual Paulista (Unesp), Faculdade de Ciências Agronômicas, Botucatu
Orientador: Otávio Camargo Campoe
Coorientador: Iraê Amaral Guerrini

1. Fisiologia vegetal. 2. Ecofisiologia. 3. Temperatura. 4. Eucalipto. 5. Modelo baseado em processos. I. Título.

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Botucatu

CERTIFICADO DE APROVAÇÃO

Título: Amplitude de temperaturas ótimas para o crescimento de clones de *Eucalyptus* no Brasil e Uruguai.

AUTOR: TÚLIO BARROSO QUEIROZ
ORIENTADOR: OTÁVIO CAMARGO CAMPOE
COORIENTADOR: IRAÊ AMARAL GUERRINI

Aprovado como parte das exigências para obtenção do Título de Doutor em CIÊNCIA FLORESTAL, pela Comissão Examinadora:

Prof. Dr. OTÁVIO CAMARGO CAMPOE
Ciências Florestais / Universidade Federal de Lavras

Prof. Dr. CRISTIAN RODRIGO MONTES
Warnell School of Forestry and Natural Resources / University of Georgia

Prof. Dr. FÁBIO RICARDO MARIN
Engenharia de Biossistemas / Escola Superior de Agricultura Luiz de Queiroz

Pesquisador Dr. JOANNÈS GUILLEMOT
Ciências Florestais / Escola Superior de Agricultura Luiz de Queiroz

Prof. Dr. JOSÉ LEONARDO DE MORAES GONÇALVES
Ciências Florestais / Escola Superior de Agricultura Luiz de Queiroz

Botucatu, 01 de junho de 2020.

Faculdade de Ciências Agronômicas - Câmpus de Botucatu -
Avenida Universitária, , 3780, 18610034, Botucatu - São Paulo
http://www.fca.unesp.brCNPJ: 48.031.918/0021-78.

Aos meus amados pais e irmãs,

Geraldino, Edis, Thaís,

Maira e Marina,

dedico.

AGRADECIMENTOS

A Deus.

À minha família pelo apoio incondicional.

Ao Prof. Dr. Otávio, pela oportunidade, orientação, ensinamentos, paciência e exemplo de professor.

Ao Prof. Dr. Iraê, pela co-orientação, motivação e amizade.

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), pela bolsa de estudos durante a pesquisa no Brasil (Código Financeiro 001) e pela bolsa de estudos concedida para estágio de doutoramento nos Estados Unidos (Processo nº PDSE-88881.189488/2018-01).

Ao Instituto de Pesquisa e Estudos Florestais (IPEF), que não mediu esforços para garantir a qualidade desta pesquisa.

Ao Programa Cooperativo TECHS/IPEF, em especial nas pessoas de Rafaela Lorenzato Carneiro (IPEF) e Clayton Alcarde Alvares (Suzano).

À University of Georgia (UGA), na pessoa do Prof. Dr. Cristian Montes, pela supervisão e ensinamentos durante meu estágio de doutorado no exterior.

À Plantation Management Research Cooperative (PMRC) nas pessoas de Bronson Bullock, Anil Koirala, John Young, Héctor Restrepo, Laura Quintero, Mark Porter, Maurício Zapata, Melissa Shockey, Michael Buchanon, Sameen Raut, Spencer Peay, Stephen Kinane and Thomas Harris.

Aos Profs. Dr. Dan Binkley (Northern Arizona University) e Dr. José Raimundo (UNESP), pelas considerações e sugestões.

À todas empresas associadas e pessoas colaboradoras neste estudo nas pessoas de Gabriela Moreira (International Paper), Ademir Silva (Vallourec), Marco Figura e James Stahl (Klabin), Helton Lourenço (Veracel), Claudio Silva (Montes del Plata) e Ricardo Buzzo (Forestal Oriental).

Aos meus colegas e amigos de Pós-graduação Josiana Basílio, Dany Caldeira, Rafael Lima, Gerardo Rojas e Marina Sbardella.

Aos meus colegas e amigos de Doutorado Sandwich Kércia Rocha, Letícia Oliveira e Fabrício Souza.

À todos que colaboraram para execução deste trabalho, muito obrigado!

“Provavelmente, a distinção mais importante é que uma educação de graduação ensina o que é conhecido e uma educação de pós-graduação ensina a identificar o desconhecido e torná-lo conhecido”.

RYAN, MICHAEL G. Prospecto de aconselhamento. Tradução de Túlio Queiroz, Fort Colins, Colorado, acessado 02 de Fevereiro de 2020. Disponivel em < <https://www2.nrel.colostate.edu/assets/nrel_files/labs/ryan-lab/docs/Ryan%20Advising%20Prospectus.pdf >.

RESUMO

A diversidade de climas na América do Sul, associada a grande adaptabilidade do gênero *Eucalyptus* tem estimulado a busca por materiais genéticos superiores e de alta produtividade. O melhoramento genético evoluiu no desenvolvimento de genótipos em sítios específicos, mas ainda apresenta carência de informações quanto à interação entre o comportamento dos genótipos em condições climáticas e edáficas contrastantes. O projeto TECHS (Tolerância de *Eucalyptus* Clonais aos Estresses Hídrico Térmico e Biótico) do IPEF (Instituto de Pesquisa e Estudos Florestais) conta com materiais genéticos clonais distribuídos em uma amplitude de temperatura média anual de 16 ºC a 30 ºC e disponibilidade hídrica anual de 800 mm a 1800 mm. Este trabalho objetivou avaliar o efeito da variabilidade inter e intra-anual do clima sobre a produtividade de clones comerciais de eucalipto em oito sítios localizados em: Bocaiúva (MG/Brasil), Conchillas (Uruguai), Eunápolis (BA/Brasil), Mogi Guaçu (SP/Brasil), Otacílio Costa (SC/Brasil), Paysandu (Uruguai), Telêmaco Borba (PR/Brasil) e Urbano Santos (MA/Brasil). O diâmetro na altura do peito (DAP) de genotipos de eucalipto foram monitorados em alta resolução temporal (quinzenal e/ou mensal) durante 6 anos (2012 – 2018). Além disso, estações meteorológicas coletaram informações climáticas a cada 1 h em cada sítio experimental. Nós desenvolvemos um novo método de calibração que descreve a faixa de temperatura mensal para o crescimento das árvores através da otimização dos parâmetros. Em seguida, indicamos a faixa de temperatura necessária para o crescimento dos 7 genótipos mais plantados na América do Sul. A equação polinomial de 2º grau foi recomendada para explicar os limites de temperatura para o crescimento das árvores. Por fim, os resultados deste estudo poderão ser utilizados nos programas de melhoramento genético, aprimoramento de modelos de prognose de crescimento e no zoneamento dos genótipos de eucalipto.

Palavras-chave: Crescimento de árvores. Ecofisiologia. Faixa de temperatura. Modelagem. Mudanças climáticas.

ABSTRACT

The diversity of climates in South America which is associated with the great adaptability of the genus *Eucalyptus*, has stimulated the search for superior and high productivity genetic materials. Genetic improvement has evolved in the development of genotypes at specific sites, but it still shows information insufficient the interaction between genotype behavior in contrasting climatic and edaphic conditions. The TECHS project (Cooperative Program on Clonal *Eucalyptus* Tolerance to the Hydrous and Thermal Stresses) from IPEF (Forestry Science and Research Institute) has clonal genetic materials distributed over an average annual temperature range from 16 ºC to 30 ºC and annual water availability from 800 mm to 1800 mm. This study aimed to evaluate the effect of inter and intra-annual climate variability on the productivity of *Eucalyptus* commercial clones in eight sites located in: Bocaiúva (MG / Brazil), Conchillas (Uruguay), Eunápolis (BA / Brazil), Mogi Guaçu (SP / Brazil), Otacilio Costa (SC / Brazil), Paysandu (Uruguay), Telemaco Borba (PR / Brazil) and Urbano Santos (MA / Brazil). Diameter at breast height (DBH) of *Eucalyptus* genotypes were monitored with high temporal resolution (biweekly and/or monthly) for 6 years (2012 - 2018). In addition, meteorological stations collected weather information every 1 h at each experimental site. We developed a new calibration method that describes the monthly temperature range for tree growth by parameter optimization. After that, we indicate the temperature range required for the growth of the 7 most planted genotypes in South America. The 2nd degree polynomial equation was recommended to explain temperature threshold for tree growth. Finally, the results of this study may be used in breeding programs, enhancement of growth prognosis models and zoning of *Eucalyptus* genotypes.

Keywords: Tree growth. Ecophysiology. Temperature range. Modeling. Climate changes.

SUMÁRIO

INTRODUÇÃO GERAL

Entender as interações entre a vegetação e os sistemas climáticos é indispensável para prever os impactos das mudanças climáticas em ecossistemas terrestres e avaliar a adaptação e vulnerabilidade de espécies vegetais (Hayashi et al., 2017). Neste contexto, o padrão de precipitação irá mudar (Wu et al., 2017), bem como as tendências na temperatura global (Mao et al., 2017), que são os principais limitantes em processos ecológicos fundamentais para os ecossistemas terrestres (Guo et al., 2015; Wang et al., 2017).

A radiação solar e a temperatura estão diretamente relacionadas com a evapotranspiração, que consiste em toda água perdida para a atmosfera (Sawano et al., 2015). Neste processo, devido à capacidade de absorção de água em perfis mais profundos do solo, ecossistemas florestais podem atenuar o impacto de eventos de calor extremo e/ou duradouros (Teuling et al., 2010). A análise dessas variáveis em escala temporal e espacial, além de possibilitar uma avaliação das determinantes climáticas, permite a simulação para diferentes regiões (Cristiano et al., 2015).

Alterações climáticas continuarão a afetar os diferentes biomas florestais, entretanto com padrão desigual (Ding et al., 2016). Na região do planalto da Ásia resultados baseados em projeções (2011-2040), apontam que a temperatura anual aumentará de 1,3°C para 2,3°C e a precipitação total anual 2,4% para 2,9% (Gao et al., 2016). Na África, modelos preveem aumentos de ate 5°C na região sul e leste (Christensen et al., 2007), em Sahel a média anual de precipitação tem sido estável, embora em um período de 30 anos apresentou-se mais seco cerca de 25% quando comparado as décadas anteriores ao século passado (Hulme et al., 2001). Por outro lado, modelos sugerem que em 2100, extremidades superiores da Europa passarão de 8,1 °C para 6,7°C (Christensen et al., 2007). Para a região sul da América do Sul, o aumento da temperatura depende do tempo e da região examinada, que é particularmente elevada em latitudes tropicais, além disso, observa-se um aumento da precipitação no centro da Argentina, Uruguai e sul do Brasil no verão e outono (Cabré et al., 2016).

A capacidade de adaptação a diferentes condições ecológicas (clima, solo e elevação), as altas taxas de crescimento e múltiplos usos (madeira, papel, celulose dentre outros), fizeram com que o gênero *Eucalyptus* adquirisse destaque no Brasil (Flores et al., 2016). A seleção de genótipos potenciais atuando simultaneamente com técnicas silviculturais, são fatores que contribuíram para o aumento da produtividade média, de 25 m³ $ha^{-1}ano^{-1}$ para 36 m³ $ha^{-1}ano^{-1}$ que representa a maior produtividade média do mundo (Alfenas et al., 2009; Gonçalves et al., 2013; IBÁ 2019).

A silvicultura do eucalipto era desenvolvida principalmente nas regiões Sul e Sudeste (Antonangelo and Bacha 1998), com maior concentração nos estados de Minas Gerais, São Paulo, Paraná e Santa Catarina (ABRAF, 2013). Mais recentemente, foi possível a expansão para estados como Mato Grosso do Sul, Maranhão, Pará, Piauí e Tocantins, que se diferenciam das demais regiões devido principalmente às condições de quantidade e distribuição das chuvas, e altas temperaturas (Gonçalves et al., 2013).

Além do Brasil, outros países da América latina, como o Chile e Uruguai também são casos de sucesso no desenvolvimento da silvicultura do eucalipto. De acordo com Lima-Toivanen (2013), o grau de desenvolvimento da indústria e da silvicultura pode ser classificado como baixo, médio e alto para o Uruguai, Chile e Brasil respectivamente. Esses três países, quando comparados aos demais, como a Argentina, Colômbia e Venezuela apesar de apresentar recursos naturais semelhantes foram os que se destacaram, devido principalmente as politicas governamentais de incentivo (Katz et al., 1999). De acordo com Foelkel (2008), as regiões centrais do Uruguai, ou perto da fronteira com a Argentina, demandam por clones especiais ou espécies adaptadas, tendo em vista que o clima é mais frio e as geadas são mais frequentes. Essa condição, em meio à diversidade climática da América do Sul, apresenta um grande desafio para silvicultura na identificação de clones capazes de suportar tais condições.

A produtividade primária líquida de uma floresta consiste na diferença entre a fotossíntese bruta total e a respiração, podendo ser definida como a biomassa total produzida ao longo do tempo (Clark et al., 2001). Os modelos de regressão estatística representam uma alternativa aos modelos dinâmicos baseados em processos para prever a produtividade das culturas em função das condições climáticas (Sharif et al., 2017). Entretanto, a dificuldade em identificar as variáveis de entrada mais relevantes para inclusão nos modelos de regressão, tem elevado número de variáveis candidatas e estas estão correlacionadas (Kim et al., 2015).

Fenômenos biológicos complexos que podem ser explicados por equações matemáticas simples são recomendados (Kato and Bellini 2009). A super-parametrização devido a redundância em informações e/ou cancelamento do polo/zero induz o uso de modelos inadequados para previsão da variável resposta (Poinot et al., 1997). Vale ressaltar que os diferentes números de repetições e/ou caselas vazias caracterizam um delineamento desbalanceado e portanto exige cautela no processo de verificção das hipóteses a serem testadas (Manso e Morais 2006).

O presente estudo justifica-se pela necessidade de pesquisas capazes de desenvolver modelos matemáticos que determinem o crescimento de genótipos potenciais de eucalipto em função da temperatura em regiões tropicais e subtropicais, fornecendo informações capazes de prever a redução ou incremento na produtividade. A estrutura dessa tese está organizada em dois capítulos. O capítulo 1 consiste na identificação, comparação e validação de uma função de estimação da temperatura cardinal de árvores com a utilização de recursos estátiscos de regressão através da técnica de otimização. O capítulo 2 propôs os limites de temperatura para 7 contrastantes genótipos de eucaliptos cultivados em gradiente climático com temperaturas médias mensais entre 6 ^{o}C e 29 ^{o}C e precipitação mensal entre 4.80 mm to 2010 mm.

CAPÍTULO 1

A NEW METHOD TO CALIBRATE CARDINAL TEMPERATURES FOR TREE SPECIES

Túlio Barroso Queiroz[ab]

Cristian Rodrigo Montes[b]

Otávio Camargo Campoe[ac]

[a]Universidade Estadual Paulista-UNESP, Faculdadede Ciências Agronômicas,
Botucatu, SP 18610-034, Brazil

[b]University of Georgia-UGA, Warnell School of Forestry and Natural Resources,
180E Green St., Athens, GA 30602-2152, USA

[c]Universidade Federalde Lavras-UFLA, Departamento de Ciências Florestais,
Lavras, MG 37200-000, Brazi

ABSTRACT

Developing a good understanding of the interactions between forest plantation growth and climate is essential for predicting the impact of climate change on terrestrial ecosystems and for assessing the adaptation and vulnerability of tree species. One such interaction, the response in growth rate of a forest stand to changes in temperature, may be described mathematically. Some models that run on monthly time steps assume a yearly optimum, minimum, and maximum temperature for simplicity, which may not represent well to actual forest growth. Here, we developed a finer-resolution methodology that encompasses monthly growth rates and temperature limits to calibrate the parameters for an envelope curve in *Eucalyptus* plantations in South America. Several polynomial curves were tested to determine temperature patterns, and their yearly tree growth patterns demonstrated that responses to temperature differed by as much as 10 °C among seasons. The best curve was a second-degree polynomial curve, whose extreme values indicated the optimum temperature and whose real roots limited the minimum and maximum temperatures for growth. This polynomial was fitted every month to describe yearly changes in optimum, maximum, and minimum temperatures. When fitted to annual data, it determined 7 ^{o}C, 19 ^{o}C, and 31 ^{o}C as the minimum, optimum, and maximum temperatures for tree growth, respectively. The monthly model predictions indicated that the minimum, optimum, and maximum temperatures lay between 8 ^{o}C and 16 ^{o}C, 18 ^{o}C and 22 ^{o}C, and 27 ^{o}C and 30 ^{o}C, respectively. These monthly temperature ranges can improve the estimation of productivity in process-based models. Our results contribute to the understanding of tree growth dynamics and its relationship to changes in temperature. Accurate ranges of temperature can be used to improve productivity predictions in new expanding planting regions with no previous information or to suggest a regionalization for potential species.

Keywords: Process-based modeling; Temperature range; Tree growth dynamics; Second degree polynomial curve.

1.1 INTRODUCTION

Environmental temperature is responsible for regulating the growth of trees; besides, it is a key modulator in the synthesis of proteins which are responsible for lignification (Costa et al., 2017). Ribulose 1,5-bisphosphate is a key enzyme in the Calvin–Benson–Bassham cycle in plants and plays an important role in photosynthesis (Matsumoto et al., 2019). It is, therefore, responsible for the production of all biomass and needs specific conditions for its catalytic activation (Bhat et al., 2017). Greer (2018) reported that the rates of RuBP carboxylation, oxygenation, and electron transport increase in response to environmental temperature dynamics.

Air temperature is a common variable used in physiology based models for modeling forest productivity and it has been implemented in models such as: CARBON (Bassow et al., 1990), ECOPHYS (Rauscher et al., 1990a), BIOMASS (McMurtrie et al., 1990), TREE BGC (Korol et al., 1995), 3-PG (Landsberg and Waring 1997), and CABALA (Battaglia et al., 2004a). These models predict the rate of tree growth and describe productivity on monthly, annual, and seasonal scales. Thus, the range of favorable temperatures that are used to summarize the response of the plant to air temperature can be called the cardinal temperature (Rouan et al., 2018; Baath et al., 2019).

Threshold temperature can be determined through the use of linear and nonlinear mathematical models that predict the influence of temperature on the growth of plants (Andreucci et al., 2016). In linear models, the growth rate is assumed to be proportional to the interaction with temperature (Gent and Enoch 1983; Daibes and Cardoso 2018), whereas, in nonlinear models, the response of plant growth to temperature changes is explained through a curve where in there is a peak of growth (Ryan 2010). The nonlinear models, coupled with function-derived growth rates, can show new hypotheses about plant population and community ecology (Paine et al., 2012).

Modern systems for analyzing nonparametric data stimulate to fit models with more flexibility and less assumption through the integration of stochastic processes and statistical models (Warr and Collins 2014). Some trees have unknown ecophysiologies, owing to the lack of cultivation data under different climatic conditions. Despite the availability of numerous models for estimating cardinal temperatures, it is still unclear whether a linear or a nonlinear model would be more effective for such studies (Andreucci et al., 2016).

The accurate estimation of the effects of temperature on plant development improves the ability of growth simulation models to predict the impact of weather on growth rates and to explore the adaptation abilities of plants (Luo 2011). This is challenging because different phenological stages, as well as different processes of plant growth and development, have different temperature boundaries. Mathematical models represent an alternative to process-based dynamic models for predicting crop yields as a function of climatic conditions (Sharif et al., 2017). However, it is difficult to identify the behavior of the most relevant input variables for inclusion in regression models (Kim et al., 2015). Models used to characterize real-world processes are affected by uncertainty and selecting an appropriate model is a vital aspect of the decision making process in any study (Shoaib et al., 2018).

Regression models explore the dependency between variables using the least squares method (Souza et al., 2017) or maximum-likelihood sense (González et al., 2016). However, this study provides the optimum cardinal temperatures based on the best-fit parameters for a nonlinear model using optimization capabilities. This study aims to calculate cardinal temperatures for growth of *Eucalyptus* plantations in South America, and to indicate the most appropriate model to be used for this purpose. Results can be used to establish the yearly and monthly acclimation patterns present in forest species.

1.2 MATERIAL AND METHODS

1.2.1 Experimental data and climatic classification of sites

This study is composed of data on *Eucalyptus* growth rates and air temperature measured in Brazil (six sites) and Uruguay (two sites). The study sites are part of the TECHS Project (Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses), which was started in 2011 in Brazil and northern Uruguay (Binkley et al. 2017, Fig. 1). We used eight TECHS sites covering a wide range of climates, from Cfa (humid subtropical zone with hot summer and without dry season - Site 16 and 25), Cfb (humid subtropical zone with temperate summer and without dry season - Site 23), Cwb (humid subtropical zone with temperate summer and dry winter - Site 24), Cwa (humid subtropical zone with hot summer and dry winter - Site 20), As (tropical with dry summer - Site 30), and Aw (tropical with dry winter - Site 29 and 31). This study, leaves a few months of difference of implementation date of each site. This happened because of the notorious difficulty to follow the same schedule for all partners companies. This study, leaves a few months of difference of implementation date of each site. This happened because of the notorious difficulty to follow the same schedule for all partners companies. Date of implementation of experimental plots were between April/2013 and September/2014.

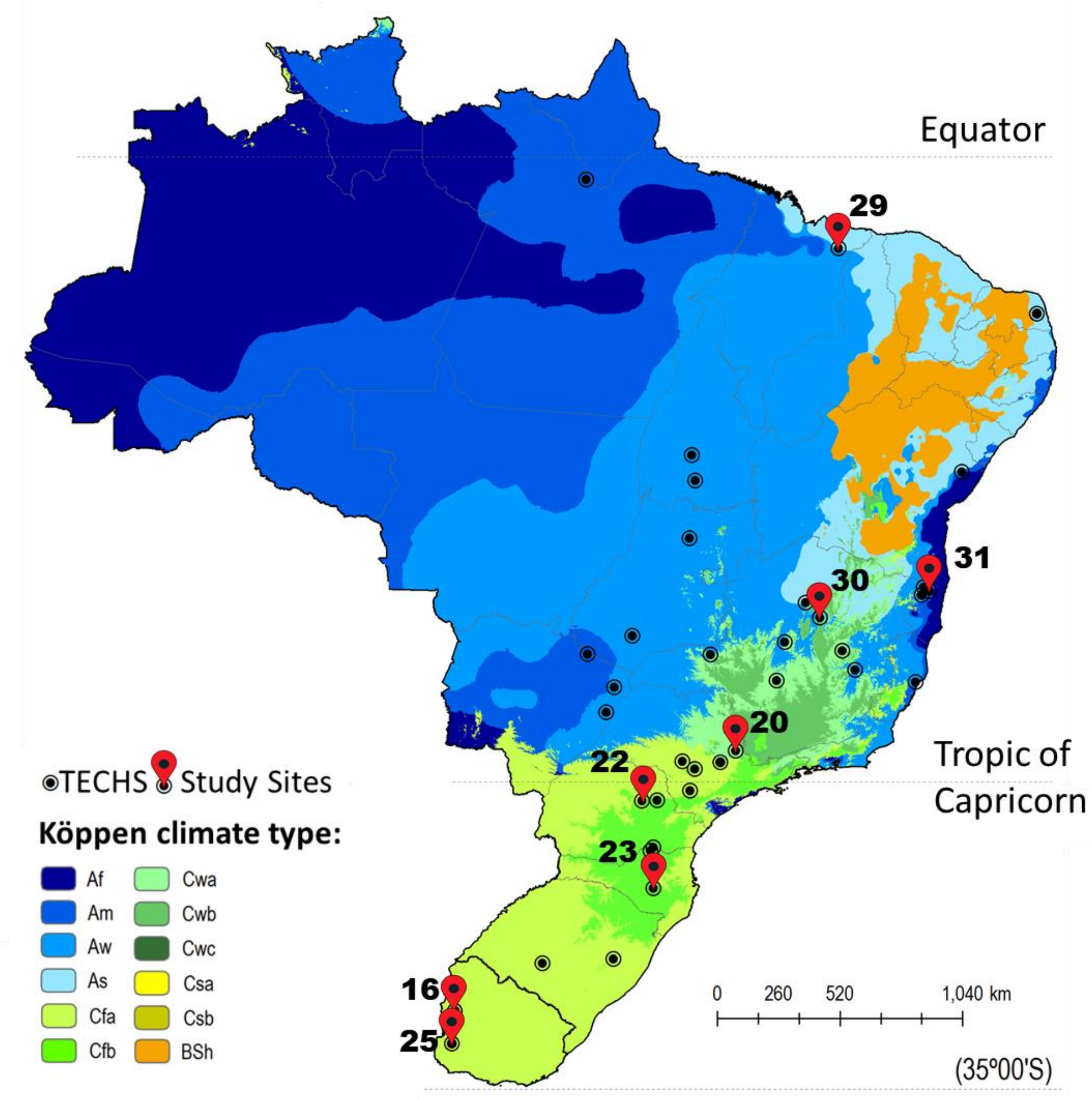


Fig. 1. Geographic distribution of TECHS sites used for establishing the threshold temperature for *Eucalyptus urophylla* in South America

The boxplot in Fig. 2 shows the mean temperature in the study sites. The gray diamond inside the box is the monthly average temperature. The sites covered a large temperature range (monthly average ranging from 12 ^{o}C to 27 ^{o}C) and were selected to represent climatic variability of tropical (between the Equator and the Tropic of Capricorn) and subtropical (below the Tropic of Capricorn) regions in a climatic gradient that encompasses a wide range of temperature in South America. The whiskers, i.e. the two lines at either end, extend from the box as far as the minimum and maximum mean temperatures. During the period from 2012 to 2018 (6 years), the variation among the minimum and maximum mean temperatures of the study sites ranged from 10 ºC to 29 ºC.

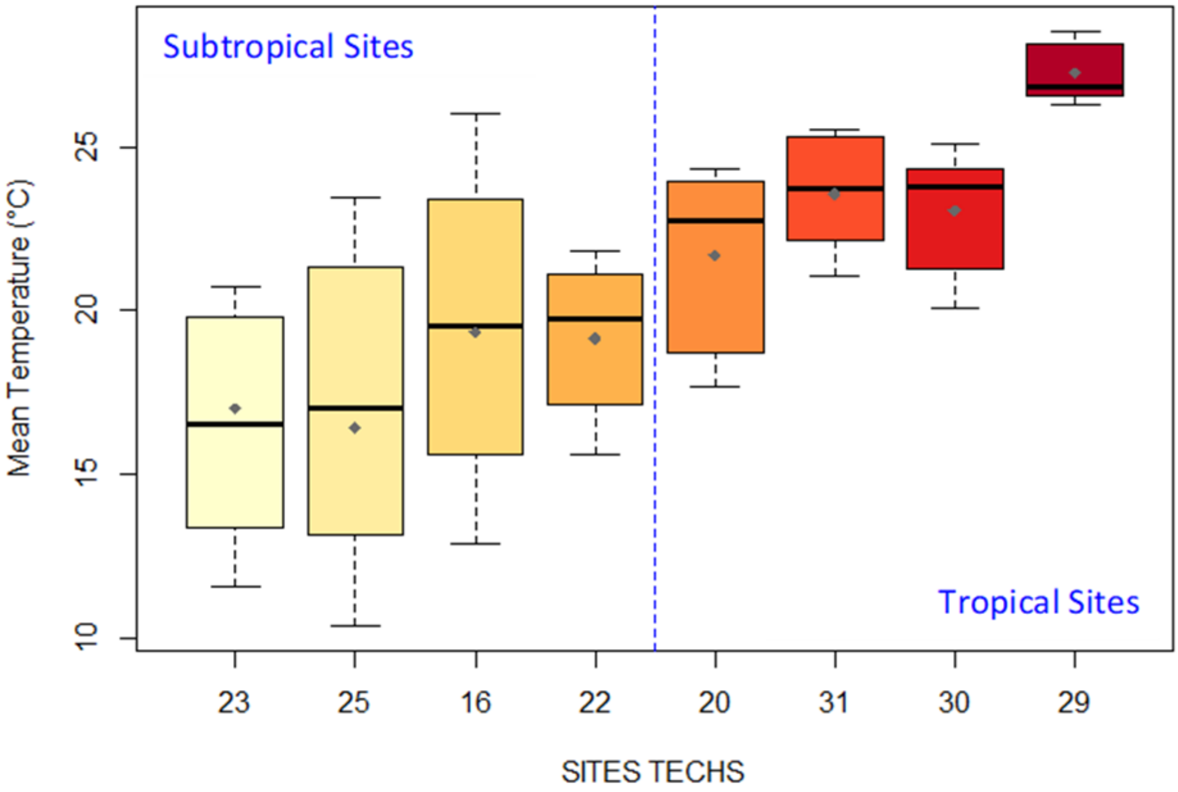


Fig. 2. Monthly climatic variability in sites located in the tropical and subtropical climates of South America

Meteorological data were recorded at the meteorological stations *in situ* (S) at each experiment site. The minimum and, maximum temperatures were recorded at 1 h intervals at all sites from 2012 to 2018. For our analysis, climatic data were aggregated on a daily basis. Days with more than four missing records (4 h in a row) were not considered when following our rigorous data processing setup (Elli et al. 2019). These data were then compensated by from the meteorological data taken from other meteorological stations (I) i.e. the National Institute of Meteorology – INMET and by the Instituto Nacional de Investigacion Agropecuaria – INIA which are managed by the Brazilian and Uruguayan governments, respectively. Information about the location (latitude, longitude, and altitude) and distance between these meteorological stations are shown in Table 1. These meteorological stations (I) were chosen due to their proximity to the sites and the similarity in altitudes.

Table 1 - Comparison of the location of the TECHS sites with the location of the meteorological stations of either the National Institute of Meteorology (INMET) or the Instituto Nacional de Investigacion Agropecuaria (INIA).

Site	**State/Country**	**Meteorological Station *in situ* (S)**			**Meteorological Station INMET or INIA* (I)**			**S ↔ I**
		Lat	Long	Alt	Lat	Long	Alt	Distance
		Graus		meters	graus		meters	kilometers
16*	Uruguay	-32.2	-57.8	50	-34.3	-57.7	72	112.9
20	Sao Paulo – Brazil	-22.4	-47.0	633	-22.0	-47.0	633	17.7
22	Parana – Brazil	-24.2	-50.5	888	-24.0	-50.0	1106	31.4
23	Santa Catarina- Brazil	-27.5	-50.1	870	-27.0	-51.0	982	53.5
25*	Uruguay	-33.3	-57.9	37	-34.3	-57.7	47	103.8
29	Maranhao - Brazil	-3.4	-43.1	81	-4.0	-43.0	91	46.7
30	Minas Gerais - Brazil	-17.3	-43.8	848	-17.0	-44.0	646	64.6
31	Bahia - Brazil	-16.3	-39.6	200	-16.0	-39.0	88	47.6

The most planted clonal eucalypts in Brazil (*Eucalyptus urophylla*) were monitored in with high temporal resolution scale. Its choice is due to the satisfactory performance in in tropical and subtropical regions (Li et al., 2015). This species occurs naturally over a wide latitudinal range from about 8 to about 10°S, especially in the islands of the West Timor, the islands of Flores and the islands of Indonesian West Timor. Aw is the most common climate classification for particular this species, but it has been found in less proportion in Af, Am, Cwa and Cwb climate classification and its annual thermal requirement is between from 16 °C to 27 °C (Flores et al. 2016).

The growth was monitored at high frequency (15 or 30 d) using the diameter at breast height (DBH) of six trees in each site from 2014 to 2018 (4 years). The height was adjusted based on the forest inventory carried out every 6 months. The destructive sampling of tree biomass was realized at the middle rotation (3 years) and end rotation (6 years) on seven trees per plot from each site. The selection of the tree was based on the central value of the seven diameter classes. To estimate total steam biomass, the Schumacher-Hall model (Schumacher and Hall 1933) was fit to DBH and total height (TH) (Eq. 1).

$$\ln(BS) = \beta_0 + \beta_1 \ln(DBH_i) + \beta_2 \ln(TH_i) + e_i \qquad \text{(Eq.1)}$$

Where the generalized logarithmic model shows dry steam biomass (BS), diameter at breast (DBH_i), total height (TH_i), residual error (e_i), and the model parameters (β0, β1, β2).

It is noteworthy that in this study we did not analyze the biomass of leaves and branches. Parameters used for this function were: $\widehat{\beta_0}$ = -5.12133, $\widehat{\beta_1}$ = 2.11419, and $\widehat{\beta_2}$= 1.19044, and the square of the adjusted R-squared (0.96), standard error (14.26), p-value (<0.0001), and minimum and maximum DBH (10.2 cm and 23.0 cm) as shown in the following.

1.2.2 The models

The growth models presented in this study were fitted for estimating the relative current increment of biomass. Here, models returned values in the growth range from 0 to 1, where 1 denotes maximum growth or potential growth. he coordinates of the peak for all functions represents the potential productivity (y) and optimum temperature for growth rate (x), thus, the Y axis received the name of Growth Rate Modifier (GRM) and was defined as the adjustment of the maximum growth via a bordering sign of the potential productivity.

Model selection is a hard task; therefore, we used the four rules or guidelines established by Ratkowsky (1990). The first rule postulates the use of fewer parameters in the model. Models that use more parameters than necessary showed poor estimation behavior and this process was called overparameterization. The second rule postulates making decisions about the goodness-of-fit of your model, i.e. checking whether the model is satisfactory for interpreting data analysis behavior. The third rule is to apply fit-most-complicated model, if the goodness-of-fit is not satisfactory. Finally, the last rule is to choose the model wherein the goodness-of-fit is improved.

The pre-selected models allow the use of inflection points, with a maximum and/or minimum value. The Beta function has been used for explaining the behavior of the growth rate of the plant as a function of temperature (Yin et al. 1995). Based on this function, the temperature modifier equation (Eq.2) was developed, which describes the response of tree growth to air temperature (Watt et al. 2014).

$$f(x) = \left[\left(\frac{x-\beta_0}{\beta_2-\beta_0}\right)\left(\frac{\beta_1-x}{\beta_1-To}\right)^{\frac{\beta_1-\beta_2}{\beta_2-\beta_0}}\right] \qquad \text{(Eq.2)}$$

This model present three parameters where $\beta_0 \leq x \leq \beta_1$, x = average monthly temperature (in ℃); β_0 = minimum or base temperature; and β_2 = optimum air temperature. We compared a nonlinear beta function with a second-grade polynomial. However, the sigmoid pattern can be represented piecewise, using a linear and a convex equation sequentially (Yu and Zhang 2018). The quadratic polynomial consists of a simple curve and it also has three parameters (β_0, β_1, and β_2). This function has a single maximum or minimum value, but without an inflection point (Eq.3), and the parameter must be greater than 0 (β_2 > 0).

$$f(x) = \beta_2 x^2 + \beta_1 x + \beta_0 \quad \text{(Eq.3)}$$

In addition to these models, the inverse second-grade polynomial is a versatile model with three parameters (Eq.4). It was used for describing the relationship between crop yield and number of plants per unit area (Holliday 1960).

$$f(x) = {}^{1}\!/_{\beta_2 x^2 + \beta_1 x + \beta_0} \quad \text{(Eq.4)}$$

A polynomial exponential is an elegant way of using a curvilinear equation and provides a gradual transition from one phase to the next (Goudriaan and Monteith 1990). In order to consider these possibilities, two functions were used (Eq.5 and Eq.6).

$$f(x) = \exp(\beta_2 x^2 + \beta_1 x + \beta_0) \quad \text{(Eq.5)}$$

$$f(x) = x^{\beta_0} * \exp(\beta_1 - \beta_2 * x) \quad \text{(Eq.6)}$$

Finally, we used a model that considered the ratio of the second-degree polynomial (Eq.5):

$$f(x) = {}^{x}\!/_{\beta_2 x^2 + \beta_1 x + \beta_0} \quad \text{(Eq.7)}$$

1.2.3 Analytical approach

For analysis of our data, we used the Data Envelopment Analysis (DEA) technique, which was initially used for describing the efficiency and productivity of economic systems through new models and interpretations (Charnes et al., 1978). In this study, we applied the same principle. The set of data for decision-making in the time (t) in high frequency, (t = 15 or 30, …, n), has non-negative inputs xt= (x1t, …, xmt) and non-negative outputs yj= (y1t, …, yst) i.e. mean temperature and growth rate, respectively.

The optimizer algorithm used for maximization of the regression models was inserted in the ‘optimx’ package (Nash et al., 2018) available for R statistical language and environment (R Core Team 2014). The fitting parameters were simulated for each model through real numbers which keep the regression curve upper in the same time closer of the observed data.

1.3 RESULTS AND DISCUSSION

1.3.1 Tree growth and air temperature

The stem biomass of the *Eucalyptus urophylla* showed synchronization with the mean air temperature. The dynamics of the agreement of biomass accumulated in the stem is reduced when the temperature is higher than 22 ^{o}C. In South America, this occurrence increases with increasing latitudes (-32.2^{o}S to -3.4^{o}S) where in the trees were able to synthesize up to 2 kg of dry biomass for stem, whereas, under limited resource conditions, the trees had stopped growth and development. Sites located in the subtropical region (Sites 16, 22, 23, and 25) presented monthly temperatures with peaks that reached temperatures around 25 ^{o}C, whereas sites located in tropical (Sites 20, 29, 30, and 31) presents longer periods with a range of among 21 ^{o}C and 26 ^{o}C. The biomass accumulated by trees is influenced by the maximum and minimum monthly average temperatures, therefore, it controls the onset or stoppage of tree growth. The following figure shows an appropriate visualization of this pattern (Fig. 3).

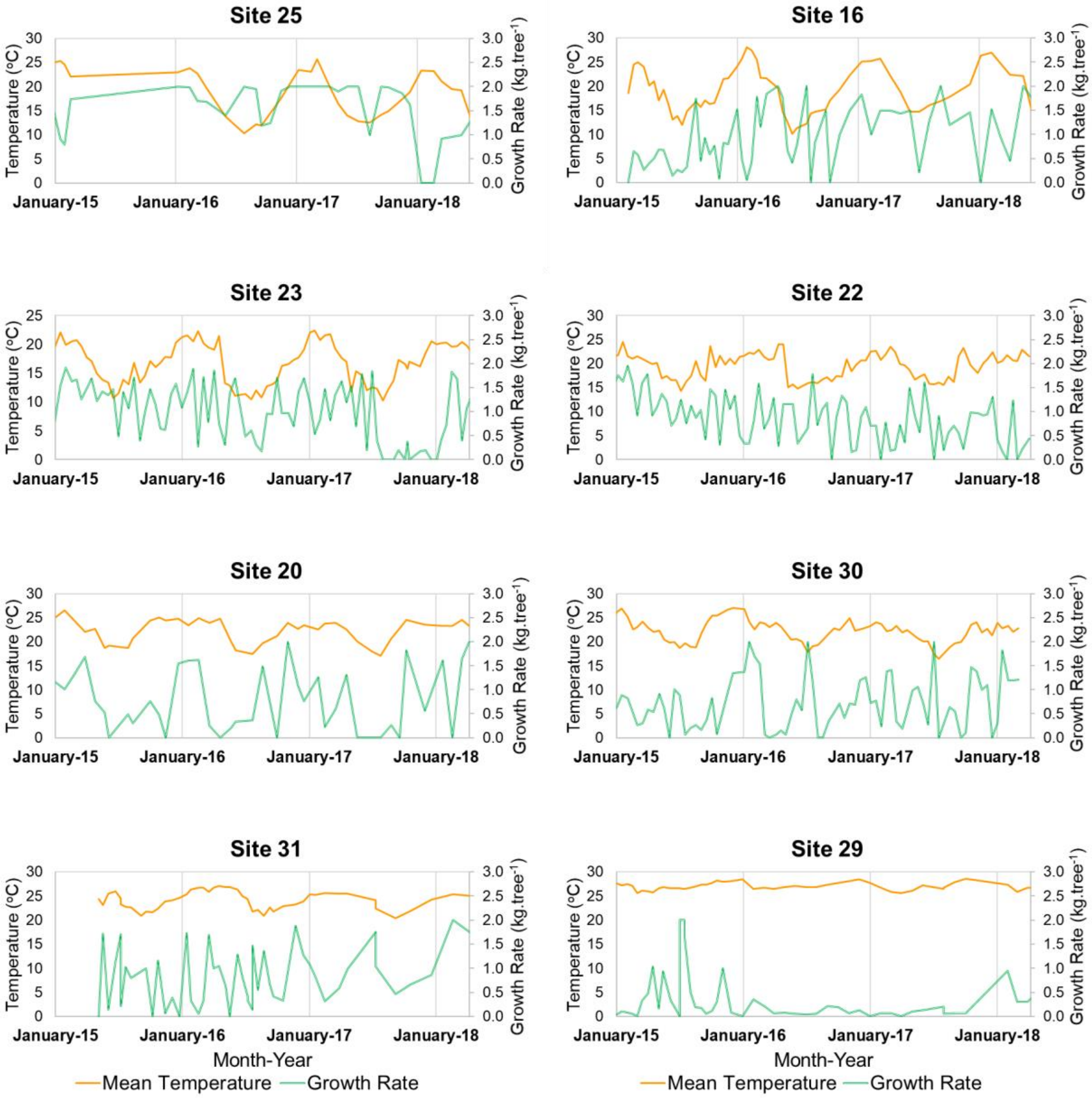


Fig. 3. Growth rate behavior of the *Eucalyptus urophylla* and mean air temperature in the Tropical and Subtropical climate in South America

The difference between the growth synchrony or growth rate for contrasting locations, in terms of dry stem biomass, depends on the inter- and intra-seasonal effects of temperature. Biomass accumulates breakpoints that depend on the species and the species adaptation to environmental conditions; therefore, the genetic variation in photosynthetic response can stimulate adaption. In this case, the stomatal responses to temperature affect the rate of carbon dioxide (CO_2) diffusion into the leaf which controls the internal CO_2 concentration and is responsible for the efficiency of carbon fixation (Ocheltree et al., 2014).

The annual temperature range needed for plant growth provides us an idea of the thermal requirements of plants. However, the temperature response occurs within a short time period so the seasonality between the months of the year cannot always be considered adequate indicators of annual mean temperature. Phenological events are regulated by temperature, therefore it can stimulate the emission of new shoots and the flowering of plants (Hänninen et al. 2019). The flowering and growth of *Eucalyptus* depends on specific ranges of temperature and the trees may be taller or shorter depending on the species and site characteristics (King et al. 2013; Rawal et al. 2015). Moreover, the effect of different temperatures on the metabolism of trees is responsible for either stimulating or causing the cessation of growth between phenological stages (Svystun et al., 2019).

1.3.2 The growth rate modifier and the models simulated

Although the nonparametric functions do not assume a particular form/shape for the experiment, it does provide a general overview of the relationship between output (growth rate) and input (temperature) For the context of this study, the limit of the vertex simulation was established based on the premise that real tree productivity corresponds to only half of its potential productivity. According to Bartels and Sunkar 2005, the loss is greater than 50% of the final yield when there are drought periods. Potential yield of plants depends on the amount of solar radiation received, efficient use of light, translocation of photosynthates in plants, and efficient synthesis of organic carbon from inorganic carbon (Ranalli 2007; Long et al. 2006). Therefore, our simulations considered the limit for reaching the potential productivity which denotes the maximum growth rate (Eq.2).

We carefully analyzed all the reasons that led to the rejection of some functions. In the first case, a curve was generated using the Beta Function (Eq.2). This function establishes the limits of the range at which the data were observed. The same curve can be described for the polynomial function (Eq.3), however its limits are greater than those in the previous curve. For other models, the minimum and maximum temperature ranges are further than the real points at which tree growth starts and ends (Eq.4, Eq.5, Eq.6, and Eq.7). Another noteworthy feature is the vertex of the Exponential Model (Eq. 6) that moves beyond potential productivity limits. Finally, the criteria to select the best model consisted of adding up the values of the integrand for each fitted function and then selecting the function with the lowest area per unit (Fig. 4).

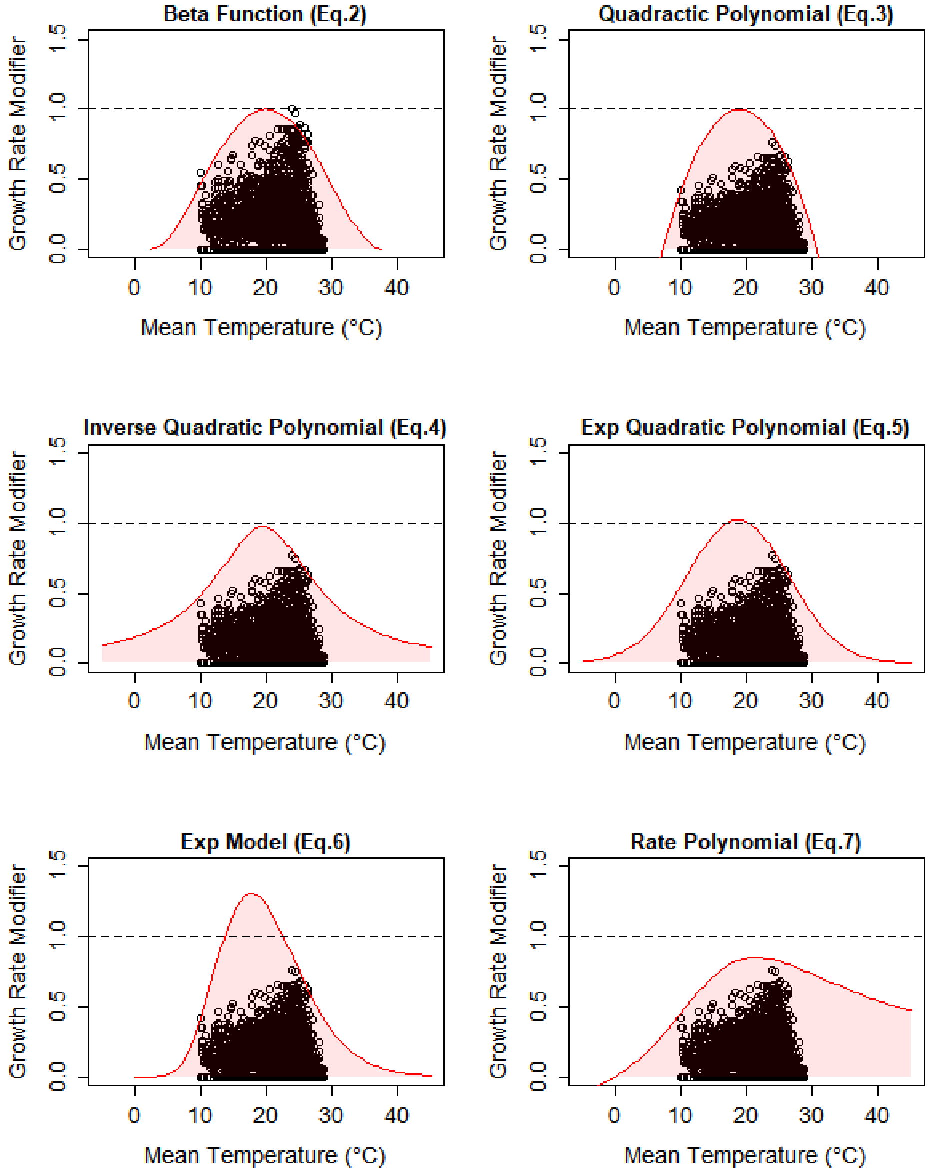


Fig. 4. Models with optimized support regression curve with maxima and minima

The function areas that were analyzed followed the order of the Quadratic Polynomial (Eq.3) < Beta Function (Eq.2) < Exp Quadratic Polynomial (Eq.5) < Rate Polynomial (Eq.7) < Inverse Quadratic Polynomial (Eq.4) < Exp Model (Eq.6). In this study, our results suggest that the Quadratic Polynomial was more adequate for fitting rate growth to air mean temperature because it can be defined as the lowest area per unit. Table 3 provides the parameters, area, and absolute error for each model that was studied.

Table 3 – Model parameters with optimized support regression curve with maxima and minima for *Eucalyptus urophylla*

Model	Name	f(x)	$\widehat{\beta_0}$	$\widehat{\beta_1}$	$\widehat{\beta_2}$	Area	Absolute Error
Eq. 2	Beta Function	$f(x) = \left[\left(\frac{x-\beta_0}{\beta_2-\beta_0}\right)\left(\frac{\beta_1-x}{\beta_1-To}\right)^{\frac{\beta_1-\beta_2}{\beta_2-\beta_0}}\right]$	2.2744	37.6508	19.9640	18.86794	< 6.5e-09
Eq. 3	Quadratic Polynomial	$f(x) = \beta_2 x^2 + \beta_1 x + \beta_0$	-1.5923	0.2732	-0.0072	15.69885	< 1.7e-13
Eq. 4	Inverse Quadratic Polynomial	$f(x) = {}^{1}/_{\beta_2 x^2} + \beta_1 x + \beta_0$	5.3897	-0.4481	0.0115	22.20823	< 2.9e-07
Eq. 5	Exp Quadratic Polynomial	$f(x) = \exp\,(\beta_2 x^2 + \beta_1 x + \beta_0)$	-2.8590	0.3094	-0.0083	19.92385	< 5.9e-05
Eq. 6	Exp Model	$f(x) = x^{\beta_0} * \exp(\beta_1 - \beta_2 * x)$	8.2905	-15.2678	0.4681	26.00404	< 0.00017
Eq. 7	Rate Polynomial	$f(x) = {}^{x}/_{\beta_2 x^2} + \beta_1 x + \beta_0$	35.5476	-2.1410	0.0773	20.36569	< 2.1e-07

The second-degree polynomial equation can be easily implemented to describe the yearly acclimation patterns present in forest species, as well as to improve process-based models. Nonmonotonic functions have the upside that each fort of a polynomial of degree ≥1 is a peak. In addition, forts of this function include peaks and points at the base of a platform, i.e. the range aton which all values are at the same constant (Yu and Zhang 2018). In this case, the discriminant can be used for finding out the ideal temperature for maximum growth (Eq.8). In addition, the minimum and maximum temperature will be determined by two real roots (Eq. 9 and Eq. 10) that should have a discriminant greater than zero.

$$Optimum\ Temperature\ (optT) = \Delta = {\beta_1}^2 - 4 * \beta_2 * \beta_0 \qquad \text{(Eq. 8)}$$

$$Minimum\ Temperature\ (minT) = x_1 = \frac{(-\beta_1 + \sqrt{optT}\,)}{2 * \beta_2} \qquad \text{(Eq. 9)}$$

$$Maximum\ Temperature\ (maxT) = x_2 = \frac{(-\beta_1 - \sqrt{optT}\,)}{2 * \beta_2} \qquad \text{(Eq. 10)}$$

Fitting the quadratic function to the data allowed the extraction of cardinal values in degree Celsius (℃) for *Eucalyptus urophylla* in tropical and subtropical climatic conditions (Fig. 5). The annual optimal air temperature for tree growth was 19 ºC, whereas the annual minimum and annual maximum temperatures needed to start and stop tree growth were 7 ºC and 31 ºC, respectively. The observations by Watt et al. 2014 strengthen the idea that the climatic requirements of different Eucalyptus species range between temperatures of 15 ºC to 27 ºC for optimum temperature, between 3 ºC to 6 ºC for minimum temperature, and 22 ºC to 30 ºC for maximum temperature. However, these authors used fitted Beta Function in their models which resulted in the underperformance of the former in the determination of threshold temperature for growing *Eucalyptus urophylla*.

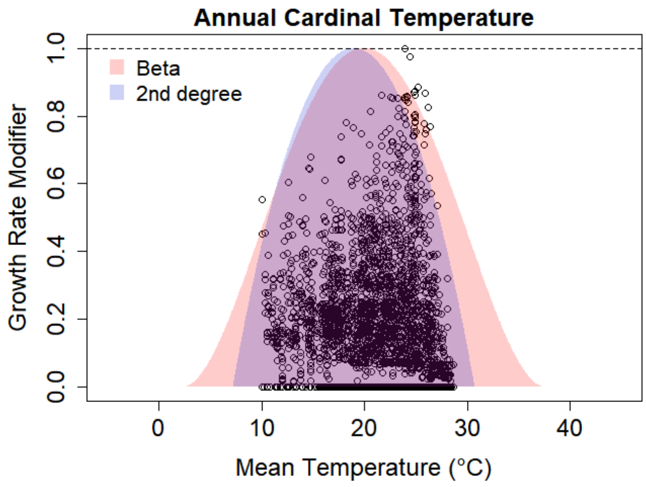


Fig. 5. Beta function and quadratic models with optimized support regression curve for *Eucalyptus urophylla* in annual scale

1.3.3 Cardinal temperature and process-based models

The Beta Function was used (Yin et al. 1995) for describing the effect of temperature on the rate of crop rice growth. Later, process-based models, such as the 3-PG (Physiological Principles Predicting Growth) developed by Landsberg and Waring 1997, incorporated the same function to improve the models for studying forest growth (Sands and Landsberg 2002). Recently, annual thermal requirement of *Eucalyptus urophylla* found out trough of this study showed high performed in the 3-PG model (Caldeira et al. 2020) so, the optimized support regression curve is a way to determine the acclimation patterns of trees suggest improvement in process-based models.

We compared the beta distribution reported in literature with a second-degree polynomial equation. This was the first step for understanding the dynamics of Eucalyptus growth, after that, we analyze the beta function with functions second degree polynomial equation on a monthly scale. This relationship between tree growth and second-degree polynomial equation became stronger and more evident when we analyzed high resolution time scales (Fig. 6).

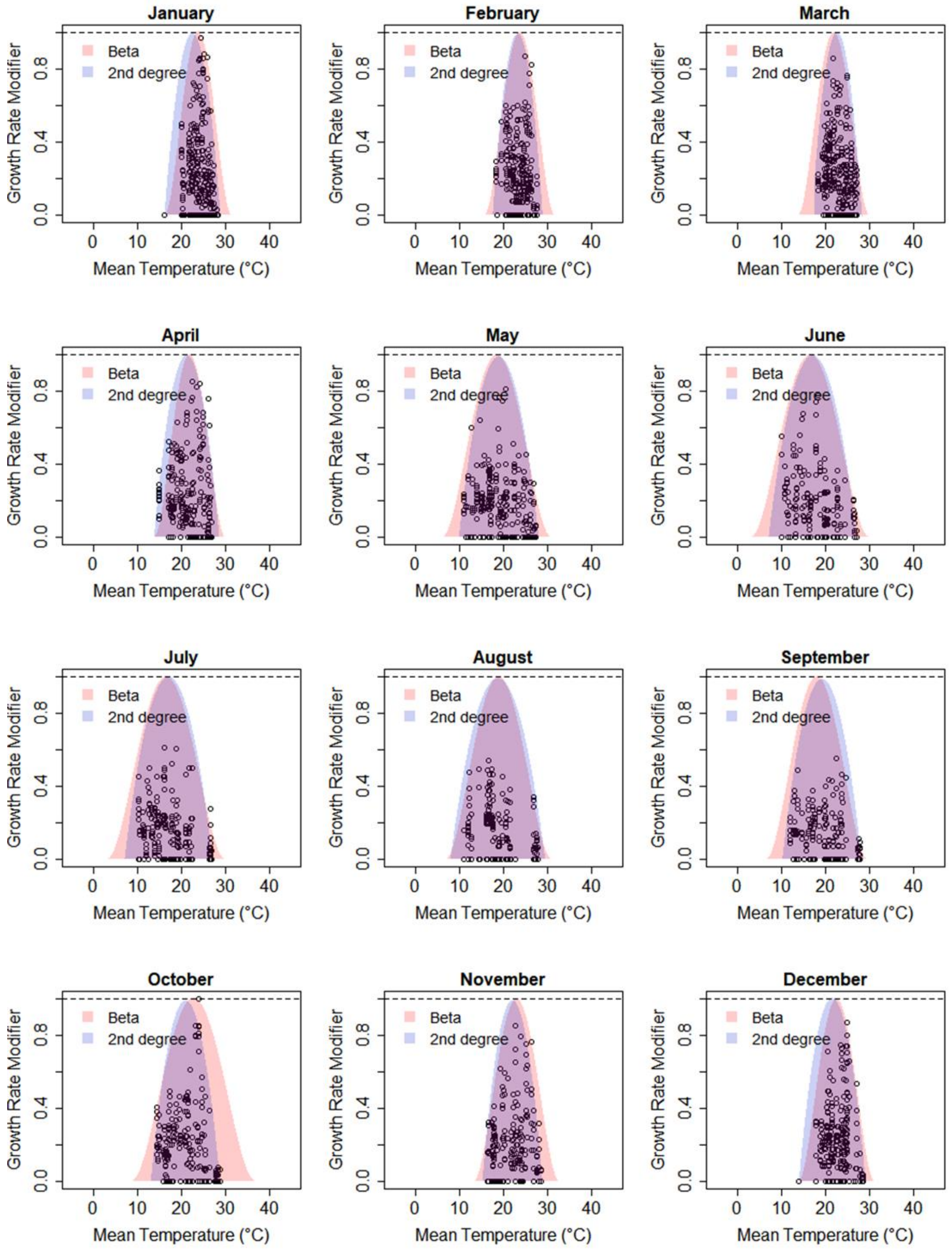


Fig. 6. Beta function and quadratic models with optimized support regression curve for *Eucalyptus urophylla* in montlhy scale

The second-degree function was also able to describe the temperature range required for tree growth on the monthly scale. The fitted function followed the same process from simulation for identifying model parameters, area, and absolute error for each model studied (Table. 4). We believe that this determination can drive management decisions based on expected scenarios of climate change and the thermal requirements for *Eucalyptus urophylla.* The majority of the months fitted the growth rate to air mean temperature with the lowest area per unit, therefore our results also recommend that the quadratic polynomial is more adequate for explaining variations throughout the year.

Table 4 – Quadratic model and Beta function parameters with optimized support regression curve and cardinal temperature for *Eucalyptus urophylla*

Month	**2nd degree polynomial**					**Beta function**				
	$\widehat{\beta_0}$	$\widehat{\beta_1}$	$\widehat{\beta_2}$	Area	Absolute error	$\widehat{\beta_0}$	$\widehat{\beta_1}$	$\widehat{\beta_2}$	Area	Absolute error
January	-11.5092	1.1100	-0.0246	8.4520	< 9.4e-14	16.1375	23.3863	31.4918	8.0729	< 4.9e-05
February	-15.7086	1.4359	-0.0309	7.5211	< 8.4e-14	15.6712	23.4399	31.7432	8.4867	< 2.8e-05
March	-14.8584	1.4004	-0.0309	7.5279	< 8.4e-14	13.7724	21.6694	30.0155	8.5889	< 2.2e-05
April	-7.1868	0.7713	-0.0182	9.8281	< 1.1e-13	13.7724	21.6694	30.0155	8.5889	< 2.2e-05
May	-3.3387	0.4562	-0.0120	11.9704	< 1.3e-13	6.0409	18.2299	30.9412	13.1905	< 2.4e-05
June	-1.9104	0.3395	-0.0099	13.3144	< 1.5e-13	3.0467	16.2665	30.0540	14.3065	< 2.6e-05
July	-1.9210	0.3409	-0.0100	13.3400	< 1.5e-13	3.0467	16.2665	30.0540	14.3065	< 2.6e-05
August	-2.0265	0.3219	-0.0086	14.2415	< 1.6e-13	6.8377	18.8862	31.0061	12.8763	< 1.4e-06
September	-3.5280	0.4690	-0.0122	11.8531	< 1.3e-13	6.5255	17.8706	29.5968	12.2376	< 1.6e-05
October	-6.0212	0.6695	-0.0160	10.4198	< 1.2e-13	8.5334	22.1008	36.9952	14.9869	< 7.4e-05
November	-9.3220	0.9343	-0.0212	9.0602	< 1e-13	13.2544	22.8786	32.7458	10.3517	< 9e-06
December	-7.1279	0.7536	-0.0175	10.1607	< 1.1e-13	13.8997	22.4568	31.1807	9.1860	< 5.5e-06

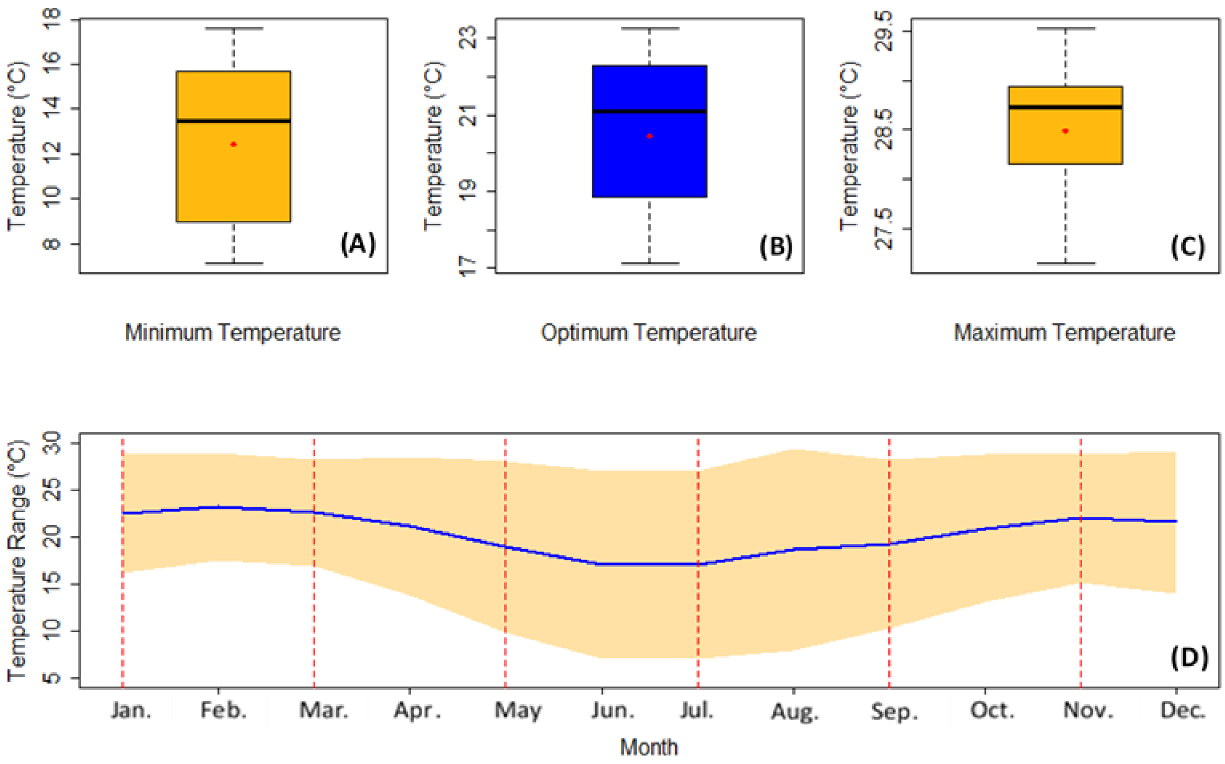
Based on monthly average temperatures and the high frequency monitoring of tree growth, monthly temperature ranges were identified for each month. The monthly acclimation patterns of *Eucalyptus urophylla* in the contrasting weather of South America are indicated in Table 5.

Table 5 – Quadratic model parameters with optimized support regression curve and cardinal temperatures for *Eucalyptus urophylla*

	Minimum Temperature (*minT* - °C)	**Optimum Temperature (*optT* - °C)**	**Maximum Temperature (*maxT* - °C)**
Month	$minT = \frac{(+\beta_1 + \sqrt{optT})}{2*\beta_2}$	$\text{optT}= {\beta_1}^2 - 4 * \beta_2 * \beta_0$	$\text{maxT} = \frac{(+\beta_1 - \sqrt{optT})}{2*\beta_2}$
January	16.17	22.53	28.89
February	17.59	23.26	28.94
March	16.96	22.65	28.34
April	13.82	21.22	28.62
May	9.90	18.97	28.05
June	7.10	17.12	27.15
July	7.11	17.13	27.15
August	8.00	18.76	29.52
September	10.25	19.26	28.26
October	13.07	20.95	28.83
November	15.23	22.08	28.93
December	14.00	21.58	29.17

To make it easier to understand, we classified the temperature range that we found out for growing *Eucalyptus urophylla* in tropical and subtropical climatic conditions (Fig.7). The following boxplot shows each mean temperature range (minimum, optimum, and maximum). The red diamond inside the box is the monthly average temperature. The whiskers, the two lines at either end, extend from the box as far as the minimum and maximum mean temperature for each temperature range. The lowest seasonal average minimum temperature for starting the growth of the trees was observed in May, June, July, and August. The minimum temperatures in this period reached values ranging from 7 °C to 10 °C. In the same period, the average monthly optimum temperature for maximum growth was 18 °C (±0.87 °C). However, the minimum temperatures in the months of January, February, March, and April had values that ranged from 14 °C to 18 °C, whereas in the months of September, October, November, and December the average monthly temperature for starting Eucalyptus growth lay between 10 °C and 15 °C. The optimum temperature for the four initial and the four final months of the year was around to 22 °C. Overall, the average maximum temperature for stopping growth is 29 °C and it had lower standard deviation (±0.71 °C).

Fig.7. Mean temperature range minimum (A), optimum (B), maximum(C) and cardinal temperature for growing *Eucalyptus urophylla* in tropical and subtropical climatic conditions (D)



Finally, we are faced with the question - if we use monthly temperature range, can we improve process-based models? The deductive manner developed here shows that our research paper is logically developed and used monthly mean temperatures in association with growth rates. Therefore, this scale becomes more appropriate for studying the phenological behavior of plants. The variation in temperature determines the biological activities of the cells and therefore it regulates the growth of the trees through temperature synchronization with carbon assimilation, as can be seen in Fig.3. Furthermore, it is not possible to assess proper physiological information at a yearly or rotational time scale. Presumably, the most frequent mistake of a process-based model is to assume that seasonal variability does not exist. In most cases, insufficiently sampled data are processed at an inappropriate scale, which then shows a reduced accuracy of results.

The reduction of the enzymatic activity and reduction of the membrane flexibility are two main direct effects of low temperature (Zoldan et al. 2012). When plants are incapacitated due to this effect, it causes cellular damage or death, and the widespread variation in biochemical responses depends on the genetic and physiological differences between different species (Raju et al. 2018). High temperature conditions, that exceed the threshold level, are responsible for causing irreversible injury/harm to overall plant growth, metabolism, and productivity (Wahid et al. 2007). Very high temperatures (above 40 ^{o}C) weaken root growth and can kill them (Celestian and Martin 2004). Our studies determine that tree growth in South America happens an average temperature of up to 29 °C; however, it is worth remembering that during the hottest periods of the year, monthly temperature is able to reduce until 10 °C so, the stress time was directly related to the proportion of the damage and monthly average temperature. Temperatures above 40 °C caused serious damage to the photosystem II, which did not recover when heat stress happens of more than 15 min (Zhang et al. 2018). Finally, appropriate genotypes should be recommended for an area according to their thermal requirements. Thus, the evidence of our findings shows us why we must care about monthly temperatures, and why it is important to study the annual trend to make an estimate of biological processes.

1.4 CONCLUSION

A second-degree model has been fitted to describe tree cardinal temperatures. The main features of this model can be summarized as the detection of minimum, optimum and maximum temperatures required for tree growth at the annual and monthly scale.

The knowledge of temperature range required for tree growth is important to optimize process-based prognosis models, in addition to selecting suitable species depending on the climatic conditions of the region and consequently to improve the yield and support genetic breeding programs.

The temperature ranges needed to maintain tree growth show variations throughout the year. Mean annual values undoubtedly improve the quality of the model, however the variability between the months should be considered for accurate estimates. As a result of this study, growth modelers will be able to use adequate temperature data to predict the productivity in Eucalyptus plantations.

Finally, in times of climate change, forest species with good adaptation potential can be more often recommended based on thermal requirements. The thermal amplitude studied in tropical and subtropical regions of South America can be a reference for decision making in other regions of the world with potential for the development of the forest sector.

ACKNOWLEDGMENTS

The authors thank the Forest Science and Research Institute (IPEF - Brazil), the TECHS project, and the Plantation Management Research Cooperative at The University of Georgia (PMCR – United States). We also thank all the companies, universities, and research institutions involved in the TECHS Project.

REFERENCES

Andreucci, M.P., Moot, D.J., Black, A.D., Sedcole, R., 2016. A Comparison of Cardinal Temperatures Estimated by Linear and Nonlinear Models for Germination and Bulb Growth of Forage Brassicas. **European Journal of Agronomy**, 81 (November): 52–63. DOI: https://doi.org/10.1016/j.eja.2016.08.010.

Baath, G.S., Kakani, V.G., Gowda, P.H., Rocateli, A.C., Northup, B.K., Singh, H. and Katta, J.R., 2019. Guar Responses to Temperature: Estimation of Cardinal Temperatures and Photosynthetic Parameters. **Industrial Crops and Products**, November, 111940. DOI: https://doi.org/10.1016/j.indcrop.2019.111940.

Bartels, D., Sunkar. R., 2005. Drought and Salt Tolerance in Plants. *Critical Reviews in Plant* ***Sciences****,* 24 (1): 23–58. DOI: https://doi.org/10.1080/07352680590910410.

Bassow, S.L., Ford, E.D., Kiester, A.R. 1990. A Critique of Carbon-Based Tree Growth Models. In *Process Modeling of Forest Growth Responses to Environmental Stress, Timber Press,* 50–57.

Battaglia, M., Sands, P., White, D., Mummery, D. 2004. CABALA: A Linked Carbon, Water and Nitrogen Model of Forest Growth for Silvicultural Decision Support. **Forest Ecology and Management,** 193 (1–2): 251–82. DOI: https://doi.org/10.1016/j.foreco.2004.01.033.

Bhat, J.Y., Miličić, G., Thieulin-Pardo, G., Bracher, A., Maxwell, A., Ciniawsky, S., Mueller-Cajar, S., Engen, J.R., Hartl, F.U., Wendler, P., Hayer-Hartl, M., 2017. Mechanism of Enzyme Repair by the AAA+ Chaperone Rubisco Activase. **Molecular Cell**, 67 (5): 744-756.e6. DOI: https://doi.org/10.1016/j.molcel.2017.07.004.

Binkley, D., Campor, O.C., Alvares, C.; Carneiro, R. L.; Cegatta, I., Stape, J.L. 2017. The Interactions of Climate, Spacing and Genetics on Clonal Eucalyptus Plantations across Brazil and Uruguay. **Forest Ecology and Management***,* 405 (December): 271–83. DOI: https://doi.org/10.1016/j.foreco.2017.09.050.

Caldeira, D.R.M., Alvares, C.A., Campoe, O.C., Hakamada, R.E., Guerrini, I.A., Cegatta, I.R., Stape, J.L. 2020. Multisite Evaluation of the 3-PG Model for the Highest Phenotypic Plasticity Eucalyptus Clone in Brazil. **Forest Ecology and Management***,* 462 (April): 117989. DOI: https://doi.org/10.1016/j.foreco.2020.117989.

Celestian, S.B., Martin, C.A., 2004. Rhizosphere Surface, and Air Temperature Patterns at Parking Lots in Phoenix, Arizona, U.S**. Journal of Arboriculture***,* 30 (4): 245–52.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the Efficiency of Decision Making Units. **European Journal of Operational Research***,* 2 (6): 429–44. DOI: https://doi.org/10.1016/0377-2217(78)90138-8.

Costa, M.G.S., Mazzafera, P., Balbuena, T.S. 2017. Insights into Temperature Modulation of the Eucalyptus Globulus and Eucalyptus Grandis Antioxidant and Lignification Subproteomes. **Phytochemistry***,* 137 (May): 15–23. DOI: https://doi.org/10.1016/j.phytochem.2017.01.017.

Daibes, L. F., Cardoso, V.J.M. 2018. Seed Germination of a South American Forest Tree Described by Linear Thermal Time Models. **Journal of Thermal Biology***,* 76 (August): 156–64. DOI: https://doi.org/10.1016/j.jtherbio.2018.07.019.

Daniel, R.M., Danson, M.J. 2013. Temperature and the Catalytic Activity of Enzymes: A Fresh Understanding. **FEBS Letters**, 587 (17): 2738–43. DOI: https://doi.org/10.1016/j.febslet.2013.06.027.

Elli, E.F., Sentelhas, P.C., Freitas, C.H., Carneiro, R.L., Alvares, C.A. 2019. Intercomparison of Structural Features and Performance of Eucalyptus Simulation Models and Their Ensemble for Yield Estimations. **Forest Ecology and Management**, 450 (October): 117493. DOI: https://doi.org/10.1016/j.foreco.2019.117493.

Flores, T.B, Alvares, C.A., Souza, V.C., Stape, J.L., 2016. *Eucalyptus No Brasil: Zonemaneto Climático e Guia Para Identificação*. Piracicaba: IPEF.

Martin P.N.G., Enoch, H.Z. 1983. Temperature Dependence of Vegetative Growth and Dark Respiration: A Mathematical Model. **Plant Physiology***,* 71 (3): 562–67. DOI: https://doi.org/10.1104/pp.71.3.562.

González, M., Minuesa, C. del Puerto, I., 2016. Maximum Likelihood Estimation and Expectation–Maximization Algorithm for Controlled Branching Processes. **Computational Statistics & Data Analysis**, 93 (January): 209–27. DOI: https://doi.org/10.1016/j.csda.2015.01.015.

Goudriaan, J., Monteith. J.L., 1990. A Mathematical Function for Crop Growth Based on Light Interception and Leaf Area Expansion. **Annals of Botany***,* 66 (6): 695–701. DOI: https://doi.org/10.1093/oxfordjournals.aob.a088084.

Hänninen, H., Kramer, K., Tanino, K., Zhang, R., Wu, J., Yongshuo H. Fu, 2019. Experiments Are Necessary in Process-Based Tree Phenology Modelling. **Trends in Plant Science***,* 24 (3): 199–209. DOI: https://doi.org/10.1016/j.tplants.2018.11.006.

Holliday, R. 1960. “Plant Population and Crop Yield. **Nature**, 186 (4718): 22–24. DOI: https://doi.org/10.1038/186022b0.

Kim, S., Kano, M., Nakagawa, H., Hasebe, S., 2015. Input Variable Scaling for Statistical Modeling. **Computers & Chemical Engineering**, 74 (March): 59–65. DOI: https://doi.org/10.1016/j.compchemeng.2014.12.016.

King, G., Fonti, P., Nievergelt, D., Büntgen, Ulf, Frank, D., 2013. Climatic Drivers of Hourly to Yearly Tree Radius Variations along a 6°C Natural Warming Gradient. **Agricultural and Forest Meteorology, 168 (January):** 36–46. DOI: https://doi.org/10.1016/j.agrformet.2012.08.002.

Korol, R.L., Running, S.W., Milner, K.S., 1995. Incorporating Intertree Competition into an Ecosystem Model. **Canadian Journal of Forest Research***,* 25 (3): 413–24. DOI: https://doi.org/10.1139/x95-046.

Landsberg, J.J., Waring, R.H., 1997. A Generalised Model of Forest Productivity Using Simplified Concepts of Radiation-Use Efficiency, Carbon Balance and Partitioning. **Forest Ecology and Management**, 95 (3): 209–28. DOI: https://doi.org/10.1016/S0378-1127(97)00026-1.

Li, L.M., Ouyang, L., Gan, S.M. 2015. Towards an Efficient Regeneration Protocol for Eucalyptus Urophylla. ***Journal of Tropical Forest Science****,* 27 (3): 289–97.

Long, S.P., Zhu, X.-G., , Naidu, S.L., Ort, D. R., 2006. Can Improvement in Photosynthesis Increase Crop Yields? **Plant, Cell and Environment**, 29 (3): 315–30. DOI: https://doi.org/10.1111/j.1365-3040.2005.01493.x.

Luo, Q., 2011. Temperature Thresholds and Crop Production: A Review. ***Climatic Change**,* 109 (3–4): 583–98. DOI: https://doi.org/10.1007/s10584-011-0028-6.

Matsumoto, K., Juri, S., Toshinori, Y., Hori, C., Nagata, A., Kudoh, Y., Ooi, T., Taguchi, S., 2019. Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase (RuBisCO)-Mediated de Novo Synthesis of Glycolate-Based Polyhydroxyalkanoate in Escherichia Coli. **Journal of Bioscience and Bioengineering**, April, S1389172318311915. DOI: https://doi.org/10.1016/j.jbiosc.2019.03.002.

McMurtrie, R.E., Rook, D.A., Kelliher, F.M., 1990. Modelling the Yield of Pinus Radiata on a Site Limited by Water and Nitrogen. **Forest Ecology and Management**, 30 (1–4): 381–413. DOI: https://doi.org/10.1016/0378-1127(90)90150-A.

Nash, J.C., Ravi, V., Gabor, G., 2018. Expanded Replacement and Extension of the ‘optim’ Function. https://cran.rstudio.com/web/packages/optimx/optimx.pdf.

Ocheltree, T.W., Nippert, J.B., Prasad, P.V.V., 2014. Stomatal Responses to Changes in Vapor Pressure Deficit Reflect Tissue-Specific Differences in Hydraulic Conductance: Stomatal Sensitivity of C3 and C4 Grasses. **Plant, Cell & Environment***,* 37 (1): 132–39. DOI: https://doi.org/10.1111/pce.12137.

Paine, C.E. Timothy, Toby R.M., Vogt, D.R., Purves, D., Rees, M., Hector, A., Turnbull, L.A. 2012. How to Fit Nonlinear Plant Growth Models and Calculate Growth Rates: An Update for Ecologists: Nonlinear Plant Growth Models. **Methods in Ecology and Evolution***,* 3 (2): 245–56. DOI: https://doi.org/10.1111/j.2041-210X.2011.00155.x.

R Core Team. 2014. *R: A Language and Environment for Statistical Computing*. http://www.R-project.org/.

Raju, S.K.K., Barnes, A.C., Schnable, J.C., Roston. R.L., 2018. Low-Temperature Tolerance in Land Plants: Are Transcript and Membrane Responses Conserved? **Plant Science***,* 276 (November): 73–86. DOI: https://doi.org/10.1016/j.plantsci.2018.08.002.

Ranalli, P., ed. 2007. **Improvement of Crop Plants for Industrial End Uses**. Dordrecht: Springer Netherlands, 533 p.

Ratkowsky, D.A., 1990. **Handbook of Nonlinear Regression Models**. M. Dekker edition,. New York.

Rauscher, H.M., Isebrands, J.G., Host, G.E., Dickson, R.E., Dickmann, D.I., Crow, T.R., Michael, D.A., 1990. ECOPHYS: An Ecophysiological Growth Process Model for Juvenile Poplar. **Tree Physiology**, 7 (1-2-3–4): 255–81. DOI: https://doi.org/10.1093/treephys/7.1-2-3-4.255.

Rawal, D.S., Sabine, K., Keatley, M.R., Nitschke, C.R., 2015. Climatic and Photoperiodic Effects on Flowering Phenology of Select Eucalypts from South-Eastern Australia. **Agricultural and Forest Meteorology,** 214–215 (December): 231–42. DOI: https://doi.org/10.1016/j.agrformet.2015.08.253.

Rouan, L., Audebert, A., Luquet, D., Roques, S., Dardou, A., Gozé, E., 2018. Cardinal Temperatures Variability within a Tropical *Japonica* Rice Diversity Panel. **Plant Production Science**, 21 (3): 256–65. DOI: https://doi.org/10.1080/1343943X.2018.1467733.

Ryan, M.G., 2010. Temperature and Tree Growth. **Tree Physiology***,* 30 (6): 667–68. DOI: https://doi.org/10.1093/treephys/tpq033.

Sands, P.J., Landsberg, J.J., 2002. Parameterisation of 3-PG for Plantation Grown Eucalyptus Globulus. **Forest Ecology and Management**, 163 (1–3): 273–92. DOI: https://doi.org/10.1016/S0378-1127(01)00586-2.

Schumacher, F.X., Hall, F.S., 1933. Logarithmic Expression of Tree Volume. **Journal of Agricultural Research*,*** 47 (9): 719–34.

Sharif, B., Makowski, D., Plauborg, F., Olesen, J.E., 2017. Comparison of Regression Techniques to Predict Response of Oilseed Rape Yield to Variation in Climatic Conditions in Denmark. **European Journal of Agronomy***,* 82 (January): 11–20. DOI: https://doi.org/10.1016/j.eja.2016.09.015.

Shoaib, S.A., Marshall, L., Sharma, A. 2018. Attributing Uncertainty in Streamflow Simulations Due to Variable Inputs via the Quantile Flow Deviation Metric. **Advances in Water Resources**, 116 (June): 40–55. DOI: https://doi.org/10.1016/j.advwatres.2018.01.022.

Souza, L.C., Souza, R.M.C.R., Amaral, G.J.A., Silva Filho, T.M., 2017. A Parametrized Approach for Linear Regression of Interval Data. **Knowledge-Based Systems***,* 131 (September): 149–59. DOI: https://doi.org/10.1016/j.knosys.2017.06.012.

Svystun, T., Bhalerao, R.P., Jönsson, A.M., 2019. Modelling Populus Autumn Phenology: The Importance of Temperature and Photoperiod. **Agricultural and Forest Meteorology**, 271 (June): 346–54. DOI: https://doi.org/10.1016/j.agrformet.2019.03.003.

Wahid, A., Gelani, S., Ashraf, M., Foolad, M., 2007. Heat Tolerance in Plants: An Overview. **Environmental and Experimental Botany**, 61 (3): 199–223. DOI: https://doi.org/10.1016/j.envexpbot.2007.05.011.

Warr, R.L., Collins, D.H., 2014. Bayesian Nonparametric Models for Combining Heterogeneous Reliability Data. **Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability***,* 228 (2): 166–75. DOI: https://doi.org/10.1177/1748006X13503319.

Watt, M.S, Rubilar, R., Kimberley, M.O., Kriticos, D.J., Emhart, V., Mardones, O., Acevedo, M., Pincheira, M., Stape, J., Fox, T., 2014. Using Seasonal Measurements to Inform Ecophysiology: Extracting Cardinal Growth Temperatures for Process-Based Growth Models of Five Eucalyptus Species/Crosses from Simple Field Trials. **New Zealand Journal of Forestry Science**, 44 (1): 9. DOI: https://doi.org/10.1186/s40490-014-0009-4.

Yin, X., Martin J.K., McLaren, G., Visperas, R.M., 1995. A Nonlinear Model for Crop Development as a Function of Temperature. **Agricultural and Forest Meteorology**, 77 (1–2): 1–16. DOI: https://doi.org/10.1016/0168-1923(95)02236-Q.

Yu, Z., Weinian, Z., 2018. Forts of Quadratic Polynomials under Iteration. **Journal of Computational and Applied Mathematics**, 331 (March): 1–10. DOI: https://doi.org/10.1016/j.cam.2017.09.008

Zhang, K., Chen, B-h., Hao, Y., Yang, R., Wang, Y-a., 2018. Effects of Short-Term Heat Stress on PSII and Subsequent Recovery for Senescent Leaves of Vitis Vinifera L. Cv. Red Globe. **Journal of Integrative Agriculture**, 17 (12): 2683–93. DOI: https://doi.org/10.1016/S2095-3119(18)62143-4.

Zoldan, D., Band, R.S., Guy, C.L., Porat, R., 2012. Understanding Chilling Tolerance Traits Using Arabidopsis Chilling-Sensitive Mutants. **In Environmental Adaptations and Stress Tolerance of Plants in the Era of Climate Change**, edited by Parvaiz Ahmad and M.N.V. Prasad, 159–73. New York, NY: Springer New York. DOI: https://doi.org/10.1007/978-1-4614-0815-4_7

CAPÍTULO 2

TEMPERATURE THRESHOLDS FOR *EUCALYPTUS* GENOTYPES GROWTH ACROSS TROPICAL AND SUBTROPICAL RANGES IN SOUTH AMERICA

Túlio Barroso Queiroz[ab]

Otávio Camargo Campoe[ac]

Cristian Rodrigo Montes[b]

Clayton Alcarde Alvares[a]

Mauricio Zapata Cuartas[b]

Iraê Amaral Guerrini[a]

[a]Universidade Estadual Paulista-UNESP, Faculdadede Ciências Agronômicas,
Botucatu, SP 18610-034, Brazil

[b]University of Georgia-UGA, Warnell School of Forestry and Natural Resources,
180E Green St., Athens, GA 30602-2152, USA

[c]Universidade Federalde Lavras-UFLA, Departamento de Ciências Florestais,
Lavras, MG 37200-000, Brazi

ABSTRACT

Temperature is a crucial factor influencing the growth of forest plantations, and a key variable used in process-based models of forest productivity. In the present study, we evaluated the relationship between temperature and growth of seven *Eucalyptus* genotypes in eight sites across a 3500 km latitude gradient in South America. From 18 months after planting until 72 months of age, climatic data and tree diameter increments at breast height (1.3 m above ground level) were monitored in each site intensively (every 15-30 days). The optimum temperature to growth varied among genotypes, ranging from 18–22 °C. The minimum annual temperature required for growth was 6 °C, while the maximum was 31 °C. The results at a monthly scale indicate that the minimum temperature to growth is between 7 °C and 23 °C, while the monthly maximum temperature is between 15 °C and 31 °C. When we used annual temperature or large temporal scales, we potentially minimize the effects of climate on plant metabolism; this should be taken into account in process based-models. The study results enhance our understanding of the influence of air temperature on tree growth dynamics. The *Eucalyptus* genotypes most planted in Brazil and Uruguay have specific thermal demands for growth maintenance and different optimal temperatures for maximum growth. Understanding variation in growth under different climatic conditions would facilitate accurate prediction of forest productivity based on thermal requirements. In addition, the data presented here could facilitate tree breeding by enhancing phenotypic analyses based on ecophysiological factors during the selection process.

Keywords: Climate Change; Dendrometer; Meteorological Seasonality; Phenology

2.1 INTRODUCTION

Temperature is a crucial factor influencing tree biological processes that are essential for growth. Previous research has found that temperature has a direct effect on photosynthesis and, therefore, on trees growth rate (Farquhar et al. 1980; Farquhar and von Caemmerer, 1982; Von Caemmerer, 2000). Temperature also is one of the main drivers used in process-based models such as BIOMASS (McMurtrie et al.,1990), CARBON (Bassow et al. (1990), ECOPHYS (Rauscher et al. 1990b), TREE BGC (Korol et al., 1995), 3-PG (Landsberg and Waring 1997) and CABALA (Battaglia et al. 2004b). The models above can be used to predict plant growth, make inferences about the potential physiological mechanisms by which temperature influences tree growth, and to understand how temperature influences plant productivity based on weather conditions.

Temperature influences quantum efficiency directly (Farquhar et al.,1980; Giuliani et al., 2016). However, the application of models based on quantum flux requires specialized knowledge and growth model parameterization, at least on an hourly basis. Researchers have bridged the gap between hours and years by conducting empirical analysis such as those found in Yin et al. 1995; Gustafson et al. (2017), and Wu et al., (2020). Such empirical appeal is based on the assumption of a specific limiting temperature range, which is used to predict net photosynthetic production. It has been implemented in models such as Regional Hydro Ecologic Simulation System (Tague and Band 2004), MAESPA (Duursma and Medlyn 2012), Individual-based Forest Landscape and Disturbance (Seidl et al. 2012), 3-PGmix (Forrester and Tang 2016), the big-leaf model (Ueyama et al. 2016; Farquhar et al., 1980), and Forest Landscape Models (McKenzie et al. 2019). All the above models explore the radial growth of trees and attempt to describe plant productivity at daily, monthly, annual, and seasonal scales.

Air temperature varies dramatically at time and space across the South American continent. Northern Brazil, which includes an extensive equatorial area, has average air temperature ranging from 23 °C in winter to 33 °C in summer, with an annual mean of 27 °C. Southern and southeastern Brazil (Santa Catarina, Paraná, São Paulo, Minas Gerais states) faces air temperatures relatively high depending of local altitude and distance from ocean. However, in highlands of the central region of Santa Catarina and Paraná, the temperatures are low, with an annual mean temperature of 17 °C, ranging from 13 °C in July and 20.5 °C in January (Alvares et al. 2013a, Alvares et al., 2013b).

In its native range (Australian region) of Eucalyptus species comprises tropical to temperate regions whose bioclimatic traits are pretty similar with Brazil. In Australia, in the equatorial region, the average annual temperature is higher than 25 °C, and temperature overflow occurs mainly in the summer months (December and January) when the average temperature is higher than 28 °C (Flores et al. 2016). Unique *Eucalyptus* phenology outside its native environments could offer insights into the capacity of species and genotypes to tolerate and adapt to different climatic conditions (Booth et al. 2015).

Numerous studies have investigated climatic requirements in *Eucalyptus* species growth. The responses of physiological processes over time to weather conditions can occur at different scales, ranging from sub-hourly (Downes et al., 1999), daily (Aspinwall et al. 2019), biweekly (Sette Jr et al. 2016), monthly (Hay et al., 1999; Lim et al. 2020), to annual scales (Naidoo et al. 2010). However, forest plantation productivity is often assessed annually, mostly because data collection at high resolutions has considerable operational and financial cost demands, which has prevented the examination of tree growth responses to weather conditions at high resolutions.

The objective of this study was to determine the temperature thresholds for stem growth at high resolution in clonal *Eucalyptus* stands in Brazil and Uruguay. In addition, this study explores the differences between warm sites and cool sites at a rotation time scale intending to determine the minimum and maximum threshold temperatures for tree growth. The results of this study could enhance further studies on climate issues, particularly concerning thermal requirements. For example, predict future spatial-temporal growth habits following increases or decreases in the air temperature. Also, determining temperature ranges could improve productivity predictions in new planting sites and facilitate regionalization of *Eucalyptus* genotypes.

2.2 MATERIAL AND METHODS

2.2.1 Study area

The study was conducted in 8 sites established by the TECHS Project (Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses, (Binkley et al. 2017; 2020)). The air temperature gradient of sites used comprise the major annual mean temperatures in different regions in Brazil and Uruguay. In the project, there were gaps of a few months across sites; however, the strategy could not adequately reveal differences in the phenological traits of *Eucalyptus* genotypes primarily because of the challenge of coordinating the same schedule across several organizations. We aimed to reveal the effect of climatic variability between tropical (within Equator and Tropic of Capricorn) and Subtropical (below Tropic of Capricorn) regions on tree growth along a climatic gradient that covers a broad temperature range in South America. The sites also have a large annual temperature range, with temperatures ranging from 10 °C to a little more than 26 °C (Fig. 1).

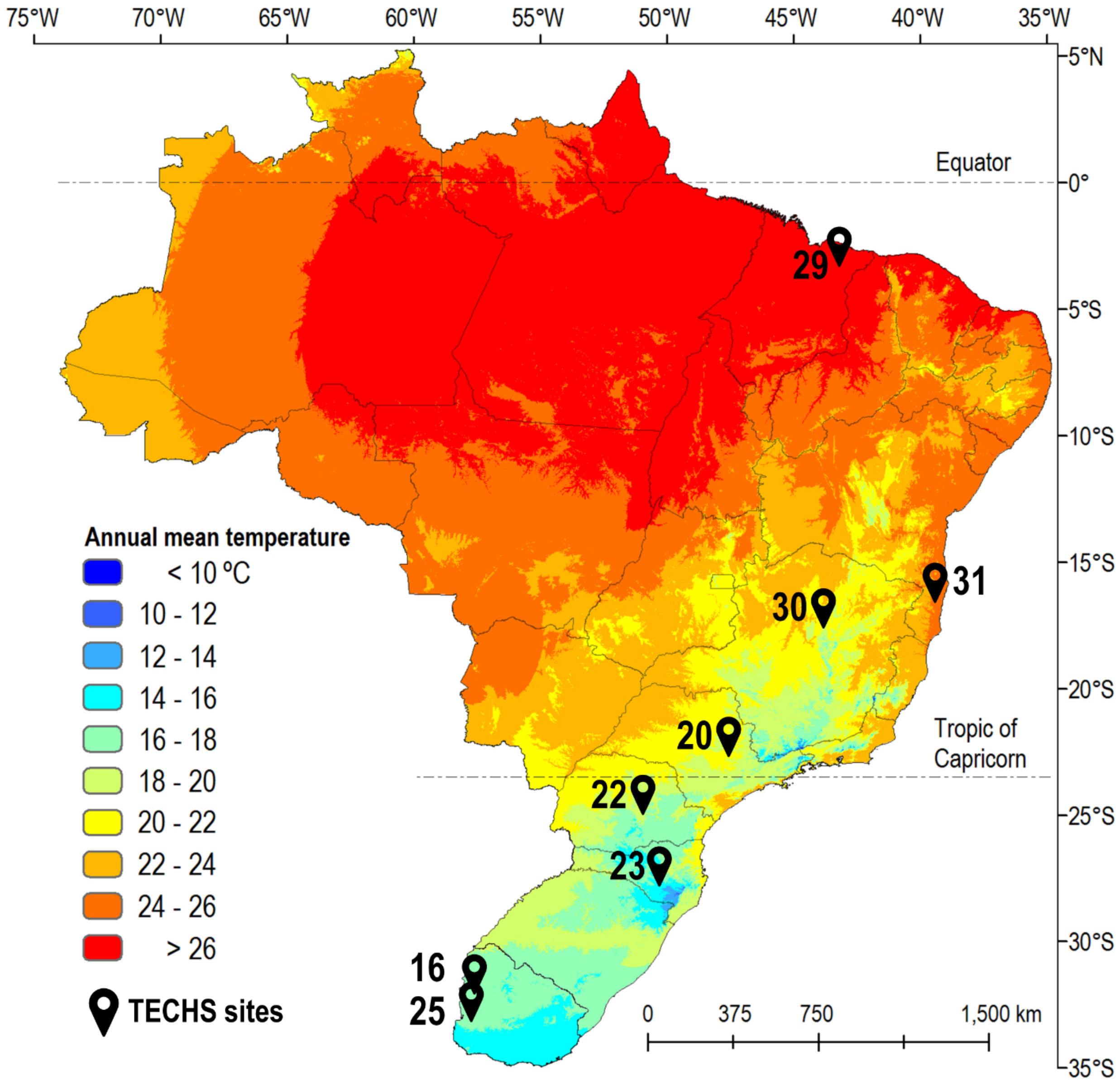


Fig. 1. Geographical distribution of TECHS sites and annual mean temperature in Brazil and Uruguay

Tree seedling were provided by company nurseries members of TECHS project. Plantation date of experimental plots were between April/2013 and September/2014. Soil characteristics considerably influence tree growth performance, and there were substantial variations in soils across the sites studied (Table 1). Each study site consisted of eight rows with 10 plants per row in a 3 × 3 m array for a total plot area of 720 m^2. All plots received a similar amount of fertilizer. All sites were fertilized intensively during the first year (70 kg N ha^{-1}, 45 kg P ha^{-1}, 85 kg K ha^{-1}, 500 kg Ca ha^{-1}, 90 kg Mg ha^{-1}, 40 kg S ha^{-1}, 3 kg B ha^{-1}, 1 kg Cu ha^{-1}, and 1 kg Zn ha^{-1}). In the cover fertilization, they were 2–4 applications within 12 months of planting. In addition, herbicides were used to prevent competition from weeds. More details about the study design are available in Binkley et al. (2017).

Table 1 – Locations of the 8 TECHS sites, soil characteristics (0–40 cm depth) and Köppen climate classification system

Site	City	State/Country	Clay (%)	Silt (%)	Sand (%)	Köppen Climate[1]
16	Paysandu	- / Uruguay	25.00	29.00	46.00	Cfa
20	Mogi Guaçu	Sao Paulo / Brazil	41.33	16.29	42.38	Cwa
22	Telêmaco Borba	Paraná / Brazil	55.81	22.72	21.47	Cwb
23	Otacílio Costa	Santa Catarina / Brazil	42.85	27.73	29.43	Cfb
25	Conchilas	- / Uruguay	37.00	42.00	21.00	Cfa
29	Urbano Santos	Maranhão / Brazil	8.76	4.60	86.65	Aw
30	Bocaiuva	Minas Gerais / Brazil	76.38	14.05	9.57	As
31	Eunápolis	Bahia / Brazil	24.53	2.86	72.62	Aw

[1]Köppen Climate Classification System = Cfa (humid subtropical zone with hot summer and without dry season), Cfb (humid subtropical zone with temperate summer and without dry season), Cwb (humid subtropical zone with temperate summer and dry winter), Cwa (humid subtropical zone with hot summer and dry winter), As (tropical with dry summer), and Aw (tropical with dry winter).

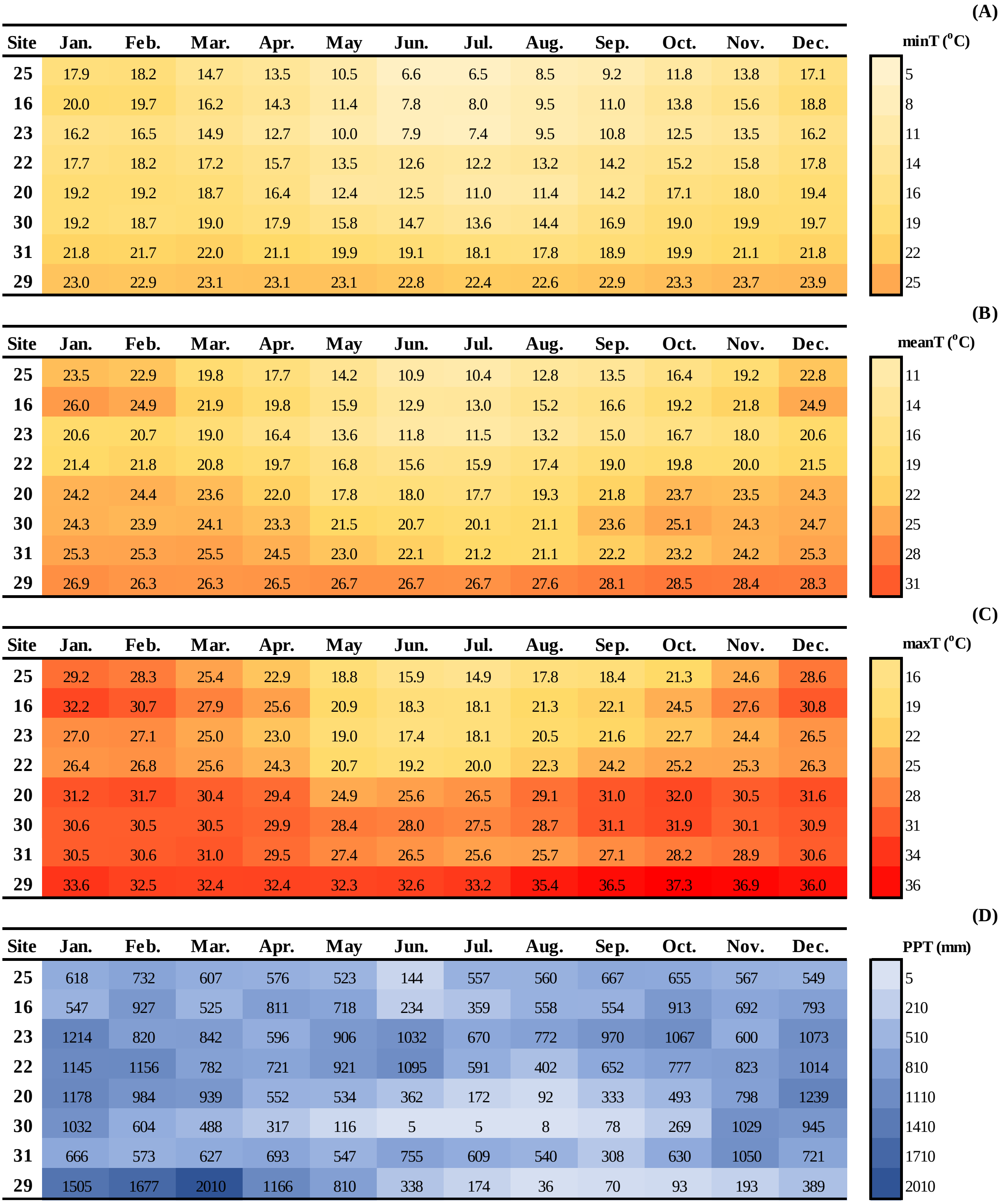
2.2.2 Weather station network and climate condition records for *Eucalyptus* genotypes

Meteorological data were recorded using *in situ* weather stations (s) installed near the each experimental field. Temperature sensors were located 2 m above the ground. Climate data was processed rigorously according to Elli et al., (2019). All meteorological data were interpolated with meteorological data from other meteorological stations (I) provided by the National Institute of Meteorology (INMET) or Instituto Nacional de Investigación Agropecuaria (INIA), which are managed by the Brazilian and Uruguayan governments, respectively (Table 2).

Table 2 - Location of the TECHS sites with the location of the meteorological stations of the National Institute of Meteorology (INMET) or Instituto Nacional de Investigación Agropecuaria (INIA).

Site	**State/Country**	**Meteorological Station in Situ (S)**			**Meteorological Station INMET or INIA* (I)**			**S ↔ I**
		Lat	Long	Alt	Lat	Long	Alt	Distance
		degrees		meters	degrees		meters	kilometers
16*	Uruguay	-32.2	-57.8	50	-34.3	-57.7	72	112.9
20	Sao Paulo - Brazil	-22.4	-47.0	633	-22.0	-47.0	633	17.7
22	Parana - Brazil	-24.2	-50.5	888	-24.0	-50.0	1106	31.4
23	Santa Catarina-Brazil	-27.5	-50.1	870	-27.0	-51.0	982	53.5
25*	Uruguay	-33.3	-57.9	37	-34.3	-57.7	47	103.8
29	Maranhao - Brazil	-3.4	-43.1	81	-4.0	-43.0	91	46.7
30	Minas Gerais - Brazil	-17.3	-43.8	848	-17.0	-44.0	646	64.6
31	Bahia - Brazil	-16.3	-39.6	200	-16.0	-39.0	88	47.6

In the study sites, from 2012 to 2018, the monthly minimum temperatures ranged from 6 to 24 °C, while the monthly maximum temperatures ranged from 14 to 38 °C. The monthly mean temperature ranged from 10 to 29 °C, and the monthly accumulated precipitation (PPT) ranged between 4.80 mm and 2010 mm (**Fig. 2**).



(A)

Site	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
25	17.9	18.2	14.7	13.5	10.5	6.6	6.5	8.5	9.2	11.8	13.8	17.1
16	20.0	19.7	16.2	14.3	11.4	7.8	8.0	9.5	11.0	13.8	15.6	18.8
23	16.2	16.5	14.9	12.7	10.0	7.9	7.4	9.5	10.8	12.5	13.5	16.2
22	17.7	18.2	17.2	15.7	13.5	12.6	12.2	13.2	14.2	15.2	15.8	17.8
20	19.2	19.2	18.7	16.4	12.4	12.5	11.0	11.4	14.2	17.1	18.0	19.4
30	19.2	18.7	19.0	17.9	15.8	14.7	13.6	14.4	16.9	19.0	19.9	19.7
31	21.8	21.7	22.0	21.1	19.9	19.1	18.1	17.8	18.9	19.9	21.1	21.8
29	23.0	22.9	23.1	23.1	23.1	22.8	22.4	22.6	22.9	23.3	23.7	23.9

(B)

Site	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
25	23.5	22.9	19.8	17.7	14.2	10.9	10.4	12.8	13.5	16.4	19.2	22.8
16	26.0	24.9	21.9	19.8	15.9	12.9	13.0	15.2	16.6	19.2	21.8	24.9
23	20.6	20.7	19.0	16.4	13.6	11.8	11.5	13.2	15.0	16.7	18.0	20.6
22	21.4	21.8	20.8	19.7	16.8	15.6	15.9	17.4	19.0	19.8	20.0	21.5
20	24.2	24.4	23.6	22.0	17.8	18.0	17.7	19.3	21.8	23.7	23.5	24.3
30	24.3	23.9	24.1	23.3	21.5	20.7	20.1	21.1	23.6	25.1	24.3	24.7
31	25.3	25.3	25.5	24.5	23.0	22.1	21.2	21.1	22.2	23.2	24.2	25.3
29	26.9	26.3	26.3	26.5	26.7	26.7	26.7	27.6	28.1	28.5	28.4	28.3

(C)

Site	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
25	29.2	28.3	25.4	22.9	18.8	15.9	14.9	17.8	18.4	21.3	24.6	28.6
16	32.2	30.7	27.9	25.6	20.9	18.3	18.1	21.3	22.1	24.5	27.6	30.8
23	27.0	27.1	25.0	23.0	19.0	17.4	18.1	20.5	21.6	22.7	24.4	26.5
22	26.4	26.8	25.6	24.3	20.7	19.2	20.0	22.3	24.2	25.2	25.3	26.3
20	31.2	31.7	30.4	29.4	24.9	25.6	26.5	29.1	31.0	32.0	30.5	31.6
30	30.6	30.5	30.5	29.9	28.4	28.0	27.5	28.7	31.1	31.9	30.1	30.9
31	30.5	30.6	31.0	29.5	27.4	26.5	25.6	25.7	27.1	28.2	28.9	30.6
29	33.6	32.5	32.4	32.4	32.3	32.6	33.2	35.4	36.5	37.3	36.9	36.0

(D)

Site	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
25	618	732	607	576	523	144	557	560	667	655	567	549
16	547	927	525	811	718	234	359	558	554	913	692	793
23	1214	820	842	596	906	1032	670	772	970	1067	600	1073
22	1145	1156	782	721	921	1095	591	402	652	777	823	1014
20	1178	984	939	552	534	362	172	92	333	493	798	1239
30	1032	604	488	317	116	5	5	8	78	269	1029	945
31	666	573	627	693	547	755	609	540	308	630	1050	721
29	1505	1677	2010	1166	810	338	174	36	70	93	193	389

Fig. 2 - The monthly minimum temperature – minT (A), the monthly maximum temperature – maxT (B), the monthly mean temperature – meanT (C) and monthly accumulated precipitation– PPT (D) during each month from 2012 (January) to 2018 (July).

Eucalyptus genotypes were classified based on the climate of the origin of the clone (Binkley et al. 2017) so that there were three genotypes based on climatic origins: Plastic Clone (C3 and K2), Tropical Clone (B2 and P7), and Subtropical Clone (F6, I9, J1). The genetic diversity highlighted the need to match genotypes with local site conditions (Table 3).

Table 3 –Absolute temperature ranges where the genotypes were planted from 2012 to 2018

Clone	**Genotype**	**Clone type**	**Sites**	**minT**[2] (°C)	**maxT**[3] (°C)	**meanT**[4] (°C)
B2	*E. urophylla* × *E. grandis*	Tropical	20 and 29	10.9	37.3	24.47
C3	*E. grandis* × *E. camaldulensis*	Plastic	20, 22 and 30	10.9	31.9	21.2
F6	*E. benthamii*	Subtropical	16 and 25	6.4	32.1	18.1
I9	*E. dunnii*	Subtropical	16, 23 and 25	6.4	32.1	17.1
J1	*E. benthamii*	Subtropical	16, 23 and 25	6.4	32.1	17.1
K2	*E. saligna*	Plastic	16, 20, 22, 23, 25 and 29	6.4	37.3	20.1
P7	*E. urophylla* × *E. tereticornis*	Tropical	20, 22, 29, 30 and 31	11.0	37.3	22,9

[2]minT= Minimum Temperature, [3]maxT = Maximum Temperature and [4]meanT= Mean Temperature

2.2.3 Tree growth evaluation

Diameter at breast height (DBH at 1.30 m above the ground) was measured in all trees in the plots (80 trees) every six months from 12 months to 75 months after planting. Using the data in the inventories, we selected six trees (two trees per diameter class) and then investigated *Eucalyptus* genotype growth at high-resolution scales (bi-weekly or monthly), monitoring from 15 months to 70 months of age. We did not evaluate all trees in the plots considering the time and operational constraints.

We applied the model proposed by Schumacher and Hall (1933) to estimate the wood volume for each genotype at each site. The model was fitted using the complete forestry inventories obtained every six months (Equation 1).

$$V = \beta_0 * DBH^{\beta_1} * Ht^{\beta_2} * e \qquad \text{(Eq. 1)}$$

Where: V = volume (m^{-3} tree^{-1}); DBH = diameter at breast (cm); Ht = total height of the tree (m); β_0, β_1 and β_2= parameters; and e = random error

Logarithmic transformation allows the estimation of the parameters in (1) using ordinary least square regression (de Mattos et al. 2020). The final model is:

$$ln(V) = \beta_0 + \beta_1 * ln(DBH) + \beta_2 * ln(Ht) + e \qquad \text{(Eq. 2)}$$

Therefore, the calculation of wood volume biweekly/monthly was carried out through the interpolation of the volume calculated using Equation 1, and the DBH obtained every six months. The Thin-Plate Spline model (TPS), as defined by Bookstein (1989), was used to interpolate DBH based on volume (Equation 3); therefore, the volume data every six months was adjusted for estimating volume at high resolution. The models used to estimate wood volume at high resolution were based on site-specific predictions, i.e., we used a site-by-predictor matrix with a column for each clone. The method is ideal for examining the effect of continuous predictors. In the present case, the dependent variable, DBH, in centimeters (*x*), is used as a function of the volume expressed in cubic meters per tree (*y*).

$$I[f(x,y)] = \iint_{R^2} (fxx^2 + 2fxy^2 + fyy^2) dx.dy \qquad \text{(Eq. 3)}$$

All statistical analyses were carried out using R (R Core Team 2014). DBHs of 6 trees, monitored at high resolution (15 or 30 days), were adjusted based on the forest inventory data carried out every six months and then they were adjusted using the "Tps" function in the 'field' package (Nychka et al. 2019).

2.2.4 Threshold temperature for tree growth

The temperature responses of each genotype were based on a quadratic function. The equation provides the threshold of plant growth rate as a function of temperature, returning a value in the 0–1 range, where 1 corresponds to a theoretical maximum growth rate under entirely unconstrained conditions. The value is also referred to as the Growth Rate Modifier (GRM), which is defined as an adjustment of the maximum growth via a bordering sign of the potential productivity, is able to reach additionally until 50% of the final yield. The second degree function (Equation 4) consists of a simple curve that has three parameters (β_0, β_1, and β_2). The function has a single maximum or a minimum, but without an inflection point and the parameter used to describe the threshold temperature needs to be larger than 0 ($\beta_2 > 0$). Consequently, the optimum (*optT*), minimum (*minT*), and maximum (*maxT*) temperatures were determined using Equations 5, 6, and 7.

$$f(x) = \beta_2 x^2 + \beta_1 x + \beta_0 \qquad \text{(Eq. 4)}$$

$$optT = {\beta_1}^2 - 4 * \beta_2 * \beta_0 \qquad \text{(Eq. 5)}$$

$$minT = x_1 = \frac{(-\beta_1 + \sqrt{optT}\,)}{2*\beta_2} \qquad \text{(Eq. 6)}$$

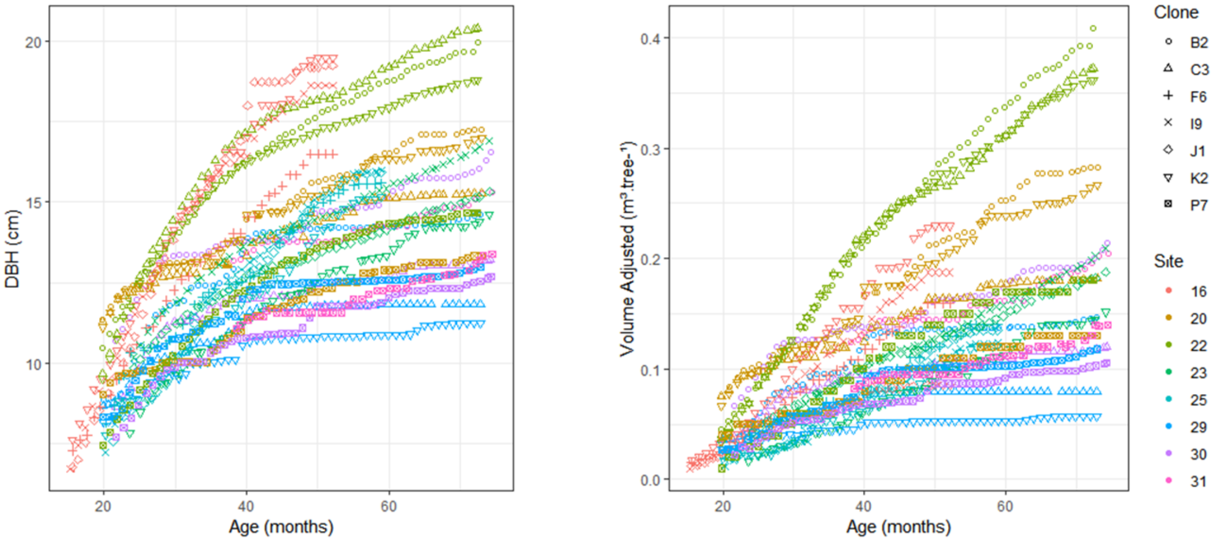
$$maxT = x_2 = \frac{(-\beta_1 - \sqrt{optT}\,)}{2*\beta_2} \qquad \text{(Eq. 7)}$$

2.3 RESULTS AND DISCUSSION

Tree volume varied considerably among the eight sites studied, ranging from 0.05 $m^3.tree^{-1}$ to 0.4 $m^3.tree^{-1}$ (Figure 3). Genotype, environment, and interaction between neighboring plants influenced the volume per tree of *Eucalyptus*, and more competitive clones (C3 and K2 recommended for the tropical region) were more productive under high temperatures (>25 °C), and less competitive clones (F6, I9 and

J1) could optimize their productivity when air mean temperature was <25 °C. Although all genotypes were present at each study site, the productivity and vigor of the clones was influenced by the characteristics of the site. The aim of the present study was not to determine which site had the highest levels of productivity. Our objective was to determine the thermal thresholds for the genotypes most planted under tropical and subtropical climatic conditions.

Fig. 3 – DBH and Volume adjusted for bi-weekly/monthly monitoring of DBH according to age for each Eucalyptus genotype from 2012 to 2018.



The Quadratic Polynomial at the annual scale indicated that the minimum average temperature required for the growth of the genotypes studied was 6.3 °C. The function illustrates the general relationship between output (GRM) and the input (temperature). The lowest difference between the minimum thermal demands of the *Eucalyptus* genotypes studied was 10.4 °C. Table 4 lists the parameters and annual cardinal temperature determined in the present study. Some clones (F6, I9, J1, and K2) began to grow from 6.3 °C, while other clones adapted to high temperatures (B2) and only initiated growth at a minimum average annual temperature of 12.6 °C. Low temperatures are common in regions classified as subtropical (Cwa), where the mean temperature is lower than 16 °C (Sites 16, 23, and 25). Maximum growth can be achieved in temperatures ranging between 18.2 °C and 21.9 °C. A difference of 4.0 °C between annual maximum temperatures tolerated by trees is sufficient to limit the growth of clones that are more sensitive when compared to more resistant clones. Although some clones (C3, J1, I9, and P7) stopped growing at around 31 °C, other clones (B2, F6, and K2) stopped growing at around 28 °C, which was mostly associated with tropical regions (Aw). Therefore, for growth to be maintained, the maximum average temperature of the air should be less than 28 °C. In a study by Watt et al. (2014), approximately 45 km south of Los Angeles in the Bio-Bio region of Chile, researchers observed that the optimum air temperature for *E. camaldulensis* × *E. globulus* was 26.9 °C and ranged from 15.4–18.7 °C for other four species/crosses. In the study, mean minimum temperatures ranged from 6.6–7.4 °C, while the mean maximum temperatures ranged from 21.1–29.8 °C.

Table 4 – Coefficient of optimized support regression curve for annual temperature range for *Eucalyptus* genotypes planted in Brazil and Uruguay followed by the respective standard deviation (±) about the 12 months of the year.

Clone	$\widehat{\beta_0}$		$\widehat{\beta_1}$		$\widehat{\beta_2}$		***minT (ºC)***	***optT (ºC)***	***maxT (ºC)***
B2	-16.4410	± 33.66	1.5949	± 2.69	-0.0365	± 0.06	16.64	21.87	27.1
C3	-4.7462	± 11.35	0.5333	± 0.93	-0.0124	± 0.02	12.55	21.56	30.56
F6	-1.8971	± 6.28	0.3158	± 0.57	-0.0086	± 0.02	7.57	18.35	29.13
I9	-1.5380	± 5.19	0.2718	± 0.75	-0.0073	± 0.03	6.95	18.65	30.34
J1	-1.2706	± 4.08	0.2429	± 0.60	-0.0065	± 0.02	6.29	18.68	31.07
K2	-1.6327	± 6.08	0.2891	± 0.52	-0.0080	± 0.01	6.99	18.18	29.36
P7	-5.1532	± 2.37	0.5665	± 0.19	-0.0130	± 0.00	12.97	21.71	30.44

The relationship becomes clear when we analyze the hump function of each genotype in the same plot. Thus, we gather all the temperature ranges into a single image, which allows the visualization of differences in temperature ranges among the different genotypes (Fig. 4). All functions regard limits range of the data observed, and the limits represent the conditions under which tree growth begins or stops. The limit of the vertex simulation was established as the potential yield of plants, which depends on the amount of solar radiation, and the factor is influenced directly by mean air temperature, which regulates stomata opening and closing, and, in turn, the increase or decrease in tree biomass or wood volume in a forest during a particular period.

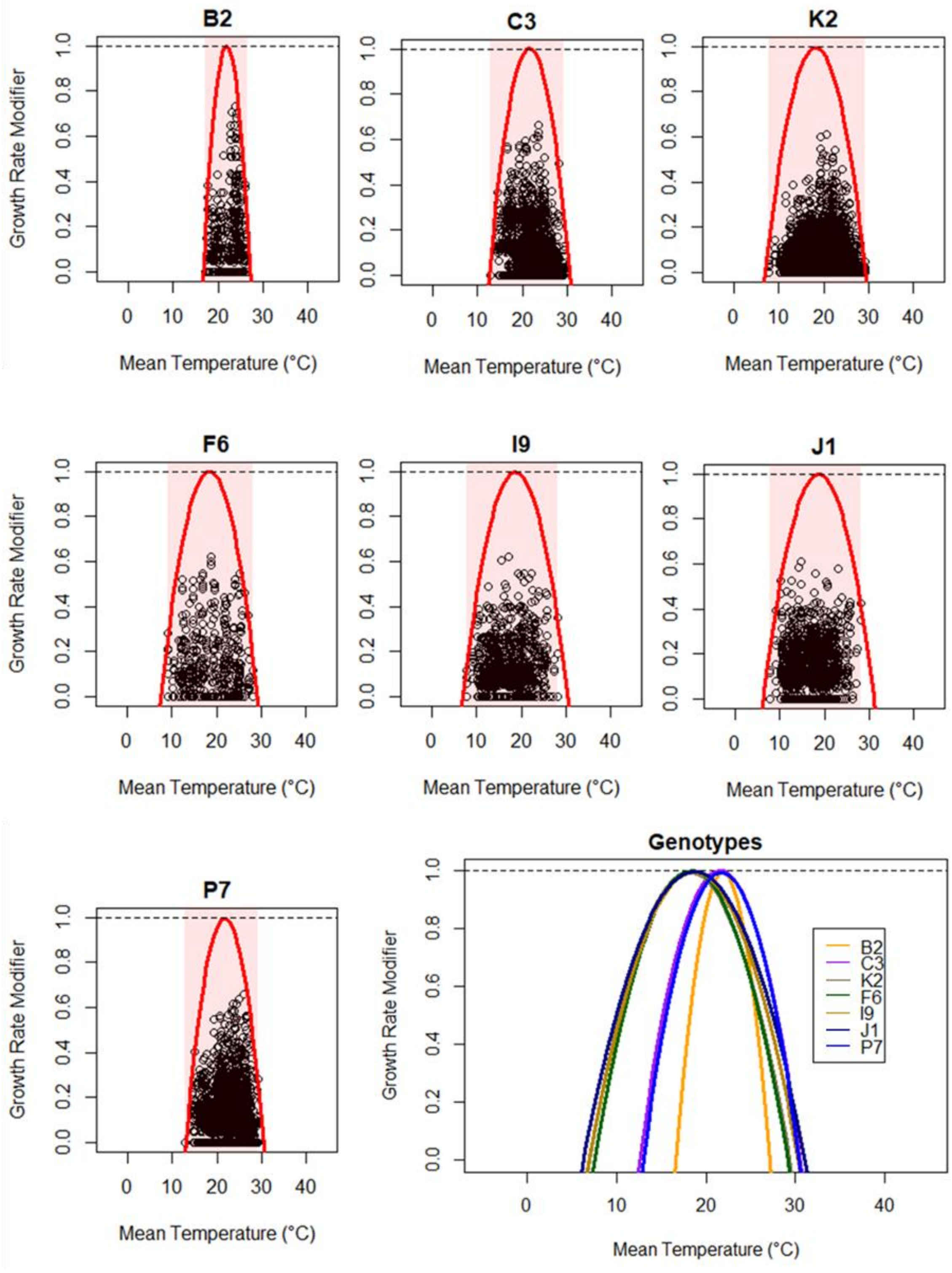


Fig. 4 – Annual temperature range for *Eucalyptus* genotypes planted in Brazil and Uruguay

The Annual temperature threshold for tree growth is in one of the inputs in the process-based tree growth or productivity models. Its parameterization with regard to the growth of trees, such as *Eucalyptus,* requires the investigation of the growth of eucalyptus plantations based on analyses at contrasting sites and based on contrasting genotypes. For example, in the 3-PG model, the beta function was used to establish an annual pre-defined minimum (7.5 °C), optimum (15 °C), and maximum (35 °C) temperature ranges for *Eucalyptus globulus*. The lack of information on some genotypes that support such models used threshold temperatures similar (8, 25, and 35 °C, respectively, according to Almeida et al., (2004). Later, a temperature modifier was fitted for process-based models (Gupta and Sharma 2019).

Based on daily average temperatures and the high-resolution tree growth data recorded in the present study, monthly temperature ranges for different *Eucalyptu*s genotypes were determined (Fig. 5). Although numerous studies have described cardinal temperatures for numerous agronomic crops and plant species, there is little information on the thermal requirements of *Eucalyptus* plantations, particularly with regard to tropical and subtropical regions of South America. Overall, it has remained unclear whether tree growth responses to short-term (sub-monthly) weather patterns provide more insights than growth responses at annual time scales. In the present study, we present differences in monthly temperature range requirements for some *Eucalyptus* genotypes. Such sub-annual insights could be particularly important where forest plantations are cultivated under relatively short rotations, such as in Brazil.

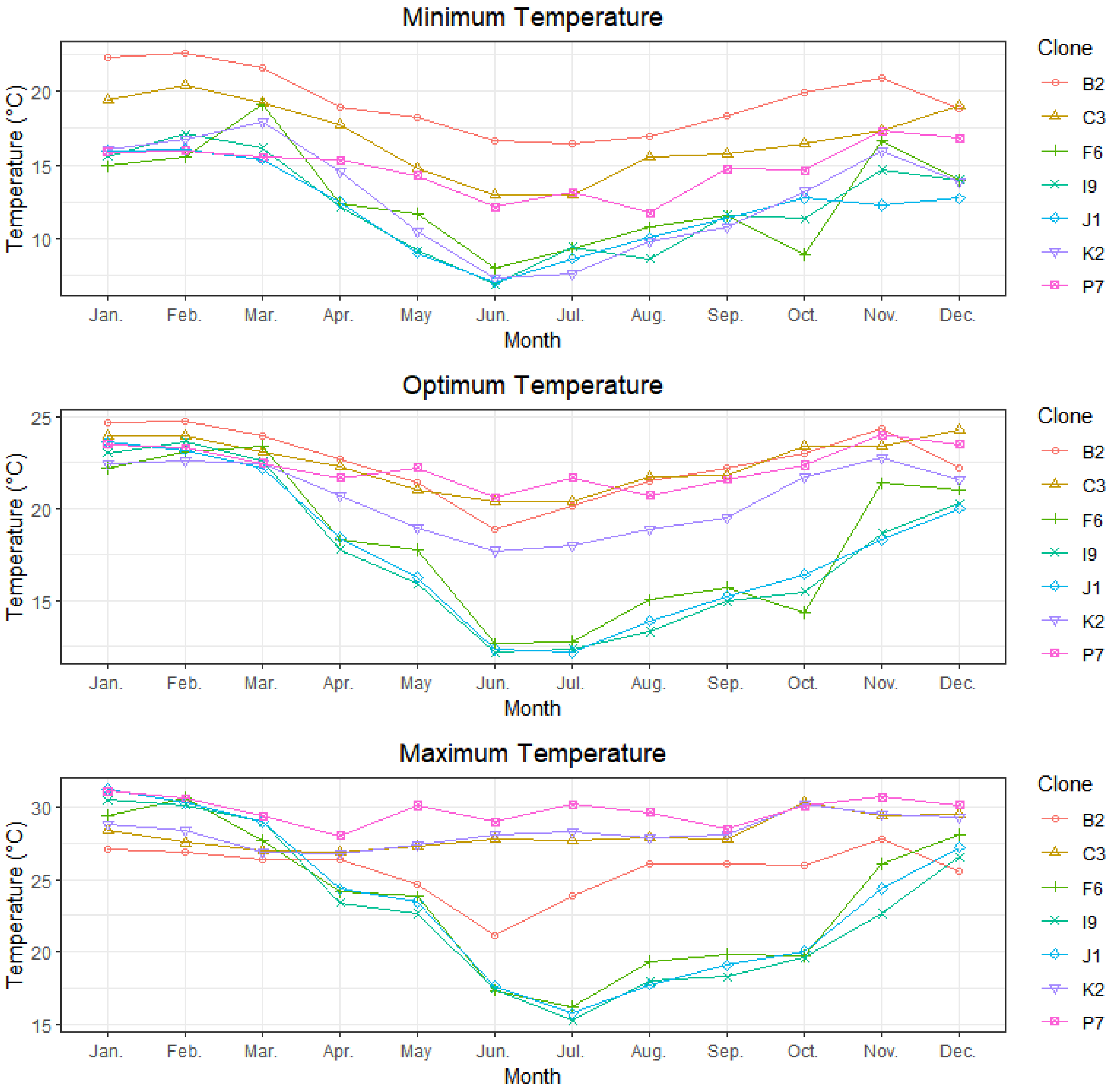


Fig. 5 - Monthly temperature range requirements for the growth of *Eucalyptus* in Brazil and Uruguay

The minimum thermal requirements for *Eucalyptus* clones in South America were as low as 15 °C in the coldest month (June, July, August). Conversely, we estimated lower temperature thresholds between December and March, so that the differences in threshold temperatures across genotypes were lower than 10 °C. Tropical clones (B2 and P7) exhibited such a trend, in contrast to the subtropical clones

(F6, I9, and J1) and the plastic clones (C3 and K2). Under climate change scenarios, potential increases in air temperature could reduce or increase *Eucalyptus* productivity, which would be more pronounced among the least productive stands.

Temperature ranges influence essential biological processes. In addition, their efficiency could be reduced or enhanced by shifts in temperature, which could also depend on other factors such as precipitation (Asfaw et al., 2018). In *Eucalyptus*, thermal stimulus activates the *Eucgr.B03930* gene; furthermore, proteins involved lignin biosynthesis are stimulated differentially across species (Costa et al., 2017). In addition, *E. globulus* requires low temperature for growth, while high temperatures stimulate *E. grandis* growth.

High temperatures in combination with drought stimulate stomatal closure, reduce carbon uptake, and induce the storage of non-structural carbon (starch and sugars) with ensuing effects on metabolic activity, defense against pathogens, and osmoregulation, to facilitate survival (McDowell et al. 2011). Conversely, low temperatures reduce net photosynthesis and biomass accumulation per plant (Liu et al. 2019). Consequently, wood production and growth would depend on stimuli (high or low temperature) that activate such biosynthetic pathways, while the magnitude of stimulus required varies across species (Costa et al., 2017). Increases in temperature do not always increase productivity (Gustafson et al. 2017). The effect of temperature is modulated in part by water supply in the soil (Hatfield and Prueger 2015). The temperature ranges of *Eucalyptus* genotypes that are most planted in tropical and subtropical regions in South America are listed in Table 5A and Table 5B.

Table 5A - Monthly temperature range requirements for *Eucalyptus* growth in Brazil and Uruguay

Minimum Temperature (ºC)							
	B2	**C3**	**F6**	**I9**	**J1**	**K2**	**P7**
January	22.33	19.46	14.93	15.59	15.95	16.09	15.90
February	22.60	20.40	15.52	17.13	16.07	16.76	15.99
March	21.55	19.19	19.11	16.15	15.38	17.90	15.54
April	18.97	17.70	12.44	12.16	12.49	14.57	15.34
May	18.20	14.72	11.69	9.21	9.05	10.50	14.29
June	16.66	12.97	7.99	6.93	7.08	7.35	12.15
July	16.48	12.98	9.32	9.47	8.66	7.64	13.17
August	16.94	15.55	10.76	8.66	10.07	9.86	11.76
September	18.36	15.78	11.58	11.62	11.38	10.85	14.73
October	19.95	16.45	8.93	11.39	12.78	13.23	14.64
November	20.86	17.37	16.67	14.67	12.28	15.94	17.29
December	18.85	19.03	13.99	13.99	12.76	13.86	16.80

Optimum Temperature (ºC)							
	B2	**C3**	**F6**	**I9**	**J1**	**K2**	**P7**
January	24.69	23.95	22.19	23.03	23.60	22.44	23.49
February	24.75	23.97	23.07	23.64	23.17	22.58	23.30
March	23.94	23.08	23.42	22.57	22.18	22.41	22.46
April	22.67	22.27	18.28	17.76	18.41	20.69	21.68
May	21.44	21.00	17.76	15.92	16.25	18.94	22.21
June	18.88	20.38	12.65	12.18	12.35	17.71	20.57
July	20.15	20.35	12.75	12.36	12.20	17.99	21.67
August	21.52	21.70	15.03	13.30	13.90	18.89	20.70
September	22.20	21.78	15.72	14.95	15.23	19.47	21.59
October	22.97	23.37	14.33	15.48	16.42	21.74	22.35
November	24.34	23.38	21.37	18.66	18.32	22.72	23.99
December	22.22	24.25	21.04	20.26	19.99	21.57	23.48

Maximum Temperature (ºC)							
	B2	**C3**	**F6**	**I9**	**J1**	**K2**	**P7**
January	27.06	28.43	29.44	30.48	31.24	28.78	31.08
February	26.89	27.54	30.62	30.15	30.28	28.39	30.60
March	26.33	26.97	27.73	29.00	28.99	26.91	29.37
April	26.37	26.84	24.12	23.36	24.32	26.81	28.02
May	24.67	27.28	23.83	22.64	23.45	27.38	30.12
June	21.09	27.80	17.32	17.43	17.62	28.07	28.99
July	23.82	27.72	16.17	15.25	15.75	28.33	30.17
August	26.10	27.86	19.30	17.95	17.74	27.92	29.63
September	26.04	27.79	19.85	18.27	19.08	28.10	28.45
October	25.99	30.30	19.73	19.57	20.06	30.25	30.07
November	27.82	29.39	26.08	22.65	24.36	29.51	30.69
December	25.59	29.47	28.09	26.54	27.23	29.28	30.16

Genotypes: B2 (*E. urophylla* × *E. grandis)*; C3 (*E. grandis* × *E. camaldulensis)*; F6 (*E. benthamii)*; I9 (*E. benthamii)*; J1 (*E. benthamii)*; K2 (*E. saligna)*; P7 (*E. urophylla* × *E. tereticornis).*

Table 5B – Quadratic function parameters for the establishment cardinal temperatures of the growth rate modifier for *Eucalyptus* in Brazil and Uruguay

Month	Parameters	B2	C3	F6	I9	J1	K2	P7
January	$\widehat{\beta_0}$	-109.2910	-27.6419	-8.4045	-8.5843	-8.4992	-11.4570	-8.5774
	$\widehat{\beta_1}$	8.9340	2.3924	0.8483	0.8324	0.8049	1.1101	0.8154
	$\widehat{\beta_2}$	-0.1809	-0.0500	-0.0191	-0.0181	-0.0171	-0.0247	-0.0174
February	$\widehat{\beta_0}$	-131.2570	-44.1801	-8.3382	-12.1868	-9.6144	-13.9289	-9.0809
	$\widehat{\beta_1}$	10.6892	3.7705	0.8095	1.1155	0.9159	1.3214	0.8647
	$\widehat{\beta_2}$	-0.2160	-0.0787	-0.0175	-0.0236	-0.0198	-0.0293	-0.0186
March	$\widehat{\beta_0}$	-97.6753	-34.3460	-28.7008	-11.4154	-9.6744	-23.8971	-9.6576
	$\widehat{\beta_1}$	8.2426	3.0630	2.5369	1.1007	0.9627	2.2229	0.9503
	$\widehat{\beta_2}$	-0.1722	-0.0664	-0.0542	-0.0244	-0.0217	-0.0496	-0.0212
April	$\widehat{\beta_0}$	-36.6783	-22.8083	-8.7264	-9.0338	-8.6509	-10.5053	-10.7820
	$\widehat{\beta_1}$	3.3249	2.1380	1.0630	1.1294	1.0481	1.1130	1.0875
	$\widehat{\beta_2}$	-0.0733	-0.0480	-0.0291	-0.0318	-0.0285	-0.0269	-0.0251
May	$\widehat{\beta_0}$	-43.1538	-10.1558	-7.6252	-4.6216	-4.1060	-4.0308	-6.8604
	$\widehat{\beta_1}$	4.1200	1.0620	0.9720	0.7061	0.6288	0.5310	0.7077
	$\widehat{\beta_2}$	-0.0961	-0.0253	-0.0274	-0.0222	-0.0194	-0.0140	-0.0159
June	$\widehat{\beta_0}$	-72.2925	-6.5623	-6.3648	-4.4009	-4.5002	-1.9394	-5.0030
	$\widehat{\beta_1}$	7.7656	0.7422	1.1640	0.8872	0.8908	0.3328	0.5843
	$\widehat{\beta_2}$	-0.2057	-0.0182	-0.0460	-0.0364	-0.0361	-0.0094	-0.0142
July	$\widehat{\beta_0}$	-29.1053	-6.6041	-13.0821	-17.3961	-10.9177	-2.0381	-5.5233
	$\widehat{\beta_1}$	2.9878	0.7470	2.2130	2.9775	1.9545	0.3386	0.6025
	$\widehat{\beta_2}$	-0.0741	-0.0184	-0.0868	-0.1204	-0.0801	-0.0094	-0.0139
August	$\widehat{\beta_0}$	-21.1304	-11.5425	-11.3149	-7.3113	-12.1347	-3.3563	-4.3985
	$\widehat{\beta_1}$	2.0570	1.1566	1.6382	1.2516	1.8895	0.4605	0.5224
	$\widehat{\beta_2}$	-0.0478	-0.0266	-0.0545	-0.0470	-0.0680	-0.0122	-0.0126
September	$\widehat{\beta_0}$	-32.2557	-12.1071	-13.3299	-19.3539	-14.7038	-4.0704	-8.9688
	$\widehat{\beta_1}$	2.9952	1.2031	1.8226	2.7250	2.0632	0.5201	0.9240
	$\widehat{\beta_2}$	-0.0675	-0.0276	-0.0580	-0.0912	-0.0678	-0.0134	-0.0214
October	$\widehat{\beta_0}$	-56.5798	-10.3985	-5.9897	-13.3687	-19.4388	-5.4694	-7.3848
	$\widehat{\beta_1}$	5.0135	0.9755	0.9745	1.8574	2.4901	0.5941	0.7502
	$\widehat{\beta_2}$	-0.1091	-0.0209	-0.0340	-0.0600	-0.0758	-0.0137	-0.0168
November	$\widehat{\beta_0}$	-48.3542	-14.0953	-19.2421	-20.9183	-8.2040	-10.1673	-11.7605
	$\widehat{\beta_1}$	4.0560	1.2911	1.8923	2.3496	1.0046	0.9825	1.0634
	$\widehat{\beta_2}$	-0.0833	-0.0276	-0.0443	-0.0630	-0.0274	-0.0216	-0.0222
December	$\widehat{\beta_0}$	-42.3616	-20.5818	-7.9094	-9.5167	-6.6302	-6.7980	-11.3818
	$\widehat{\beta_1}$	3.9018	1.7796	0.8469	1.0388	0.7632	0.7226	1.0550
	$\widehat{\beta_2}$	-0.0878	-0.0367	-0.0201	-0.0256	-0.0191	-0.0168	-0.0225

Genotypes: B2 (*E. urophylla × E. grandis)*; C3 (*E. grandis × E. camaldulensis)*; F6 (*E. benthamii)*; I9 (*E. benthamii)*; J1 (*E. benthamii)*; K2 (*E. saligna)*; P7 (*E. urophylla x E. tereticornis).*

2.4 CONCLUSION

The annual range of favorable temperature of *Eucalyptus* genotypes in tropical and subtropical regions of South America is 6–31 °C. However, the most planted *Eucalyptus* genotypes demand monthly optimal temperatures in the 18–22 °C range to achieve maximum growth. Such data could be used to optimize process-based prediction models.

The clones classified as F6, I9, and J1 exhibited the highest growth potential over a wide climatic range in South America. Conversely, some genotypes (B2, C3, and P7) had higher thermal requirements, which are recommended for growth under tropical conditions where the mean temperatures are closer to 20 °C. Growth projections based on future climate scenarios showed a trend to enhance phenotypic analyzes.

The results of the present study could facilitate growth modeling activities aimed at supporting the selection or recommendation of appropriate species for cultivation in different localities. Inter- and intraseasonal variations should be added to the models to enhance tree growth predictions. Finally, the patterns of growth responses to temperature reported in the present study could facilitate decision-making with regard to the regionalization potential of *Eucalyptus* species.

ACKNOWLEDGMENTS

The authors are particularly grateful to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES - Brazil) for the scholarship provided to conduct the research (Finance Code 001 and PDSE-88881.189488/2018-01), the Forest Science and Research Institute (IPEF - Brazil) and the TECHS project, and the Plantation Management Research Cooperative at The University of Georgia (PMCR –

United States). We thank all the organizations, universities, and research institutions involved in the TECHS Project. The project was funded by the following 7 organizations, with a main researcher: International Paper (Gabriela Moreira), Forestal Oriental (Ricardo Buzzo), Klabin (James Stahl and Marco Figura), Montes del Plata (Claudio Silva), Suzano (Luiz Fabiano de Moraes), Vallourec (Ademir Silva) and Veracel (Helton Lourenço). We thank Dan Binkley for comments on an earlier version of the manuscript.

REFERENCES

Almeida, A.C., Landsberg, J.J., Sands, P.J., 2004. Parameterisation of 3-PG Model for Fast-Growing *Eucalyptus Grandis* Plantations. **Forest Ecology and Management,** 193 (1–2): 179–95. DOI: https://doi.org/10.1016/j.foreco.2004.01.029.

Alvares, C.A., Stape, J.L., Sentelhas, P.S., Gonçalves, J,L.M., Sparovek, G., 2013. Koppen's Climate Classification Map for Brazil. **Meteorologische Zeitschrif**, 22 (6): 711–28. DOI: 10.1127/0941-2948/2013/0507

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.LM., 2013. Modeling Monthly Mean Air Temperature for Brazil. **Theoretical and Applied Climatology**, 113 (3–4): 407–27. DOI: https://doi.org/10.1007/s00704-012-0796-6.

Asfaw, A., Simane, B., Hassen, A., Batinder, A.,2018. Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. **Weather and Climate Extremes**, 19 (29-41). DOI: https://doi.org/10.1016/j.wace.2017.12.002

Aspinwall, M.J., Pfautsch, S., Tjoelker, M.G., Vårhammar, V., Possell, M., Drake, J.E., Reich, P.B., Tissue, D.T., Atkin, O.K., Rymer, P.D., Dennison, S., Van Sluyter, S.C., 2019. Range Size and Growth Temperature Influence *Eucalyptus* Species Responses to an Experimental Heatwave. **Global Change Biology**, 25 (5): 1665–84. DOI: https://doi.org/10.1111/gcb.14590.

Bassow, S.L., Ford, E.D., Kiester, A.R. 1990. A Critique of Carbon-Based Tree Growth Models. **In Process Modeling of Forest Growth Responses to Environmental Stress**, Timber Press, 50–57.

Battaglia, M., Sands, P., White, D., Mummery, D., 2004. CABALA: A Linked Carbon, Water and Nitrogen Model of Forest Growth for Silvicultural Decision Support. **Forest Ecology and Management,** 193 (1–2): 251–82. DOI: https://doi.org/10.1016/j.foreco.2004.01.033.

Binkley, D., Campoe, O.C., Alvares, C.A., Carneiro, R.L., Stape, J.L., 2020. Variation in Whole-Rotation Yield among *Eucalyptus* Genotypes in Response to Water and Heat Stresses: The TECHS Project. **Forest Ecology and Management**, 462 (April): 117953. DOI: https://doi.org/10.1016/j.foreco.2020.117953.

Binkley, D., Campoe, O.C., Alvares, C., Carneiro, R.L., Cegatta, I., Stape, J.L., 2017. The Interactions of Climate, Spacing and Genetics on Clonal *Eucalyptus* Plantations across Brazil and Uruguay. **Forest Ecology and Management,** 405 (December): 271–83. DOI: https://doi.org/10.1016/j.foreco.2017.09.050.

Bookstein, Fred L. 1989. Principal Warps: Thin Plate Splines and the Decomposition of Deformations. **IEEE Transactions on Patterm Analysis and Machine Intelligence**, 11 (6): 567–85. DOI: https://doi.org/10.1109/34.24792

Booth, T.H., Broadhurst, L.M E. Pinkard, S.M. Prober, S.K. Dillon, D. Bush, K. Pinyopusarerk, J.C. Doran, M. Ivkovich, and A.G. Young. 2015. Native Forests and

Climate Change: Lessons from Eucalypts. **Forest Ecology and Management**, 347 (July): 18–29. DOI: https://doi.org/10.1016/j.foreco.2015.03.002.

Costa, M.G.S, Mazzafera, P. Balbuena, T.S., 2017. Insights into Temperature Modulation of the Eucalyptus Globulus and *Eucalyptus Grandis* Antioxidant and Lignification Subproteomes. **Phytochemistry**, 137 (May): 15–23. DOI: https://doi.org/10.1016/j.phytochem.2017.01.017.

Downes, G., Beadle, C., Worledge, D., 1999. Daily Stem Growth Patterns in Irrigated Eucalyptus Globulus and E. Nitens in Relation to Climate. **Trees** 14 (2): 102–11. DOI: https://doi.org/10.1007/PL00009752.

Duursma, R.A., Medlyn, B.E., 2012. MAESPA: A Model to Study Interactions between Water Limitation, Environmental Drivers and Vegetation Function at Tree and Stand Levels, with an Example Application to [CO2] × Drought Interactions. **Geoscientific Model Development,** 5: 919–40. DOI: https://doi.org/10.5194/gmd-5-919-2012.

Elli, E.F., Sentelhas, P.C., Freitas, C.H., Carneiro, R.L., Alvares, C.A, 2019. Intercomparison of Structural Features and Performance of *Eucalyptus* Simulation Models and Their Ensemble for Yield Estimations. **Forest Ecology and Management**, 450 (October): 117493. DOI: https://doi.org/10.1016/j.foreco.2019.117493.

Farquhar, G. D., S. von Caemmerer. 1982. Modelling of Photosynthetic Response to Environmental Conditions. **In Physiological Plant Ecology II**, edited by Lange, O.L., Nobel, P.S., Osmond, C.B., Ziegler, H. Berlin, Heidelberg: Springer Berlin Heidelberg. DOI: https://doi.org/10.1007/978-3-642-68150-9

Farquhar, G.D., Von Caemmerer, S., Berry, J.A., 1980. A Biochemical Model of Photosynthetic CO_2 Assimilation in Leaves of C_3 Species. **Planta**, 149: 78–90. DOI: https://doi.org/10.1007/BF00386231.

Flores, T.B, Alvares, C.A., Souza, V.C., Stape. J.L., 2016. **Eucalyptus No Brasil: Zonemaneto Climático e Guia Para Identificação**. Piracicaba: IPEF.

Forrester, D.I., Xiaolu,T., 2016. Analysing the Spatial and Temporal Dynamics of Species Interactions in Mixed-Species Forests and the Effects of Stand Density Using the 3-PG Model. **Ecological Modelling**, 319 (January): 233–54. DOI: https://doi.org/10.1016/j.ecolmodel.2015.07.010.

Giuliani, R., Magnanini, E., Muzzi, E., Nerozzi, F., Tombesi, S., Palliotti, A., Gatti, M., Poni, S., 2016. An Enhanced Method to Infer Gas Exchange Function in Peach Trees Having Different Canopy Shapes Based on Canopy Quantum Flux Absorption Assessment. **Agricultural and Forest Meteorology**, 221 (May): 1–12. DOI: https://doi.org/10.1016/j.agrformet.2016.01.141.

Gupta, R., Sharma, L.K., 2019. The Process-Based Forest Growth Model 3-PG for Use in Forest Management: A Review. **Ecological Modelling**, 397 (April): 55–73. DOI: https://doi.org/10.1016/j.ecolmodel.2019.01.007.

Gustafson, E.J., Miranda, B.R., De Bruijn, M.G., Sturtevant, B.R., Kubiske, M.E., 2017. Do Rising Temperatures Always Increase Forest Productivity? Interacting Effects of Temperature, Precipitation, Cloudiness and Soil Texture on Tree Species Growth and

Competition. **Environmental Modelling & Software**, 97 (November): 171–83. DOI: https://doi.org/10.1016/j.envsoft.2017.08.001.

Hatfield, J.L., and John H. Prueger. 2015. “Temperature Extremes: Effect on Plant Growth and Development. **Weather and Climate Extremes**, 10 (December): 4–10. DOI: https://doi.org/10.1016/j.wace.2015.08.001.

Hay, A.E, KIimberley, M.O., Kampfraath, B.M.P., 1999. Monthly Diameter and Height Growth of Young Eucalyptus Fastigata, E. Regnans, and E. Saligna. **New Zealand Journal of Forestry Scienc,** 29 (2): 263–27.

Korol, R.L., Running, S.W., Milner, K.S, 1995. Incorporating Intertree Competition into an Ecosystem Model. **Canadian Journal of Forest Research**, 25 (3): 413–24. DOI: https://doi.org/10.1139/x95-046.

Landsberg, J.J., Waring, R.H., 1997. A Generalised Model of Forest Productivity Using Simplified Concepts of Radiation-Use Efficiency, Carbon Balance and Partitioning. **Forest Ecology and Management**, 95 (3): 209–28. DOI: https://doi.org/10.1016/S0378-1127(97)00026-1.

Lim, H., Alvares, C.A., Ryan, M.G., Binkley, D., 2020. Assessing the Cross-Site and within-Site Response of Potential Production to Atmospheric Demand for Water in Eucalyptus Plantations. **Forest Ecology and Management**, 464 (May): 118068. DOI: https://doi.org/10.1016/j.foreco.2020.118068.

Liu, L., Hongting J., Junpeng A., Kejia, S., Ma, J., Liu, B., Tang, L., Cao, W., Zhu, Y. 2019. Response of Biomass Accumulation in Wheat to Low-Temperature Stress at Jointing and Booting Stages. **Environmental and Experimental Botany**, 157: 46–57. DOI: https://doi.org/10.1016/j.envexpbot.2018.09.026.

Mattos, E.M., Binkley, D., Campoe, O.C., Alvares, C.A., Stape, J.L., 2020. Variation in Canopy Structure, Leaf Area, Light Interception and Light Use Efficiency among Eucalyptus Clones. **Forest Ecology and Management**, 463 (May): 118038. DOI: https://doi.org/10.1016/j.foreco.2020.118038.

McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., Stitt, M., 2011. The Interdependence of Mechanisms Underlying Climate-Driven Vegetation Mortality. **Trends in Ecology & Evolution**, 26 (10): 523–32. DOI: https://doi.org/10.1016/j.tree.2011.06.003.

McKenzie, P.F., Duveneck, M.J., Morreale, L.L., Thompson, J.R., 2019. Local and Global Parameter Sensitivity within an Ecophysiologically Based Forest Landscape Model. **Environmental Modelling & Software**, 117 (July): 1–13. DOI: https://doi.org/10.1016/j.envsoft.2019.03.002.

McMurtrie, R.E., Rook, D.A., Kelliher, F.M., 1990. Modelling the Yield of Pinus Radiata on a Site Limited by Water and Nitrogen. **Forest Ecology and Management**, 30 (1–4): 381–413. DOI: https://doi.org/10.1016/0378-1127(90)90150-A.

Naidoo, S., Ahmed, F., Pammenter, N.W., Zboňák, A., 2010. A Technique to Identify Annual Growth Rings in *Eucalyptus Grandis* Usingannual Measurements of Diameter at Breast Height and Gamma Raydensitometry. **Southern Forests: A Journal of**

Forest Science, 72 (3–4): 191–200. DOI: https://doi.org/10.2989/20702620.2010.547271.

Nychka, D., Furrer, R., Paige, J., Sain, S., 2019. **Tools for Spatial Data**. R Topics Documented, October, 215. DOI: https://doi.org/doi:10.5065/D6W957CT.

R Core Team. 2014. **R: A Language and Environment for Statistical Computing**. http://www.R-project.org/.

Rauscher, H.M., Isebrands, J.G., Host, G.E., Dickson, R.E., Dickmann, D.I., Crow, T.R., Michael, D.A., 1990. ECOPHYS: An Ecophysiological Growth Process Model for Juvenile Poplar. **Tree Physiology**, 7 (1-2-3-4): 255–81. DOI: https://doi.org/10.1093/treephys/7.1-2-3-4.255.

Schumacher, F.X., Hall, F.S., 1933. Logarithmic Expression of Tree Volume. **Journal of Agricultural Research**, 47 (9): 719–34.

Seidl, R., Rammer, W., Scheller, R.M., Spies, T.A, 2012. An Individual-Based Process Model to Simulate Landscape-Scale Forest Ecosystem Dynamics. **Ecological Modelling,** 231 (April): 87–100. DOI: https://doi.org/10.1016/j.ecolmodel.2012.02.015.

Sette Jr, C.R., Tomazello, M., Lousada, J.L., Lopes, D., Laclau, J.P., 2016. Relationship between climate variables, trunk growth rate and wood density of Eucalyptus Grandis W. Mill Ex Maiden trees. **Revista Árvore**, 40 (2): 337–46. DOI: https://doi.org/10.1590/0100-67622016000200016.

Tague, C.L., Band, L.E., 2004. RHESSys: Regional Hydro-Ecologic Simulation System-an Object-Oriented Approach to Spatially Distributed Modeling of Carbon, Water, and Nutrient Cycling. **Earth Interactions**, 8 (19): 1–42. DOI: https://doi.org/10.1175/1087-3562(2004)8<1:RRHSSO>2.0.CO;2.

Ueyama, M., Narumi, T., Iwata, H., Euskirchen, E.S., Ikawa, H., Kobayashi, H., Nagano, H., Nakai, T., Yoshinobu, H., 2016. Optimization of a Biochemical Model with Eddy Covariance Measurements in Black Spruce Forests of Alaska for Estimating CO2 Fertilization Effects. **Agricultural and Forest Meteorology**, 222 (May): 98–111. DOI: https://doi.org/10.1016/j.agrformet.2016.03.007.

Von Caemmerer, S. 2000. **Biochemical Models of Leaf Photosynthesis**. In . Commonwealth Scientific and Industrial Research Organization Publications. 145p.

Watt, M.S., Rubilar, R., Kimberley, M.O., Kriticos, D.J., Emhart, V., Mardones, O., Acevedo, M., Pincheira, M., Stape, J., Fox, T., 2014. Using Seasonal Measurements to Inform Ecophysiology: Extracting Cardinal Growth Temperatures for Process-Based Growth Models of Five *Eucalyptus* Species/Crosses from Simple Field Trials. **New Zealand Journal of Forestry Science,** 44 (1): 9. DOI: https://doi.org/10.1186/s40490-014-0009-4.

Dingrong, W., Wang, P., Jiang, C., Jianying, Y., Huo, Z., Kuiqiao, S., Yang, S., Qiang, Y., 2020. Use of a Plastic Temperature Response Function Reduces Simulation Error of Crop Maturity Date by Half. **Agricultural and Forest Meteorology**, 280 (January): 107770. DOI: https://doi.org/10.1016/j.agrformet.2019.107770.

Yin, X., Kropff, M.J., McLaren, G., Visperas, R.M., 1995. A Nonlinear Model for Crop Development as a Function of Temperature. **Agricultural and Forest Meteorology**, 77 (1–2): 1–16. DOI: https://doi.org/10.1016/0168-1923(95)02236-Q.

CONSIDERAÇÕES FINAIS

A resolução temporal, abrangência climática e genótipos envolvidos neste estudo foram capazes de determinar a produtividade potencial e as faixas de temperatura específicas que deverão ser consideradas para o planejamento e manejo florestal. Ao longo de uma sequência de idades de alta frequência, considerando desde plantas jovens até adultas, este estudo possibilitou adequada parametrização de um modelo para descrever à exigência térmica para manter o incremento da biomassa.

Neste estudo sugerimos o uso do polinomio de segundo grau como mais adequado para indicar os limites de temperatura necessário para manter o crescimento de árvores, sendo altamente recomendado para implementação em modelos baseados em processos como o 3-PG. Além disso, os requisitos térmicos poderão ser usados para auxiliar os programas de melhoramento genético, aprimorar os modelos de prognose de crescimento e o zoneamento de diferentes genótipos de eucalipto em condições climáticas contrastantes.

Por fim, a grande variabilidade ao longo do ano deve ser considerada para estimativas mais precisas da produtividade. Apesar dos requisitos térmicos anuais para o crescimento de árvores serem frequentemente usados em modelos baseados em processos nós recomendamos e indicamos faixas de temperatura em escala mensal.

REFERÊNCIAS

ABRAF. 2013. Associação Brasileira de Produtores de Florestas Plantadas. **Anuário Estatístico Da ABRAF: Ano Base 2012.** Brasília, 2013. 142 p.

Alfenas, A. C., *et al*. ***Clonagem e Doenças do Eucalipto***. 2 nd. Viçosa, MG : UFV, 2009. 500 p.

Antonangelo, A.; Bacha, C. J. C. **As Fases Da Silvicultura No Brasil**, v. 52, n.1, p. 207–238, 1998. Disponível em: < http://bibliotecadigital.fgv.br/ojs/index.php/rbe/article/view/721/8086> Acesso em: 09 Jul. 2020.

Cabré, M. F.; Solman, S.; Núñez, M. Regional Climate Change Scenarios over Southern South America for Future Climate (2080-2099) Using the MM5 Model. Mean, Interannual Variability and Uncertainties. **Atmósfera**, v. 29, n. 1, p. 35–60, 2016. DOI: https://doi.org/10.20937/ATM.2016.29.01.04

Christensen, J. H., *et al.* **Regional Climate Projections**. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University, 2007.

Clark, D. A., *et al.* Measuring net primary production in forests: concepts and field methods. **Ecological Applications***,* v. 11, n. 2, p. 356–70, 2001. DOI: https://doi.org/10.1890/1051-0761(2001)011[0356:MNPPIF]2.0.CO;2

Cristiano, P. M., *et al*. Evapotranspiration of Subtropical Forests and Tree Plantations: A Comparative Analysis at Different Temporal and Spatial Scales. **Agricultural and Forest Meteorology***,* v. 203, n. April, p. 96–106, 2015. DOI: https://doi.org/10.1016/j.agrformet.2015.01.007

Ding, H., *et al*. Valuing Climate Change Impacts on European Forest Ecosystems. **Ecosystem Services***,* v. 18, n. April, p. 141–53, 2016 https://doi.org/10.1016/j.ecoser.2016.02.039

Flores, T. B., *et al*. ***Eucalyptus No Brasil: Zonemaneto Climático e Guia Para Identificação***. Piracicaba: IPEF, 2016. 447 p.

Foelkel, C. The World of Eucalyptus: Uruguay. **Eucalyptus Online Book & Newsletter**, 2008. Disponivel em: <http://www.eucalyptus.com.br/newseng_oct08.html#tres> acesso em: 09 de Julho de 2020.

Gao, Q., *et al*. 2016. Climate Change and Its Impacts on Vegetation Distribution and Net Primary Productivity of the Alpine Ecosystem in the Qinghai-Tibetan Plateau. **Science of The Total Environment,** v. 554–555, n. June, p. 34–41, 2016. DOI: https://doi.org/10.1016/j.scitotenv.2016.02.131

Gonçalves, J. L. M., *et al*. Integrating Genetic and Silvicultural Strategies to Minimize Abiotic and Biotic Constraints in Brazilian Eucalypt Plantations. **Forest Ecology and Management***,* v. 301, n. August, p. 6–27, 2013. DOI: https://doi.org/10.1016/j.foreco.2012.12.030

Guo, Q., *et al*. Contrasting Responses of Gross Primary Productivity to Precipitation Events in a Water-Limited and a Temperature-Limited Grassland Ecosystem. **Agricultural and Forest Meteorology***,* v. 214–215, n. December, p. 169–177, 2015. DOI: https://doi.org/10.1016/j.agrformet.2015.08.251

Hayashi, R., *et al*. Vegetation and Endemic Tree Response to Orbital-Scale Climate Changes in the Japanese Archipelago during the Last Glacial–Interglacial Cycle Based on Pollen Records from Lake Biwa, Western Japan. **Review of Palaeobotany and Palynology***,* v. 241, n. June, p. 85–97, 2017. DOI: https://doi.org/10.1016/j.revpalbo.2017.02.008

Hulme, M., *et al*. African Climate Change: 1900-2100. **Climate Research***,* v. 17, p. 145–68, 2001. DOI: https://doi.org/10.3354/cr017145

IBÁ. 2019. **Indústria Brasileira de Árvores: RELATÓRIO 2019 - REPORT 2019**. Disponível em: <https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf>. Acesso em: 10 Jul. 2020.

Kato, L. A.; Bellini, M. Atribuição de Significados Biológicos Às Variáveis Da Equação Logística: Uma Aplicação Do Cálculo Nas Ciências Biológicas. **Ciência & Educação (Bauru),** v. 15, n. 1, p. 175–88, 2009. DOI: https://doi.org/10.1590/S1516-73132009000100011

Katz, J.; Stumpo, G.; Varela, F.. **El complejo forestal chileno**. Versión Final. División de Desarrollo Productivo y Empresarial. CEPAL. Santiago Kerosky S (2007) Chile's senate passes native forest Law. The Santiago Times (Santiago, 19 August 2007), 1999.

Kim, S., *et al*. 2015. Input Variable Scaling for Statistical Modeling. ***Computers &* Chemical Engineering**, v. 74, n. March, p. 59–65, 2015. DOI: https://doi.org/10.1016/j.compchemeng.2014.12.016

Lima-Toivanen, M. B. A Evolução Da Indústria Sul-Americana de Celulose e Papel: Foco No Brasil, Chile e Uruguai. **Revista O Papel***,* v. 74, n. 9, p. 51–66, 2013. Disponível em: <http://www.revistaopapel.org.br/noticia-anexos/1380634191_6d5aac0f077350b8c8a7820ccbd798db_189840160.pdf>. Acesso em: 09 Jul. 2020.

Manso, E. M.; Morais, A. R. Emprego Do Modelo Superparametrizado Em Experiemento Fatorial Desbalanceado Com Dois Fatores. **Ciência e Agrotecnologia***,* v. 30, n. 2, p. 234–242, 2006. DOI: https://doi.org/10.1590/S1413-70542006000200007

Mao, K. B., *et al*. Global Surface Temperature Change Analysis Based on MODIS Data in Recent Twelve Years. **Advances in Space Research***,* v. 59, n. 2, p. 503–512, 2017. DOI: https://doi.org/10.1016/j.asr.2016.11.007

Poinot, T.; Trigeassou, J-c.; Coirault, P. Overparametrization: A Tool for System Identification. **IFAC Proceedings Volumes,** v.30, n. 11, p. 1175–1180, 1997. DOI: https://doi.org/10.1016/S1474-6670(17)43000-X

Sawano, S., *et al*. Development of a Simple Forest Evapotranspiration Model Using a Process-Oriented Model as a Reference to Parameterize Data from a Wide Range of Environmental Conditions. **Ecological Modelling**, v. 309–310, n. August, p. 93–109, 2015. DOI: https://doi.org/10.1016/j.ecolmodel.2015.04.011

Sharif, B., *et al*. Comparison of Regression Techniques to Predict Response of Oilseed Rape Yield to Variation in Climatic Conditions in Denmark. **European Journal of Agronomy**, v.82, n. January, p. 11–20, 2017. DOI: https://doi.org/10.1016/j.eja.2016.09.015

Teuling, A. J., *et al*. Contrasting Response of European Forest and Grassland Energy Exchange to Heatwaves. **Nature Geoscience**, v. 3, n. 10, p. 722–727, 2010. DOI: https://doi.org/10.1038/ngeo950

Wang, S., *et al*. Responses of Net Primary Productivity to Phenological Dynamics in the Tibetan Plateau, China. **Agricultural and Forest Meteorology**, v. 232, n. January, p. 235–46, 2017. DOI: https://doi.org/10.1016/j.agrformet.2016.08.020

Wu, J., *et al*. Detecting the Quantitative Hydrological Response to Changes in Climate and Human Activities. **Science of The Total Environment**, v. 586, n. May, p. 328–337, 2017. DOI: https://doi.org/10.1016/j.scitotenv.2017.02.010