

**University of São Paulo
“Luiz de Queiroz” College of Agriculture**

***Eucalyptus simulation models: understanding and mitigating the impacts of
climate variability and change on forest productivity across Brazil***

Elvis Felipe Elli

Thesis presented to obtain the degree of Doctor in Science.
Area: Agricultural Systems Engineering

**Piracicaba
2020**

Elvis Felipe Elli
Agronomist

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Advisor:
Prof. Dr. **PAULO CESAR SENTELHAS**

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EPIGRAPH

“Life is like riding a bicycle. To keep your balance, you must keep moving”.

Albert Einstein

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RESUMO

Modelos de simulação do eucalipto: entendendo e mitigando os impactos da variabilidade e das mudanças climáticas sobre produtividade florestal no Brasil

As plantações de eucalipto apresentam alta variabilidade produtiva, o que é resultado das distintas condições ambientais em que as florestas são plantadas e suas interações com o genótipo e o manejo florestal. Modelos de simulação são ferramentas importantes para auxiliar no planejamento e tomadas de decisão no setor florestal, pois integram aspectos biofísicos com variáveis do clima, solo, manejo e genética para predizer a produtividade florestal. O objetivo deste estudo foi utilizar diferentes modelos de simulação para avaliar os efeitos da variabilidade e das mudanças climáticas sobre a produtividade do eucalipto no Brasil e, então, propor ações estratégicas que possam mitigar os possíveis impactos negativos à produtividade. Os modelos FAO, APSIM-growth, APSIM-*Eucalyptus* e 3PG foram adaptados, calibrados e avaliados, utilizando-se dados experimentais de produtividade do período de 2012 a 2017 de oito clones de eucalipto distribuídos em 23 localidades no Brasil. Em seguida, os modelos foram utilizados para (i) determinar as magnitudes e causas das quebras de produtividade do eucalipto no Brasil; (ii) quantificar os efeitos da variabilidade climática sobre a sua produtividade; (iii) realizar uma análise de sensibilidade global de diferentes características genéticas sob clima atual e futuro e (iv) avaliar a suscetibilidade das plantações de eucalipto aos cenários climáticos futuros, bem como quantificar as incertezas das projeções futuras. Todos os modelos de simulação apresentaram desempenho satisfatório para estimar a produtividade da cultura do eucalipto, sendo que o uso de uma abordagem *ensemble* reduziu levemente as incertezas nas simulações, quando comparado ao desempenho individual dos modelos. O déficit hídrico foi a principal causa das quebras de produtividades no Centro-Norte do Brasil, enquanto na região Sul, o manejo sub-ótimo foi a principal causa. A variabilidade climática, tanto espacial como temporal, afetou substancialmente o incremento médio anual (IMA) do eucalipto no Brasil. Localidades no Norte do Paraná e Sul de São Paulo foram as mais produtivas. O coeficiente de variação do MAI foi maior em locais mais secos. Características relacionadas à eficiência do uso da radiação, partição de folhas e raízes finas e coeficiente de extinção foram os que mais influenciaram a produtividade do eucalipto sob condições de clima atual. Características relacionadas à resposta fotossintética à temperatura se tornarão mais importantes em climas futuros. É esperado que resposta da produtividade do eucalipto às mudanças climáticas seja altamente dependente da localidade e vai depender em grande parte do balanço entre os possíveis impactos negativos de estresses climáticos e os potenciais incrementos de produtividade devido ao aumento da concentração de CO₂. De modo geral, é esperado que as plantações localizadas no Sul e Sudeste do Brasil apresentem aumentos no IMA em cenários de mudanças climáticas, já aquelas localizadas no Norte do Brasil deverão apresentar reduções. Projeções climáticas futuras podem proporcionar informações importantes a fim de facilitar a exploração de estratégias adaptativas em escala regional ou nacional. Entretanto, silvicultores devem ser cautelosos ao usar tais informações visando adaptação em escala local, uma vez que as incertezas nas projeções futuras são consideravelmente altas. Os modelos de simulação empregados apresentaram bom desempenho para simular a produtividade do eucalipto em diferentes climas, solos e para diferentes genótipos e, portanto, são ferramentas promissoras para o planejamento e as tomadas de decisão por parte dos silvicultores e empresas florestais, auxiliando na busca por estratégias mitigadoras para aumentar a resiliência e a produtividade florestal frente à variabilidade e às mudanças climáticas no Brasil.

Palavras-chave: Modelo da Zona Agroecológica – FAO, 3PG, APSIM, Déficit hídrico, Manejo sub-ótimo, Estresse por temperatura

ABSTRACT

***Eucalyptus* simulation models: understanding and mitigating the impacts of climate variability and change on forest productivity across Brazil**

Eucalyptus plantations in Brazil face a large productivity variability, as a result of the effects of contrasting environmental conditions across the cultivated regions, genotype and management practices. Simulation models are important tools to guide forest planning and decision-making since they integrate biophysical aspects with climate, soil, management and genetic factors, predicting forest productivity. This study aimed to use different simulation models for assessing the effects of climate variability and change on *Eucalyptus* productivity across Brazil, and then to propose strategies for mitigating potential negative impacts on forest production. The models FAO, APSIM-growth, APSIM-*Eucalyptus* and 3PG were adapted, calibrated and evaluated using experimental yield data from 2012 to 2017 of eight *Eucalyptus* clones distributed over 23 locations in Brazil. After that, simulation models were applied to (i) determine the magnitudes and causes of *Eucalyptus* growth gaps in Brazil, (ii) gauge the effects of climate variability on *Eucalyptus* productivity; (iii) perform a global sensitivity analysis of various genetic traits under present and future climate scenarios and (iv) assess the susceptibility of *Eucalyptus* plantations to future climate scenarios and quantify the uncertainties in future projections. All assessed models performed well to predict *Eucalyptus* growth and yield across Brazil, and the use of an ensemble approach reduced the uncertainties in yield simulations when compared to the individual performance of the models. The water deficit was the main cause of *Eucalyptus* growth gaps in Central Northern Brazil, while in Southern Brazil, the sub-optimal forestry management was the main one. Spatial and temporal climate variability strongly affected *Eucalyptus* mean annual increment (MAI) across Brazil. Sites located in North Paraná and South São Paulo were the most productive ones. A higher MAI coefficient of variation was observed in drier environments. Traits for radiation use efficiency, leaf partitioning, fine root partitioning and extinction coefficient were the most influential for *Eucalyptus* yield under present climate. Traits for photosynthetic temperature response will become more important under future climates. The responses of *Eucalyptus* productivity to climate change will be highly site-specific and will mostly depend on the balance between the possible negative effects of climate stresses and the potential productivity increments by elevated CO₂ concentration. In general, *Eucalyptus* plantations located in South and Southeast Brazil are expected to experience increases in attainable MAI under climate change scenarios, while those located in North Brazil will experience more pronounced MAI reductions. Future climate projections may provide valuable information that may facilitate the exploration of improved potential strategies for forestry adaptation on a regional or global scale. However, forest companies and foresters should be cautious when using projected information for local-scale adaptation options, since the uncertainties in future projections are substantially large. *Eucalyptus* simulation models performed well in simulating *Eucalyptus* productivity across a wide range of climates and soil types and for different Brazilian genotypes and, therefore, are promising tools forest planning and decision making, helping foresters and companies to assess mitigation strategies for increasing forestry resilience and productivity in the face of climate variability and change across Brazil.

Keywords: FAO Agroecological Zone Model, 3PG, APSIM, Water deficit, Sub-optimal management, Temperature stress

1. GENERAL INTRODUCTION

1.1. *Eucalyptus* plantations

The high adaptability of *Eucalyptus* plantations to a wide range of environments together with their fast growth and superior wood properties has driven their rapid adoption in more than 100 countries across six continents, with a total planted area of over 20 million hectares (Borralho et al., 2018; Myburg et al., 2014; Trabado, 2009). Brazil plays an important role in this context since the area cultivated with *Eucalyptus* is approximately 7.5 million hectares (IBGE, 2019). The largest *Eucalyptus* plantations in Brazil are mostly located in the States of Minas Gerais (26% of the national planted area), Mato Grosso do Sul (15%), São Paulo (12%), Paraná (9%), Rio Grande do Sul (8%) and Bahia (8%) (IBGE, 2019). However, in the last years, plantations expanded to other Brazilian regions, known as “new forest frontiers”, covering some states in Central-Northern and Northeastern regions, such as Mato Grosso, Maranhão, Piauí and Tocantins, where water deficit is more intense, lasts longer and is commonly accompanied by high temperatures (Binkley et al., 2020, 2017; Gonçalves et al., 2017, 2013).

The *Eucalyptus* wood consumption in Brazil is mostly designated for pulp and paper (48% of the total consumption). Industrial firewood is the second most important segment (28%), followed by charcoal (14%), reconstituted panels (4%), lumber industry (4%) and others (2%) (IBÁ, 2019). The average stemwood mean annual increment (MAI) in Brazil is around $36 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (IBÁ, 2019), however, values of over $80 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ can be reached when plantations are conducted under favorable environmental conditions, near optimum forestry management and using highly productive genotypes (Almeida et al., 2020; Binkley et al., 2017; Rocha et al., 2019).

1.2. Impacts of climate variability and change on *Eucalyptus* plantations productivity

Despite the high productivity levels of *Eucalyptus* plantations in Brazil, huge variability across the different regions is observed, as a result of the effects of climate, genetic and management factors (Binkley et al., 2017; Elli et al., 2017; Gonçalves et al., 2004; Ryan et al., 2010; Scolforo et al., 2017, 2019; Stape et al., 2010). However, the climate is the only factor that foresters have little or no control. Therefore, climatic risk assessment has become a very important tool for improving forestry planning and management. Furthermore, concerns about climate change impacts and their uncertainties on *Eucalyptus* productivity have been raised (Almeida et al., 2009; Booth, 2013). Atmospheric CO₂ concentration has increased from 280 ppm in the pre-industrial time to about 408 ppm in the present and is continuing to rise at around

2 ppm yr⁻¹ (NOAA, 2019). Increases of 1 °C in global average temperature have been observed in comparison to pre-industrial levels, and the projection for the period between 2030 and 2052 is to reach 1.5 °C, considering the current rate of increase (IPCC, 2018).

Studies of climate change impacts on *Eucalyptus* productivity are still scarce. Based on findings of different studies (Almeida et al., 2009; Booth, 2013; Ellsworth et al., 2017; Pinkard et al., 2010), it is expected that the impacts on *Eucalyptus* plantations will be highly site-specific and will depend, in part, on the balance between the possible negative effects of increasing temperatures and decreasing rainfall and the potential productivity increments promoted by elevated CO₂ concentration. However, uncertainties in climate change projections arising from different Global Circulation Models (GCMs) and related to the structure, parameters, input data and CO₂ fertilization functions of the process-based models used to predict *Eucalyptus* productivity are large (Asseng et al., 2013; Corbeels et al., 2018; Mearns, 2010; Tao et al., 2018; Torres and Marengo, 2013). Therefore, gauging and including uncertainty on decision-making for forestry adaptation to climate change would be of high importance.

1.3. *Eucalyptus* simulation models

Simulation models, also known as process-based or mechanistic models, are promising tools that integrate biophysical aspects with climate, soil, management and genetic factors, for predicting forest productivity (Ewert et al., 2015; Holzworth et al., 2018; Landsberg, 2003). After properly adapted, calibrated and evaluated against measured data, these models can be used to predict forest productivity according to current conditions of soil and weather, under changing climate projections, as well as to assess effects of different management options (e.g. different planting dates, spatial arrangement, fertilization rates, genotypes, thinning, defoliation) on forest growth, which may be crucial to guide forest planning and decision-making (Lemos et al., 2018; Pinkard et al., 2010; Scolforo et al., 2016). Simulation models also may be used to assess the magnitude and causes of forestry growth gaps (Freitas, 2018). Furthermore, these models can be coupled with statistical methods, such as global sensitivity analysis methods (Morris, 1991) to identify suitable genetic traits that may provide certain advantages under stressed conditions (Makowski et al., 2006).

There are several process-based models available for predicting *Eucalyptus* growth and yield, such as the G'DAY (Comins and McMurtrie, 1993; Marsden et al., 2013), 3PG (Landsberg and Waring, 1997), CABALA (Battaglia et al., 2004), Forest-DNDC (Li et al., 2000), FAO (Doorenbos and Kassam, 1979; Freitas, 2018), APSIM-Growth (Huth et al., 2001) and APSIM *Eucalyptus* (<https://www.apsim.info/>). Some studies have prioritized the use of

multimodel approaches (ensemble), especially for two reasons: (i) it is expected that an ensemble of models' outputs leads to improvements in accuracy and reductions in the uncertainties of forest yield simulations, compared to the individual performance of the models (Hanson et al., 2004; Wang et al., 2014); (ii) knowing the main structural features, advantages and limitations of different simulation models is important to analyze which model is more suitable for certain applications. Most of the studies on *Eucalyptus* process-based modelling in Brazil use the 3PG model (e.g. Almeida et al., 2004; Almeida and Sands, 2016; Caldeira et al., 2020; Lemos, 2012; Londero et al., 2015). This demonstrates the importance of studying and validating new forest modelling approaches under Brazilian conditions.

1.4. General hypothesis

Given the importance of Brazilian *Eucalyptus* plantations to the forest sector at national and global levels and the lack of studies on process-based modelling with this genus, the following hypothesis motivated us to perform the present study: *Eucalyptus* simulation models are able to predict *Eucalyptus* growth and yield for a wide range of climates, soil types and genotypes, and they are suitable tools to assess alternatives for understanding and mitigating the impacts of climate variability and change on forest productivity across Brazil.

1.5. General objective

The general objective of this study was to use simulation models for assessing the effects of climate variability and change on *Eucalyptus* plantations productivity across Brazil, and then to propose adaptation strategies for mitigating possible negative impacts on forest production.

1.6. Thesis structure

The present thesis is organized into eight chapters. The first one brings a short introduction to the research subject. The second one provides an intercomparison of structural features and performance of different *Eucalyptus* simulation models and their ensemble for yield estimations. The third one assesses the magnitudes and causes of *Eucalyptus* growth gaps in Brazil and proposes potential mitigation strategies. The fourth chapter demonstrates the inclusion of new functions into the APSIM Next Generation *Eucalyptus* model to improve its ability to simulate the effects of different environmental conditions and genetics on yield-related traits. The fifth one gauges the effects of temporal and spatial climate variability on *Eucalyptus* plantations productivity across Brazil; whereas the sixth chapter proposes a global sensitivity analysis to identify suitable *Eucalyptus* genetic traits for adaptation to climate

variability and change. The seventh chapter assesses the susceptibility of *Eucalyptus* plantations to future climate scenarios across a geographic gradient in Brazil and gauges the uncertainties in future projections. Finally, the eighth one provides some concluding remarks for the present study.

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2. INTERCOMPARISON OF STRUCTURAL FEATURES AND PERFORMANCE OF *EUCALYPTUS* SIMULATION MODELS AND THEIR ENSEMBLE FOR YIELD ESTIMATIONS*

Abstract

Eucalyptus process-based models are the most promising tools available for assisting foresters and companies in the pursuit of appropriate planning, long-term management and for assessing the impact of climate variability and change on the forest sector. Reducing errors of *Eucalyptus* yield simulations is of high importance since it increases the accuracy and credibility of decision making in forest systems. Furthermore, information on ensemble approach for *Eucalyptus* yield estimations is still scarce. The aims of this study were: to calibrate and evaluate the performance (goodness-of-fit) of the FAO, APSIM and 3PG models for different major Brazilian *Eucalyptus* clones; to perform an intercomparison of the structural features of *Eucalyptus* simulation models; and to assess the performance of an ensemble approach of these models. To these ends, experimental yield data from 2012 to 2017 from eight *Eucalyptus* clones distributed over 23 locations with several and contrasting environmental conditions in Brazil were used. During the evaluation phase, the R^2 ranged from 0.81 to 0.88, the modelling efficiency index (E) ranged from 0.75 to 0.81 and the root mean square error (RMSE) ranged from 37.1 to 42.3 $m^3 ha^{-1}$, when the models were individually assessed. The multimodel ensemble approach improved the performance of *Eucalyptus* yield estimations, with higher R^2 (0.89), E (0.85) and lower RMSE ($33.1 m^3 ha^{-1}$), compared to the individual performance of the models. Forest simulation models were able to estimate *Eucalyptus* yield across a wide range of climates and soil types when properly calibrated. The use of a multimodel ensemble reduced the errors of *Eucalyptus* yield estimations.

Keywords: model calibration; model evaluation; FAO – Agroecological Zone model; APSIM; 3PG.

2.1. Introduction

Eucalyptus is the most planted hardwood tree in the world (Myburg et al., 2014). It adapts to a wide range of different soil and climatic conditions and is known for its fast growth and

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superior wood properties (Flores et al., 2018). These characteristics have driven its rapid adoption as planted forest in more than 100 countries, with a total area of about 20 million ha (Byrne, 2008; Myburg et al., 2014; Trabado, 2009). In Brazil, the area cultivated with *Eucalyptus* is about 7.4 million hectares, which represents about 37% of the world's area with this genus (IBGE, 2017; Trabado, 2009), and its average yield is $36 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (IBÁ, 2017).

A slight reduction in *Eucalyptus* yield in Brazil has been observed compared to previous years. The reason is the advancing of planted areas to less suitable environments, where the water deficit is higher than in the subtropical traditional regions (Gonçalves et al., 2017) *Eucalyptus* plantations provide renewable resources for pulp and paper production, the lumber industry, beekeeping, firewood and charcoal, and for reducing deforestation of native forests (Bauhus et al., 2010; Diaz-Balteiro and Rodriguez, 2006; IBÁ, 2017). Furthermore, the ongoing increase in world population has been accompanied by an increase in renewable resource demand from forest plantations, such as *Eucalyptus* ones.

Eucalyptus yield is influenced by several factors, such as chemical, physical and biological soil characteristics, soil water availability, seedling quality, genetic material, management practices, pests and diseases, and weather conditions (Binkley and Fisher, 2013; Eldridge et al., 1994; Elli et al., 2017; Jesus et al., 2015; Ryan et al., 2010; Stape et al., 2010, Alvares et al., 2017). These factors lead to considerable variability in *Eucalyptus* yield. In this context, the use of simulation models for assessing *Eucalyptus* yield may assist in forest planning, management and decision-making in the forestry sector. After properly calibrated and evaluated, these models can be used to predict forest productivity according to specific conditions of soil and weather, including changing climate. Besides that, process-based forest modelling can be used to assess effects of different management options (e.g. different planting spacings, fertilization rates, genotypes, thinning, defoliation) on forest growth and yield, which may be highly useful for foresters.

There are several simulation models available for estimating *Eucalyptus* yield, such as FAO (Food and Agriculture Organization) - Agroecological Zone (Freitas, 2018), APSIM - Agricultural Production Systems Simulator (Mccown et al., 1996) and 3PG - Physiological Principles in Predicting Growth (Landsberg and Waring, 1997). These models present differences in terms of their structures, parameters, input data, level at which they simulate dynamic processes (such as biomass partitioning, photosynthesis and respiration, and biomass senescence) and consider climate, soil and management effects on productivity (Doorenbos and Kassam, 1979; Landsberg and Waring, 1997; Mccown et al., 1996). Comparative studies on the performance of models with structural differences under contrasting environments are

needed, in order to analyse which model is more suitable for certain applications. Recent studies show that the use of a multimodel approach (ensemble) improves accuracy and reduces uncertainties related to the estimates produced by simulation models, for annual crops such as soybean (Battisti et al., 2017), sugarcane (Dias and Sentelhas, 2017), corn (Bassu et al., 2014), wheat (Asseng et al., 2013; Martre et al., 2015) and rice (Li et al., 2015). According to Challinor et al. (2013), the uncertainty is used to denote a lack of predictive precision due to limitations related to predictability (e.g. unknown future greenhouse gas emissions) or to a lack of predictive skill (e.g. errors in the design of a model). Uncertainty could be also defined as the distribution of errors of prediction (Nissanka et al., 2017; Wallach and Thorburn, 2017).

In forestry studies, a multimodel approach was performed by Hanson et al. (2004), who simulated carbon and water flux in a deciduous forest ecosystem (mixed species) in the United States. These authors found that an ensemble of model outputs was the best fit to the field observations. Wang et al. (2014) performed multimodel simulations to assess forest harvesting effects on yield, carbon and nitrogen cycling in aspen forests (*Populus tremuloides*), in the United States also. They concluded that a multimodel approach is a robust option when sufficient long-term field data for calibration and evaluation of an individual model are lacking. A study with different simulation models for *Eucalyptus globulus* was performed by Miehle et al. (2009) in Australia; however, these authors did not consider an ensemble analysis. Information on the use of this approach for *Eucalyptus* and the performance of different *Eucalyptus* simulation models under several and contrasting environmental conditions is still scarce around the world.

In this context, the following questions arise: (i) Are the FAO, APSIM and 3PG models able to estimate *Eucalyptus* yield across a wide range of climates and soil types and for different genotypes? (ii) Is a model intercomparison an appropriate approach for identifying model advantages and limitations? (iii) Does the ensemble of *Eucalyptus* simulation models reduce the errors of yield estimations? To answer these questions, the present study aimed to: (i) calibrate and evaluate the performance (goodness-of-fit) of the FAO, APSIM and 3PG models for different major Brazilian *Eucalyptus* clones; (ii) perform an intercomparison of the *Eucalyptus* simulation models, demonstrating their main structural differences, advantages and limitations and (iii) assess the performance of an ensemble approach of these models for estimating *Eucalyptus* yield ($\text{m}^3 \text{ ha}^{-1}$).

2.2. Material and methods

2.2.1. Yield data

The study was conducted using yield data (stem volume, $\text{m}^3 \text{ ha}^{-1}$) of eight major *Eucalyptus* clones: A1 - *E. urophylla*, C3 - *E. grandis* x *E. camaldulensis*, K2 - *E. saligna*, Q8 - *E. grandis*, B2 - *E. urophylla* x *E. grandis*, R9 - *E. urophylla*, N5 - *E. dunnii* and O6 - *E. grandis*, which were cultivated in 23 experimental locations in Brazil (Figure 1). This dataset belongs to the Project "Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses" (TECHS), from the Forestry Science and Research Institute – IPEF. The aim of the TECHS project is to evaluate growth patterns and interactions between genetics and environmental conditions. Clones A1, C3, K2 and Q8 were planted at all of the 23 sites, due to their expected suitability to a wide range of environmental conditions (considered as "plastic" clones). Clones B2 and R9 present expected suitability to warmer conditions and were planted at 18 tropical locations (considered as tropical clones). Clones N5 and O6 present expected suitability to cooler conditions (considered as subtropical) and were planted at 4 and 3 subtropical locations, respectively. During 2010, at beginning of the TECHS Project, Brazilian forestry companies planted dozens of thousands of hectares with this set of *Eucalyptus* clones. For detailed information on these clones, see Binkley et al. (2017).

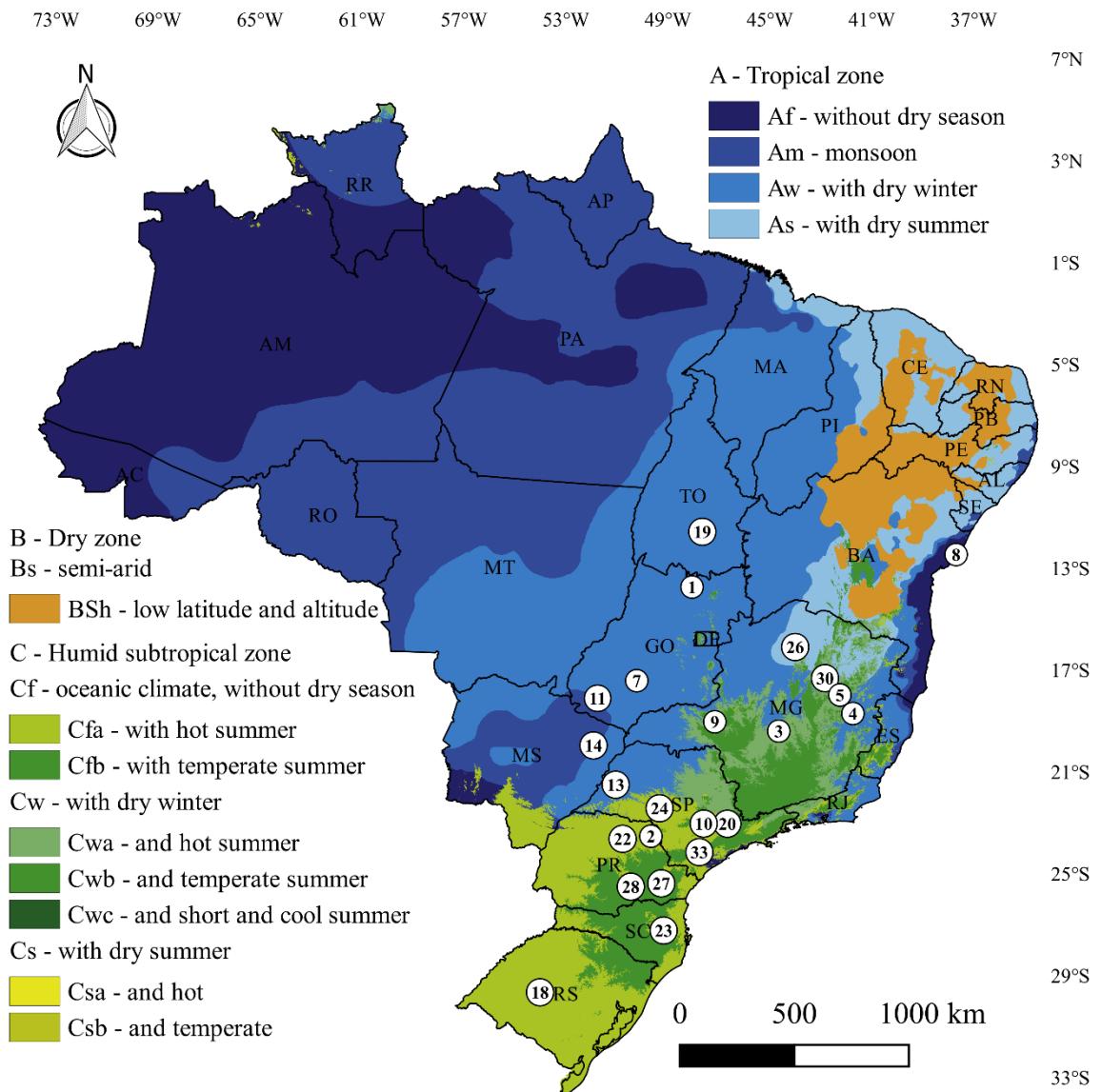


Figure 1. Locations of field experiments used for the processes of calibration and evaluation of the models and their respective Köppen climate classification in Brazil (map adapted from Alvares et al., 2013). The description of map codes and further information on the characteristics of each location are presented in Table 1.

Planting was performed from Dec/2011 to Jul/2012 (varying according to the location) for a planned rotation length of six years (Table 1). All experimental areas were prepared with subsoiling and fertilized with 70 kg Nitrogen ha^{-1} , 45 kg Phosphorus ha^{-1} , 85 kg Potassium ha^{-1} , 500 kg Calcium ha^{-1} , 90 kg Magnesium ha^{-1} , 40 kg Sulphur ha^{-1} , 3 kg Boron ha^{-1} , 1 kg Copper ha^{-1} , and 1 kg Zinc ha^{-1} . Fertilizer was applied from two to four times (varying among locations) from the preplanting through 12 months. Subsequent fertilizations were performed according to specific characteristics of each region. Preplanting fertilizers were applied in

straight lines together with the subsoiling, while subsequent fertilizers were applied throughout the tree canopy projection. Herbicides were used to control weeds in the experimental areas when necessary.

Table 1. Locations of field experiments used for the processes of model calibration and evaluation and their respective planting date and soil order.

TECHS Code	Location and State	Lat. ^a	Long.	Alt.	Planting date	Soil order ^b
		degrees	m			
1	Niquelândia, Goiás (GO)	-14.3	-48.7	545	2012/03	Oxisol
2	Arapoti, Paraná (PR)	-24.2	-49.9	770	2011/12	Oxisol
3	Bom Despacho, Minas Gerais (MG)	-19.6	-45.4	727	2012/05	Oxisol
4	Belo Oriente, Minas Gerais (MG)	-19.3	-42.4	243	2011/12	Oxisol
5	Guanhães, Minas Gerais (MG)	-18.5	-42.9	873	2012/12	Oxisol
7	Rio Verde, Goiás (GO)	-18	-50.8	681	2012/02	Entisol
8	Inhambupe, Bahia (BA)	-11.8	-38.3	218	2012/07	Ultisol
9	Estrela do Sul, Minas Gerais (MG)	-18.7	-47.9	969	2011/12	Oxisol
10	Botucatu, São Paulo (SP)	-23	-48.5	869	2011/12	Oxisol
11	Chapadão do Sul, Mato Grosso do Sul (MS)	-18.7	-52.5	783	2011/12	Oxisol
13	Três Lagoas, Mato Grosso do Sul (MS)	-20.9	-51.8	361	2012/05	Oxisol
14	Inocência, Mato Grosso do Sul (MS)	-19.9	-51.5	480	2012/03	Entisol
18	São Gabriel, Rio Grande do Sul (RS)	-30.3	-54.3	102	2012/11	Oxisol
19	Peixe, Tocantins (TO)	-12.1	-48.5	255	2012/03	Entisol
20	Mogi Guaçu, São Paulo (SP)	-22.3	-46.9	633	2012/02	Oxisol
22	Telêmaco Borba, Paraná (PR)	-24.2	-50.5	888	2012/02	Oxisol
23	Otacílio Costa, Santa Catarina (SC)	-27.5	-50.1	870	2012/01	Inceptisol
24	Borebi, São Paulo (SP)	-22.7	-49	656	2012/01	Entisol
26	Coração de Jesus, Minas Gerais (MG)	-16.7	-44.3	926	2011/12	Oxisol
27	Antônio Olinto, Paraná (PR)	-25.9	-50.1	916	2012/02	Ultisol
28	Três Barras, Santa Catarina (SC)	-26.1	-50.2	812	2012/02	Oxisol
30	Bocaiúva, Minas Gerais (MG)	-17.3	-43.7	848	2011/12	Oxisol
33	Buri, São Paulo (SP)	-23.8	-48.7	695	2011/12	Oxisol

^a Lat. = Latitude; Long. = Longitude; Alt. = Altitude.

^b Reported by forestry companies. Classified from US Soil Taxonomy (Soil Survey Staff, 2014).

Seedlings were transplanted in plots in eight rows of 15 trees at a spacing of 3×3 m (1111 trees ha⁻¹), resulting in a total plot size of 1080 m². The first five trees in each row were used for destructive sampling throughout the experiment period and were, therefore, not used for this study. A plot with eight rows of ten trees was considered for measuring the diameter at breast height (DBH, at 1.3 m above ground level) and total height (H). All the trees of this plot were measured. In this context, 80 trees (eight rows x ten trees) of each clone were periodically measured. The DBH and H were measured every 6 months (March/April and

September/October), from the planting date to March/April 2017. From these data, stem volume was estimated by allometric equations fitted from a destructive analysis of six trees for each clone at location 33-DUR (Buri, SP), in April 2014. The linearized model of Schumacher and Hall (1933) was fitted, with a specific intercept for each clone. Details of the methodological procedures for determining the volume and fit of allometric equations are presented in the Supplementary Material (Table S1).

2.2.2. Leaf area index data

Leaf area index (LAI) was estimated based on the Norman and Jarvis (1975) theory, by using a ceptometer device (AccuPAR LP-80, Decagon Devices, USA). This method considers sky conditions and the effects of canopy architecture and foliage optical properties, assuming a random foliage orientation distribution (Campbell, 1986; Norman and Jarvis, 1975; Wang et al., 2007). LAI evaluations were made for six different ages of *Eucalyptus* from 2013, following the same schedule of DBH and H measurements, for sites 2, 5, 7, 9, 10, 14, 24, 26 and 30. Six measurement locations under tree canopy were considered for each plot, three of them in the row and three between rows. In each measurement location, four readings of photosynthetically active radiation (PAR) were performed, with a total of 24 measurements per plot. For each plot, one measurement was done outside the canopy. All measurements were taken from 10:00 to 14:00. Further information about the procedures for estimating LAI are presented in Mattos (2015).

2.2.3. Weather and soil data

The weather data (maximum, minimum and mean temperatures, solar radiation, rainfall, relative humidity and wind speed) were obtained from the weather stations located in the experimental areas of each forestry company, member of the TECHS project, and when data were not available, we obtained them from the nearest weather stations belonging to the National Institute of Meteorology (INMET). The missing data was completed from the nearest weather stations of the National Water Agency (ANA), and from daily gridded meteorological data, such as (i) “CHIRPS” – Climate Hazards Group InfraRed Precipitation with Station (Funk et al., 2015), with a spatial resolution of 0.05°, (ii) “XAVIER” – Daily gridded meteorological variables in Brazil, with a spatial resolution of 0.25° (Xavier et al., 2016) and (iii) NASA/POWER – NASA Langley Research Center POWER Project, with a spatial resolution of 1° (Stackhouse et al., 2015). A summary of the weather conditions during the field experiments is described in the Supplementary Material (Table S2).

The soil order was reported by forestry companies. For the FAO and 3PG models, pedotransfer functions fitted for Brazilian soils (Assad et al., 2001; Reichert et al., 2009) were used to estimate the soil water content at the permanent wilting point, field capacity and then the soil water holding capacity, considering an effective root depth of 3 m (Christina et al., 2017; Pinheiro et al., 2019). For fitting these functions, water retained at a tension of 10 kPa was taken as field capacity and at 1,500 kPa taken as the permanent wilting point. For APSIM, which requires more detailed and complex data on the physical and hydraulic soil characteristics, RadamBrasil (1974) and Wise (Batjes, 2009) database were used for building and adjusting the soil profile, according to the characteristics of each location.

2.2.4. *Eucalyptus* simulation models

The FAO, APSIM and 3PG models were chosen due to their wide use around the world, ability to successfully simulate *Eucalyptus* yield in previous studies and have different features and complexity levels (Almeida and Sands, 2016; Freitas, 2018; Huth et al., 2008; Huth et al., 2001; Paydar et al., 2005; Sands and Landsberg, 2002). The FAO is a mathematical-physiological model that simulates gross photosynthesis at a daily time step according to the carbon fixation mechanism and climate adaptation of the plant. Potential yield (Y_p) is simulated according to the interactions of the genotype with solar radiation, photoperiod and air temperature. Subsequently, Y_p is penalized by water deficit at different periods of the *Eucalyptus* rotation and according to the intensity of the accumulated water deficit. A general approach of this model is presented as follows:

$$Y_a = PGP \times C_{LAI} \times C_{RESP} \times C_F \times Ffrost \times C_{Ky} \times Fw \quad (1)$$

where: Y_a is the attainable yield, PGP the gross photosynthesis; C_{LAI} the depletion coefficient for leaf area index; C_{RESP} the depletion coefficient associated with the maintenance respiration process; C_F the forest harvest index; $Ffrost$ the frost penalization factor; C_{Ky} the relative yield reduction by water deficit and Fw the mortality index by extreme water deficit.

The FAO simulation model is often used for annual crops (Battisti et al., 2017; Dias and Sentelhas, 2017; Monteiro and Sentelhas, 2017; Sentelhas et al., 2015). Therefore, to adapt it for *Eucalyptus* plantations, wood density functions, frost penalization and water deficit mortality indexes were added to this version by Freitas (2018). For detailed information on this model, see Doorenbos and Kassam (1979) and Freitas (2018).

The APSIM framework presents models for over 30 crops. The simulation model used for *Eucalyptus* is known as “APSIM-Growth” (Huth et al., 2001). The version 7.9 was used in the present study. The APSIM - Growth model calculates daily biomass production from intercepted solar radiation and radiation use efficiency, which is affected by soil and climatic factors. Interception of solar radiation is calculated assuming an exponential decay of light within a canopy. Its general approach can be described by the following expression:

$$\Delta G = R_{\text{int}} \times \varepsilon \times \min(F_T, F_N, F_{VPD}) \times F_W \quad (2)$$

where: ΔG is the daily growth; R_{int} the daily intercepted solar radiation; ε the radiation use efficiency (g MJ^{-1} of global solar radiation); and F_T , F_N , F_{VPD} and F_W growth modifiers for air temperature, nitrogen, vapor pressure deficit and soil water, respectively.

Detailed information about this model can be seen in Mccown et al. (1996) and Huth et al. (2001). The APSIM model does not present the variable “stem volume” as output. This model presents the variable “stem dry matter” (excluding branches) only. Thus, the following wood density function proposed by Sands and Landsberg (2002) was used:

$$\rho = \rho_1 + (\rho_0 - \rho_1) e^{-0.69315 \left(\frac{\text{Age}}{t\rho} \right)^{2.99}} \quad (3)$$

where: ρ is the basic density at a certain age (t m^{-2}); ρ_0 is the basic density of young trees (t m^{-2}); ρ_1 the basic density of old trees (t m^{-2}) and $t\rho$ the age that the trees present intermediate basic density ($t\rho = (\rho_0 + \rho_1)/2$).

Using the wood density curve according to age, the *Eucalyptus* stem volume was calculated using the following equation:

$$\text{Volume} = \sum_{i=1}^n \left(\frac{\text{SDM}_i}{\rho_i} \right) \quad (4)$$

where: Volume is the *Eucalyptus* stem volume ($\text{m}^3 \text{ ha}^{-1}$); i the day of the rotation, ranging from the first (1) until the last day of the *Eucalyptus* rotation (n); SDM the stem dry matter (excluding branches) according to *Eucalyptus* age (t ha^{-1}); and ρ_i the wood density (t m^{-3}), which varies throughout the rotation.

The 3PG model is based on a solar radiation absorption model that calculates photosynthetically active radiation intercepted by the forest stand (APAR) at a monthly time step. APAR is converted to gross primary production by using the canopy quantum efficiency,

which is modified by environmental factors, such as vapor pressure deficit, air temperature, days of frost, available soil water, soil fertility and stand age. The general approach of this model can be seen in the following expression:

$$P_G = f_T \times f_N \times f_F \times \varphi \times \alpha_{Cx} \times \phi_{pa} \quad (5)$$

where: P_G is the gross primary production; f_T , f_N and f_F the temperature, nutritional and frost modifiers, respectively; φ the physiological modifier; α_{Cx} the theoretical maximum canopy efficiency; and ϕ_{pa} the APAR by the forest stand according to Beer's Law.

The 3PG model version 2.7 as used in this study is presented in Visual Basic for Applications language. This is a model specific to forest species. For detailed information on this model, see Landsberg and Waring (1997), Sands (2004a) and Sands and Landsberg (2002). An intercomparison of the main structural features, processes and approaches of the *Eucalyptus* simulation models used in the present study are described in the Supplementary Material (Table S3). The simulations of all models began six months before the *Eucalyptus* planting in order to normalize water balance in the models.

2.2.5. Model calibration and evaluation

The *Eucalyptus* yield data were randomly divided into two sets, the first one (about 70% of the total yield data) used to calibrate and the second (about 30% of the total yield data) to evaluate the models. Further information about the number of *Eucalyptus* yield results used for the calibration and evaluation processes of each Brazilian clone are presented in the Supplementary Material (Table S4). The model calibration was performed manually based on field data (stem volume, LAI, basic wood density, and soil water holding capacity) and by data and parameterization already described in the literature, until a suitable fit was obtained between the simulated and observed values. The parameters calibrated for all clones and models are presented in the Supplementary Material (Tables S5, S6, S7, S8, S9 and S10).

Model performance in the calibration and evaluation phases was tested using the following statistical indexes and errors: Coefficient of determination – R^2 , Willmott Agreement Index – d (Willmott et al., 1985), Modelling Efficiency Index – E (Nash and Sutcliffe, 1970), Confidence Index – C (Camargo and Sentelhas, 1997), Mean Absolute Error – MAE , Mean Error – ME and Root Mean Square Error – $RMSE$, which are presented in the Supplementary Material (Table S11). The relationships between observed and estimated stem volume in the calibration and evaluation phases, as well as with a number of the statistical indexes for each

clone, were examined. Locations with contrasting climate and soil characteristics were selected to plot the observed and estimated volume and LAI throughout the *Eucalyptus* rotation for all assessed clones, in order to demonstrate the performance of the models under different climate and soil conditions. The observed and estimated mean annual increment (MAI) of two clones with contrasting environmental responses (A1 and C3) are also presented in the Supplementary Material (Tables S12 and S13) for demonstrating the yield variability in the 23 sites.

2.2.6. Ensemble approach

After calibration and evaluation of the models, a multimodel ensemble was performed, by determining the average of the estimated *Eucalyptus* volume of the tree models. The same statistical indexes and errors used in the calibration and evaluation phases were also considered for the ensemble approach, aiming to compare its performance with the individual performance of the models.

2.3. Results

2.3.1. Performance of Eucalyptus simulation models and their ensemble in the calibration process

The performances of all the simulation models were sufficient ($R^2 \geq 0.73$, $d \geq 0.92$, $E \geq 0.73$ and $C \geq 0.79$) for estimating the *Eucalyptus* stem volume during the calibration phase (Figure 2). The FAO model presented slightly greater precision ($R^2 = 0.80$) compared to the APSIM ($R^2 = 0.73$) and 3PG ($R^2 = 0.75$) models. The level of accuracy was the same for all of them ($d = 0.92$). The C index (which takes into account precision and accuracy indexes together) was slightly higher for the FAO model (0.83) compared to the APSIM (0.79) and 3PG (0.80) models, and all the values were considered “very good” (Camargo and Sentelhas, 1997).

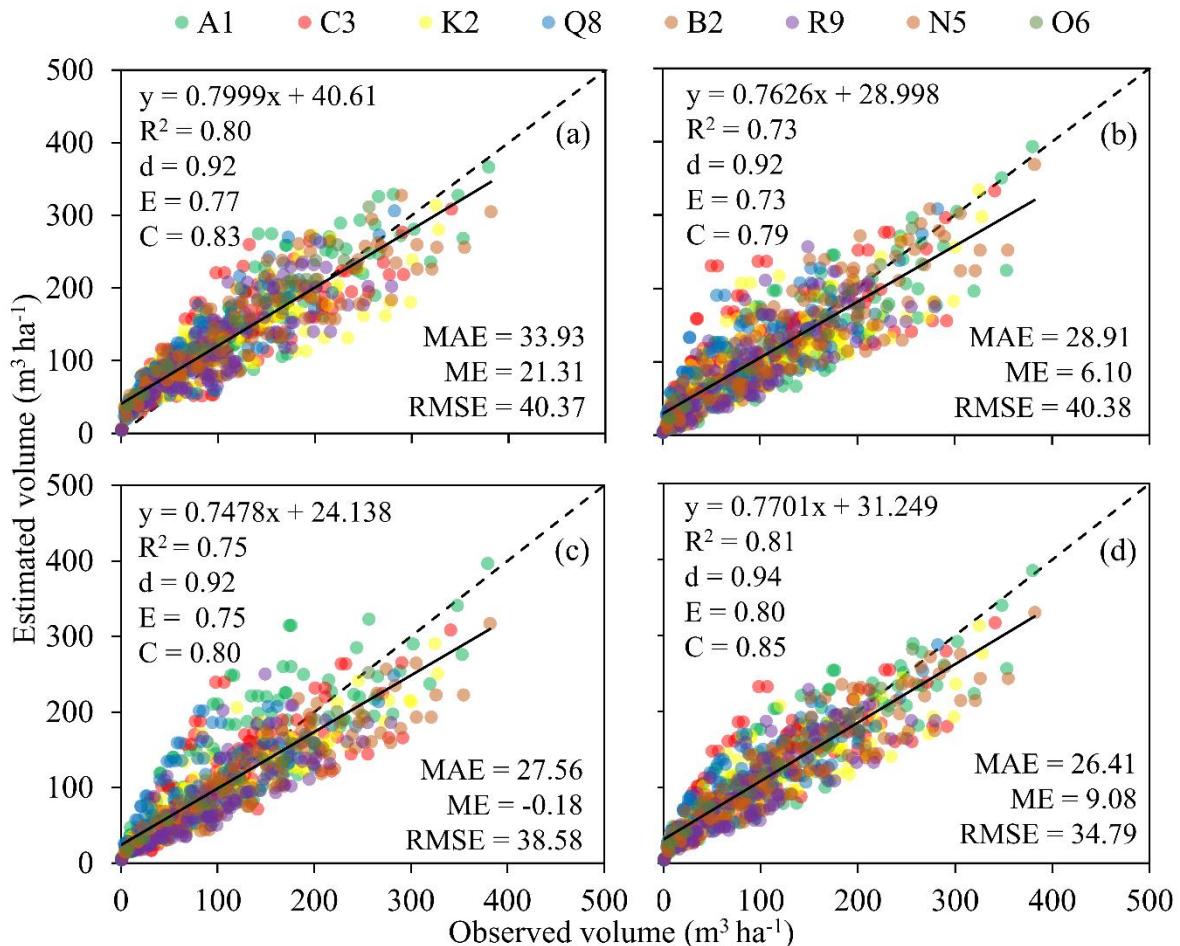


Figure 2. Relationship between the observed and estimated *Eucalyptus* stem volume by the FAO (a), APSIM (b) and 3PG (c) models and their ensemble (d), during the calibration phase. *Colors indicate the different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6); R² = coefficient of determination; d = Willmott Agreement Index; E = Modelling Efficiency Index; C = Confidence Index; MAE = Mean Absolute Error ($\text{m}^3 \text{ha}^{-1}$); ME = Mean Error ($\text{m}^3 \text{ha}^{-1}$); RMSE = Root Mean Square Error ($\text{m}^3 \text{ha}^{-1}$).

The 3PG model presented the smallest errors (MAE = 27.6 $\text{m}^3 \text{ha}^{-1}$; ME = -0.18 $\text{m}^3 \text{ha}^{-1}$ and RMSE = 38.6 $\text{m}^3 \text{ha}^{-1}$), while the FAO model presented the largest ones (MAE = 33.9 $\text{m}^3 \text{ha}^{-1}$; ME = 21.3 $\text{m}^3 \text{ha}^{-1}$ and RMSE = 40.4 $\text{m}^3 \text{ha}^{-1}$). The multimodel ensemble approach led to improvements in the performance of *Eucalyptus* yield estimations, with slightly higher R² (0.81), d (0.94), E (0.80) and C (0.85) indexes and lower MAE (26.4 $\text{m}^3 \text{ha}^{-1}$) and RMSE (34.89 $\text{m}^3 \text{ha}^{-1}$), compared to the individual performance of the models.

2.3.2. Performance of the *Eucalyptus* simulation models and their ensemble in the evaluation process

Satisfactory performances were obtained sufficient ($R^2 \geq 0.81$, $d \geq 0.94$, $E \geq 0.75$ and $C \geq 0.85$) when the *Eucalyptus* simulation models were evaluated with independent data (Figure 3). A similar trend to the calibration phase was found for the R^2 , d and C indexes. The E index was slightly higher for the 3PG model (0.81) compared to the APSIM (0.79) and FAO (0.75) models. The multimodel ensemble approach improved the performance of *Eucalyptus* yield estimations, with higher R^2 (0.89), d (0.96), E (0.85) and C (0.90) and lower MAE ($25.78 \text{ m}^3 \text{ ha}^{-1}$) and RMSE ($33.1 \text{ m}^3 \text{ ha}^{-1}$), compared to the individual performance of the models.

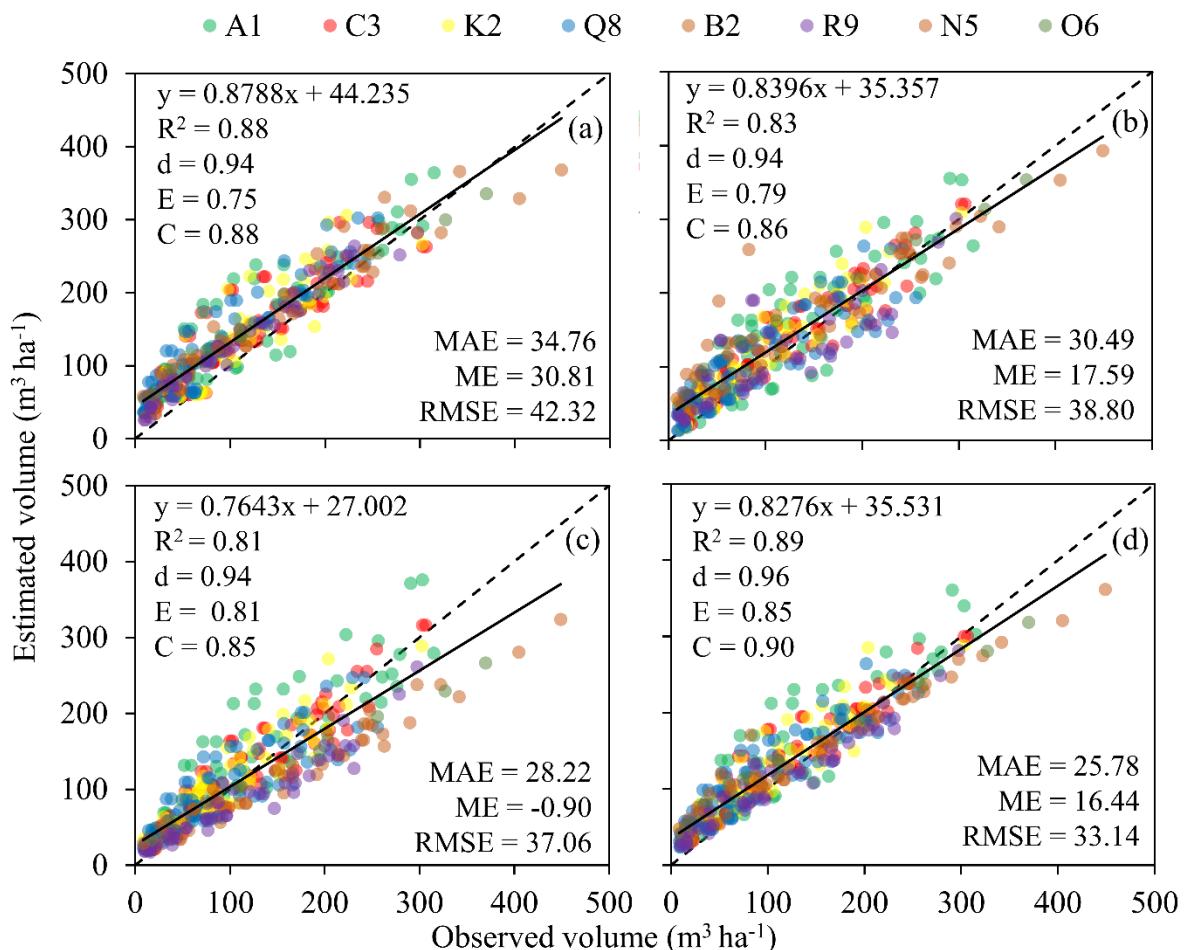


Figure 3. Relationship between the observed and estimated *Eucalyptus* stem volume by the FAO (a), APSIM (b) and 3PG (c) models and their ensemble (d) during the evaluation phase. * Colors indicate the different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6); R^2 = coefficient of determination; d = Willmott Agreement Index; E = Modelling Efficiency Index; C = Confidence Index; MAE = Mean Absolute Error ($\text{m}^3 \text{ ha}^{-1}$); ME = Mean Error ($\text{m}^3 \text{ ha}^{-1}$); $RMSE$ = Root Mean Square Error ($\text{m}^3 \text{ ha}^{-1}$).

2.3.3. Performance of the *Eucalyptus* simulation models and their ensemble by individually assessing the clones

The models presented a different performance for yield estimations when *Eucalyptus* clones were individually assessed during the calibration and evaluation phases, with satisfactory precision ($R^2 \geq 0.62$) and accuracy ($d \geq 0.87$) both in the calibration and evaluation phases (Table 2). Generally, the ensemble of models showed slightly higher values of R^2 , d , E and C indexes and lower MAE for most *Eucalyptus* clones.

Table 2. Statistical indexes (SI) and errors from the relationship between the observed and estimated volume of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6) determined by the FAO, APSIM and 3PG models and their ensemble (Ens.), during the calibration and evaluation phases.

SI/Errors	Clon.	Calibration				Evaluation			
		FAO	APSIM	3PG	Ens.	FAO	APSIM	3PG	Ens.
R^2	A1	0.85	0.78	0.73	0.84	0.85	0.77	0.81	0.83
	C3	0.75	0.62	0.72	0.74	0.84	0.89	0.91	0.92
	K2	0.77	0.72	0.85	0.82	0.82	0.87	0.89	0.89
	Q8	0.83	0.69	0.67	0.81	0.88	0.79	0.79	0.86
	B2	0.84	0.84	0.88	0.88	0.93	0.84	0.97	0.96
	R9	0.76	0.68	0.73	0.77	0.97	0.71	0.92	0.93
	N5	0.79	0.66	0.93	0.82	0.99	0.99	0.99	0.99
	O6	0.97	0.91	0.97	0.96	0.99	0.99	0.99	0.99
d	A1	0.94	0.94	0.92	0.95	0.92	0.92	0.93	0.93
	C3	0.90	0.88	0.91	0.91	0.92	0.96	0.97	0.96
	K2	0.91	0.91	0.94	0.93	0.90	0.94	0.96	0.95
	Q8	0.90	0.89	0.89	0.92	0.90	0.93	0.93	0.94
	B2	0.94	0.95	0.92	0.96	0.96	0.94	0.90	0.97
	R9	0.92	0.90	0.91	0.93	0.96	0.90	0.92	0.97
	N5	0.90	0.87	0.97	0.93	0.96	0.95	0.96	0.97
	O6	0.95	0.97	0.98	0.98	0.97	0.97	0.92	0.97
E	A1	0.78	0.78	0.69	0.82	0.68	0.70	0.74	0.74
	C3	0.65	0.57	0.71	0.70	0.69	0.83	0.89	0.85
	K2	0.71	0.72	0.82	0.80	0.58	0.76	0.85	0.78
	Q8	0.55	0.61	0.63	0.71	0.52	0.73	0.78	0.76
	B2	0.81	0.83	0.77	0.86	0.87	0.80	0.72	0.90
	R9	0.71	0.67	0.70	0.77	0.87	0.70	0.76	0.90
	N5	0.67	0.64	0.91	0.80	0.87	0.85	0.89	0.91
	O6	0.81	0.89	0.94	0.93	0.92	0.89	0.79	0.92
C	A1	0.87	0.83	0.79	0.87	0.85	0.81	0.84	0.85
	C3	0.78	0.69	0.77	0.78	0.85	0.90	0.92	0.92
	K2	0.80	0.78	0.87	0.84	0.82	0.88	0.91	0.89
	Q8	0.81	0.74	0.73	0.83	0.84	0.82	0.83	0.87
	B2	0.86	0.87	0.87	0.89	0.93	0.86	0.89	0.95
	R9	0.80	0.75	0.77	0.82	0.95	0.76	0.89	0.93
	N5	0.80	0.71	0.94	0.84	0.96	0.95	0.96	0.97
	O6	0.94	0.92	0.97	0.96	0.97	0.96	0.92	0.97
MAE ($m^3 \text{ ha}^{-1}$)	A1	34.18	29.91	36.77	29.18	39.31	38.61	33.85	34.19
	C3	35.91	31.24	26.98	29.68	33.82	25.59	21.59	22.69
	K2	34.30	29.18	24.92	25.83	34.12	25.00	21.54	24.07
	Q8	35.69	27.63	27.48	26.69	40.22	29.60	25.76	27.06
	B2	31.75	28.58	29.36	25.14	32.42	34.68	44.93	24.57
	R9	30.21	27.69	25.69	23.38	26.06	33.09	28.60	21.12
	N5	35.84	30.27	16.10	24.30	29.16	33.50	28.34	24.76
	O6	31.73	20.83	16.30	16.57	30.75	36.41	44.99	32.61

^a R^2 = coefficient of determination; d = Willmott agreement Index; E = modelling efficiency index; C = confidence index; MAE = mean absolute error.

During the calibration phase, R^2 ranged from 0.75 to 0.97 for FAO model, from 0.62 to 0.91 for APSIM, from 0.67 to 0.97 for 3PG and from 0.74 to 0.96 for the ensemble of the three models. The d index, in the same sequence, ranged from 0.90 to 0.95, from 0.87 to 0.97, from

0.89 to 0.98 and from 0.91 to 0.98, whereas E index ranged from 0.55 to 0.81, from 0.57 to 0.89, from 0.63 to 0.94 and from 0.70 to 0.93, respectively. The C index ranged from 0.78 to 0.94 for FAO model, from 0.69 to 0.92 for APSIM, from 0.73 to 0.97 for 3PG and from 0.78 to 0.96 for the ensemble of the models. The MAE ranged from 30.2 to 35.9 m³ ha⁻¹ for FAO model, from 20.8 to 31.2 m³ ha⁻¹ for APSIM, from 16.1 to 36.8 m³ ha⁻¹ for 3PG and from 16.57 to 29.7 m³ ha⁻¹ for the ensemble of the models.

During the evaluation phase with independent data, R² ranged from 0.71 to 0.99 for the models when considered individually and from 0.83 to 0.99 for their ensemble. The d index ranged from 0.90 to 0.97 for each individual model and from 0.93 to 0.97 for their ensemble, whereas the E index ranged from 0.52 to 0.92 for the individual models and from 0.74 to 0.92 when their ensemble was considered. The C index ranged from 0.76 to 0.97 for the models when considered individually and from 0.85 to 0.97 for their ensemble. Finally, MAE ranged from 21.5 to 45.0 m³ ha⁻¹ for the single models and from 21.1 to 34.2 m³ ha⁻¹ when all models were combined in an ensemble.

*2.3.4. Stem volume growth, LAI throughout the *Eucalyptus* rotation and some limitations during process-based simulations*

The models were able to simulate forest yield under different climate and soil conditions, as well as the differences among the eight genotypes assessed (Figure 4). For example, clone A1 reached 380 m³ ha⁻¹ at 58 months of age, with mean annual increment of 79 m³ ha⁻¹ year⁻¹, in TECHS site 33, while clone C3 had a yield of 144 m³ ha⁻¹ at 60 months of age (MAI = 29 m³ ha⁻¹ year⁻¹), in TECHS site 19, and clone K2 reached 34 m³ ha⁻¹ at 34 months of age (MAI = 12 m³ ha⁻¹ year⁻¹), in TECHS site 8. Another important aspect to be highlighted is that in most cases the models presented yield overestimation at the beginning of the *Eucalyptus* rotation. In this context, we must evidence the importance of assessing field data from different ages to build a growth curve and not only use final yield. This helps researchers to identify possible limitations of the models and fix them.

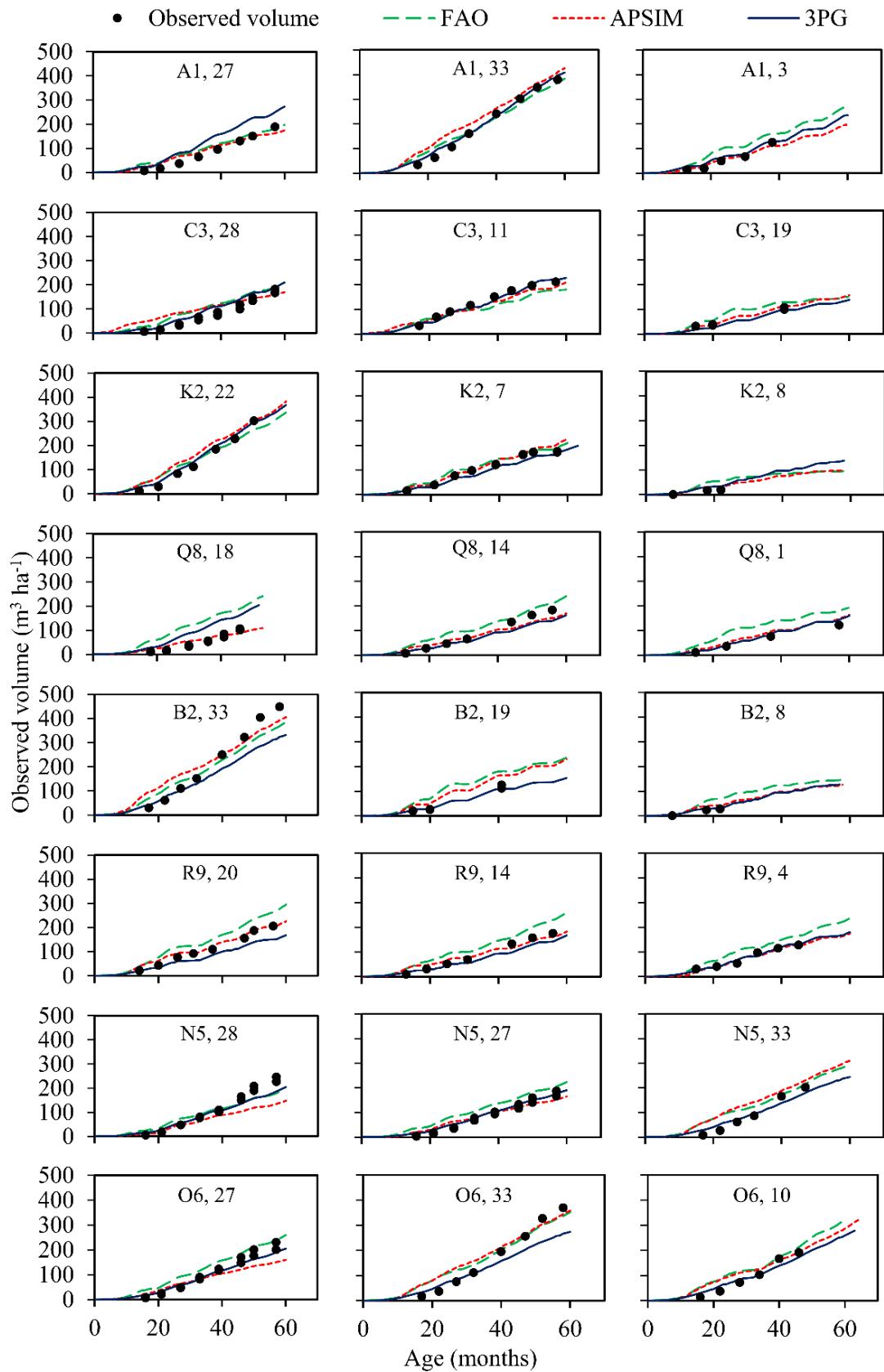


Figure 4. Observed and estimated stem volume throughout the rotation of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6) by the FAO, APSIM and 3PG models at locations (TECHS codes in the figure) with varying climates and soil types.

A huge yield variability was also observed when analysing two contrasting clones cultivated in the 23 locations (see Tables S12 and S13 in the Supplementary Material). Comparatively, the *Eucalyptus* simulation models were able to simulate yield more accurately for clone A1. The observed yield of this clone presented lower standard deviation ($SD = 15.9\text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) and coefficient of variation ($CV = 31.8\%$) when compared to clone C3 ($SD = 17.4\text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, $CV = 46.1\%$). It denotes that clone C3 is more sensitive to environmental variations than clone A1. A number of limitations were observed in the *Eucalyptus* simulation models, mainly in locations with: (i) very dry conditions (site 19, for clone A1, and 1, 3, and 8, for clone C3); (ii) low temperatures (site 23, for both A1 and C3 clones); and (iii) poorly drained soils (site 18, for both A1 and C3 clones)

The LAI variation throughout the *Eucalyptus* rotation depended on the clone and environment (Figure 5). Generally, maximum LAI was observed from 16 to 26 months of age, with seasonal variation observed. The APSIM and 3PG models presented a good capacity for identifying seasonal LAI variations. The FAO model, on the other hand, was not able to simulate that since it uses a fixed theoretical potential LAI curve, which reaches the maximum value at 30 months, reducing slightly afterwards until the end of the rotation. Subsequently, the yield of this model is penalized by water deficit sensitivity indexes (ky and Fw).

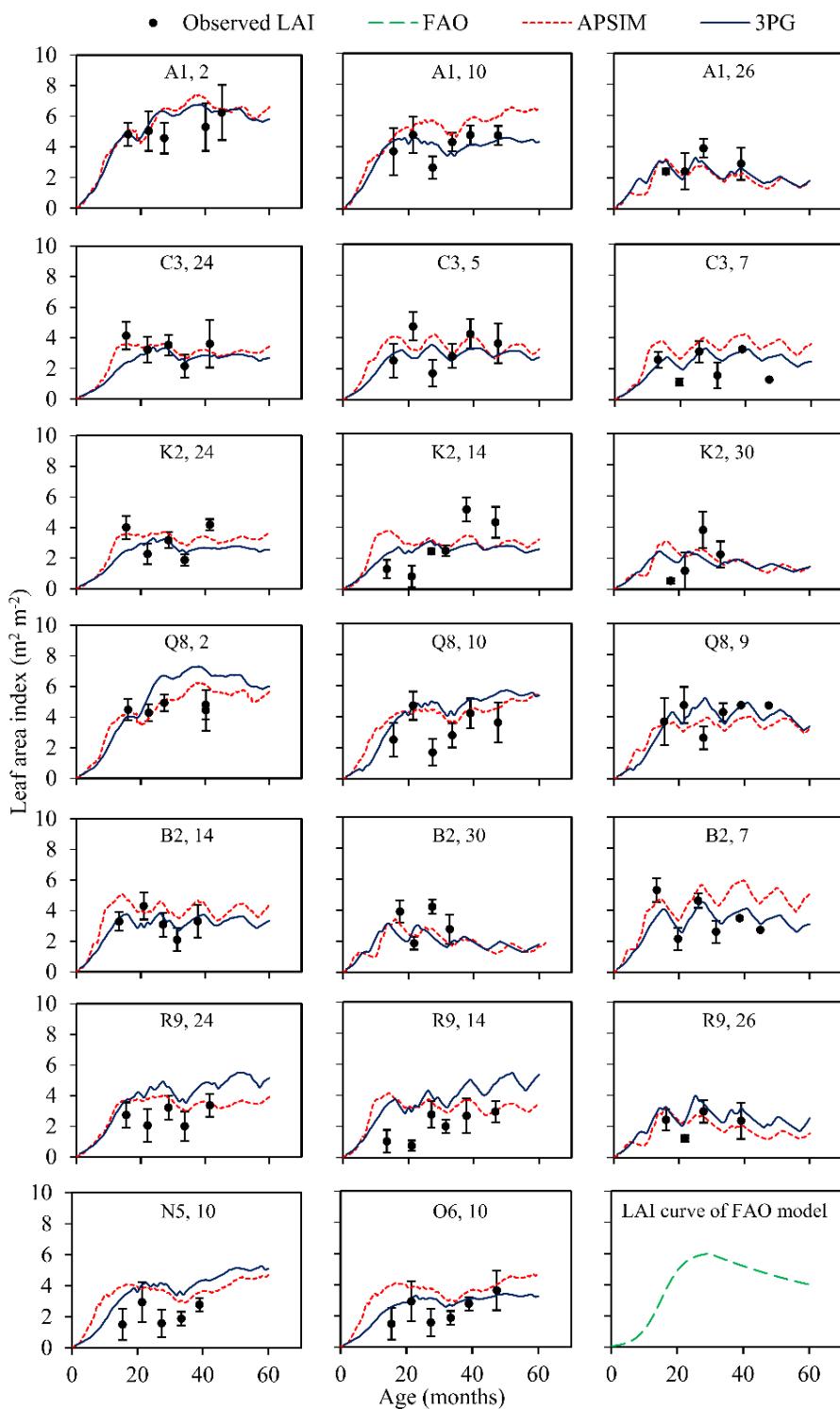


Figure 5. Observed and estimated LAI throughout the rotation of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6) by the APSIM and 3PG models at locations (TECHS codes in the figure) with varying climates and soil types and the theoretical potential LAI curve of the FAO model. *Statistical indexes and errors from the relationship between the observed and estimated LAI are presented in the Supplementary Material (Table S14).

2.4. Discussion

The statistical indexes and errors agree with several other studies involving different *Eucalyptus* simulation models. For the FAO model, no results of *Eucalyptus* yield estimations were found in the literature. For the APSIM model, Paydar et al. (2005) modeled *Eucalyptus grandis* growth in irrigated areas in Australia. No statistical indexes were presented in that study, but the authors found a good relationship between observed and estimated stem volumes. Huth et al. (2008) studied the growth and survival of *Eucalyptus melliodora* and *Eucalyptus populnea* under a range of drought conditions in Australia and observed a satisfactory model ability to estimate aboveground biomass.

For the 3PG model, Sands and Landsberg (2002) found $R^2 = 0.71$ for volume MAI estimations of *Eucalyptus globulus* in Australia. Stape et al. (2004) obtained R^2 from 0.71 to 0.83, E index from 0.61 to 0.75 and RMSE from 5.6 to 7.6 Mg ha⁻¹ year⁻¹ for wood production estimations of *Eucalyptus grandis* x *urophylla* grown under different fertilization treatments in the state of São Paulo, Brazil. Borges et al. (2012) found an $R^2 = 0.92$ for stem volume estimations of *Eucalyptus grandis* x *urophylla* clonal hybrid in the state of Minas Gerais, Brazil. González-García et al. (2016) observed $R^2 = 0.84$, E index = 0.79 and RMSE = 29.51 m³ ha⁻¹ for stem volume estimations of *Eucalyptus nitens* in Spain.

The improvement in performance of the forest simulations with the multimodel ensemble approach had also been found by Hanson et al. (2004), who established model inter-comparisons for estimating carbon and water flux in a mixed-species stand in the United States. These authors demonstrated that ensemble provided a better representation of observed daily evapotranspiration than any the predictions of any single model. These authors found a R^2 ranging from 0.34 to 0.80 and the E ranging from 0.32 to 0.79 for models individually assessed, while for their ensemble the R^2 was increased to 0.85 and the E to 0.84. For soil water content estimations, these authors found the multimodel ensemble presented similar or better performance when compared to the best individually assessed model.

A multimodel approach for simulating *Populus tremuloides* growth in the United States was used by Wang et al. (2014). No statistical results of the model performance were presented; however, the authors suggested that ensemble approach is a robust option when sufficient field data for processes of calibration and evaluation for an individual model are lacking. A comparison of four process-based models for yield estimation of *Eucalyptus globulus* in Australia was made by Miehle et al. (2009). These authors evaluated the models individually and found an E index of 0.22, 0.57, -0.55, and 0.30, respectively for 3PG+, 3PG, CABALA and Forest-DNDC models, using yield data from eight years after planting. E index values in the

present study were greater than or similar to those reported by these authors. As one can see, there are no results from the literature which used a multimodel approach (ensemble) for *Eucalyptus* yield estimations. This approach is still not widespread in forest science community, which suggests that more studies about that should be developed for other forest species and countries.

The yield overestimation under lower temperatures could be related to the models' incapacity to penalize growth by extreme minimum temperatures and frost occurrence. Comparatively, the 3PG model presents a more simplistic approach for considering the impact of frosts on forest growth (Waring and Gao, 2016). This model assumes there is no photosynthesis (stomata will remain closed) on frost days, but tree mortality is not simulated. Monthly frost days are counted, and growth is zero on such days. The FAO and APSIM models consider the intensity of frost. For the FAO model, frost effects are considered for up to two years of age, given by two ways: reduction in gross photosynthesis during frost days and mortality rate. The intensity of frosts was based on daily minimum temperature. For the APSIM model, the intensity of frost is considered by the growth modifier by frost (ff), which ranges from zero to one and is linearly interpolated for different limits in daily minimum temperature. Senescence of foliage may occur due to frost days, but tree mortality (reduction of plant stand in more severe frosts) is not considered.

The lower agreement between estimated and observed *Eucalyptus* yield in TECHS site 18 is justified by both the lack of penalization by frosts and by the occurrence of soil waterlogging during the rainy season. Long periods waterlogging may cause root rotting, permanent wilting, defoliation and anoxia, constraining respiration (Basak et al., 2015). The FAO and 3PG models do not consider any function related to waterlogging. The APSIM model presents a penalization index that takes into account the effects of the pore space filled with air (parameter "x_afps"; mm³ air mm⁻³ soil volume) on a root function modifier (parameter "y_afps_fac", ranging from zero to one). As default, this function is not calibrated for affecting root growth ("y_afps_fac" is equal to 1 for any value of "x_afps"). Even this function does not directly affect the yield, it could be an alternative for improving the model performance in such specific conditions, but to calibrate this parameter, more detailed soil data would be required, as well as information related to *Eucalyptus* root growth.

Forest yield overestimations were also observed in a number of cases with severe water deficit. In this context, root growth functions and extractable soil water approaches deserve attention and could be improved in the *Eucalyptus* simulation models. Generally, the APSIM model presented a better performance under severe water deficit. This model presents a more

complex and detailed approach to soil water dynamics and water balance approach, and obviously requires a higher number of soil data. Different soil layers to describe the vertical distribution of soil moisture are considered in the APSIM model, and available water in each layer depends on the extraction front progressing to greater depths. In the FAO model, the soil water holding capacity (SWHC) varies throughout the *Eucalyptus* rotation according to the potential root growth, while in the 3PG, a single-layer soil water balance is used throughout the *Eucalyptus* rotation. On the other hand, the 3PG model takes into account intercepted rainfall by canopy for calculating the water balance, while the FAO model does not simulate this process.

A high mortality rate due to water deficit may occur in *Eucalyptus* plantations in Brazil, depending on the intensity of water deficit and the genotype. The clone C3 presented a higher sensitivity to water deficit compared to the clone A1. An example for the differences between the genotypes, in TECHS site 1, long periods of water deficit caused a mortality of 4% for clone A1 whereas for clone C3 the mortality reached 30%. It could explain the more pronounced difference between estimated and observed *Eucalyptus* yields in the sites where there are very dry conditions, mainly for the clone C3.

In addition to the root growth functions and extractable soil water approaches of the models, water deficit mortality functions could be very important to properly simulate the *Eucalyptus* yield in semiarid regions or where the dry season is very intense in Brazil. In this context, the FAO model presents the parameter “Fw”, which considers the mortality of the stand for different ranges of accumulated water deficit in the last month, and it is calibrated for each *Eucalyptus* clone. This function is applied throughout all the *Eucalyptus* rotation. In the APSIM model, a plant mortality rate is considered according to the accumulated water stress days, in order to simulate the decline in population with increasing duration of drought conditions. As default, plant mortality rate is 2% per stress day, and this function is considered until the age of 6 months or a total above-ground biomass of 6 g plant⁻¹. In the 3PG model, stem mortality and self-thinning functions are considered, but they are not directly affected by the water deficit (Sands, 2004b). Even for the FAO model, which presents a relatively more complex approach for water deficit mortality, it was not able to properly identify the effects of mortality rate on the *Eucalyptus* yield in these specific cases. This is an important aspect that should be improved by more complex *Eucalyptus* simulation models.

The overestimation of models at the beginning of the *Eucalyptus* rotation (Figure 4) was also found by Almeida et al. (2004), who parameterized the 3PG model for *Eucalyptus grandis* plantations in Brazil, by Battaglia et al. (2004) applying the CABALA model to *Eucalyptus*

globulus plantations in Australia and by Miehle et al. (2009) who used process-based and statistical regression models on *Eucalyptus globulus* plantations in Australia. For the FAO model, such overestimation in the first stages of the forest rotation can be justified by its simpler biomass partitioning approach.

For the APSIM and 3PG models, certain possible causes of overestimation give rise to difficulties when modelling the development of canopy crown architecture and its effect on radiation absorption and rainfall interception, mainly before canopy closure (Pury and Farquhar, 1997; Law et al., 2001), as well as to the simulations of leaf photosynthetic properties changes and the persistence of young foliage (Beadle et al., 1989). In the present study, simulation models tended to self-correct their growth curve according to the *Eucalyptus* age, as also observed by Miehle et al. (2009). Therefore, precise and accurate stem volume estimations at early ages were not necessarily a prerequisite for adequate simulations during the final stage of the rotation. Additionally, process-based simulations at the beginning of the *Eucalyptus* rotation are usually not of interest for commercial, scientific or policy applications (Miehle et al., 2009).

The LAI variation throughout the *Eucalyptus* rotation (Figure 5) was influenced by seasonal variation in weather conditions. Greater annual LAI values were mainly observed after rainy seasons. In southern Brazil (such as TECHS site 2), this variation was less evident due to a regular rainfall distribution over the year. These results agree with those from several other studies. Lemos (2012) found maximum LAI at 18 months of age and seasonal oscillations according to weather conditions (greater LAI after rainy seasons) in *Eucalyptus* plantations in São Paulo, Brazil. Hakamada et al. (2016) observed peaks of LAI at 24 months of age and a subsequent reduction in this variable over the rotation of *Eucalyptus* plantations in the states of Bahia and São Paulo, Brazil. Additional studies from Brazil and other countries showed that the age at which *Eucalyptus* canopy is closed ranged from one to three years (Almeida and Sands, 2016; Borges et al., 2012; González-García et al., 2016; Guimarães et al., 2007; Williams et al., 2009).

A decrease in estimated LAI by the APSIM and 3PG models was observed mainly after periods of water deficit, and a number of differences in the magnitude of the values were observed (such as for clone A1 in TECHS site 10, for clone B2 in site 7 and for clone R9 in site 14). The differences in the estimated LAI by these models could be related to the sensitivity of biomass production and biomass partitioning functions to climate stresses, such as water deficit and high vapor pressure deficit and temperature.

For example, in the APSIM model, limits of average daily temperature are used as growth parameters. From these limits, photosynthesis modifier for temperature (ft) factor is linearly interpolated by the model. ft increases to some range of optimum temperature (remaining constant in this range), and then declines. In the 3PG model, ft increases to some single value of optimum temperature (not for a range), and then declines. In the FAO model, even though this model does not estimate the actual leaf area, temperature will influence other plant's processes through the correction factors (cTn and cTc), which simulate the effect of air temperature on gross photosynthesis. These factors are polynomials (Barbieri and Tuon, 1992) and vary according to the groups of carbon fixation metabolism (C3 and C4).

Another important approach that differentiates the models used in the present study is the dynamics of nutrients in the soil, especially nitrogen. Comparatively, the APSIM model features a wider range of processes related to nitrogen fertilization, whereas FAO model does not simulate nitrogen dynamics, considering always that the forest is well supplied with this nutrient, and 3PG model uses a general parameter (soil fertility rating, FR), which describes soil fertility level in the rooting zone, ranging from 0 (low fertility) to 1 (non-limiting fertility). This parameter is usually calibrated according to the knowledge on the soils of each location (Almeida et al., 2004; Landsberg et al., 2003; Lemos, 2012).

In the APSIM model, plant nitrogen demand depends on the size of biomass pools and a target nitrogen concentration for each pool. The partitioning of nitrogen taken up from the soil mineral pools depends on the sink strengths calculated from nitrogen deficits in each part of the plant. Nitrogen from litterfall from the living plants is returned to the soil or to the surface fresh organic matter pools, depending on the source of the material. Soil temperature and moisture of each layer affects the decomposition rate (Paydar et al., 2005; Probert et al., 1998). A detailed information on these approaches for the APSIM model can be found in Probert et al. (1998).

Considering the different approaches used by the three models assessed in this study, a question that arises is why the multimodel ensemble improved the performance of *Eucalyptus* yield estimations? Taking into account the differences in the structure features (parameters, input data, biomass partitioning) and processes of forest models, as well as the different soil and climate conditions where the models were developed, calibrated and/or adapted, it is expected the multimodel ensemble would consider a broader and more comprehensive approach to the process-based interactions in forest systems, as also considered for annual crops by Martre et al. (2015). These authors also reported that the multimodel ensemble reduces the need for site- and varietal-specific model calibrations. One possible explanation is that

individual models are commonly developed and calibrated based on limited datasets, while ensemble approaches are in a sense averaging over these datasets, considering a broader database than any individual model (Martre et al., 2015).

In addition to the sources of errors related to the structure of simulation models, consistent weather and soil dataset are also of high importance for reducing errors. In this context, the number of frost days and rainfall deserves special attention, considering the high impact of them on *Eucalyptus* yield and mortality. Despite a large number of possible sources of errors associated to the simulations done in the present study and considering the wide range of climates, soil types and yield levels during calibration and evaluation of *Eucalyptus* models used in this study, they presented a good performance for simulating *Eucalyptus* yield. The multimodel approach improved the estimates, presenting better results than any individual model. Therefore, such approach should be prioritized for forest yield estimations whenever possible, helping foresters and companies for estimating yield more accurately, making forest planning, management and decision making more accurate. Also, by assessing the potential, attainable and actual *Eucalyptus* yields, they would be able for determining yield gaps as well as the impact of future climate scenarios on yield; however, it would be a more complex task for growers and companies.

2.5. Conclusions

All the *Eucalyptus* simulation models assessed in this study were able to estimate *Eucalyptus* yield across a wide range of climates and soil types when properly calibrated and evaluated. The use of a multimodel ensemble of *Eucalyptus* simulation models reduced the errors of yield estimations, compared to the individual performance of the models. The knowledge of the main structural features, advantages and limitations of *Eucalyptus* simulation models is extremely important for their proper calibrations and applications to different purposes in the forestry sector.

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Supplementary material

Table S1. Methodological procedures for fitting allometric equations and estimating the steam volume of *Eucalyptus* clones.

Steps	Description
DBH and H data	Eight lines of ten trees formed the plot used for periodic evaluations of diameter at breast height (DBH, at 1.3 m above ground level) and total height (H). The DBH and H were measured every 6 months (March/April and September/October), from the planting to March/April 2017.
Biomass data	A destructive analysis of six trees for each clone at location 33-DUR was performed in April 2014. DBH and H of these trees were measured. Subsequently, stem biomass was separated from the other tree components and weighed individually. Representative samples were collected and dried at 105 °C to constant weight for dry mass determination.
Fitting of allometric equations	The basic density of each clone was determined. From stem biomass and wood basic density, the stem volume was determined. The linearized model of (Schumacher and Hall, 1933) was fitted with a specific intercept for each clone (adjusted R ² = 0.98, n = 93): $\ln SV_j = a_j + 1.6552 \ln(DBH) + 1.2800 \ln(H)$ where SV_j is the stem volume, respectively, of the j-th clone; a_j the model intercept for the j-th clone (A1 = -10.1385; C3 = -10.2215; K2 = -10.2043; Q8 = -10.2444; B2 = -10.1944; R9 = -10.2370; N5 = -10.1548; O6 = -10.2057); DBH the diameter at breast height and H the total height. The coefficients were fitted by using the ordinary least squares of the function lm in “R” (R Core Team, 2018). The best allometric equation was selected by the residual analysis, mean absolute error and adjusted R ² .
Final steam volume (m ³ ha ⁻¹)	The steam volume at plot level was calculated by the sum of the individual tree steam volumes. Yields were then extrapolated to a hectare. From this, steam volume was estimated every six months (March/April and September/October), from the planting to March/April 2017.

Table S2. Summary of the weather conditions during the field experiments.

TECHS code ^a	Clim.	Tmea	Tmax	Tmin	SR	RH	Rain	ETc	ETr	WD	WS	ETr/ETc
		°C		MJ m ⁻² day ⁻¹	%	mm year ⁻¹						
1	Aw	25.6	31.5	19.7	19.4	63.3	1475	1362	859	503	631	0.63
2	Cfb	19.1	23.6	14.6	17.3	77.2	1664	1020	938	82	727	0.92
3	Cwa	23.1	29.2	17.1	19.3	66.2	1150	1259	785	474	382	0.62
4	Aw	23.6	28.4	18.9	16.4	70.7	1188	1071	755	316	434	0.71
5	Cwa	21.8	27.4	16.2	17.9	74.6	1099	1108	797	311	308	0.72
7	Aw	23.8	29.9	17.6	18.8	66.9	1580	1225	843	382	739	0.69
8	As	25.6	30.9	20.3	18.8	74.5	696	1317	618	699	98	0.47
9	Cwb	23.6	28.7	18.5	19.1	64.2	1382	1257	842	415	547	0.67
10	Cfa	21.6	26.8	16.3	18.0	73.0	1506	1118	901	217	611	0.81
11	Am	23.5	29.0	18.0	19.4	68.3	1239	1255	819	436	422	0.65
13	Aw	26.0	32.2	19.7	17.5	66.2	1267	1181	901	280	368	0.76
14	Am	25.1	31.3	19.0	18.7	68.2	1224	1279	908	372	324	0.71
18	Cfa	20.5	26.0	15.0	16.8	74.7	1695	1025	907	118	790	0.88
19	Aw	27.6	33.8	21.4	20.1	66.8	1239	1382	851	532	394	0.62
20	Cwa	22.9	29.3	16.5	17.6	69.0	1340	1092	868	224	473	0.80
22	Cfb	19.1	23.7	14.6	17.4	77.1	1662	1034	941	93	723	0.91
23	Cfb	17.6	22.6	12.5	16.3	80.2	1746	903	853	50	895	0.94
24	Cfa	22.6	28.3	16.9	15.8	73.2	1326	1018	814	204	515	0.80
26	As	24.3	30.6	18.1	20.2	61.0	699	1336	511	824	208	0.38
27	Cfb	18.5	24.7	12.3	13.9	84.5	1836	786	744	42	1093	0.95
28	Cfb	18.0	23.4	12.6	14.6	84.5	1258	818	738	80	521	0.90
30	Aw	24.8	31.2	18.4	20.5	57.8	712	1401	509	892	220	0.36
33	Cfa	21.1	26.2	16.0	17.3	76.8	1471	1049	897	152	576	0.86

^aThe complete descriptions of each location are presented in Table 1 of the manuscript. Clim. = Köppen climate type; Tmea = mean air temperature; Tmax = average maximum air temperature; Tmin = average minimum air temperature; SR = average daily solar radiation; RH = average relative humidity; Rain = accumulated annual rainfall; ETc = accumulated annual forest evapotranspiration, which is calculated by multiplying the reference evapotranspiration (Allen et al., 1998) by the forest coefficient (kc); ETr = accumulated annual actual forest evapotranspiration by water balance from Thornthwaite and Mather (1955) approach; WD = accumulated annual water deficit by water balance from Thornthwaite and Mather (1955) approach and WS = accumulated annual water surplus by water balance from Thornthwaite and Mather (1955) approach.

Table S3. Intercomparison of the main structural features, processes and approaches of the *Eucalyptus* simulation models: FAO, APSIM and 3PG.

FAO	APSIM	3PG
1. General approach		
The FAO is a generical model that simulates gross photosynthesis according to the carbon fixation mechanism and climate adaptation of the plant. Potential yield (Y_p) is simulated according to interactions of genetic materials, solar radiation, photoperiod and temperature. Subsequently, Y_p is penalized by water deficit at different points on the <i>Eucalyptus</i> growth curve and according to the intensity of water deficit.	The APSIM - Growth model calculates daily biomass production from daily intercepted solar radiation and light use efficiency (LUE). LUE is affected by soil and climatic factors. Interception of solar radiation is calculated assuming an exponential decay of light within a canopy. Growth and structural pools are considered by the model.	The 3PG model takes into account the solar radiation absorption model for calculating the photosynthetically active radiation intercepted by the forest stand (APAR). APAR is converted into gross primary production by using the canopy quantum efficiency, which is modified by environmental factors, such as vapor pressure deficit, temperature, days of frost, available soil water, soil fertility and stand age.
2. Time step		
Daily	Daily	Monthly
3. Weather data required by the model		
Solar radiation, maximum and minimum air temperature, rainfall, wind speed, relative humidity.	Solar radiation, maximum and minimum air temperature, rainfall, wind speed, relative humidity.	Solar radiation, maximum and minimum air temperature, rainfall, vapor pressure deficit, number of frost days.
4. Soil data required by the model		
Soil water holding capacity - SWHC (difference between field capacity and permanent wilting point).	Number of soil layers and their depth, Bulk density, air-dry water content, permanent wilting point, field capacity, saturation point, saturated hydraulic conductivity, parameters KL (fraction of available water that can be extracted per day) and XF (exploration factor), initial nitrogen content, organic carbon, albedo, bare soil runoff curve number, root and soil C:N ratio, pH.	Fertility rating (FR) and modifiers (m_0 , f_0N and n_0N), soil class, maximum and minimum available soil water (ASW) and two parameters ($c\theta$ and $n\theta$) which characterize the soil water-dependent growth modifier $f\theta$.
5. Forest evapotranspiration		
Forest evapotranspiration (E_{tc}) is calculated by multiplying the reference evapotranspiration (ETo) by the forest coefficient (K_c). ETo is estimated using the Penman-Monteith approach (Allen et al., 1998). K_c is estimated based on an empirical model according to the theoretical potential LAI curve and ranges from 0.5 to 1.2 over the <i>Eucalyptus</i> rotation.	Potential evaporation (Eo) is calculated using the Priestley and Taylor (1972) approach [$Eo = f(\text{temperature, solar radiation, albedo, cover})$]. Actual evaporation is based on Ritchie's two-stage evaporation algorithm (Ritchie, 1972). It is assumed that half the evaporation of intercepted rainfall occurs at night. There are no functions to estimate interception of irrigation, just rainfall (based on an equation with empirical parameters describing the relationship between rainfall and LAI). Potential transpiration for each soil layer is based on the Penman-Monteith approach (described by Snow and Huth, 2004). The plant water demand depends on the depth of the extraction front and the ability of the roots to extract available moisture.	The Penman-Monteith approach for canopy transpiration is adapted to model evapotranspiration by the stand, including soil evaporation plus canopy and understory transpiration (Landsberg and Gower, 1997). For this, a stand-level canopy conductance g_C is required, which increases linearly with increasing canopy LAI to a maximum value. Intercepted rainfall increases linearly with canopy LAI to a maximum and it is subsequently independent of LAI. The intercepted rainfall subsequently evaporates according to the weather conditions.
6. Water balance approach		

The Thornthwaite and Mather (1955) approach is used. Rainfall and/or irrigation, ET_c and soil water holding capacity (SWHC) are the model inputs. SWHC varies throughout the *Eucalyptus* rotation, according to root growth. Actual soil water content, actual forest evapotranspiration, water deficit and surplus are the model outputs. Water deficit occurs when actual evapotranspiration is less than forest evapotranspiration.

Different soil layers to describe the vertical distribution of soil moisture are considered. Available water of each layer depends as the extraction front progresses to greater depths. Potential extraction front velocity defines the rate of progress, which varies according to the soil water content of each layer. CERES (Jones and Kiniry, 1986) and PERFECT (Littleboy et al., 1989) models are considered for simulating water balance dynamics within the soil profile. "KL" parameter represents the fraction of remaining available soil moisture that can be extracted by roots per day (taking into account the effects of soil hydraulic conductivity and root length upon root water uptake).

A single-layer soil water balance is used. Monthly changes in available soil water (ASW) are calculated by the monthly rainfall and/or irrigation less the sum of the intercepted rainfall by canopy, surface run-off and forest evapotranspiration.

7. Root growth

A theoretical potential root growth curve is used, reaching the maximum value at 30 months (coinciding with the highest LAI) and remaining constant afterwards until the end of *Eucalyptus* rotation.

Root length depends on the root front velocity and specific root length (model parameters). The root is partitioned spatially according to water and nitrogen supplies and demands. Root senescence is simulated and varies according to a root senescence rate (model parameter).

This model considers the soil profile is homogeneous with a fixed depth. Roots always have access to all water stored in the profile. Root turnover rates are considered, although these functions have no effect on their general performance, once the root mass is no longer used to modify estimates of the rooting depth. Maximum and minimum fractions of net primary production to roots are model parameters.

8. Phenological processes and effects

Phenological processes are not modelled.

Phenological processes are not modelled. Changes in biomass partitioning with plant growth (according to plant size) and in leaf characteristic with plant age are considered.

Phenological processes are not simulated. Age-related changes in leaf characteristics are considered. Biomass partitioning occurs in terms of stem diameter at breast height.

9. Leaf area growth

A theoretical potential LAI curve is used, reaching maximum value at 30 months and thereafter reducing slightly until the end of the *Eucalyptus* rotation.

LAI is calculated by the foliage mass and specific leaf area (SLA). Foliage mass depends on the senescence processes and the biomass partitioning according to tree size. SLA is age-dependent (Huth et al., 2001).

LAI is determined from foliage mass and input values of specific leaf area. The ratio of foliage to stem biomass partitioning presents an allometric relationship to the stem diameter at breast height. SLA is given by an empirical relationship with stand age.

10. Biomass partitioning

Biomass partitioning is not simulated. A forest coefficient (F_c) is used, which represents the relationship between the harvested part (in this case, the stem) and the total dry matter of the tree at harvest time.

Daily growth is partitioned to leaf, stem, bark, branch, taproot and roots and varies according to tree size, water and/or nitrogen stress (N. Huth et al., 2001). Biomass components can undergo senescence and detachment. Stresses from water and nutrients generally imply greater root:shoot ratio. Fraction of growth going into structure

Monthly biomass is partitioned into leaf, stem, roots, branches and bark (the last two are estimated together). Biomass allocated to roots is influenced by soil nutrition and available soil water. Allometric functions are used for describing stem and foliage biomass in terms of stem

(agnd_structure_fraction), fraction of growth going below ground (below_gnd_fraction), Fractions of stem (stem_partition_fr), branch (branch_partition_fr), bark (bark_partition_fr) and root (tap_root_partition_fr) are model parameters that change the biomass partitioning pattern of the model.

diameter at breast height (DBH). Biomass partitioning is controlled by the ratio of foliage to stem biomass allocation in terms of stem diameter at breast height of 2 and 20 cm. Foliage/stem partitioning ratio at DBH = 2 and 20 cm, maximum and minimum fraction of NPP to roots are model parameters related to the biomass partitioning over the *Eucalyptus* rotation.

11. Photosynthesis and respiration

Gross photosynthesis is simulated according to the carbon fixation mechanism and climate adaptation of the plant. Gross photosynthesis depends on the solar radiation availability (cloudy or clear sky) and temperature conditions. A depletion coefficient related to the maintenance respiration process is considered, which is 0.6 for temperatures higher than 20°C and 0.5 for temperatures lower than 20°C. From this, potential dry biomass is simulated and, subsequently, yield is corrected by water deficit.

The radiation use efficiency (RUE) approach is used for estimating daily biomass production, which also depends on the solar radiation intercepted by the canopy. Maximum RUE is a model parameter, which is penalized by growth modifiers for temperature (FT), nitrogen (FN), vapor pressure deficit (FVPD) and soil water (FW). A “minimum” function is used to select one of the growth modifiers (FT, FN or FVPD) to penalize the RUE. FW is taken into account separately during the penalization. Specific functions of respiration are not considered.

Monthly biomass production is driven by solar radiation intercepted and the maximum (theoretical) canopy quantum efficiency (α_{Cx}), which is a model parameter. α_{Cx} is limited by temperature, days of frost, vapor pressure deficit, available soil water, soil fertility and stand age. Net primary production:gross primary production ratio is a model parameter, which represents the respiration process. This model assumes that the respiratory rate is constant.

12. Growth modifier by temperature

Correction factors (cTn and cTc) are used to simulate the effect of temperature on biomass production. These factors are polynomials (Barbieri and Tuon, 1992) and vary according to the carbon fixation mechanism and climate adaptation of the plant.

Limits of average daily temperature are used as growth parameters (avg_temp) of the model, which affect the light use efficiency. From these limits, photosynthesis modifier for temperature (ft) factor is linearly interpolated by the model. Ft increases to some range of optimum temperature (remaining constant in this range), and then declines.

Temperature response function is applied directly to canopy quantum efficiency. The temperature-dependent growth modifier increases as the temperature increases to the optimum temperature, and then declines. Minimum (Tmin), optimum (Topt) and maximum (Tmax) temperatures for growth are the three species-specific parameters for this function, also known as cardinal temperatures.

13. Growth modifier by frost

Growth is penalized according to severity of frosts. This is represented by the calibration of the frost sensitivity index (Ffrost) for different ranges of daily minimum temperatures. The frost effects are attributable to two factors: a) reduction of gross photosynthesis on frost days and b) mortality rate. The growth modifier was applied to up to two years of age.

Growth depends on the frost intensity. The photosynthesis modifier for the frost (ff) factor is linearly interpolated for different limits of the daily minimum temperature. Senescence of foliage may occur due to frost days.

It is assumed there is no photosynthesis (stomata will be assumed to remain closed) on frosty days. Monthly frosty days are counted, and growth is null on these days. This could be adjusted to more than one null growth day per frost day, according to the appropriate empirical evidence.

14. Growth modifier by water deficit

There are two growth modifiers: Water deficit sensitivity index (K_y) and water deficit mortality index (F_w). The K_y take into account the relative yield reduction by the corresponding relative reduction in evapotranspiration. K_y differs among genetic materials and is fitted at different points on the *Eucalyptus* growth curve. F_w considers the mortality of the stand for different ranges of accumulated water deficit in the last month and differs among *Eucalyptus* clones.

Growth modifier by water deficit (F_w) is determined by the relation between soil water supply (sw_supply) and soil water demand (sw_demand). The sw_supply represents the sum of potential root water uptake from each profile layer occupied by root. Soil water demand is calculated by the MICROMET module (Snow and Huth, 2004). Tree water uptake is determined by the SWIM module (Verburg et al., 1996). A plant mortality rate is considered according to the accumulated water stress days, in order to simulate the decline in population with increasing duration of drought conditions. As default, plant mortality rate is 2% per stress day, and this function is considered until an age of 6 months or a total above-ground biomass of 6 g plant⁻¹. The parameters related to this function are as follows: $crit_cum_stress$, $mortality_rate$, $mortality_age$ and $mortality_size$

Soil water modifier is calculated from the moisture ratio (current available soil water divided by maximum available soil water) and also the parameters "SWconst" and "SWpower", which varies according to the soil types. Landsberg and Waring, (1997) proposed the following values: "SWconst" = 0.7, 0.6, 0.5 and 0.4 for sand, sandy-loam, clay-loam and clay soils, respectively, and "SWpower" = 9, 7, 5 and 3 for the same soil textures. There is no mortality index by water deficit. Stem mortality and self-thinning functions are considered, but they are not directly affected by the water deficit.

15. Growth modifier by vapor pressure deficit (VPD)

There is no growth modifier by VPD. VPD is considered during the calculation of ETo by Penman-Monteith approach (Allen et al., 1998).

Different Limits of VPD are used as model parameters (vpd in Kpa). From these limits, functions of photosynthesis modifier for VPD (F_{VPD}) are fitted for considering the effect of VPD on the radiation use efficiency. A weighting factor for daily VPD from maximum and minimum VPD is considered as a model parameter. The F_{VPD} declines with increasing VPD.

An exponential function is used, which takes into account a model parameter called "response of canopy conductance to VPD" and the actual VPD of the environment. The growth modifier by VPD (f_{VPD}) declines as the VPD increases. The f_{VPD} is considered during the calculation of the physiological modifier.

16. Growth modifier by age

There is no growth modifier by age.

This is a generic factor used to capture yield loss of productivity as tree stands mature. A model parameter (F_{Age}) is specified for different ages of *Eucalyptus* stands (0, 1, 2, 3, 4 and 80 years old). As a default model, this growth modifier begins to influence growth after four years old.

Reduction in stomatal conductance and hydraulic conductivity as trees age implies a reduction in photosynthesis, and less carbon is available to maintain the acquired LAI. Therefore, the age-dependent modifier simulates a possible decline in hydraulic properties and yield with age. The age modifier takes into account the relative age (ratio of actual age to the maximum age attained by the tree stand) and the parameter n_{age} (power of relative age for f_{Age} function).

17. Growth modifier by [CO₂]

There is no Growth modifier by [CO₂].

There is no Growth modifier by [CO₂].

The canopy quantum efficiency increases, and canopy conductance declines as atmospheric [CO₂] increases. Functions and fitting coefficients can be seen from Almeida et al. (2009).

18. Litterfall dynamics

Litterfall dynamic is not simulated Simple first-order decay rates are used for simulating senescence of growth pools. Leaf residence time at different ages and rates of senescence of different above-ground pools are model parameters. Foliage senescence is affected by factors such as extreme temperatures and water stress (Huth et al., 2008). Above-ground biomass is returned to the surface residues. A logistic model for simulating litterfall rate according to age is used. Young tree stands have a lower litterfall rate and increase with age until it becomes constant after canopy closure. Environmental factors are not considered in this process. Maximum litterfall rate, litterfall rate at $t = 0$ and age at which litterfall rate has median value are the parameters of this function.

19. Nitrogen dynamics

Nitrogen dynamic is not simulated The nitrogen demand by plant depends on the size of biomass pools and a target nitrogen concentration for each pool. The partitioning of Nitrogen taken up from the soil mineral pools depends on the sink strengths calculated from nitrogen deficits of each part of the plant. Nitrogen of detached biomass from the living plants is returned to the soil or surface fresh organic matter pools depending on the source of the material (Paydar et al., 2005). Initial values of soil organic carbon, nitrate and ammonium are specified. Soil organic matter is divided into two pools ("biom" and "hum"). The "biom" pool represents the more labile, soil microbial biomass and microbial products. The "hum" pool comprises the rest of the soil organic matter. Soil temperature and moisture in each layer affect the decomposition rate. For more information, see (Probert et al., 1998).

A general parameter (fertility rating, FR) is considered for describing the soil fertility in the rooting zone, which ranges from 0 (low fertility) to 1 (nutrition non-limiting). This parameter is usually calibrated according to the knowledge on the physical and chemical characteristics of the soils location (Almeida et al., 2004; Landsberg et al., 2003; Lemos, 2012). From this, the fertility-dependent growth modifier (fNutr) is calculated and declines with declining FR. Two parameters are used for calculating fNutr: fN0 (Value of 'fNutr' when FR = 0) and fNn [Power of (1-FR) in 'fNutr']. Dye et al. (2004) and Landsberg (2003) highlighted the difficult to describe the soil nutritional status in quantitative terms, due to factors such as its complex biogeochemical cycle and the dynamics of tree roots in soil.

* Model intercomparison was also based on documentations of the APSIM (<https://www.apsim.info/Documentation.aspx>) and 3PG (http://3pg.sites.olt.ubc.ca/files/2014/04/3PGpj_s_UserManual.pdf) models.

Table S4. Number of *Eucalyptus* yield results ($\text{m}^3 \text{ ha}^{-1}$, n) used for the calibration (C) and evaluation (E) processes of each Brazilian clone.

TECHS code ^a	A1 ^b		C3		K2		Q8		B2		R9		N5		O6	
	Set	n	Set	n	Set	n	Set	n	Set	n	Set	n	Set	n	Set	n
1	C	8	C	4	C	4	C	4	C	8	C	8	-	-	-	-
2	C	6	C	12	C	6	C	12	C	6	C	12	-	-	-	-
3	C	5	C	10	C	10	C	10	E	5	E	10	-	-	-	-
4	C	8	C	8	C	8	C	8	C	8	C	8	-	-	-	-
5	E	8	E	16	E	16	E	8	C	8	C	16	-	-	-	-
7	C	8	C	8	C	16	C	16	E	16	E	8	-	-	-	-
8	C	8	C	8	C	8	C	8	C	8	C	8	-	-	-	-
9	E	8	E	8	E	8	E	8	C	8	C	8	-	-	-	-
10	E	8	E	8	E	8	E	8	-	-	-	-	C	8	C	8
11	C	8	C	8	C	16	C	8	C	16	C	16	-	-	-	-
13	C	6	C	6	C	6	C	6	E	6	E	6	-	-	-	-
14	C	7	C	8	C	7	C	7	C	7	C	7	-	-	-	-
18	E	9	E	12	E	6	E	12	-	-	-	-	-	-	-	-
19	C	10	C	10	C	10	C	10	C	6	C	6	-	-	-	-
20	C	8	C	8	C	8	C	8	C	8	C	8	-	-	-	-
22	E	7	E	14	E	7	E	14	C	7	C	7	-	-	-	-
23	C	14	C	14	C	7	C	14	-	-	-	-	-	-	-	-
24	E	9	E	18	E	9	E	18	E	9	E	16	-	-	-	-
26	E	8	E	8	E	16	E	14	C	16	C	8	-	-	-	-
27	C	8	C	16	C	16	C	16	-	-	-	-	C	16	C	16
28	C	16	C	16	C	16	C	16	-	-	-	-	C	16	-	-
30	C	8	C	8	C	8	C	8	C	8	C	8	-	-	-	-
33	C	8	C	8	C	8	C	8	C	8	C	8	E	8	E	8
Total n	C	136		152		154		159		122		128		40		24
	E	57		84		70		82		36		40		8		8

^aThe complete descriptions of each location are presented in Table 1 of the manuscript.

^bA1 = *E. urophylla*; C3 = *E. grandis* x *E. camaldulensis*; K2 = *E. saligna*; Q8 = *E. grandis*; B2 = *E. urophylla* x *E. grandis*; R9 = *E. urophylla*; N5 = *E. dunnii*; O6 = *E. grandis*.

^cLocations where the clone was not evaluated.

Table S5. FAO model parameters calibrated for plastic Brazilian *Eucalyptus* clones (A1, C3, K2, and Q8).

Parameters ^a	Description	Units	A1 ^b	C3	K2	Q8
BD _y	Basic wood density of young trees	t m ⁻²	0.38	0.38	0.38	0.38
BDo	Basic wood density of old trees	t m ⁻³	0.43	0.43	0.44	0.44
DMseedlings	Seedlings dry matter	kg ha ⁻¹	21.00	21.00	21.00	21.00
Ky	Water deficit sensitivity index					
Ky ₁	at the first month of age	-	1.30	1.50	1.40	1.50
Ky ₁₀	at 10 months of age	-	1.10	1.30	1.40	1.40
Ky ₃₀	at 30 months of age	-	1.40	1.80	1.80	1.70
Ky ₆₀	at 60 months of age	-	1.10	1.50	1.30	1.20
Ky ₈₄	at 84 months of age	-	0.80	1.00	0.80	1.00
Cfrost	Frost sensitivity index for minimum daily temperatures					
Ffrost _(1 to 2)	from 1 to 2 °C	-	0.99	1.00	1.00	0.98
Ffrost _(0 to 1)	from 0 to 1 °C	-	0.99	1.00	0.99	0.98
Ffrost _(-1 to 0)	from -1 to 0 °C	-	0.98	0.99	0.99	0.98
Ffrost _(-2 to -1)	from -2 to -1 °C	-	0.98	0.99	0.98	0.98
Ffrost _(-3 to -2)	from -3 to -2 °C	-	0.96	0.96	0.96	0.96
Ffrost _(-4 to -3)	from -4 to -3 °C	-	0.95	0.95	0.95	0.95
Ffrost _(< -4)	lower than -4 °C	-	0.93	0.93	0.93	0.93
Fw	Water deficit mortality index for accumulated water deficit in the last month					
Fw _(100 to 150)	from 100 to 150 mm	-	0.98	0.88	0.87	0.92
Fw _(150 to 200)	from 150 to 200 mm	-	0.95	0.80	0.85	0.85
Fw _(200 to 250)	from 200 to 250 mm	-	0.90	0.75	0.80	0.80
Fw _(250 to 300)	from 250 to 300 mm	-	0.85	0.70	0.75	0.75
Fw _(>300)	from 300 to 350 mm	-	0.75	0.65	0.70	0.70
F _c	Relationship of the harvested part (in this case, the stem) to the total dry matter of the tree	-	0.72	0.64	0.67	0.65

^a The calibration process was performed according to observed data, parameter fitting and information and data already existing in the literature (Campoe et al., 2012; Freitas, 2018; Gonçalves et al., 2017; Mattos, 2015; Ryan et al., 2010).

^b A1 = *E. urophylla*; C3 = *E. grandis* × *E. camaldulensis*; K2 = *E. saligna*; Q8 = *E. grandis*.

Table S6. FAO model parameters calibrated for tropical (B2 and R9) and subtropical (N5 and O6) Brazilian *Eucalyptus* clones.

Parameters ^a	Description	Units	B2 ^b	R9	N5	O6
BD _y	Basic wood density of young trees	t m ⁻³	0.38	0.38	0.38	0.38
BDo	Basic wood density of old trees	t m ⁻³	0.44	0.48	0.46	0.40
DMseedlings	Seedlings dry matter	kg ha ⁻¹	21.00	21.00	21.00	21.00
Ky	Water deficit sensitivity index					
Ky ₁	at the first month of age	-	1.20	1.40	1.60	1.60
Ky ₁₀	at 10 months of age	-	1.10	1.30	1.50	1.50
Ky ₃₀	at 30 months of age	-	1.40	1.50	1.90	1.80
Ky ₆₀	at 60 months of age	-	1.10	1.00	1.60	1.40
Ky ₈₄	at 84 months of age	-	0.80	0.90	1.20	1.20
Ffrost	Frost sensitivity index for minimum daily temperatures					
Ffrost _(1 to 2)	from 1 to 2 °C	-	1.00	0.94	1.00	1.00
Ffrost _(0 to 1)	from 0 to 1 °C	-	0.99	0.94	1.00	1.00
Ffrost _(-1 to 0)	from -1 to 0 °C	-	0.99	0.94	0.99	1.00
Ffrost _(-2 to -1)	from -2 to -1 °C	-	0.97	0.93	0.99	0.97
Ffrost _(-3 to -2)	from -3 to -2 °C	-	0.96	0.93	0.97	0.96
Ffrost _(-4 to -3)	from -4 to -3 °C	-	0.94	0.93	0.96	0.95
Ffrost _(< -4)	lower than -4 °C	-	0.92	0.90	0.93	0.93
Fw	Water deficit mortality index for accumulated water deficit in the last month					
Fw _(100 to 150)	from 100 to 150 mm	-	0.94	0.98	0.90	0.90
Fw _(150 to 200)	from 150 to 200 mm	-	0.85	0.95	0.80	0.85
Fw _(200 to 250)	from 200 to 250 mm	-	0.85	0.90	0.80	0.80
Fw _(250 to 300)	from 250 to 300 mm	-	0.80	0.80	0.70	0.75
Fw _(>300)	from 300 to 350 mm	-	0.75	0.70	0.65	0.70
F _c	Relationship of the harvested part (in this case, the stem) to the total dry matter of the tree	-	0.74	0.66	0.64	0.65

^a The calibration process was performed according to observed data, parameter fitting and information and data already existing in the literature (Campoe et al., 2012; Freitas, 2018; Gonçalves et al., 2017; Mattos, 2015; Ryan et al., 2010).

^b B2 = *E. urophylla* × *E. grandis*; R9 = *E. urophylla*; N5 = *E. dunnii*; O6 = *E. grandis*.

Table S7. APSIM model parameters calibrated for plastic Brazilian *Eucalyptus* clones (A1, C3, K2, and Q8).

Parameters ^a	Description	Units	A1 ^b	C3	K2	Q8
rue	Radiation use efficiency	g MJ ⁻¹	1.53	1.60	1.47	1.30
x_min_temp	Limits of daily minimum temperature affecting the ff ^c	°C	-5/0/2	-5/0/2	-5/0/2	-5/0/2
ff	Photosynthesis modifier for frost	-	0.9/0.95/1 ^e	0.99/1/1	0.97/0.99/1	0.90/0.94/1
x_av_temp	Limits of average daily temperature affecting the ft ^d	°C	8/18/23/40 ^e	8/18/23/40	8/18/23/40	8/18/23/40
agnd_structur_e_fraction	Fraction of growth going into structure (above+below)	-	0.2/0.3/0.83 ^e	0.2/0.3/0.83	0.2/0.3/0.83	0.2/0.3/0.83
stem_partition_fr	Fraction of stem	-	0.62	0.59	0.59	0.53
branch_partition_fr	Fraction of branch	-	0.13	0.11	0.13	0.18
bark_partition_fr	Fraction of bark	-	0.10	0.09	0.10	0.09
tap_root_partition_fr	Fraction of root	-	0.15	0.21	0.18	0.20
specific_leaf_area	Specific leaf area at the planting	mm ² g ⁻¹	9000	9000	9000	9500
	at 1 year of age	mm ² g ⁻¹	7500	7600	7500	7500
	at 2 years of age	mm ² g ⁻¹	7000	7000	7000	7000
	at 3 years of age	mm ² g ⁻¹	7000	7000	7000	7000
	at 4 years of age	mm ² g ⁻¹	6000	6000	6000	6000
	at 80 years of age	mm ² g ⁻¹	6000	6000	6000	6000
leaf_residence_time	Leaf residence time at the planting	days	365	365	365	365
extinction_coeff	Light extinction coefficient	-	0.54/0.54	0.31/0.31	0.41/0.41	0.58/0.58

^aThe calibration process was performed according to observed data, parameter fitting and parametrization and data already existing in the literature (Christina et al., 2017; N. Huth et al., 2001; Huth et al., 2008; Lemos, 2012; Mattos, 2015; Paydar et al., 2005).

^bA1 = *E. urophylla*; C3 = *E. grandis* × *E. camaldulensis*; K2 = *E. saligna*; Q8 = *E. grandis*.

^cPhotosynthesis modifier for frost.

^dPhotosynthesis modifier for temperature.

^eDifferent points are needed to make the parameter response curve.

Table S8. APSIM model parameters calibrated for tropical (B2 and R9) and subtropical (N5 and O6) Brazilian *Eucalyptus* clones.

Parameters ^a	Description	Units	B2 ^b	R9	N5	O6
rue	Radiation use efficiency	g MJ ⁻¹	1.65	1.42	1.48	1.42
x_min_temp	Limits of daily minimum temperature affecting the ff ^c	°C	-5/0/2	-5/0/2	-5/0/2	-5/0/2
ff	Photosynthesis modifier for frost	-	0.89/0.97/1 ^e	0.87/0.95/1	1/1/1	1/1/1
x_av_temp	Limits of average daily temperature affecting the ft ^d	°C	10/19/24/40 ^e	10/19/24/40	6/17/22/38	6/17/22/38
agnd_structur_e_fraction	Fraction of growth going into structure (above+below)	-	0.2/0.3/0.83 ^e	0.2/0.3/0.83	0.2/0.3/0.83	0.2/0.3/0.83
stem_partition_fr	Fraction of stem	-	0.57	0.53	0.6	0.55
branch_partition_fr	Fraction of branch	-	0.11	0.13	0.13	0.14
bark_partition_fr	Fraction of bark	-	0.09	0.09	0.1	0.1
tap_root_partition_fr	Fraction of root	-	0.22	0.25	0.17	0.21
specific_leaf_area	Specific leaf area at the planting	mm ² g ⁻¹	11000	10000	9000	10000
	at 1 year of age	mm ² g ⁻¹	8000	7600	7500	7600
	at 2 years of age	mm ² g ⁻¹	7500	7500	7000	6200
	at 3 years of age	mm ² g ⁻¹	7000	7000	6000	6000
	at 4 years of age	mm ² g ⁻¹	6000	6000	5500	6000
	at 80 years of age	mm ² g ⁻¹	6000	6000	5500	6000
	leaf_residence_time	days	500	400	365	400
extinction_coeff	Light extinction coefficient	-	0.39/0.39	0.45/0.45	0.37/0.37	0.44/0.44

^aThe calibration process was performed according to observed data, parameter fitting and parametrization and data already existing in the literature (Christina et al., 2017; N. Huth et al., 2001; Huth et al., 2008; Lemos, 2012; Mattos, 2015; Paydar et al., 2005).

^bB2 = *E. urophylla* x *E. grandis*; R9 = *E. urophylla*; N5 = *E. dunnii*; O6 = *E. grandis*.

^cPhotosynthesis modifier for frost.

^dPhotosynthesis modifier for temperature.

^eDifferent points are needed to make the parameter response curve.

Table S9. 3PG model parameters calibrated for plastic Brazilian *Eucalyptus* clones (A1, C3, K2, and Q8).

Parameters	Description	Units	Continued			
			A1 ^a	C3	K2	Q8
pFS2	Foliage:stem partitioning ratio at D=2 cm	-	0.7	0.7	0.7	0.7
pFS20	Foliage:stem partitioning ratio at D=20 cm	-	0.12	0.12	0.15	0.15
aS	Constant in the stem mass v. diam. relationship	-	0.02	0.02	0.02	0.02
nS	Power in the stem mass v. diam. relationship	-	3.11	3.11	3.11	3.11
pRx	Maximum fraction of NPP to roots	-	0.5	0.8	0.8	0.8
pRn	Minimum fraction of NPP to roots	-	0.1	0.12	0.11	0.11
gammaFx	Maximum litterfall rate	1/month	0.07	0.07	0.07	0.07
gammaF0	Litterfall rate at t = 0	1/month	0.001	0.001	0.001	0.001
tgammaF	Age at which litterfall rate has median value	months	4	4	4	4
gammaR	Average monthly root turnover rate	1/month	0.025	0.025	0.025	0.025
Tmin	Minimum temperature for growth	deg. C	8	8	8	8
Topt	Optimum temperature for growth	deg. C	21	21	21	21
Tmax	Maximum temperature for growth	deg. C	40	40	40	40
kF	Production days lost per frost day	days	5	4	5	5
fCalpha700	Assimilation enhancement factor at 700 ppm	-	1.4	1.4	1.4	1.4
fCg700	Canopy conductance enhancement factor at 700 ppm	-	0.7	0.7	0.7	0.7
m0	Value of 'm' when FR = 0	-	0	0	0	0
fN0	Value of 'fNutr' when FR = 0	-	0.6	0.6	0.6	0.6
fNn	Power of (1-FR) in 'fNutr'	-	1	1	1	1
SWconst	Moisture ratio deficit for $f_q = 0.5$	-	Determined according to the soil texture ^b			
SWpower	Power of moisture ratio deficit	-				
gammaNx	Mortality rate for large t	%/year	0	0	0	0
gammaN0	Seedling mortality rate (t = 0)	%/year	0	0	0	0
tgammaN	Age at which mortality rate has median value	years	0	0	0	0
ngammaN	Shape of mortality response	-	1	1	1	1
wSx1000	Max. stem mass per tree at 1000 trees/hectare	kg/tree	300	300	300	300
thinPower	Power in self-thinning rule	-	1.5	1.5	1.5	1.5
mF	Fraction mean single-tree foliage biomass lost per dead tree	-	0	0	0	0
mR	Fraction mean single-tree root biomass lost per dead tree	-	0.2	0.2	0.2	0.2
mS	Fraction mean single-tree stem biomass lost per dead tree	-	0.2	0.2	0.2	0.2
SLA0	Specific leaf area at age 0	m^2/kg	13	9.5	10	10
SLA1	Specific leaf area for mature leaves	m^2/kg	6	6.5	6	6.5
tSLA	Age at which specific leaf area = $(\text{SLA0} + \text{SLA1})/2$	years	1.23	1.5	1.5	2

^a A1 = *E. urophylla*; C3 = *E. grandis* x *E. camaldulensis*; K2 = *E. saligna*; Q8 = *E. grandis*.

^b The parameters were SWconst = 0.7, 0.6, 0.5 and 0.4 for sand, sandy-loam, clay-loam and clay soils, respectively, and SWpower = 9, 7, 5 and 3 for the same soil textures (Landsberg and Waring, 1997).

Table S9. 3PG model parameters calibrated for plastic Brazilian *Eucalyptus* clones (A1, C3, K2, and Q8).

Parameters ^a	Description	Units	Conclusion			
			A1 ^{bc}	C3	K2	Q8
k	Extinction coefficient for absorption of PAR by canopy	-	0.54	0.31	0.41	0.58
fullCanAge	Age at canopy cover	years	2	2	2	2
MaxIntcptn	Maximum proportion of rainfall evaporated from canopy	-	0.15	0.15	0.15	0.15
LAImaxIntcptn	LAI for maximum rainfall interception	-	3.33	3.33	3.33	3.33
alpha	Canopy quantum efficiency	molC/molPAR	0.08	0.08	0.075	0.06
Y	Ratio NPP/GPP	-	0.47	0.47	0.47	0.47
CoeffCond	Defines stomatal response to VPD	1/mBar	0.047	0.047	0.047	0.047
BLcond	Canopy boundary layer conductance	m/s	0.2	0.2	0.2	0.2
fracBB0	Branch and bark fraction at age 0	-	0.319	0.319	0.319	0.35
fracBB1	Branch and bark fraction for mature stands	-	0.1	0.093	0.15	0.19
tBB	Age at which fracBB = (fracBB0+fracBB1)/2	years	4	4	4	4
rhoMin	Minimum basic density - for young trees	t/m ³	0.382	0.382	0.382	0.382
rhoMax	Maximum basic density - for older trees	t/m ³	0.43	0.43	0.44	0.44
tRho	Age at which rho = (rhoMin+rhoMax)/2	years	2.264	2.264	2.264	2.264
aH	Constant in the stem height relationship	-	0.9051	0.9051	0.9051	0.9051
nHB	Power of DBH in the stem height relationship	-	1.194	1.194	1.194	1.194
FR	Fertility rating	-	0.9 ^d	0.9	0.9	0.9

^aFor the parameters not described here, the default value was considered.

^bA1 = *E. urophylla*; C3 = *E. grandis* x *E. camaldulensis*; K2 = *E. saligna*; Q8 = *E. grandis*.

^cThe calibration process was performed according to observed data, parameter fitting and parametrization and data already existing in the literature (Almeida et al., 2004; Almeida and Sands, 2016; Jarbas Silva Borges et al., 2012; Dye et al., 2004; Guimarães et al., 2007; Lemos, 2012; Londero et al., 2015; Mattos, 2015; Sands and Landsberg, 2002; Williams et al., 2009).

^dThis parameter was the same for all locations.

Table S10. 3PG model parameters calibrated for tropical (B2 and R9) and subtropical (N5 and O6) Brazilian *Eucalyptus* clones.

Parameters	Description	Units	Continued			
			B2 ^a	R9	N5	O6
pFS2	Foliage:stem partitioning ratio at D=2 cm	-	0.7	0.7	0.7	0.7
pFS20	Foliage:stem partitioning ratio at D=20 cm	-	0.12	0.22	0.17	0.11
aS	Constant in the stem mass v. diam. relationship	-	0.02	0.02	0.02	0.02
nS	Power in the stem mass v. diam. relationship	-	3.11	3.11	3.11	3.11
pRx	Maximum fraction of NPP to roots	-	0.8	0.8	0.8	0.8
pRn	Minimum fraction of NPP to roots	-	0.15	0.15	0.11	0.13
gammaFx	Maximum litterfall rate	1/month	0.07	0.07	0.07	0.07
gammaF0	Litterfall rate at t = 0	1/month	0.001	0.001	0.001	0.001
tgammaF	Age at which litterfall rate has median value	months	4	4	4	4
gammaR	Average monthly root turnover rate	1/month	0.025	0.025	0.025	0.025
Tmin	Minimum temperature for growth	deg. C	10	10	6	6
Topt	Optimum temperature for growth	deg. C	22	22	20	20
Tmax	Maximum temperature for growth	deg. C	40	40	38	38
kF	Production days lost per frost day	days	5	5	0	0
fCalpha700	Assimilation enhancement factor at 700 ppm	-	1.4	1.4	1.4	1.4
fCg700	Canopy conductance enhancement factor at 700 ppm	-	0.7	0.7	0.7	0.7
m0	Value of 'm' when FR = 0	-	0	0	0	0
fN0	Value of 'fNutr' when FR = 0	-	0.6	0.6	0.6	0.6
fNn	Power of (1-FR) in 'fNutr'	-	1	1	1	1
SWconst	Moisture ratio deficit for $f_q = 0.5$	-	Determined according to the soil texture ^b			
SWpower	Power of moisture ratio deficit	-				
gammaNx	Mortality rate for large t	%/year	0	0	0	0
gammaN0	Seedling mortality rate (t = 0)	%/year	0	0	0	0
tgammaN	Age at which mortality rate has median value	years	0	0	0	0
ngammaN	Shape of mortality response	-	1	1	1	1
wSx1000	Max. stem mass per tree at 1000 trees/hectare	kg/tree	300	300	300	300
thinPower	Power in self-thinning rule	-	1.5	1.5	1.5	1.5
mF	Fraction mean single-tree foliage biomass lost per dead tree	-	0	0	0	0
mR	Fraction mean single-tree root biomass lost per dead tree	-	0.2	0.2	0.2	0.2
mS	Fraction mean single-tree stem biomass lost per dead tree	-	0.2	0.2	0.2	0.2
SLA0	Specific leaf area at age 0	m ² /kg	13	12	9.5	9
SLA1	Specific leaf area for mature leaves	m ² /kg	6.5	6.5	6	5.5
tSLA	Age at which specific leaf area = (SLA0+SLA1)/2	years	1.5	1.23	1.5	1.23

^a B2 = *E. urophylla* x *E. grandis*; R9 = *E. urophylla*; N5 = *E. dunnii*; O6 = *E. grandis*.

^b The parameters were SWconst = 0.7, 0.6, 0.5 and 0.4 for sand, sandy-loam, clay-loam and clay soils, respectively, and SWpower = 9, 7, 5 and 3 for the same soil textures (Landsberg and Waring, 1997).

Table S10. 3PG model parameters calibrated for tropical (B2 and R9) and subtropical (N5 and O6) Brazilian *Eucalyptus* clones.

Parameters ^a	Description	Units	Conclusion			
			B2 ^{bc}	R9	N5	O6
k	Extinction coefficient for absorption of PAR by canopy	-	0.39	0.45	0.37	0.44
fullCanAge	Age at canopy cover	years	2	2	2	2
MaxIntcptn	Maximum proportion of rainfall evaporated from canopy	-	0.15	0.15	0.15	0.15
LAImaxIntcptn	LAI for maximum rainfall interception	-	3.33	3.33	3.33	3.33
alpha	Canopy quantum efficiency	molC/molPAR	0.08	0.07	0.065	0.07
Y	Ratio NPP/GPP	-	0.47	0.47	0.47	0.47
CoeffCond	Defines stomatal response to VPD	1/mBar	0.047	0.047	0.047	0.047
BLcond	Canopy boundary layer conductance	m/s	0.2	0.2	0.2	0.2
fracBB0	Branch and bark fraction at age 0	-	0.3	0.3	0.32	0.34
fracBB1	Branch and bark fraction for mature stands	-	0.093	0.093	0.14	0.19
tBB	Age at which fracBB = (fracBB0+fracBB1)/2	years	4	4	4	4
rhoMin	Minimum basic density - for young trees	t/m ³	0.382	0.382	0.382	0.382
rhoMax	Maximum basic density - for older trees	t/m ³	0.44	0.48	0.46	0.4
tRho	Age at which rho = (rhoMin+rhoMax)/2	years	2.264	2.264	2.264	2.264
aH	Constant in the stem height relationship	-	0.9051	0.9051	0.9051	0.9051
nHB	Power of DBH in the stem height relationship	-	1.194	1.194	1.194	1.194
FR	Fertility rating	-	0.9 ^d	0.9	0.9	0.9

^aFor the parameters not described here, the default value was considered.

^bB2 = *E. urophylla* × *E. grandis*; R9 = *E. urophylla*; N5 = *E. dunnii*; O6 = *E. grandis*.

^cThe calibration process was performed according to observed data, parameter fitting and parametrization and data already existing in the literature (Almeida et al., 2004; Almeida and Sands, 2016; Jarbas Silva Borges et al., 2012; Dye et al., 2004; Guimarães et al., 2007; Lemos, 2012; Londero et al., 2015; Mattos, 2015; Sands and Landsberg, 2002; Williams et al., 2009).

^dThis parameter was the same for all locations.

Table S11. Statistical indexes and errors used for analysing the performance of the *Eucalyptus* simulation models and their ensemble during the calibration and evaluation processes.

Statistical indexes and errors	Formula ^a
Coefficient of determination (R^2)	$R^2 = \frac{\frac{1}{n} \times \sum_{i=1}^n [(Est_i - \overline{Obs}) \times (Obs_i - \overline{Obs})]^2}{\left[\frac{1}{n} \times \sum_{i=1}^n (Est_i - \overline{Est})^2 \right] \times \left[\frac{1}{n} \times \sum_{i=1}^n (Obs_i - \overline{Obs})^2 \right]}$
Willmott Agreement Index (d)	$d = \frac{\sum_{i=1}^n (Est_i - Obs_i)^2}{\sum_{i=1}^n (Est_i - \overline{Obs} + Obs_i - \overline{Obs})^2}$
Modelling Efficiency Index (E)	$E = \frac{\sum_{i=1}^n (Est_i - Obs_i)^2}{\sum_{i=1}^n (Obs_i - \overline{Obs})^2}$
Confidence Index (C)	$C = \sqrt{R^2 \times d}$
Mean Absolute Error (MAE)	$MAE = \frac{1}{n} \times \sum_{i=1}^n (Est_i - Obs_i)$
Mean Error (ME)	$ME = \frac{1}{n} \times \sum_{i=1}^n (Est_i - Obs_i)$
Root Mean Square Error (RMSE)	$RMSE = \sqrt{\frac{1}{n} \times \sum_{i=1}^n (Est_i - Obs_i)^2}$

^a Est_i and Obs_i are the estimated and observed *Eucalyptus* yields (steam volume; m³ ha⁻¹); n is the number of observations.

Table S12. Observed (MAI_{obs}) and estimated final Mean Annual Increment by the FAO (MAI_{FAO}), APSIM (MAI_{APSIM}) and 3PG (MAI_{3PG}) models and their ensemble ($MAI_{ensemble}$) for *Eucalyptus* clone A1 at locations with varying climates and soil types.

TECHS code ^{a,b}	MAI_{obs}	MAI_{FAO}	MAI_{APSIM}	MAI_{3PG}	$MAI_{ensemble}$
	$m^3 \text{ ha}^{-1} \text{ year}^{-1}$				
1	35.9	54.5	45.7	47.5	49.3
2	68.4	66.2	84.8	86.2	79.1
3	39.7	50.7	35.0	39.9	41.9
4	45.3	57.0	45.7	51.1	51.3
5	57.0	61.0	59.7	53.1	57.9
7	60.8	57.3	57.6	53.6	56.2
8	20.6	38.2	26.5	29.8	31.5
9	55.8	57.4	57.9	55.6	57.0
10	59.1	72.3	76.8	75.6	74.9
11	74.3	56.6	50.9	58.1	55.2
13	59.2	69.3	39.8	41.6	50.2
14	56.2	61.6	45.5	46.5	51.2
18	33.1	62.2	31.5	60.5	51.4
19	29.7	55.0	40.8	39.7	45.2
20	56.9	69.9	60.3	53.0	61.0
22	72.7	70.0	88.8	90.2	83.0
23	41.2	47.7	56.4	74.1	59.4
24	60.0	69.4	54.4	53.2	59.0
26	33.7	24.7	20.5	28.2	24.5
27	39.8	38.2	34.2	52.6	41.7
28	36.2	33.4	28.1	54.8	38.8
30	35.5	22.6	20.1	25.3	22.7
33	78.5	75.9	84.8	82.1	80.9
Average ($m^3 \text{ ha}^{-1} \text{ year}^{-1}$)	50.0	55.3	49.8	54.5	53.2
SD ^c ($m^3 \text{ ha}^{-1} \text{ year}^{-1}$)	15.9	15.0	20.1	17.6	16.2
CV ^d (%)	31.8	27.1	40.3	32.3	30.5

^a The complete names of each location are presented in Table 1 of the manuscript.

^b The final mean annual increment refers to the last measurement of the stem volume in the field experiments and ranged from 34 to 63 months (average = 54 months), according to the location.

^c Standard deviation.

^d Coefficient of variation.

Table S13. Observed (MAI_{obs}) and estimated final Mean Annual Increment by the FAO (MAI_{FAO}), APSIM (MAI_{APSIM}) and 3PG (MAI_{3PG}) models and their ensemble ($MAI_{ensemble}$) for *Eucalyptus* clone C3 at locations with varying climates and soil types.

TECHS code ^{a,b}	MAI_{obs}	MAI_{FAO}	MAI_{APSIM}	MAI_{3PG}	$MAI_{ensemble}$
	$m^3 \text{ ha}^{-1} \text{ year}^{-1}$				
1	16.0	34.5	34.4	35.8	34.9
2	61.4	59.7	74.7	70.4	68.3
3	16.8	35.8	29.4	31.2	32.2
4	29.7	43.2	34.5	39.0	38.9
5	42.1	44.8	43.4	41.7	43.3
7	47.1	39.5	42.2	35.2	39.0
8	13.1	26.4	20.5	24.5	23.8
9	39.4	37.4	43.3	43.0	41.3
10	51.8	58.6	58.0	58.0	58.2
11	44.5	37.2	40.2	46.4	41.3
13	27.9	54.8	30.6	34.0	39.8
14	29.3	41.6	34.5	37.1	37.7
18	35.4	57.9	27.3	47.2	44.1
19	27.4	30.4	30.9	30.5	30.6
20	41.7	56.8	42.4	40.1	46.4
22	73.1	63.2	77.3	75.9	72.1
23	24.1	52.1	56.5	56.4	55.0
24	43.9	56.5	40.3	39.8	45.6
26	15.4	13.0	16.6	21.9	17.2
27	59.8	46.0	33.4	35.0	38.2
28	36.7	40.1	30.2	39.9	36.7
30	19.8	11.1	16.3	19.8	15.7
33	70.5	63.9	69.2	63.9	65.7
Average ($m^3 \text{ ha}^{-1} \text{ year}^{-1}$)	37.7	43.7	40.3	42.0	42.0
SD ^c ($m^3 \text{ ha}^{-1} \text{ year}^{-1}$)	17.4	14.7	16.8	14.5	14.5
CV ^d (%)	46.1	33.6	41.8	34.5	34.5

^a The complete names of each location are presented in Table 1 of the manuscript.

^b The final mean annual increment refers to the last measurement of the stem volume in the field experiments and ranged from 34 to 63 months (average = 54 months), according to the location.

^c Standard deviation.

^d Coefficient of variation.

Table S14. Statistical indexes and errors from the relationship between the observed and estimated LAI of different *Eucalyptus* clones by the APSIM and 3PG models at locations with varying climates and soil types.

Clones	TECHS code	Model	R ^{2*}	d	E	C	MAE	ME	RMSE
A1	2	APSIM	0.11	0.47	-3.45	0.16	0.87	0.86	1.22
		3PG	0.15	0.55	-1.95	0.21	0.70	0.70	0.99
	10	APSIM	0.02	0.46	-2.69	0.07	1.20	1.20	1.47
		3PG	0.01	0.24	-0.21	-0.02	0.71	0.05	0.84
	26	APSIM	0.00	0.35	-0.57	0.01	0.67	-0.27	0.76
		3PG	0.31	0.66	0.09	0.37	0.55	-0.26	0.58
C3	24	APSIM	0.70	0.80	0.56	0.67	0.38	-0.05	0.43
		3PG	0.01	0.45	-0.91	-0.03	0.68	-0.49	0.91
	5	APSIM	0.15	0.24	-0.81	-0.09	1.11	0.26	1.38
		3PG	0.16	0.21	-0.47	-0.08	1.06	-0.32	1.25
	7	APSIM	0.70	0.58	-1.94	0.48	1.37	1.37	1.47
		3PG	0.29	0.60	-0.05	0.32	0.73	0.47	0.88
K2	24	APSIM	0.27	0.52	0.13	0.27	0.79	0.28	0.85
		3PG	0.04	0.35	-0.37	-0.07	0.90	-0.33	1.07
	14	APSIM	0.00	0.31	-0.13	0.00	1.45	0.38	1.63
		3PG	0.33	0.37	0.18	0.21	1.17	-0.13	1.39
	30	APSIM	0.03	0.36	-0.35	-0.07	1.28	0.37	1.43
		3PG	0.01	0.10	-0.07	-0.01	1.21	-0.06	1.28
Q8	2	APSIM	0.23	0.53	-4.18	0.25	0.63	0.48	0.84
		3PG	0.26	0.32	-20.41	0.16	1.56	1.44	1.72
	10	APSIM	0.08	0.51	-0.85	0.15	1.14	0.99	1.40
		3PG	0.06	0.49	-1.87	0.12	1.43	1.38	1.74
	9	APSIM	0.17	0.28	-1.27	-0.12	1.06	-0.67	1.15
		3PG	0.21	0.23	-1.22	-0.10	0.89	-0.12	1.14
B2	14	APSIM	0.02	0.28	-2.48	0.04	1.07	0.94	1.22
		3PG	0.06	0.45	0.00	0.11	0.55	0.08	0.65
	30	APSIM	0.39	0.62	-0.11	0.38	0.93	-0.65	0.98
		3PG	0.01	0.46	-1.14	0.05	1.29	-0.98	1.37
	7	APSIM	0.25	0.54	-0.89	0.27	1.43	1.18	1.55
		3PG	0.44	0.54	0.31	0.36	0.83	0.06	0.93
R9	24	APSIM	0.15	0.48	-2.41	0.18	0.91	0.91	1.05
		3PG	0.48	0.45	-6.90	0.31	1.55	1.55	1.60
	14	APSIM	0.03	0.42	-3.04	-0.07	1.39	1.39	1.72
		3PG	0.82	0.53	-3.50	0.48	1.77	1.77	1.81
	26	APSIM	0.11	0.49	-0.23	0.16	0.62	0.30	0.70
		3PG	0.99	0.73	-0.36	0.72	0.73	0.73	0.73
N5 and O6	10 (N5)	APSIM	0.11	0.49	-2.64	0.17	1.30	1.30	1.50
		3PG	0.60	0.52	-3.58	0.40	1.61	1.61	1.68
	10 (O6)	APSIM	0.11	0.49	-2.64	0.17	1.30	1.30	1.50
		3PG	0.47	0.61	-0.20	0.42	0.69	0.58	0.86

^a R² = coefficient of determination; d = Willmott Agreement Index; E = Modelling Efficiency Index; C = Confidence Index; MAE = Mean Absolute Error; ME = Mean Error; RMSE = Root Mean Square Error.

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3. ASSESSING THE GROWTH GAPS OF *EUCALYPTUS* PLANTATIONS IN BRAZIL – MAGNITUDES, CAUSES AND POSSIBLE MITIGATION STRATEGIES*

Abstract

Eucalyptus growth (stemwood volume, $m^3 \text{ ha}^{-1} \text{ yr}^{-1}$) is conditioned by biotic and abiotic factors, which are related to the climate, genotype, chemical and physical soil conditions, silvicultural practices and forest management. These factors impose a huge temporal and spatial variability of *Eucalyptus* growth, leading to growth gaps. Therefore, identifying *Eucalyptus* growth gaps (GG), their magnitudes and causes may be a powerful tool for establishing strategies to increase forest resiliency and productivity. In this context, the aims of this study were to determinate the *Eucalyptus* growth gaps by a multimodel approach for different production locations in Brazil and to identify their main causes, possible solutions and mitigation strategies. Three *Eucalyptus* simulation models (FAO, APSIM and 3PG) were used for simulating the potential and attainable growth. Actual growth data were obtained from 30 producing locations in Brazil from experimental plantations of the TECHS Project. The growth gaps at all locations in Midwest and Northeast regions of the country were predominantly caused by water deficit. In Southeast and North regions, the water deficit was the main cause of GG in 87% and 67% of the locations, respectively. On the other hand, in Southern Brazil, the sub-optimal forest management was the main cause of growth gap at all locations, since water deficit is very low in this region. In general, the water deficit represented the main cause of *Eucalyptus* growth gap in Brazil; therefore, the use of drought-tolerant genotypes, wider spacing, deeper subsoiling for heavy and cohesive soils, and soil conservation practices for improving water infiltration and root growth are the main strategies to reduce this kind of gap. On the other hand, for reducing the growth gap caused by sub-optimal forest management, the main strategies are better nutrition management, use of high-quality seedlings (improved genetic materials and high nursery quality), and weed control, pests and diseases. In addition to these practices, better monitoring of forest fires, windstorms and waterlogging events by integrating climate, management and genetic strategies also could help to improve *Eucalyptus* productivity in Brazil.

Keywords: Potential growth; attainable growth; actual growth; forest modelling; water deficit; forestry management.

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3.1. Introduction

The ongoing increase in world population has been accompanied by an increase in renewable resources demand, including those from forest plantations. *Eucalyptus* plantations have a high potential to meet this demand, since they can be used to pulp and paper production, lumber industry, biomaterials (chemical industry, pharmacology, cosmetics and animal feed), and bioenergy, representing an important alternative for reducing the deforestation of native forests (Albaugh et al., 2017; Bauhus et al., 2010; de Oliveira et al., 2018; Diaz-Balteiro and Rodriguez, 2006; Eufrade-Junior et al., 2018; Flores et al., 2018; IBÁ, 2017). In Brazil, the area cultivated with *Eucalyptus* is about 7.4 million hectares, which represents approximately 37% of the world's area with this genus (IBGE, 2017; Trabado, 2009). The *Eucalyptus* plantations are mostly located in the States of Minas Gerais (26% of the national planted area), Mato Grosso do Sul (15%), São Paulo (12%), Paraná (9%), Rio Grande do Sul (8%) and Bahia (8%) (IBGE, 2017).

The average *Eucalyptus* mean annual volume increment in Brazil is around $36 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (IBÁ, 2017). This stemwood productivity is conditioned by biotic and abiotic factors (Figure S1 in the supplementary material), which are related to the climate, genetics, chemical and physical soil conditions, pests and diseases, silvicultural practices and forest management (Binkley et al., 2017; Campoe et al., 2016; Elli et al., 2017; Gonçalves et al., 2004; Ryan et al., 2010; Sentelhas et al., 2017; Stape et al., 2010). In this context, a huge temporal and spatial variability of *Eucalyptus* yield is observed in the different production regions, leading to yield gaps. In order to increase *Eucalyptus* yield in both traditional and non-traditional areas and improve the forest planning and management, the magnitudes of the yield gaps that occur across the different production regions need to be estimated, as well as their main causes and the strategies to close them.

The yield gap analysis is based on the differences between yield types (Figure S1 in the supplementary material). In this context, we can highlight three yield types: potential (Y_p), attainable (Y_{att}) and actual (Y_{act}) yields. The Y_p is obtained from a given species or clone without any water, nutritional and phytosanitary constrains, being affected only by determining factors, such as solar radiation, air temperature, photoperiod, CO_2 concentration and their interactions with the genotype and plant population (Fischer, 2015; Sentelhas et al., 2015; van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013). The Y_{att} is influenced by the determining and also limiting factors. The main limiting factor is related to the soil water availability, which causes water deficit. In this context, the Y_{att} is affected by interannual and seasonal rainfall variability, soil water holding capacity, forest evapotranspiration, topography

and sensitivity of the species/clone to the water deficit. The Yatt is also affected by the nutritional deficit caused by the reduction of water uptake by the roots (Lobell et al., 2009; Sentelhas et al., 2017).

The Yact is influenced, in addition to determining and limiting factors, by the reducing factors, which refer to the losses caused by pests, diseases and weeds when not properly controlled (van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013), as well as other forest management practices such as soil preparation and fertilization. Lastly, the final yield (Yf) takes into account aspects related to the losses during harvesting and transporting processes (Sentelhas et al., 2017). In the sector of planted forests for industrial supply, yield gaps caused during harvest and transport are generally not considered, since these losses are minimal. Using these concepts, the difference between Yp and Yatt determines the yield gap caused by water deficit (YGwd), whereas the difference between Yatt and Yact results in the yield gap caused by sub-optimal forest management (YGm) (Sentelhas et al., 2015). The total yield gap (YGt) can be determined by the difference between the Yp and Yact.

The main challenge for determining these yield gaps is associated to how to simulate Yp and Yatt of a given species/clone. It can be solved by using process-based simulation models (van Ittersum et al., 2013), which integrate the determining and limiting factors in a conceptual framework, producing reliable estimates when properly calibrated and validated. There are several *Eucalyptus* simulation models available in the literature. Some of the most promising ones are: FAO - Agroecological Zone (Doorenbos and Kassam, 1979) adapted for *Eucalyptus* plantations by Freitas (2018); APSIM - Agricultural Production Systems Simulator (Mccown et al., 1996); and 3PG - Physiological Principles in Predicting Growth (Landsberg and Waring, 1997). These models present differences in terms of their structural features (parameters, input data, biomass partitioning, growth modifiers, and state variables) and processes. Some studies have shown that a multimodel approach (ensemble of models), which takes into account a broader and more comprehensive way to express the process-based interactions in forest systems, can reduce the uncertainties of forest yield estimations (Hanson et al., 2004; Wang et al., 2014). It may help researchers, forest companies and growers for estimating yield more accurately, improving forest researches, planning, management and decision making.

The yield gap analysis has been widely discussed around the world and provides the basis for identifying the main sources of losses, caused by water or management deficiencies. In Brazil, this analysis has been performed for several annual crops, such as sunflower (Marin et al., 2000), dry bean (Meireles et al., 2003), sorghum (Marin et al., 2006), soybean (Sentelhas et al., 2015), sugarcane (Dias and Sentelhas, 2018a; Marin et al., 2016; Monteiro and Sentelhas,

2017) and maize (Duarte, 2018). For forest species, this approach was used firstly by Freitas (2018), who assessed the magnitude and major causes of yield gaps of *Eucalyptus* plantations in the state of Minas Gerais, Brazil, by using a single model. Based on that, it is clear that there is a lack of studies about the yield gaps in forest plantations both in Brazil and around the world, mainly by using a multimodel approach. Therefore, the present study may provide important and innovative information for helping all the players in the forest sector to estimate the magnitude and main causes of losses and then to establish strategies to mitigate them and increase forest resiliency and yield. In the present study, we have replaced the terms "yield" and "yield gap" by "growth" and "growth gap", respectively, since the volume MAI ($m^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was used for the calculations, which is considered a growth variable in the forestry (Pretzsch, 2009).

In this context, the following hypotheses were formulated: (i) FAO, APSIM and 3PG models are suitable for assessing *Eucalyptus* growth gaps at national level and (ii) *Eucalyptus* growth gap analysis is useful for estimating the magnitude and main causes of growth losses of *Eucalyptus* plantations and could be used to suggest measures to reduce them. Based on that, the aims of this study were: (i) to determinate the *Eucalyptus* growth gaps by a multimodel approach for different producing regions in Brazil, and (ii) to identify the main causes and possible strategies to mitigate the gaps in these regions.

3.2. Material and methods

3.2.1. Eucalyptus actual growth

Actual growth data (MAI, $m^3 \text{ ha}^{-1} \text{ yr}^{-1}$) from 30 producing locations in Brazil were used in this study (Figure 1). These data were obtained from the average of different *Eucalyptus* clones (D4 – *E. grandis* x *E. urophylla*, E5 – *E. urophylla*, F6 – *E. benthamii*, G7 – *E. urophylla*, H8 - *E. grandis* x *E. urophylla*, I9 – *E. dunnii*, J1 – *E. benthamii*, L3 – *E. urophylla* x *E. globulus*, M4 – *E. dunnii* and P7 - *E. urophylla* x *E. tereticornis*) from experimental plots conducted in different forestry companies as part of the project "Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses" (TECHS) (Binkley et al., 2017). Planting was performed from Dec/2011 to Jul/2012 (varying according to the location). All experimental areas were prepared with subsoiler and fertilized with 70 kg N ha^{-1} , 45 kg P ha^{-1} , 85 kg K ha^{-1} , $500 \text{ kg Ca ha}^{-1}$, 90 kg Mg ha^{-1} , 40 kg S ha^{-1} , 3 kg Bo ha^{-1} , 1 kg Cu ha^{-1} , and 1 kg Zn ha^{-1} . Fertilizer was applied from two to four times (varying among locations) from the preplanting through 12 months. Subsequent fertilizations were performed according to specific characteristics of each region. Preplanting fertilizers were applied in straight lines together with

the subsoiling, while subsequent fertilizers were applied throughout the tree canopy projection. Previously to TECHS Project, BEPP Project showed that fertilization beyond current operational rates did not increase growth in the major *Eucalyptus* production locations in Brazil (Stape et al., 2010). Herbicides were used to keep the plots weed-free. Other management practices were performed according to specific characteristics of each company.

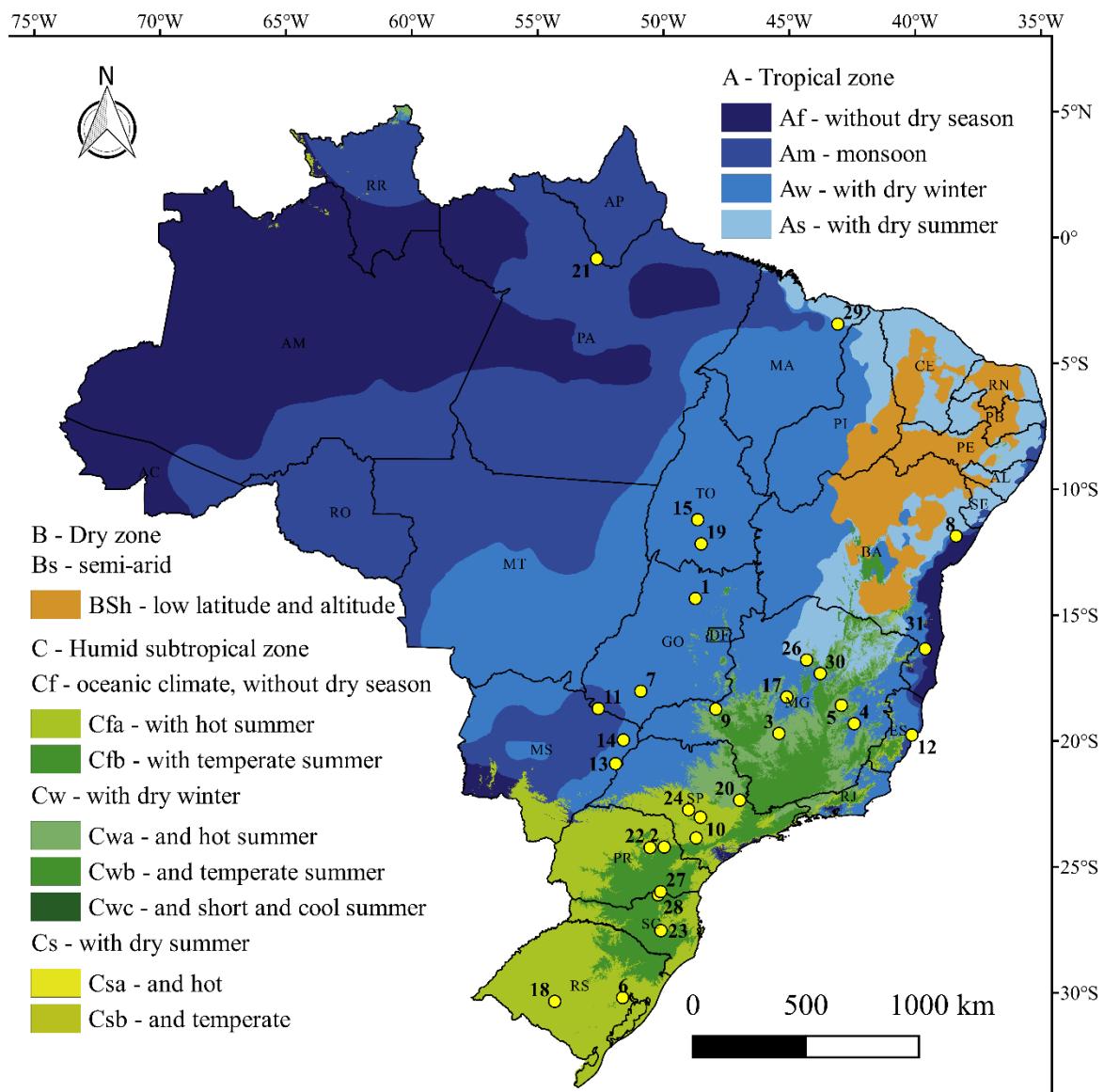


Figure 1. *Eucalyptus* producing locations used in the present study for growth assessments and their respective Köppen climate classification in Brazil (map adapted from Alvares et al., 2013). The description of map codes and further information on the characteristics of each location are presented in Table 1.

The seedlings of each clone were planted in a single plot with eight lines per 15 trees at a spacing of 3×3 m ($1,111$ trees ha^{-1}). The first five trees in each line were used for destructive sampling throughout the experiment period and were, therefore, not used for this study. In this context, a plot with eight lines of ten trees remained for evaluations of diameter at breast height (DBH, at 1.3 m above ground level) and total height (H). The age of the DBH and H evaluations was 4.5 ± 0.5 year, being a period close to maximum MAI under similar Brazilian conditions (Stape et al., 2010). A destructive analysis of six trees for each clone at location 33-DUR (Buri, SP) was performed in April 2014. From these data, the linearized model of Schumacher and Hall (1933) was fitted for estimating the individual stem volume as a function of DBH and H with a specific intercept for each clone (Mattos, 2015). Subsequently, this model, properly fitted, was used to estimate the stem volume for all locations. From the individual volume calculated by the linearized model of Schumacher and Hall (1933), the stem volume at plot level ($\text{m}^3 \text{ plot}^{-1}$) was calculated by the sum of the individual tree stem volumes. Subsequently, yields were upscaled to a hectare ($\text{m}^3 \text{ ha}^{-1}$) and then converted to MAI, which was used for growth gap calculations.

Table 1. *Eucalyptus* producing locations used in the present study for growth assessment and their respective planting date, soil type and summary of the weather conditions during the field experiments.

TECHS Code	Location, State: latitude, longitude and altitude	Planting date	Soil type ^a	SR	Tmea	Rain	RET
01	Niquelândia, GO: 14.3 S, 48.7 W, 545 m	2012/03	Oxisol	19.4	25.6	1475	0.63
02	Arapoti, PR: 24.2 S, 49.9 W, 770 m	2011/12	Oxisol	17.3	19.1	1664	0.92
03	Bom Despacho, MG: 19.6 S, 45.4 W, 727 m	2012/05	Oxisol	19.3	23.1	1150	0.62
04	Belo Oriente, MG: 19.3 S, 42.4 W, 243 m	2011/12	Oxisol	16.4	23.6	1188	0.71
05	Guanhães, MG: 18.5 S, 42.9 W, 873 m	2012/12	Oxisol	17.9	21.8	1099	0.72
06	Eldorado do Sul, RS: 30.19 S, 51.6 W, 150 m	2012/04	Ultisol	15.5	20.7	1621	0.89
07	Rio Verde, GO: 18 S, 50.8 W, 681 m	2012/02	Entisol	18.8	23.8	1580	0.69
08	Inhambupe, BA: 11.8 S, 38.3 W, 218 m	2012/07	Ultisol	18.8	25.6	696	0.47
09	Estrela do Sul, MG: 18.7 S, 47.9 W, 969 m	2011/12	Oxisol	19.1	23.6	1382	0.67
10	Botucatu, SP: 23 S, 48.5 W, 869 m	2011/12	Oxisol	18.0	21.6	1506	0.81
11	Chapadão do Sul, MS: 18.7 S, 52.5 W, 783 m	2011/12	Oxisol	19.4	23.5	1239	0.65
12	Aracruz, ES: 19.8 S, 40.1 W, 36 m	2012/06	Entisol	18.2	25.2	993	0.58
13	Três Lagoas, MS: 20.9 S, 51.8 W, 361 m	2012/05	Oxisol	17.5	26.0	1267	0.76
14	Inocência, MS: 19.9 S, 51.5 W, 480 m	2012/03	Entisol	18.7	25.1	1224	0.71
15	Brejinho de Nazaré, TO: 11.2 S, 48.6 W, 255 m	2012/02	Entisol	20.0	27.2	1423	0.58
17	Três Marias, MG: 18.3 S, 45.1 W, 806 m	2012/03	Oxisol	20.4	23.0	1039	0.51
18	São Gabriel, RS: 30.3 S, 54.3 W, 102 m	2012/11	Oxisol	16.8	20.5	1695	0.88
19	Peixe, TO: 12.1 S, 48.5 W, 255 m	2012/03	Entisol	20.1	27.6	1239	0.62
20	Mogi Guaçu, SP: 22.3 S, 46.9 W, 633 m	2012/02	Oxisol	17.6	22.9	1340	0.80
21	Monte Dourado, PA: 0.85 S, 52.6 W, 50 m	2012/09	Ultisol	18.9	27.8	2186	0.73
22	Telêmaco Borba, PR: 24.2 S, 50.5 W, 888 m	2012/02	Oxisol	17.4	19.1	1662	0.91
23	Otacílio Costa, SC: 27.5 S, 50.1 W, 870 m	2012/01	Incept.	16.3	17.6	1746	0.94
24	Borebi, SP: 22.7 S, 49 W, 656 m	2012/01	Entisol	15.8	22.6	1326	0.80
26	Coração de Jesus, MG: 16.7 S, 44.3 W, 926 m	2011/12	Oxisol	20.2	24.3	699	0.38
27	Antônio Olinto, PR: 25.9 S, 50.1 W, 916 m	2012/02	Ultisol	13.9	18.5	1836	0.95
28	Três Barras, SC: 26.1 S, 50.2 W, 812 m	2012/02	Oxisol	14.6	18.0	1258	0.90
29	Urbano Santos, MA: 3.4 S, 43.1 W, 81 m	2012/03	Entisol	20.7	28.7	1300	0.53
30	Bocaiúva, MG: 17.3 S, 43.7 W, 848 m	2011/12	Oxisol	20.5	24.8	712	0.36
31	Eunápolis, BA: 16.3 S 39.6 W, 200 m	2012/01	Ultisol	18.6	24.2	1179	0.68
33	Buri, SP: 23.8 S, 48.7 W, 695 m	2011/12	Oxisol	17.3	21.1	1471	0.86

^a Soil order was reported by forestry companies; SR = average daily solar radiation, in $\text{MJ m}^{-2} \text{ day}^{-1}$; Tmea = mean air temperature, in $^{\circ}\text{C}$; Rain = accumulated annual rainfall, in mm; RET = relative evapotranspiration, which was calculated by the relationship between actual evapotranspiration (ETr) and maximum forest evapotranspiration (ETc). ETr was obtained by the water balance from Thornthwaite and Mather (1955) approach considering an effective root depth of 3 m, and ETc was calculated multiplying the reference evapotranspiration (Allen et al., 1998) by the forest coefficient (kc). Kc was estimated based on an empirical model according to potential *Eucalyptus* LAI curve, which ranges from 0.5 to 1.2 over the *Eucalyptus* rotation (Freitas, 2018).

3.2.2. *Eucalyptus* simulation models for estimating potential and attainable growth

Three *Eucalyptus* simulation models were used for simulating the potential and attainable growth: FAO (Agroecological Zone); APSIM (Agricultural Production Systems

Simulator); and 3PG (Physiological Principles in Predicting Growth. These models were properly validated against attainable yield or “best forester yield” data from plots situated in 23 of the 30 producing locations described in Table 1, following the same experimental design previous mentioned (section 2.1), but assuming they were conducted under near optimum forest management (fertilized + non irrigated treatment). These data were randomly divided into two sets, the first one used to calibrate (70% of the data) and the second to evaluate (30% of the data) the models. Model parameters of a highly productive and homeostatic clone (A1 - *Eucalyptus urophylla*) with suitability to a wide range of environments were used. A summary of the statistical indexes and errors from the relationship between the observed and estimated *Eucalyptus* stemwood volume by the FAO, APSIM and 3PG models during the calibration and evaluation phases is presented in the Supplementary Material (Table S1 and Figure S2).

In the present version of the FAO model, adaptations for a tree species were made by adding wood density functions, frost penalization, and water deficit mortality indexes (Freitas, 2018). For modelling potential growth, water deficit sensitivity index (K_y) and water deficit mortality index (F_w) were considered null, which means that $K_y = 0$ and $F_w = 1$ throughout the whole *Eucalyptus* rotation. The age of *Eucalyptus* growth evaluations was 4.5 ± 0.5 years. For the APSIM – Growth model, version 7.9 was used. To simulate the potential growth by this model, an automatic irrigation was applied throughout the *Eucalyptus* rotation, to cover 100% of the water deficit (full irrigation).

For the 3PG model, version 2.7 was used. In this model, potential growth estimation can be done with two different approaches: (i) to simulate a constant application of a high monthly irrigation amount to ensure the coverage of 100% of water deficit; or (ii) to equalize the maximum available soil water to the minimum available soil water, since the model will apply a supplementary irrigation to cover 100% of water deficit. In the present study, the second option was adopted. In order to verify if there was any water deficit during the forest rotation simulated by the models, the growth modifier by water deficit was monitored in all the simulations, in order to keep it equal to 1 (without growth losses by water deficit). The nutritional deficit was also monitored and kept as zero for all models (non-limiting soil fertility). The attainable growth was simulated considering the rainfall conditions of each location, without considering any type of irrigation, with non-limiting soil fertility and no other management deficits.

3.2.3. Weather and soil data

The meteorological data (maximum, minimum and mean air temperatures, solar radiation, rainfall, relative humidity and wind speed) were obtained from the weather stations located in the experimental areas of each forestry company, member of the TECHS project, and when data were not available, they were obtained from the nearest weather stations belonging to the Brazilian National Institute of Meteorology (INMET). The missing data was completed from the nearest weather stations of the Brazilian National Water Agency (ANA), and from daily gridded meteorological data, following the sequence: (i) “CHIRPS” – Climate Hazards Group InfraRed Precipitation with Station (Funk et al., 2015), with a spatial resolution of 0.05°, (ii) “XAVIER” – Daily gridded meteorological variables in Brazil, with a spatial resolution of 0.25° (Xavier et al., 2016) and (iii) NASA/POWER – NASA Langley Research Center POWER Project, with a spatial resolution of 0.5° (Stackhouse et al., 2015).

The soil types (first order) were reported by forestry companies. For the FAO and 3PG models, pedotransfer functions fitted for Brazilian soils (Assad et al., 2001; Reichert et al., 2009) were used to estimate the soil water content at permanent wilting point (tension of 1,500 kPa), field capacity (tension of 10 kPa) and, then, the soil water holding capacity. An effective root depth of 3 m was considered for all sites (Christina et al., 2017; Pinheiro et al., 2019). We recognize that this is a source of uncertainty, but this justified by the lack of soil and root information required for building the soil profile of the simulation models. Input data required for pedotransfer functions (sand, silt and clay contents) were obtained by soil samples collected from each studied location, where clay and sand contents were quantified by the densiometer method (Embrapa, 1997). For the APSIM model, which requires more detailed and complex data on the physical and hydraulic soil characteristics, RadamBrasil (1974) and Wise (Batjes, 2009) database were used for building and adjusting the soil profile, according to the characteristics of each location.

3.2.4. *Eucalyptus* growth gaps, climatic and management efficiencies

After simulating the potential and attainable growth and obtaining the actual growth from 30 producing locations in Brazil, the *Eucalyptus* growth gaps, climatic and management efficiencies were determined by the following equations:

$$GGwd = Gp - Gatt \quad (1)$$

$$GGm = Gatt - Gact \quad (2)$$

$$GGt = Gp - Gact \quad (3)$$

$$Ec = \frac{Gatt}{Gp} \times 100 \quad (4)$$

$$Em = \frac{Gact}{Gatt} \times 100 \quad (5)$$

where: $GGwd$ is the growth gap caused by water deficit; GGm the growth gap caused by sub-optimal forest management; GGt the total growth gap; Ec the climatic efficiency; and Em the management efficiency.

3.2.5 Multimodel approach and data analysis

After the individual simulation of potential and attainable growth by FAO, APSIM and 3PG models, a multimodel ensemble was performed, by averaging the three values of *Eucalyptus* MAI, in order to reduce the uncertainties of the growth simulations (Hanson et al., 2004; Wang et al., 2014). The cumulative probability of occurrence of *Eucalyptus* potential, attainable and actual growth, growth gaps caused by water and sub-optimal management, climatic and management efficiencies, as well as the magnitudes of them were graphically demonstrated. The locations were grouped according to the level of climatic and/or management efficiencies, where three classes were considered: below 50%, from 50% to 75% and above 75%. From this, the relationships between (i) the *Eucalyptus* climatic efficiency and actual growth at different levels of management efficiency, and (ii) the *Eucalyptus* management efficiency and actual growth at different levels of climatic efficiency were also plotted.

3.3. Results

3.3.1. *Eucalyptus* growth, growth gaps and efficiencies

A huge variability of *Eucalyptus* growth was observed in all assessed locations (Figure 2). In 50% of them, the potential growth was greater than $88 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, while the attainable and actual growth exceeded 52 and $32 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, respectively (Figure 2a). In 20% of the producing locations, the growth gaps by water deficit and sub-optimal management were greater than 49 and $27 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Figure 2b), respectively, representing 64.4% and 35.6% of GGt. High climatic ($> 90\%$) and management ($> 80\%$) efficiencies were observed in more than 20% of the assessed regions (Figure 2c).

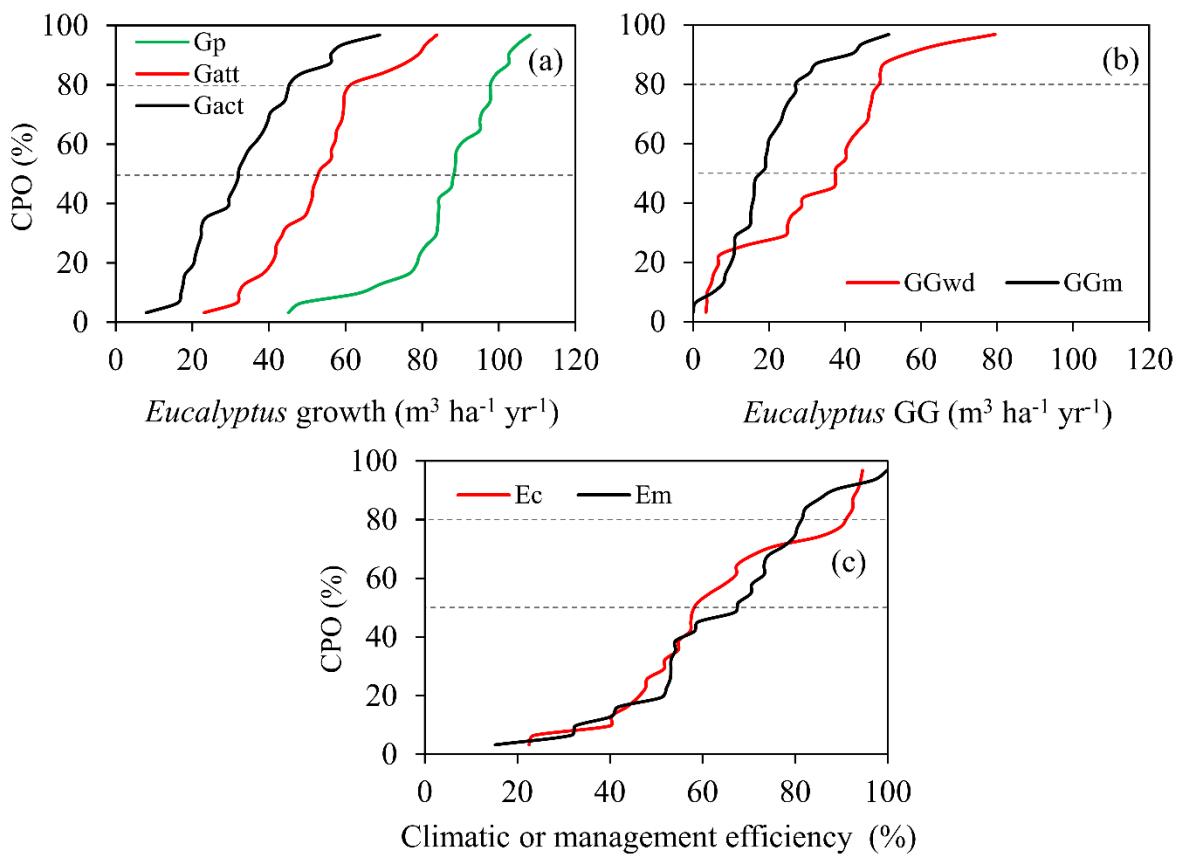


Figure 2. Cumulative probability of occurrence (CPO) of *Eucalyptus* actual (Gact), attainable (Gatt) and potential (Gp) growth (a), growth gaps (GG) by water deficit (GGwd) and sub-optimal forestry management (GGm) (b), and climatic and management efficiencies (c) from 30 producing locations in Brazil. Horizontal dashed lines represent thresholds of 50 and 80% of the cumulative probability of occurrence.

3.3.2. Magnitudes of *Eucalyptus* growth and growth gaps

The average *Eucalyptus* potential growth in Brazil considering all assessed locations was $87 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ and ranged from 45 to $108 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 2 and Figure 3a). Higher potential growth ($\geq 100 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were found at Estrela do Sul, Coração de Jesus, Bocaiúva, in the State of Minas Gerais, and Chapadão do Sul, MS. On the other hand, lower potential growth values ($\leq 50 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were obtained at Três Barras, SC, and Antonio Olinto, PR. The attainable growth ranged from 23 to $84 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 2 and Figure 3b), with an average of $53 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. Higher attainable growth values ($\geq 75 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were obtained at Arapoti and Telêmaco Borba, both in the north of the state of Paraná, and at Botucatu and Buri, in the state of São Paulo. Lower attainable growth values ($\leq 35 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were found at Inhambupe,

BA, Urbano Santos, MA, Coração de Jesus and Bocaiúva, both in the center-north of Minas Gerais.

The average *Eucalyptus* actual growth was $34 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 2 and Figure 3c), ranging from 8 to $69 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. Higher actual growth values were found in Arapoti ($56 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and Telêmaco Borba ($69 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), both in the state of Paraná, in Chapadão do Sul, MS ($56 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), and in Buri, SP ($59 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). On the other hand, lower actual growth values were found in the northern Brazil, such as in Inhambupe, BA ($16 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), Peixe, TO ($18 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), Monte Dourado, PA ($8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), Coração de Jesus, MG ($17 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), and Urbano Santos, MA ($18 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). A high *Eucalyptus* actual growth variability across the assessed locations was observed, resulting in a high coefficient of variation (CV), of 44% (Table 2), whereas for attainable and potential growth the CV values were much lower, respectively, 29% and 17%.

Table 2. Average Potential (Gp), attainable (Gatt) and actual (Gact) *Eucalyptus* growth, growth gaps by water deficit (GGwd) and sub-optimal forestry management (GGm) and total growth gap (GGt), climatic (Ec) and management (Em) efficiencies at 4.5 ± 0.5 years for 30 producing locations in Brazil.

Location, State	Gp ^a	Gatt ^a	Gact	GGwd	GGm	GGt	GGwd ^b	GGm ^b	Ec	Em
	$\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$						% -----			
Niquelândia, GO	95.4	49.3	29.1	46.1	20.2	66.3	69.5	30.5	51.7	59.0
Arapoti, PR	84.5	79.1	55.9	5.4	23.2	28.6	18.9	81.1	93.6	70.7
Bom Despacho, MG	91.1	41.9	22.3	49.2	19.6	68.8	71.5	28.5	46.0	53.2
Belo Oriente, MG	88.7	51.3	34.7	37.4	16.6	54.0	69.3	30.7	57.8	67.6
Guanhães, MG	98.0	57.7	38.6	40.3	19.1	59.4	67.8	32.2	58.9	66.9
Eldorado do Sul, RS	76.3	69.6	36.9	6.7	32.7	39.4	17.0	83.0	91.2	53.0
Rio Verde, GO	97.7	56.1	44.8	41.6	11.3	52.9	78.6	21.4	57.4	79.9
Inhambupe, BA	78.5	31.5	16.1	47.0	15.4	62.4	75.3	24.7	40.1	51.1
Estrela do Sul, MG	104.8	57.3	33.4	47.5	23.9	71.4	66.5	33.5	54.7	58.3
Botucatu, SP	99.5	75.3	23.8	24.2	51.5	75.7	32.0	68.0	75.7	31.6
Chapadão do Sul, MS	102.6	56.3	56.2	46.3	0.1	46.4	99.8	0.2	54.9	99.8
Aracruz, ES	87.4	38.2	29.6	49.2	8.6	57.8	85.1	14.9	43.7	77.5
Três Lagoas, MS	79.3	53.5	45.6	25.8	7.9	33.7	76.6	23.4	67.5	85.2
Inocência, MS	88.0	50.4	40.6	37.6	9.8	47.4	79.3	20.7	57.3	80.6
Brejinho de Nazaré, TO	84.0	40.5	21.5	43.5	19.0	62.5	69.6	30.4	48.2	53.1
Três Marias, MG	108.1	51.5	20.8	56.6	30.7	87.3	64.8	35.2	47.6	40.4
São Gabriel, RS	69.2	62.1	20.2	7.1	41.9	49.0	14.5	85.5	89.7	32.5
Peixe, TO	83.5	43.3	18.1	40.2	25.2	65.4	61.5	38.5	51.9	41.8
Mogi Guaçu, SP	89.1	59.9	43.9	29.2	16.0	45.2	64.6	35.4	67.2	73.3
Monte Dourado, PA	81.0	52.5	8.0	28.5	44.5	73.0	39.0	61.0	64.8	15.2
Telêmaco Borba, PR	88.6	83.7	68.9	4.9	14.8	19.7	24.9	75.1	94.5	82.3
Otacílio Costa, SC	63.1	59.4	32.2	3.7	27.2	30.9	12.0	88.0	94.1	54.2
Borebi, SP	84.4	59.6	48.6	24.8	11.0	35.8	69.3	30.7	70.6	81.5
Coração de Jesus, MG	102.3	24.2	17.0	78.1	7.2	85.3	91.6	8.4	23.7	70.2
Antônio Olinto, PR	45.0	41.7	30.9	3.3	10.8	14.1	23.4	76.6	92.7	74.1
Três Barras, SC	48.4	44.7	39.7	3.7	5.0	8.7	42.5	57.5	92.4	88.8
Urbano Santos, MA	84.2	33.7	17.6	50.5	16.1	66.6	75.8	24.2	40.0	52.2
Bocaiúva, MG	102.6	23.1	22.4	79.5	0.7	80.2	99.1	0.9	22.5	97.0
Eunápolis, BA	95.8	58.9	31.9	36.9	27.0	63.9	57.7	42.3	61.5	54.2
Buri, SP	95.0	80.9	59.3	14.1	21.6	35.7	39.5	60.5	85.2	73.3
South	67.9	62.9	40.7	5.0	22.2	27.2	18.4	81.6	92.6	64.7
Southeast	95.9	51.7	32.9	44.2	18.9	63.0	70.2	29.8	53.9	63.6
Midwest	92.6	53.1	43.2	39.5	9.9	49.4	80.0	20.0	57.3	81.4
Northeast	86.1	41.4	21.8	44.7	19.6	64.3	69.5	30.5	48.1	52.7
North	82.8	45.4	15.9	37.4	29.5	66.9	55.9	44.1	54.8	35.0
Overall average	86.5	52.9	33.6	33.6	19.3	52.9	58.6	41.4	63.2	64.0
SD ($\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ or %) ^c	15.1	15.4	14.7	21.0	12.3	20.6	25.8	25.8	21.0	19.9
CV (%) ^c	17.4	29.1	43.7	62.4	63.6	38.9	44.0	62.2	33.2	31.2

^a Gp and Gatt were averaged from the ensemble of FAO, APSIM and 3PG *Eucalyptus* simulation models; ^b Relative values in terms of GGt; ^c Standard deviation and coefficient of variation.

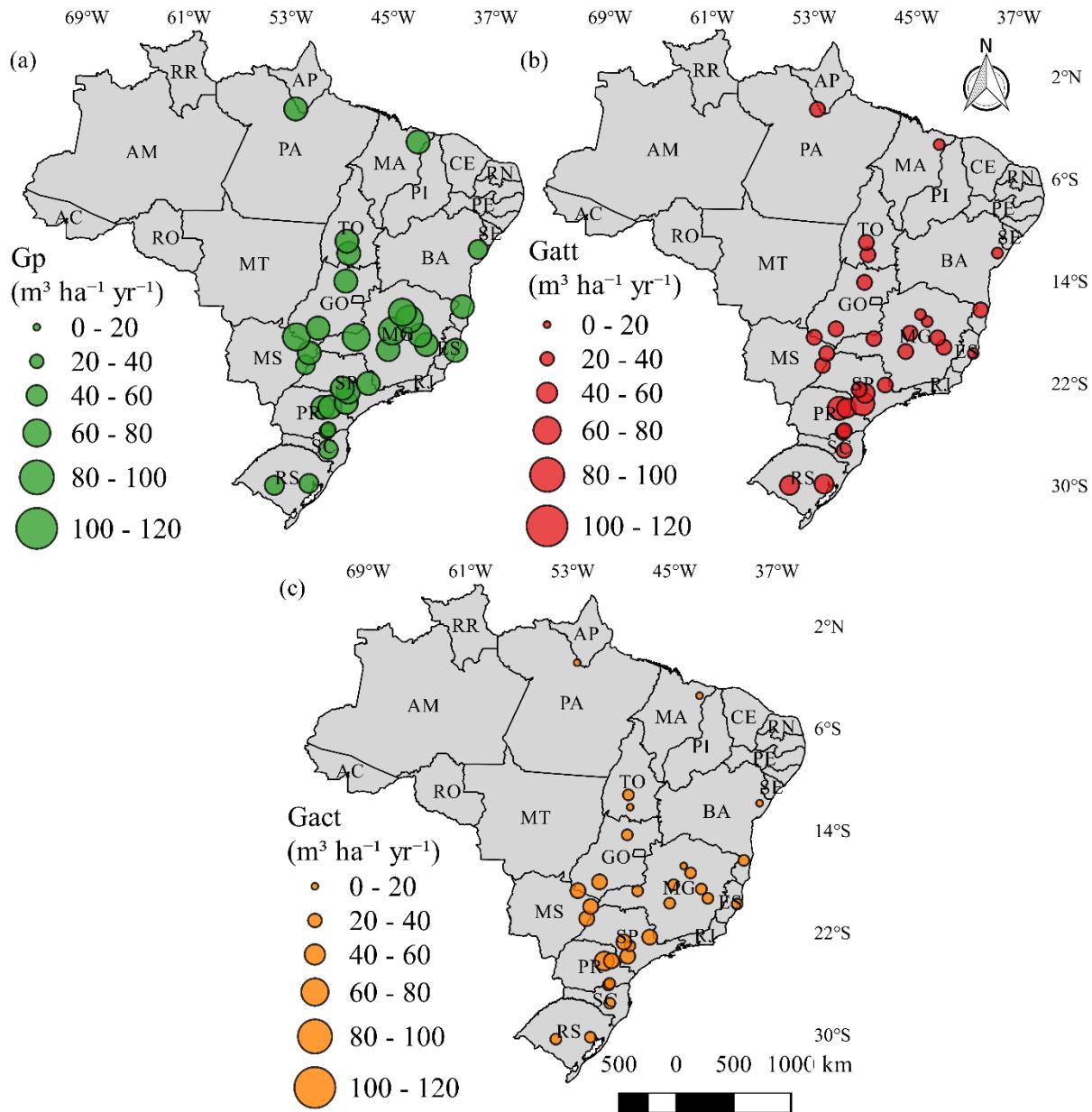


Figure 3. Average potential (Gp – a) and attainable (Gatt – b) *Eucalyptus* growth simulated by the ensemble of FAO, APSIM and 3PG simulation models, and actual *Eucalyptus* growth (Gact – c) at 30 producing locations in Brazil.

The average growth gap by water deficit was $34 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, ranging from 3 to $79 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 2 and Figure 4a). Higher GGwd ($\geq 65 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were found at Coração de Jesus and Bocaiuva, MG, while the lower values ($\leq 5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were found at Telêmaco Borba, in the state of Paraná, and Otacílio Costa and Três Barras, both in the state of Santa Catarina. The average GGwd in the Northeast and Southeast regions were, respectively, 45 and $44 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, slightly higher than in the North and Midwest regions, with 37 and $39 \text{ m}^3 \text{ ha}^{-1}$

yr^{-1} , respectively. Lower GGwd were found in Southern Brazil, where the average was only $5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.

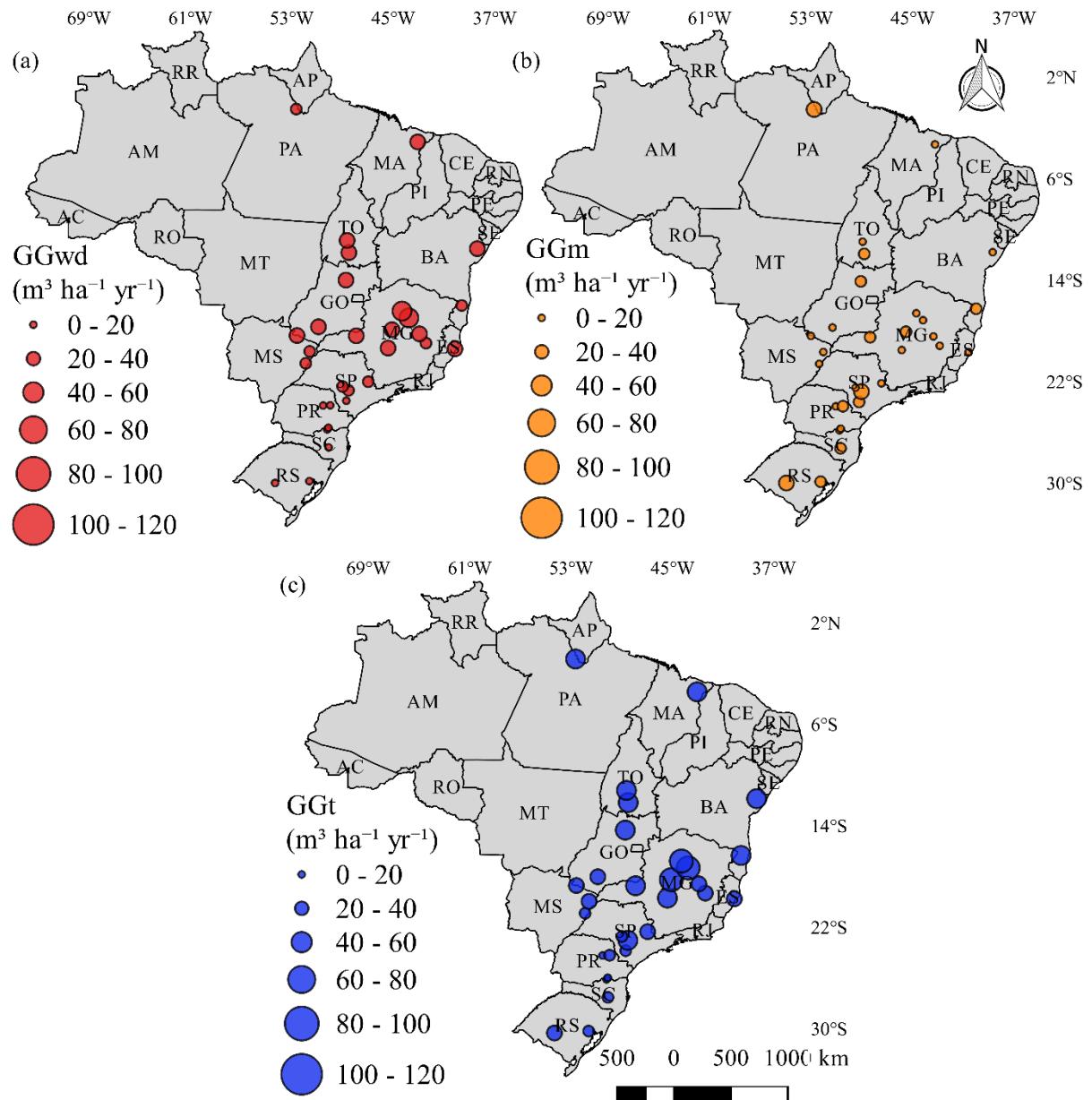


Figure 4. *Eucalyptus* growth gaps caused by water deficit (GGwd – a), sub-optimal forestry management (GGm – b), and total growth gap (GGt – c) at 30 producing locations in Brazil.

The GGm ranged from 0.1 to $51 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, with an average of $19 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 2 and Figure 4b). Higher GGm ($\geq 40 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were found at Botucatu, SP, São Gabriel, RS, and Monte Dourado, PA. On the other hand, lower GGm ($\leq 5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) were observed at Chapadão do Sul, MS, Três Barras, SC, and Bocaiúva, MG. The average total growth gap in Brazil was $53 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, but ranging from 9 to $87 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 2 and Figure 4c). Três

Marias, MG, Coração de Jesus, MG, Bocaiúva, MG, were the locations with the highest GGt ($\geq 80 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), whereas Telêmaco Borba, PR, Antonio Olinto, PR, and Três Barras, SC, presented the lowest ones ($\leq 20 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). Southeast, Northeast and North regions presented higher GGt, respectively 63, 64 and 67 $\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, than Midwest (49 $\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and South (27 $\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) regions.

The relative GG (% in relation to total GG) are presented in Table 2 and Figure 5. The GG of all companies located in Midwest and Northeast regions were predominantly caused by water deficit, with more than 50% of GGt caused by this factor. On average, the relative GGwd in these regions were above 70%. In Southeast and North regions, the water deficit was the main cause of GG in the majority of the locations, with relative GGwd reaching, respectively, 70 and 56%. On the other hand, in the South region, sub-optimal forestry management was the main cause of GG at all locations. On average, the GGm in this region represented 82% of GGt. In an overall average, the water deficit represented the main cause of *Eucalyptus* growth gap in Brazil (59%).

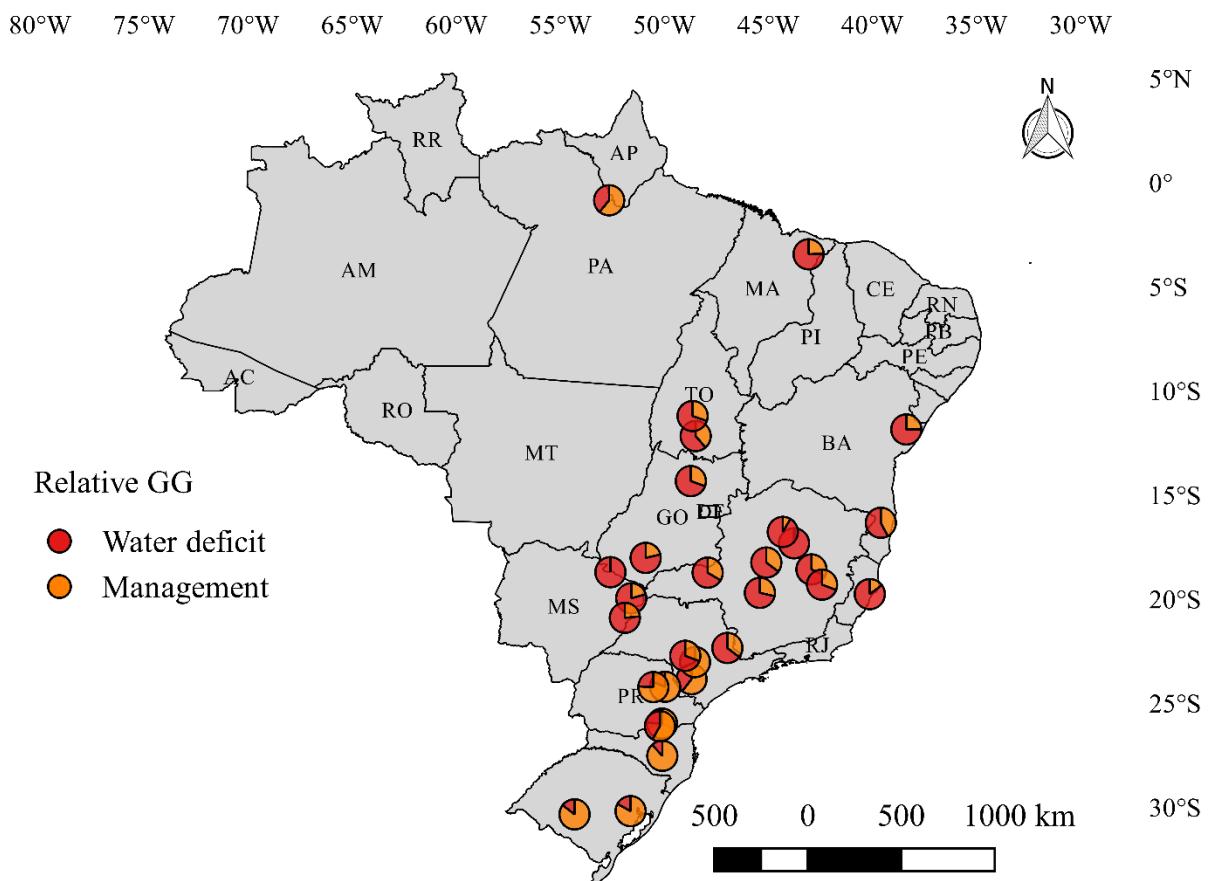


Figure 5. Relative *Eucalyptus* growth gaps (Relative GG), caused by water deficit and sub-optimal forestry management, for 30 producing locations in Brazil. Relative values are given in terms of total growth gap (GGt).

3.3.3. Climatic and forestry management efficiencies

The average *Eucalyptus* climatic (Ec) and management (Em) efficiencies considering all assessed locations were similar, respectively, 63% and 64%, but with huge variations across the country (Table 2 and Figure 6). The Ec ranged from 23 to 95%. All locations in South region presented Ec higher than 89%, while the lower values were found in Southeast region, mainly in Coração de Jesus (24%) and Bocaiúva (23%), both in the state of Minas Gerais. Em ranged from 15% in Monte Dourado, PA, to 100% in Chapadão do Sul, MS. On average, Midwest was the region with the highest Em (81%), whereas the North region presented the lowest value (35%).

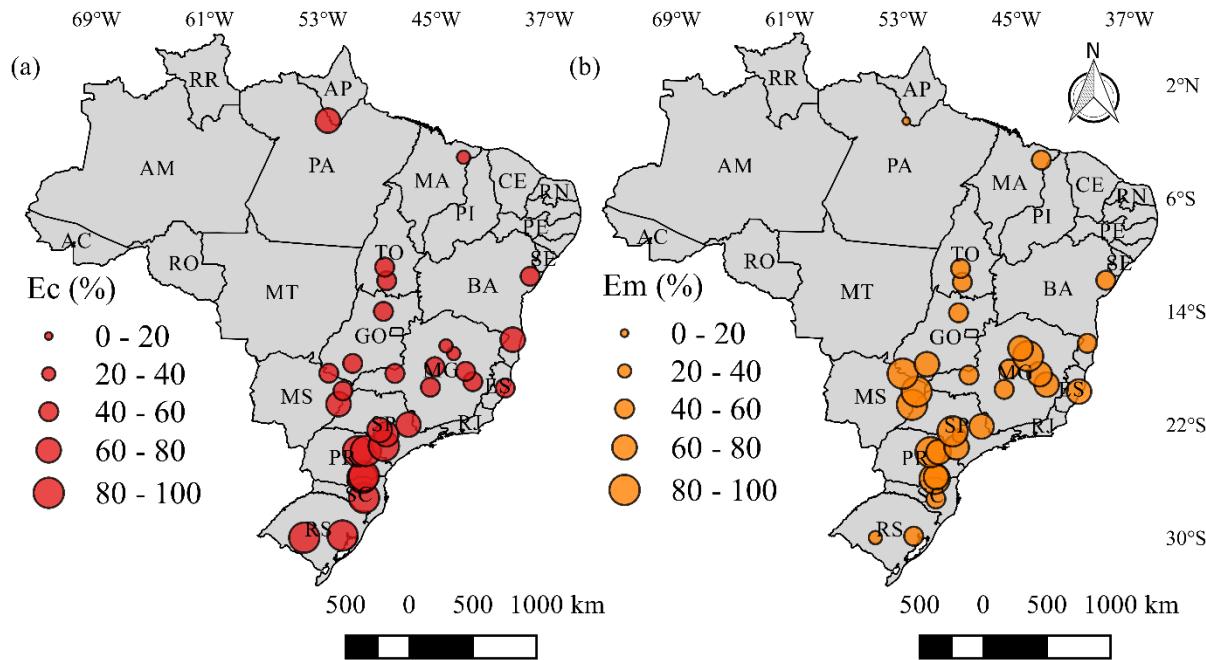


Figure 6. *Eucalyptus* climatic (Ec - a) and forestry management (Em - b) efficiencies for 30 producing locations in Brazil.

3.3.4. Actual *Eucalyptus* growth versus climatic and forestry management efficiencies

The Gact presented high rates of increase with Ec improvement for the locations with high Em (> 75%) (Figure 7a), which is expressed by the slope of the fitted regression (1.18). Similarly, the rate of Gact also increased substantially under better Em for the locations with high Ec (> 75%), with the slope of the regression being 0.88 (Figure 7b). For the locations with Em between 50 and 75%, the growth increment under better climatic conditions was lower, with the slope of fitted regression falling to 0.42 (Figure 7a). The slope of the regression between Gact and Em (Figure 7b) was also reduced for the locations with Ec between 50 and 75% (0.58). Finally, for locations with low management efficiency (< 50%), the slope of the regression between Gact and Ec was almost null (0.06) as also observed for the relationship between Gact and Em, for the same interval of Ec (0.09), which show that under poor forestry management or very dry climates, the improvement of the climatic conditions (Figure 7a) or management (Figure 7b), respectively, will not result in an expressive increase of Gact.

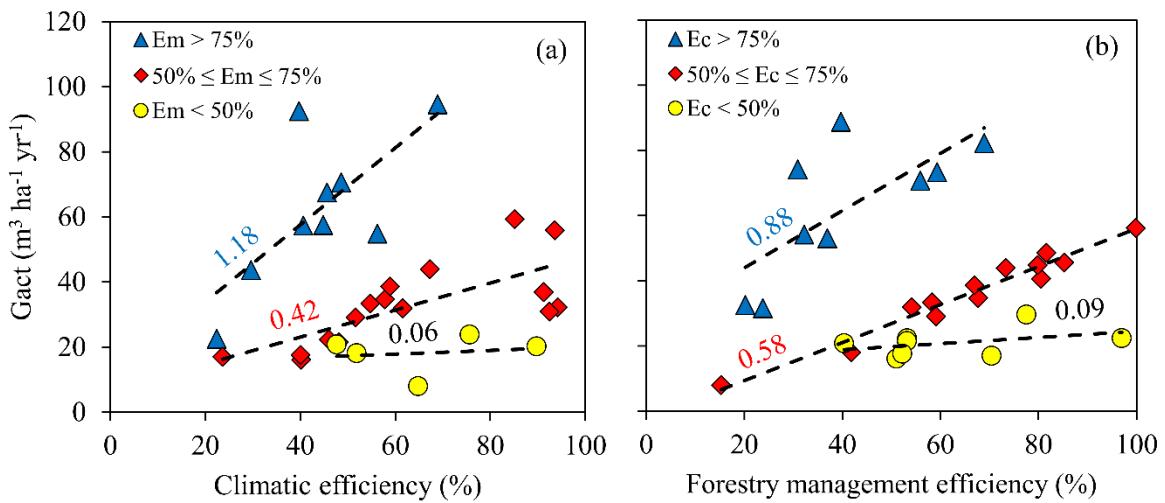


Figure 7. Relationships between the climatic efficiency and *Eucalyptus* actual growth (Gact) at different levels of management efficiency (a), and between the forestry management efficiency and Gact at different levels of climate efficiency (b), for 30 producing regions in Brazil.

3.4. Discussion

3.4.1. *Eucalyptus* growth

The highest Gp values were found at Guanhães, Estrela do Sul, Bocaiúva, all in MG, and in Botucatu, SP, and Chapadão do Sul, MS, which is justified by the combined effect of suitable air temperature for *Eucalyptus* growth, with averages between 20 and 25°C, mild nighttime air temperature, reducing maintenance respiration, and relatively high solar radiation along the year. This keeps photosynthesis, biomass production and partitioning to stemwood in good levels. On the other hand, the lowest Gp occurred in Antonio Olinto, PR, and Três Barras, SC, where mean temperature is below 19 °C, solar radiation levels are lower than $15 \text{ MJ m}^{-2} \text{ day}^{-1}$ and meteorological frost days are very frequent (Alvares et al., 2018). The results obtained in the present study agree with the results from Freitas (2018), who found an average Gp of $107 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for 22 producing locations in the state of Minas Gerais, Brazil, using the FAO model. On the other hand, Stape et al. (2010) assessed *Eucalyptus* productivity under high fertilization rates and irrigation in eight producing locations in Brazil and found an average of $63 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (ranging from 58 to $79 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), which is lower than our findings, but still within the range found. Such difference can be ascribed to problems with pests and diseases, use of different genetic materials or even with the level of irrigation applied, once the experiment was conducted under field conditions, supposing that forestry management was close to optimal.

The Gatt obtained in the present study are in agreement with other studies that assessed *Eucalyptus* yield and growth under experimental rainfed conditions in different Brazilian regions (Almeida et al., 2007; Gallo et al., 2018; Londero et al., 2015; Resende et al., 2018; Soares et al., 2017; Scolforo et al., 2019a). The lowest Gatt values were found in Inhambupe, BA, Urbano Santos, MA, Coração de Jesus, MG, and Bocaiúva, MG, locations with a very high potential growth, but with high levels of water deficit along the year, resulting in low values of relative evapotranspiration, respectively 0.47, 0.53, 0.38 and 0.36 (Table 1). Similar results were found by Gonçalves et al. (2017), who reported *Eucalyptus* MAI in Brazilian tropical regions with low water availability (Aw climate) varying between 25 and 35 m³ ha⁻¹ yr⁻¹, while in more humid regions, with higher soil water availability (Cfa and Cfb climates), *Eucalyptus* MAI ranged from 35 to 60 m³ ha⁻¹ yr⁻¹. The average *Eucalyptus* Gact from the assessed locations (34 m³ ha⁻¹ yr⁻¹) appropriately represents the average national MAI of commercial areas in Brazil, which is, according to IBÁ (2017), of 36 m³ ha⁻¹ yr⁻¹.

3.4.2. *Eucalyptus* growth gaps and their main causes

The water deficit was the main cause of *Eucalyptus* growth gap in Brazil, representing 59% of the general GGt. Freitas (2018) assessed the *Eucalyptus* growth gaps in the state of Minas Gerais, Brazil, using the FAO model, and reported that 77% of *Eucalyptus* growth gap was caused by water deficit in this state. The results found by Freitas (2018) agree with our finds for the same state, where, on average, 76% of *Eucalyptus* growth gap was caused by water deficit. Additionally, the negative effect of water deficit on *Eucalyptus* growth and yield has also been reported by several other studies in Brazil and around the world (Binkley et al., 2017; Campeo et al., 2016; Christina et al., 2018; Hubbard et al., 2010; Minhas et al., 2015; Prior and Bowman, 2014; Ryan et al., 2010; Stape et al., 2010; Scolforo et al., 2019b).

The GGm ranged from 0.1 m³ ha⁻¹ yr⁻¹, considered as optimal management, to 51 m³ ha⁻¹ yr⁻¹, which represents a poor forestry management. The highest GGm values occurred in Botucatu, SP, São Gabriel, RS, and Monte Dourado, PA, where Em were of only 32%, 33% and 15%, respectively. In Botucatu, SP, some subtropical clones used (F6 – *E. benthamii*, I9 – *E. dunnii*, J1 – *E. benthamii*, L3 – *E. urophylla* x *E. globulus* and M4 – *E. dunnii*), with an expected suitability for cool conditions, did not adapt well to the region and presented low growth rates, even with the location having an annual average temperature of 21.6 °C. It shows that genetics is an important determining factor, affecting Gp and, consequently, Gact, and must be strongly considered during the forest planning. In this context, matching suitable genotypes to the environment may be also considered as a management strategy for reducing growth gaps.

At São Gabriel, RS, the high GGm may be related to the occurrence of soil waterlogging during the rainy season, which affects trees growth by causing root rotting, permanent wilting, defoliation and anoxia, constraining respiration (Basak et al., 2015; Carvalho et al., 2016).

The high GGm obtained in Monte Dourado, PA, is mainly related to the high intensity of *Cylindrocladium* leaf blight (caused by *Cylindrocladium pteridis*) observed in this location, which also can be related to site waterlogging during the monsoon season (January to April). According to Alfenas et al. (2009) and Gonçalves et al. (2013), *Cylindrocladium* leaf blight disease may limit the growth of highly susceptible *Eucalyptus* genotypes in warm and humid regions, as is observed in Monte Dourado, which has high annual temperature and rainfall, respectively 27.8 °C and 2186 mm (Table 1), leading to very favorable conditions for this disease (Booth et al., 2000). Other possible causes of *Eucalyptus* GGm are: (i) use of low-quality seedlings; (ii) use of low-fertility, cohesive and shallow soils; (iii) inefficient control of weeds, pests and other diseases; (iv) occurrence of forest fires and/or windstorms.

3.4.3. Strategies to mitigate *Eucalyptus* growth gaps

The selection of more drought-tolerant genotypes is a key point to reduce GGwd. Genotypes with reduced leaf area index (LAI) during dry periods, deep rooting profile, lower stomatal density and sensitivity to vapour pressure deficit (VPD) are traits of interest for the breeding programs to adapt *Eucalyptus* to drought. Minimum cultivation (maintenance of litter and harvest residues over the soil) is also an important strategy for overcoming limitations of water resources for *Eucalyptus* stands during the dry season, by increasing rainfall infiltration and soil effective root depth and reducing weeds competition (Gonçalves et al., 2013). Using wider planting spacing is another possible mitigating strategy. According to Stape et al. (2001), the use of high productive clones and the negative effects of water deficit at some *Eucalyptus* producing regions in Brazil have led to the use of planting densities ranging from 830 trees ha⁻¹ (for sawtimber production) to 1,100 trees ha⁻¹ (for pulp production), where the mortality rate is between 1% and 5%, considered as acceptable. A detailed approach to *Eucalyptus* genetic and management adaptations to water deficit is presented by Gonçalves et al. (2017).

The following strategies may be used for reducing growth gaps caused by sub-optimal forest management: (i) soil fertilization (Melo et al., 2016; Silva et al., 2013); (ii) use of high-quality seedlings (South and Mexal, 1984; Stape et al., 2001); (iii) control of weeds, pests and diseases (Alvares et al., 2017; Gonçalves et al., 2017, 2013; Londero et al., 2012; Nória Júnior et al., 2018; Toledo et al., 2000; Wingfield et al., 2013); (iv) control of forest fires (Booth, 2013; Ribeiro et al., 2008; Soares, 2006) and (v) increasing resiliency to windstorms and waterlogging

events (Ataíde et al., 2015; Braz et al., 2014; Clemens et al., 1978; Coutts and Grace, 1995; Davison, 2018; Rosado et al., 2013). The results found here show the responsiveness of *Eucalyptus* growth to climate and management improvements, depending on their joint effects (Figure 7). Thus, the integration of climatic, forestry management and genetic strategies is of great importance to define the *Eucalyptus* rotation productivity, as an expression of the maximum productive potential according to the specific characteristics of each producing region.

The high Gact levels obtained in Arapoti, PR ($55.9 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), Telêmaco Borba, PR ($68.9 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), and Buri, SP ($59.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) are justified by high values of both climatic (93.6, 94.5 and 85.2%, respectively) and management (70.7, 82.3 and 73.2%, respectively) efficiencies, as well as, by relatively high Gp (84.5 , 88.6 and $95.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, respectively). Matching suitable genotypes to the best sites and management strategies is a promising strategy for closing growth gaps caused by both water deficit and sub-optimal forestry management. Assessing temporal and spatial climate variability effects on *Eucalyptus* productivity may be a useful tool for the forestry sector. In the present study, temporal climate variability effects were not addressed, since the results were presented for a particular period of time. Considering the effects that climate variability has on *Eucalyptus* growth and yield (Campoe et al., 2016; Freitas, 2018; Stape et al., 2010), future studies could focus on assessing the effects of interannual and seasonal climate variability on *Eucalyptus* growth and growth gaps.

3.5. Conclusions

The FAO, APSIM and 3PG models and their multimodel ensemble were promising tools for assessing *Eucalyptus* growth gaps at national level. The water deficit represented the main cause of *Eucalyptus* growth gaps in Central Northern Brazil, where the annual rainfall is lower and its seasonal variation is greater than in South Brazil. In this context, the use of adapted genotypes to water deficit, wider planting spacing and soil conservation practices for increasing rainfall infiltration and effective root depth are promising mitigation strategies to close the growth gap by this factor. In Southern Brazil, sub-optimal forest management was the main cause of *Eucalyptus* growth gaps. Therefore, the main strategies to reduce this growth gap are better fertilizers management, use of high-quality seedlings, and control of weeds, pests and diseases. In addition to these practices, better monitoring of forest fires, windstorms and waterlogging events by integrating climate, management and genetic strategies also could help to improve *Eucalyptus* productivity in this Brazilian region.

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Supplementary material

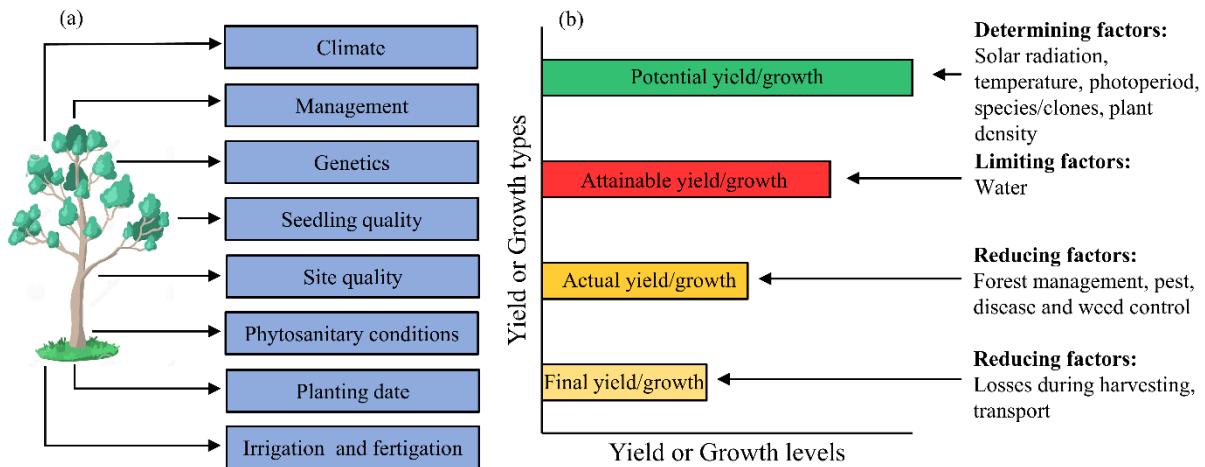


Figure S1. Factors that control *Eucalyptus* yield or growth (a) and types and levels of yield or growth and their determining, limiting and reducing factors (b). Adapted from Sentelhas et al. (2016).

Table S1. Statistical indexes (SI) and errors from the relationship between the observed and estimated volume of the *Eucalyptus* clone A1 (*Eucalyptus urophylla*) by the FAO, APSIM and 3PG models, during the calibration and evaluation phases.

SI/Errors ^a	Calibration				Evaluation			
	FAO	APSIM	3PG	Observed	FAO	APSIM	3PG	Observed
R ²	0.85	0.78	0.73	-	0.85	0.77	0.81	-
d	0.94	0.94	0.92	-	0.92	0.92	0.93	-
E	0.78	0.78	0.69	-	0.68	0.70	0.74	-
C	0.87	0.83	0.79	-	0.85	0.81	0.84	-
MAE (m ³ ha ⁻¹)	34.2	29.9	36.8	-	39.3	38.6	33.9	-
ME (m ³ ha ⁻¹)	22.1	0.0	13.5	-	35.5	20.3	20.6	-
RMSE (m ³ ha ⁻¹)	40.9	40.8	48.6	-	48.7	47.4	44.2	-
Average (m ³ ha ⁻¹)	136.4	114.3	127.7	114.3	162.4	147.3	147.6	126.9
SD (m ³ ha ⁻¹)	82.7	77.9	86.5	88.1	84.5	86.2	87.8	87.1

^a R² = coefficient of determination; d = Willmott agreement Index; E = modelling efficiency index; C = confidence index; MAE = mean absolute error; ME = mean error and RMSE = root mean square error; SD = standard deviation.

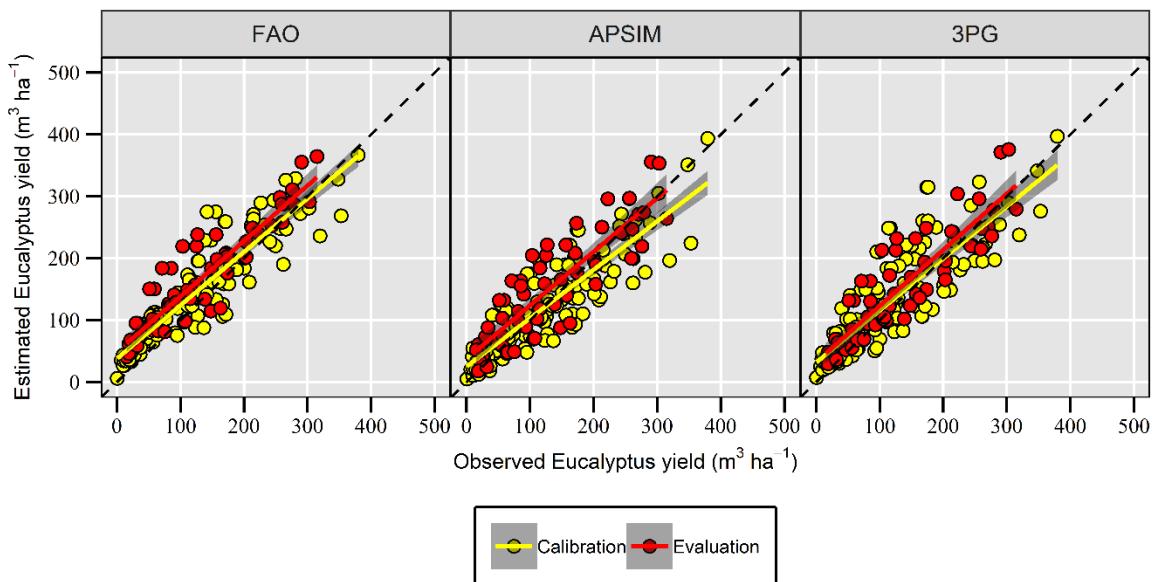


Figure S2. Relationship between the observed and estimated *Eucalyptus* attainable yield by the FAO, APSIM and 3PG models during the calibration and evaluation phases. For model calibration, the following locations were considered: 1, 2, 3, 4, 7, 8, 11, 13, 14, 19, 20, 23, 27, 28, 30 and 33. For model evaluation, the following locations were considered: 5, 9, 10, 18, 22, 24, 26. The description of location codes is presented in Table 1 of the manuscript.

References for supplementary material

Sentelhas, P.C., Battisti, R., Monteiro, L.A., Duarte, T.C.N., Visses, F.A. V, 2016. Yield gap: concepts, definitions and examples (in portuguese). Int. Plant Nutr. Inst. 155, 9–12.

4. ABILITY OF THE APSIM NEXT GENERATION *EUCALYPTUS* MODEL TO SIMULATE COMPLEX TRAITS ACROSS CONTRASTING ENVIRONMENTS*

Abstract

Process-based simulation models are promising tools to integrate biophysical process with soil and climate conditions and then simulate genetic and management impacts on forest productivity. The aim of this study was to adapt, calibrate, evaluate and improve the performance of the APSIM Next Generation *Eucalyptus* model for different major Brazilian *Eucalyptus* clones. To these ends, experimental stemwood production data from 2012 to 2017 from eight *Eucalyptus* clones distributed over 23 locations with contrasting environmental conditions in Brazil were used. The APSIM Next Generation *Eucalyptus* model, when properly adapted and calibrated, performed well in simulating stemwood biomass and volume, basal area and leaf area index in subtropical and tropical regions and for different genetic entries. For stemwood biomass, the R^2 ranged from 0.76 to 0.93 and the Willmott Agreement Index ranged from 0.93 to 0.98, indicating satisfactory precision and accuracy, respectively. As the model performed well, it may be a valuable decision support tool to help foresters in matching suitable genotypes to their sites, to simulate the best management strategies and to assist in long-term forest planning.

Keywords: process-based modelling; model adaptation; model evaluation; climate variability; management strategies.

4.1. Introduction

The *Eucalyptus* genus are cultivated in more than 20 million hectares worldwide (Trabado, 2009), and it is able to adapt to a wide range of soil and climatic conditions, presenting a fast growth and superior wood properties (Flores et al., 2018). *Eucalyptus* plantations provide renewable resources for pulp and paper production, the lumber industry, beekeeping, firewood and charcoal (Bauhus et al., 2010; Diaz-Balteiro and Rodriguez, 2006; IBÁ, 2017). In Brazil, *Eucalyptus* is the most cultivated genus to supply pulp and paper industries, lumber and panels, and steel mills, covering about 7.4 million hectares (IBGE, 2017).

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The *Eucalyptus* productivity in Brazil is highly variable due to climate and soil variability, genetic material and management practices (Binkley et al., 2017; Binkley and Fisher, 2013; Eldridge et al., 1994; Elli et al., 2017a; Jesus et al., 2015; Ryan et al., 2010; Scolforo et al., 2017, 2019b; Stape et al., 2010). In this context, the use of process-based models may be a valuable option to assist foresters and companies in appropriate planning, long-term management, and decision-making strategies and for assessing the impact of climate variability and change on the forestry (Almeida et al., 2009; Amichev et al., 2016; Battaglia et al., 2004; Freitas, 2018; Subedi and Fox, 2016; Waring and Gao, 2016; Wei et al., 2018).

There are several process-based models available for estimating *Eucalyptus* production, such as the G'DAY (Comins and McMurtrie, 1993; Marsden et al., 2013), 3PG (Landsberg and Waring, 1997), CABALA (Battaglia et al., 2004), Forest-DNDC (Li et al., 2000), FAO (Elli et al., 2019a; Freitas, 2018) and APSIM (Mccown et al., 1996). APSIM (Agricultural Production Systems Simulator) is an agricultural modelling framework used extensively worldwide and it provides biophysical models for over thirty crops, pastures and tree species (Holzworth et al., 2014). The simulation model commonly used for *Eucalyptus* is known as APSIM-Growth (Huth et al., 2001), which has been successfully used to simulate *Eucalyptus* stemwood volume across Brazil (Elli et al., 2019a). Currently, a new generation of the APSIM framework has been used, the APSIM Next Generation, with several improvements related to the execution speed, model construction and visualisation, and manager script flexibility (Holzworth et al., 2018).

Satisfactory results were found by Valadares (2018) using for the first time the APSIM Next Generation *Eucalyptus* model under some Brazilian and Australian sites, demonstrating this model is a promising tool for forest evaluations. Nevertheless, we believe that some adaptations related to frost effects, canopy crown architecture, wood density and volume functions could improve the ability of the APSIM Next Generation *Eucalyptus* model to simulate environmental and genetic effects. Furthermore, there is a gap of studies on the ability of forest process-based models to simulate complex traits (such as stem biomass, stem volume, basal area and leaf area index) from different genetic material across contrasting climate conditions. It would be of great value to the forest sector to use modelling approaches for matching suitable genotypes to sites, to simulate the best management strategies, to long-term forest plan, and to land pricing for acquisition or leasing.

In this context, we formulated the following hypothesis: APSIM Next Generation *Eucalyptus* model presents a satisfactory ability to simulate environmental and genetic effects on *Eucalyptus* yield and it may be used as a powerful tool for assisting foresters and companies

in appropriate planning and management. Therefore, the aim of this study was to adapt, calibrate and evaluate the performance of APSIM Next Generation *Eucalyptus* model for simulating complex yield-related traits for different Brazilian *Eucalyptus* clones.

4.2. Materials and methods

4.2.1. *Eucalyptus* traits

This study was conducted using yield data of eight major Brazilian *Eucalyptus* clones: A1 (*Eucalyptus urophylla*), C3 (*Eucalyptus grandis* x *Eucalyptus camaldulensis*), K2 (*Eucalyptus saligna*), Q8 (*Eucalyptus grandis*), B2 (*Eucalyptus urophylla* x *Eucalyptus grandis*), R9 (*Eucalyptus urophylla*), N5 (*Eucalyptus dunnii*) and O6 (*Eucalyptus grandis*), which were planted in 23 experimental locations in Brazil (Table 1). Detailed information on these clones can be found in Binkley et al. (2017). This dataset belongs to the Project "Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses" (TECHS), from the Forestry Science and Research Institute – IPEF. As not all the clones were planted at all locations, further information on the number of observed field data for each clone used for evaluating APSIM model can be seen in the Supplementary Material (Table S1).

Planting was performed from Dec/2011 to Jul/2012 (varying according to the planting calendar for each location) for a planned rotation length of six years. For information on soil preparation and fertilization, see Elli et al. (2019b). The seedlings were planted in a single plot with eight lines of 15 trees at a spacing of 3×3 m (1111 trees ha⁻¹), resulting in a total plot size of 1080 m². As the first five trees in each row were used for destructive sampling throughout the experiment period, a plot with eight rows of ten trees remained for measuring the diameter at breast height (DBH, at 1.3 m above ground level) and total height (H) periodically. The DBH and H were measured every 6 months (March/April and September/October), from the planting date to March/April 2017. From these data, stem biomass (t ha⁻¹) and volume (m³ ha⁻¹) were estimated by allometric equations fitted from a destructive analysis of six trees for each clone at location 33, in April 2014, while the basal area was calculated from the diameter at breast height. Leaf area index (LAI) was estimated using a ceptometer device (AccuPAR LP-80, Decagon Devices, USA), in locations with contrasting environmental conditions, following the same schedule of DBH and H measurements. Further information about the methodological procedures for fitting allometric equations and estimating LAI can be found in Mattos (2015) and Elli et al. (2019a).

Table 1. Locations of experimental plots used for the processes of model parameterization and evaluation, their respective soil order and summary of the weather conditions throughout trial time.

Code	Location, State: latitude, long. and alt.	Planting date	Soil order ^a	Clim.	Tmea	Rain	RET
01	Niquelândia, GO: 14.3 S, 48.7 W, 545 m	2012/03	Oxisol	Aw	25.6	1475	1560
02	Arapoti, PR: 24.2 S, 49.9 W, 770 m	2011/12	Oxisol	Cfb	19.1	1664	1180
03	Bom Despacho, MG: 19.6 S, 45.4 W, 727 m	2012/05	Oxisol	Cwa	23.1	1150	1430
04	Belo Oriente, MG: 19.3 S, 42.4 W, 243 m	2011/12	Oxisol	Aw	23.6	1188	1233
05	Guanhães, MG: 18.5 S, 42.9 W, 873 m	2012/01	Oxisol	Cwa	21.8	1099	1278
07	Rio Verde, GO: 18 S, 50.8 W, 681 m	2012/02	Entisol	Aw	23.8	1580	1403
08	Inhambupe, BA: 11.8 S, 38.3 W, 218 m	2012/07	Ultisol	As	25.6	696	1517
09	Estrela do Sul, MG: 18.7 S, 47.9 W, 969 m	2011/12	Oxisol	Cwb	23.6	1382	1447
10	Botucatu, SP: 23 S, 48.5 W, 869 m	2011/12	Oxisol	Cfa	21.6	1506	1292
11	Chapadão do Sul, MS: 18.7 S, 52.5 W, 783 m	2011/12	Oxisol	Am	23.5	1239	1460
13	Três Lagoas, MS: 20.9 S, 51.8 W, 361 m	2012/05	Oxisol	Aw	26.0	1267	1353
14	Inocência, MS: 19.9 S, 51.5 W, 480 m	2012/03	Entisol	Am	25.1	1224	1461
18	São Gabriel, RS: 30.3 S, 54.3 W, 102 m	2012/11	Oxisol	Cfa	20.5	1695	1191
19	Peixe, TO: 12.1 S, 48.5 W, 255 m	2012/03	Entisol	Aw	27.6	1239	1597
20	Mogi Guaçu, SP: 22.3 S, 46.9 W, 633 m	2012/02	Oxisol	Cwa	22.9	1340	1253
22	Telêmaco Borba, PR: 24.2 S, 50.5 W, 888 m	2012/02	Oxisol	Cfb	19.1	1662	1186
23	Otacílio Costa, SC: 27.5 S, 50.1 W, 870 m	2012/01	Incept.	Cfb	17.6	1746	1048
24	Borebi, SP: 22.7 S, 49 W, 656 m	2012/01	Entisol	Cfa	22.6	1326	1174
26	Coração de Jesus, MG: 16.7 S, 44.3 W, 926 m	2011/12	Oxisol	As	24.3	699	1554
27	Antônio Olinto, PR: 25.9 S, 50.1 W, 916 m	2012/02	Ultisol	Cfb	18.5	1836	906
28	Três Barras, SC: 26.1 S, 50.2 W, 812 m	2012/02	Oxisol	Cfb	18.0	1258	942
30	Bocaiúva, MG: 17.3 S, 43.7 W, 848 m	2011/12	Oxisol	Aw	24.8	712	1612
33	Buri, SP: 23.8 S, 48.7 W, 695 m	2011/12	Oxisol	Cfa	21.1	1471	1213

^a Reported by forestry companies. Classified from US Soil Taxonomy (Soil Survey Staff, 2014); Clim. = Köppen climate type; Tmea = mean air temperature, in °C; Rain = accumulated annual rainfall, in mm and RET = accumulated annual reference evapotranspiration in mm, which was calculated from Allen et al. (1998) approach.

4.2.2. APSIM Next Generation *Eucalyptus* model

The new APSIM *Eucalyptus* model takes into account the *Eucalyptus* modelling structure of the APSIM-Growth model (N. I. Huth et al., 2001), but is implemented in the Plant Modelling Framework (PMF), a software framework for creating models in APSIM Next Generation (Brown et al., 2014). Daily biomass production is calculated from daily intercepted solar radiation and a radiation use efficiency (RUE), which is affected by soil and climatic factors. Interception of solar radiation is calculated assuming an exponential light extinction coefficient. A general approach to this model is presented as follows:

$$\Delta G = R_{\text{int}} \times \varepsilon \times \min(F_T, F_F, F_N, F_{VPD}) \times F_W \quad (1)$$

where: ΔG is the daily growth; R_{int} the daily intercepted solar radiation; ε the radiation use efficiency (g MJ^{-1} of global solar radiation); and F_T , F_F , F_N , F_{VPD} and F_W growth modifiers to account for the effects of air temperature, frost, nitrogen, vapor pressure deficit and water supply, respectively.

The APSIM Next Generation *Eucalyptus* model includes five submodels related to different plant components: leaf, branch, stem, coarse root and fine root. Potential biomass production is modelled by the leaf submodel. Biomass is partitioned to the different organs according to tree size, environmental stresses and genotype-specific parametrizations. Leaf area growth is calculated from leaf growth and a specific leaf area. Similarly, root length is calculated from specific root length. Different soil layers are considered to describe the vertical distribution of various soil processes. Available water of each layer depends on the progress of the extraction front to greater depths. The potential water uptake is calculated using the product of the available water in the layer and a factor that controls the rate of absorption (KL). When plant water absorption is lower than the plant demand, reductions in growth rate are considered by water deficit. Full model documentation is available at <https://www.apsim.info/>. APSIM Next Generation platform also includes graphs and statistics that show the model performance against the observed data (Holzworth et al., 2018).

4.2.3. Weather and soil data

The weather data (maximum, minimum and mean air temperatures, solar radiation, rainfall, relative humidity and wind speed) were obtained from the weather stations located in the experimental areas of each forestry company, member of the TECHS Project, and when data were not available, we obtained them from the nearest weather stations belonging to the Brazilian National Institute of Meteorology (INMET). The missing data was filled from the nearest weather stations of the Brazilian National Water Agency (ANA), and from daily gridded meteorological data (Funk et al., 2015; Stackhouse et al., 2015; Xavier et al., 2016). The first soil order was reported by pedologists of each forestry company. The soil profile required in the APSIM model was built based on (i) pedotransfer functions fitted for Brazilian soils (Assad et al., 2001; Reichert et al., 2009), (ii) RadamBrasil (1974) and (iii) Wise (Batjes, 2009) databases. Pedotransfer functions were used to estimate the soil water content at the permanent wilting point (tension of 1500 kPa), field capacity (tension of 10 kPa) and, then, the soil water holding capacity. Input data required for these functions (sand, silt and clay contents) were

obtained by soil samples collected from each studied location, where clay and sand contents were quantified by the densiometric method (Embrapa, 1997). As site- and genotype-specific root depth information were not available, an effective root depth of 3 m was considered, according to the findings of Christina et al. (2017) and Pinheiro et al. (2019).

4.2.4. Model adaptation, calibration and evaluation

A number of functions were added into the APSIM model using PMF, as follows: wood density and volume, basal area, frost modifiers and light extinction coefficient modifiers. The documentation of the new functions added in the APSIM Next Generation *Eucalyptus* model is presented in the Supplementary Material (Section S1). The model calibration was performed based on field data (stem biomass, stem volume, basal area, LAI, biomass partitioning and soil water holding capacity) and by data and parametrization already described in the literature. Most of the parameters were manually changed within a realistic range until a suitable fit was obtained between the estimated and observed values. The parameters calibrated for all clones are presented in the Supplementary Material (Tables S2 and S3). These parameters were chosen due to their ability of predicting *Eucalyptus* genotypes differences (Elli et al., 2019a; Mattos, 2015; Valadares, 2018).

To analyze the model performance, the following statistical indexes and errors were considered: Coefficient of determination – R^2 , which describes the precision of predictions, Willmott Agreement Index – d (Willmott et al., 1985), which provides the accuracy of predictions, Modelling Efficiency Index – E (Nash and Sutcliffe, 1970), which indicates the relative magnitude of the residual variance compared to the measured variance, Confidence Index – C (Camargo and Sentelhas, 1997), which describes both precision and accuracy, Mean Absolute Error – MAE and Root Mean Square Error – RMSE, which provide the overall magnitude of the errors and Mean Error – ME, which indicates the bias in the predictions.

The relationships between the final stem biomass increment (SBI, $t\ ha^{-1}\ yr^{-1}$) and environmental variables (annual rainfall and climate moisture index - CMI) were evaluated. This was performed for both observed and estimated SBI values. Then, the slopes obtained from these relationships (observed SBI x environmental variables and estimated SBI x environmental variables) were compared for each *Eucalyptus* clone to verify if the model captured the key growth responses to climate and genetics. The CMI (Willmott and Feddema, 1992) was calculated as follows: when annual rainfall (Rain) < annual reference evapotranspiration (RET), $CMI = (Rain/RET) - 1$; when Rain \geq RET, $CMI = 1 - (RET/Rain)$.

Positive values of CMI represent wetter climates, while negative values represent drier climates (Willmott and Feddema, 1992).

4.3. Results

4.3.1. Ability of the APSIM Next Generation *Eucalyptus* model to simulate environmental effects

The APSIM model performed well in simulating stem biomass across contrasting environmental conditions for different clones (Figure 1). The R^2 ranged from 0.76 to 0.93 (among the different clones), the d index ranged from 0.93 to 0.98, the E index ranged from 0.75 to 0.93, whereas the RMSE ranged from 8.2 to 15.4 t ha⁻¹. Errors in predictions were higher for the clone C3. As data from different ages were used to evaluate the model performance, small panels with the final stem biomass increment (SBI) were plotted to assess environmental differences on final productivity. From this, a huge variation of stem biomass was observed across the contrasting environments (small panels in Figure 1).

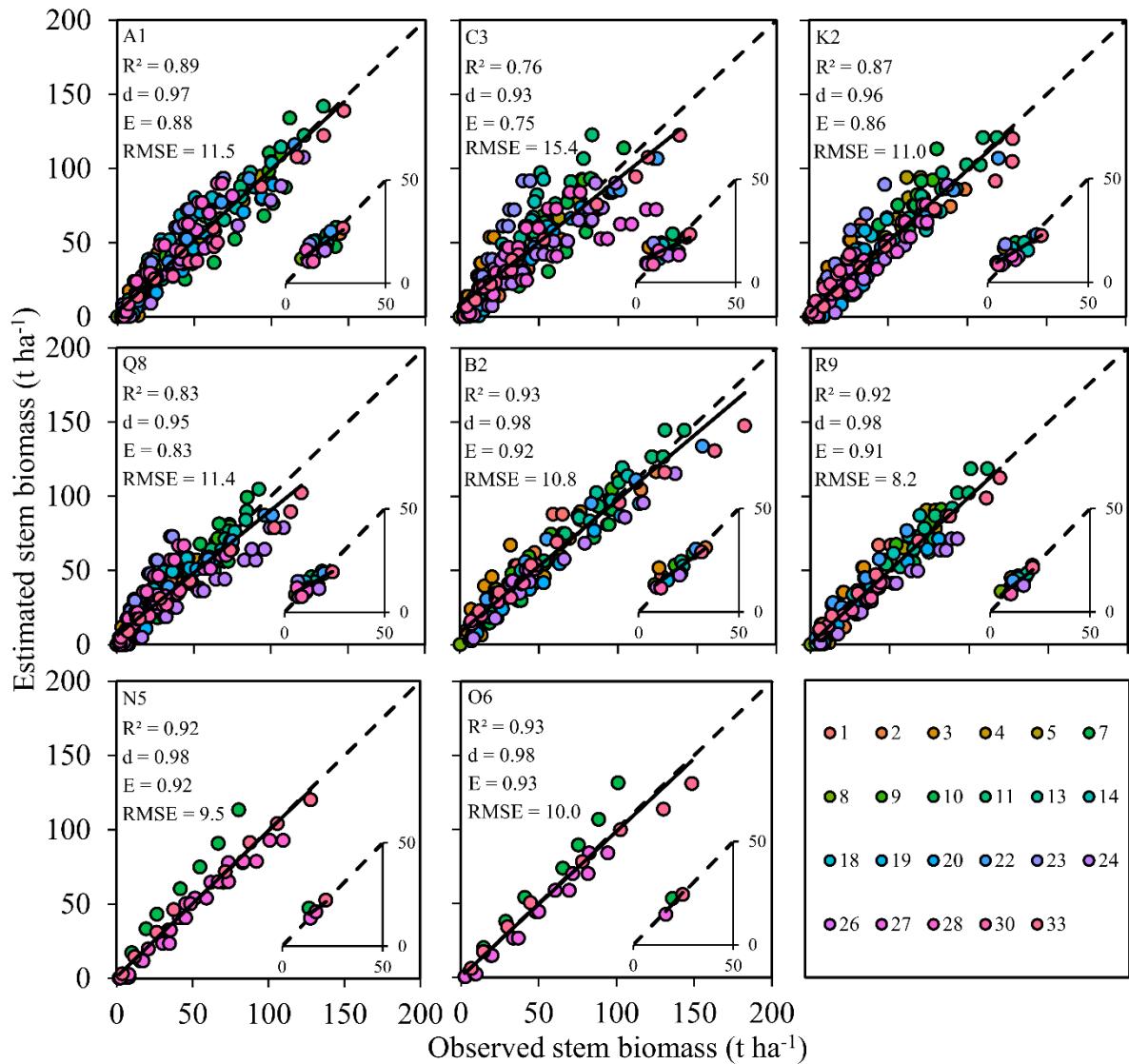


Figure 1. Ability of the APSIM Next Generation *Eucalyptus* model to simulate environmental effects on different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6). Colored points represent different locations. Statistics given in text are for coefficient of determination (R^2), Willmott agreement index (d), modelling efficiency index (E) and root mean square error (RMSE, $t\ ha^{-1}$), from the relationship between the observed and estimated *Eucalyptus* stem biomass. The small panels provide the relationship between the final observed and estimated stem biomass increment ($t\ ha^{-1}\ yr^{-1}$).

Furthermore, the APSIM model performed well in simulating the *Eucalyptus* stem volume and basal area (Figures S6 and S7 in the supplementary material). The R^2 ranged from 0.77 to 0.94 (among different clones) for stem volume and from 0.69 to 0.92 for basal area. The d index ranged from 0.94 to 0.99 and from 0.90 to 0.98, while the RMSE ranged from 21.51 to $35.9\ m^3\ ha^{-1}$ and from 2.09 to $4.15\ m^2\ ha^{-1}$, in the same sequence. In most cases, the model

presented overestimations of the basal area at the beginning of the *Eucalyptus* rotation, but after initial growth stage, usually from 12 months of age, this growth variable was predicted more accurately. Satisfactory results were also found when modelling the biomass partitioning of different *Eucalyptus* clones (Figure S8 in the supplementary material).

4.3.2 Spatial overview of model performance, uncertainties and limitations

The APSIM *Eucalyptus* model performed well in simulating stem biomass production from different clones for each location, but with huge variations among the locations (Figure 2). The E index ranged from 0.02 to 0.99, the R^2 ranged from 0.82 to 0.98, the root mean square error (RMSE) ranged from 4.04 to 14.08 t ha⁻¹, and the mean error (ME) ranged from -12.56 to 13.58 t ha⁻¹. No regional trends were found for E, R^2 and RMSE. Lesser values of E index (<0.5) were found at locations 03 and 08, dry environments, and 18, an environment with low temperatures, occurrence of frosts and poorly drained soil. No large differences in R^2 were found among the locations with the values satisfactory at all locations. The RMSE was higher (>10 t ha⁻¹) at locations 03-AMB, MG, 10-DUB and 24-LWA, SP and 18-CMS, RS. The ME tended to be negative in the States of Santa Catarina, Paraná and São Paulo.

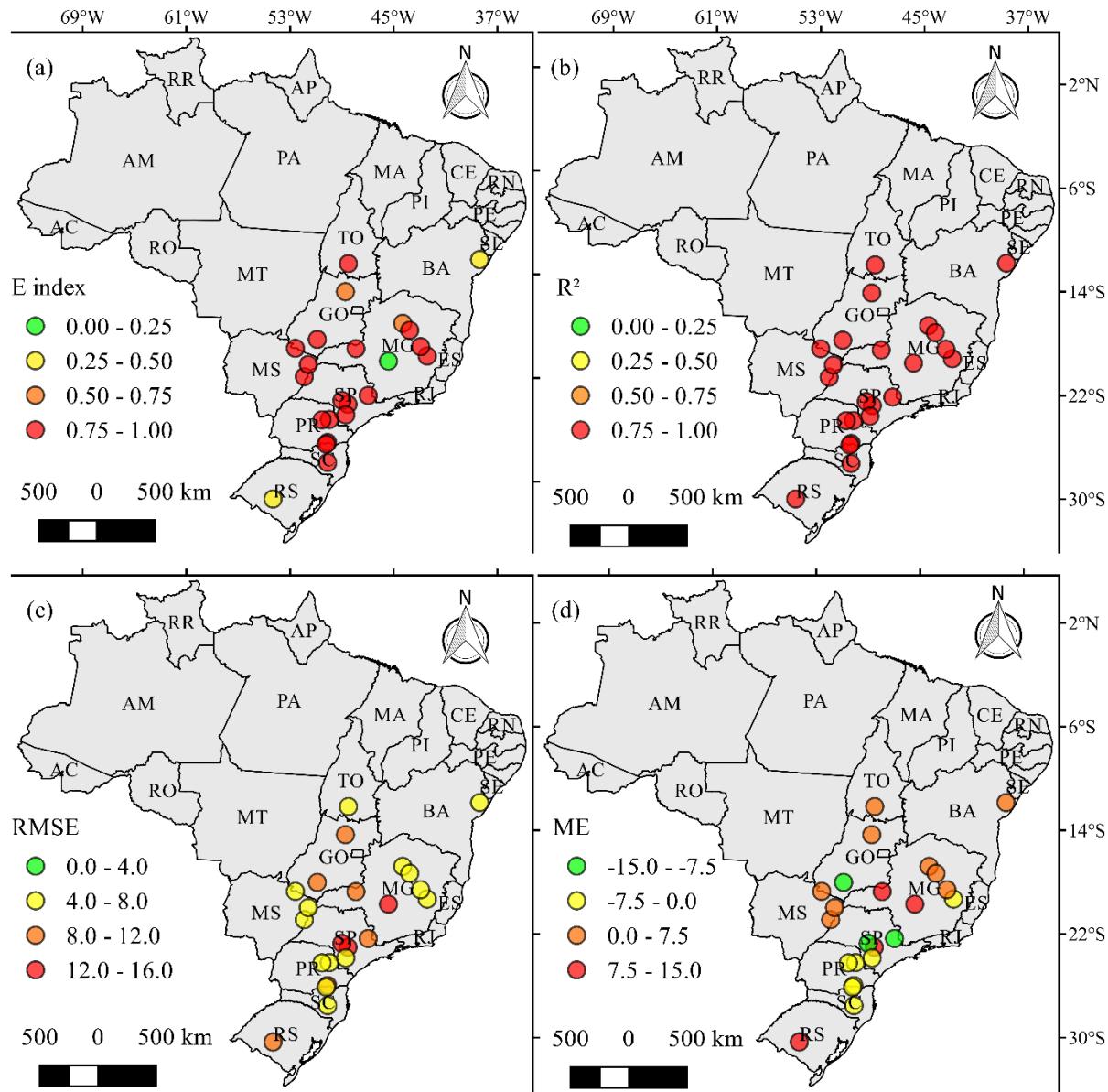


Figure 2. Spatial overview on the ability of the APSIM Next Generation *Eucalyptus* model to simulate *Eucalyptus* stem biomass from different clones in each studied location. Statistics given in map are for modelling efficiency index, E index (a), coefficient of determination, R^2 (b), root mean square error, RMSE (c, $t\ ha^{-1}$) and mean error, ME (d, $t\ ha^{-1}$) from the relationship between the observed and estimated stem biomass.

4.3.3. Differences in responsiveness of the clones to environmental conditions

APSIM *Eucalyptus* model was able to identify growth trends from different clones according to environmental variations (Figure 3). Clones varied in responsiveness to environmental conditions. For instance, clones A1 and Q8 presented lower slopes (< 0.008) from the relationship between SBI and annual rainfall for both observed and estimated values.

On the other hand, the slope for clone B2 was higher for both observed (0.019) and estimated (0.015) values, compared to the other clones. Some limitations for modelling SBI of clones with higher slope (i.e. higher sensitivity to annual rainfall and climate moisture index) were found.

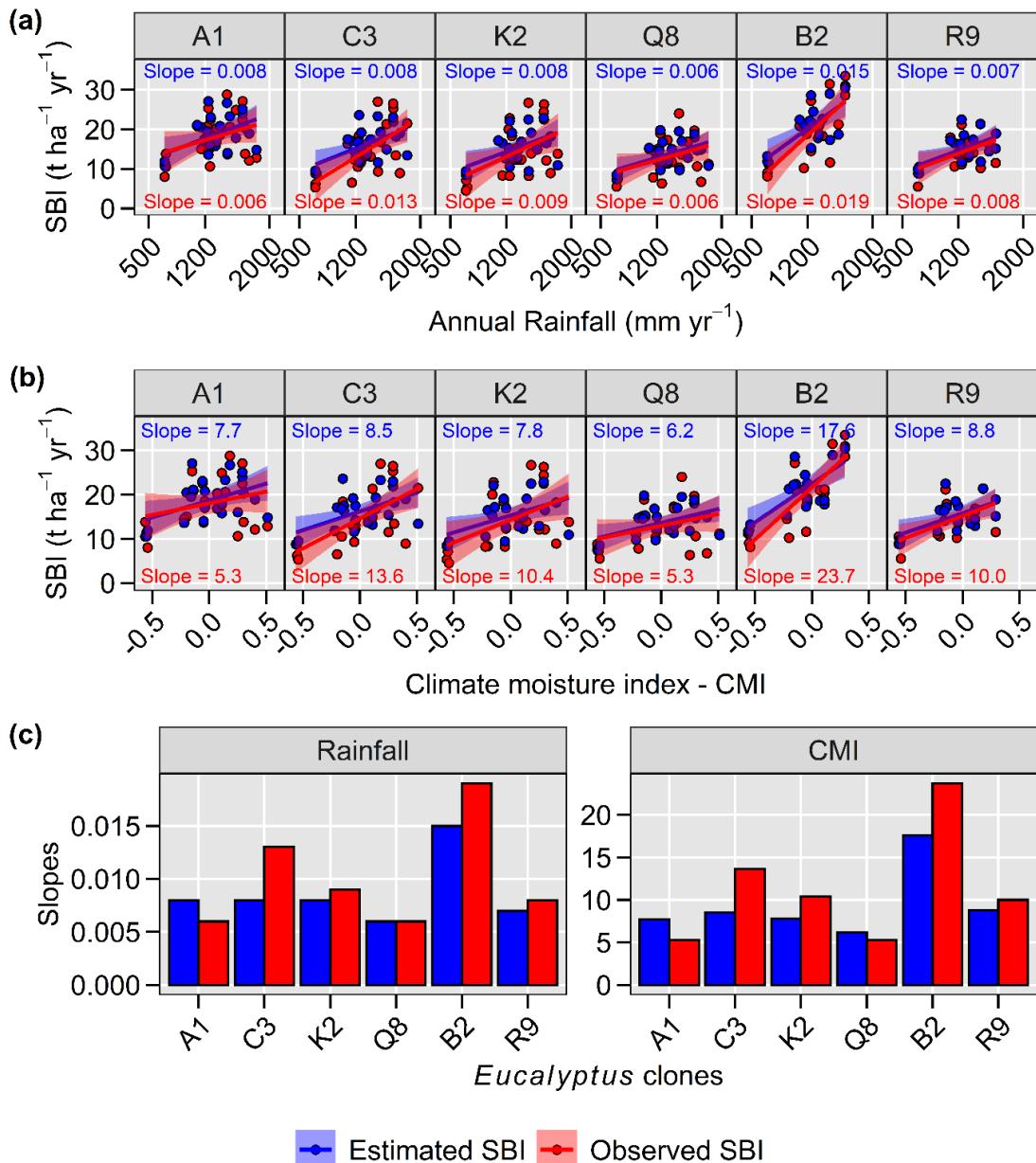


Figure 3. Ability of the APSIM Next Generation *Eucalyptus* model to simulate environmental and genetic effects. Coloured points represent the estimated and observed stem biomass increment (SBI) for each clone (A1, C3, K2, Q8, B2 and R9) at different levels of annual rainfall (a) and climate moisture index - CMI (b). The slopes obtained from the graphs (a) and (b) are compared in the graph (c). Clones N5 and O6 were not considered, due to the lack of observed data across contrasting environments.

4.3.4. *Eucalyptus* traits throughout its rotation

APSIM *Eucalyptus* model was able to simulate the stem biomass across highly contrasting environments and could identify yield differences between the clones (Figure 4). For instance, considering the *Eucalyptus* stem biomass between 3.5 and 4 years of age: in the wet location (22-KLT), for clone B2, the observed stem biomass (SB_{obs}) was 111.4 t ha^{-1} and the estimated stem biomass (SB_{est}) was 113.1 t ha^{-1} , while for clone R9, the SB_{obs} was 43.4 t ha^{-1} and the SB_{est} was 59.2 t ha^{-1} . In the dry location (26-PLA), for clone Q8, the SB_{obs} was 25.1 t ha^{-1} and the SB_{est} was 27.7 t ha^{-1} , while for clone A1, the SB_{obs} was 41.2 t ha^{-1} and the SB_{est} was 38.7 t ha^{-1} . Finally, in the Southeast location (33-DUR), for clone B2, the SB_{obs} was 129.6 t ha^{-1} and the SB_{est} was 115.5 t ha^{-1} , while for clone R9 the SB_{obs} was 87.8 t ha^{-1} and the SB_{est} was 86.0 t ha^{-1} .

Lower agreements between the observed and estimated stem biomass were observed in some cases, as can be seen in the North location, clone K2 and South location, clone A1. Reductions in observed and estimated biomass growth rate were observed in some specific seasons throughout the *Eucalyptus* rotation, generally in periods with severe soil water deficit in Southeast, Northeast and North locations and during periods with lower temperatures and occurrence of frosts in South Brazil. Inter-annual and inter-seasonal LAI variations were observed, with different responses according to the environment and clone (Figure 5). Generally, maximum LAI was observed from 16 to 26 months of age. APSIM *Eucalyptus* model performed reasonably well when estimating LAI and was able to identify LAI trends according to environmental variations, such as soil water deficit and frost events. Environment differences were more pronounced than the genetic differences for both observed and estimated LAI. In a general way, the wet location presented higher observed and estimated values of LAI, while the dry location presented the lower values.

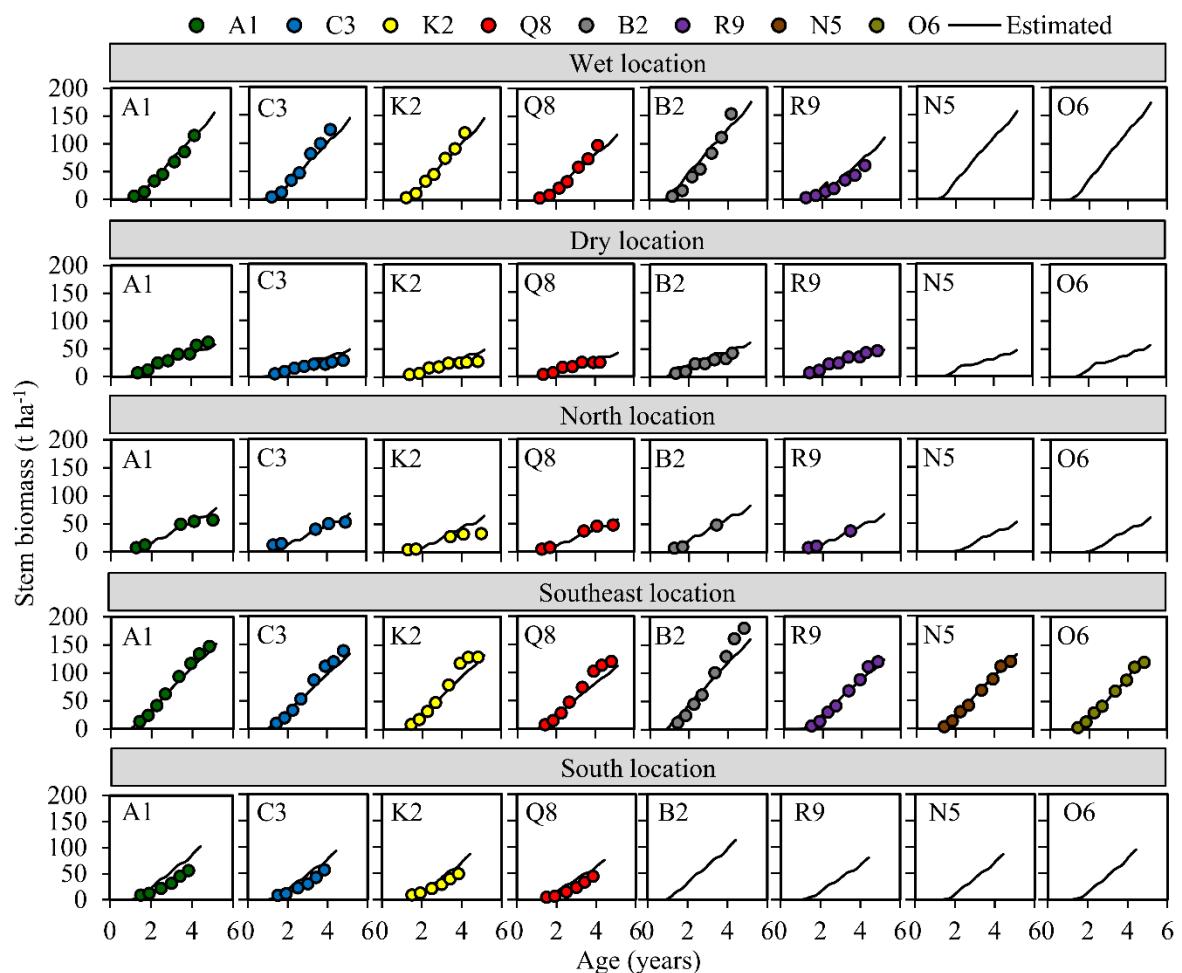


Figure 4. Observed and estimated stem biomass by the APSIM Next Generation *Eucalyptus* model throughout the rotation of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6) at locations with contrasting environmental conditions. The wet and dry locations refer to 22 and 26, respectively, while North, Southeast and South locations refer to 19, 33 and 18, respectively. Not all clones were planted in all locations. Therefore, graphs that present only the estimated values refer to locations where there is no observed data for the respective clone.

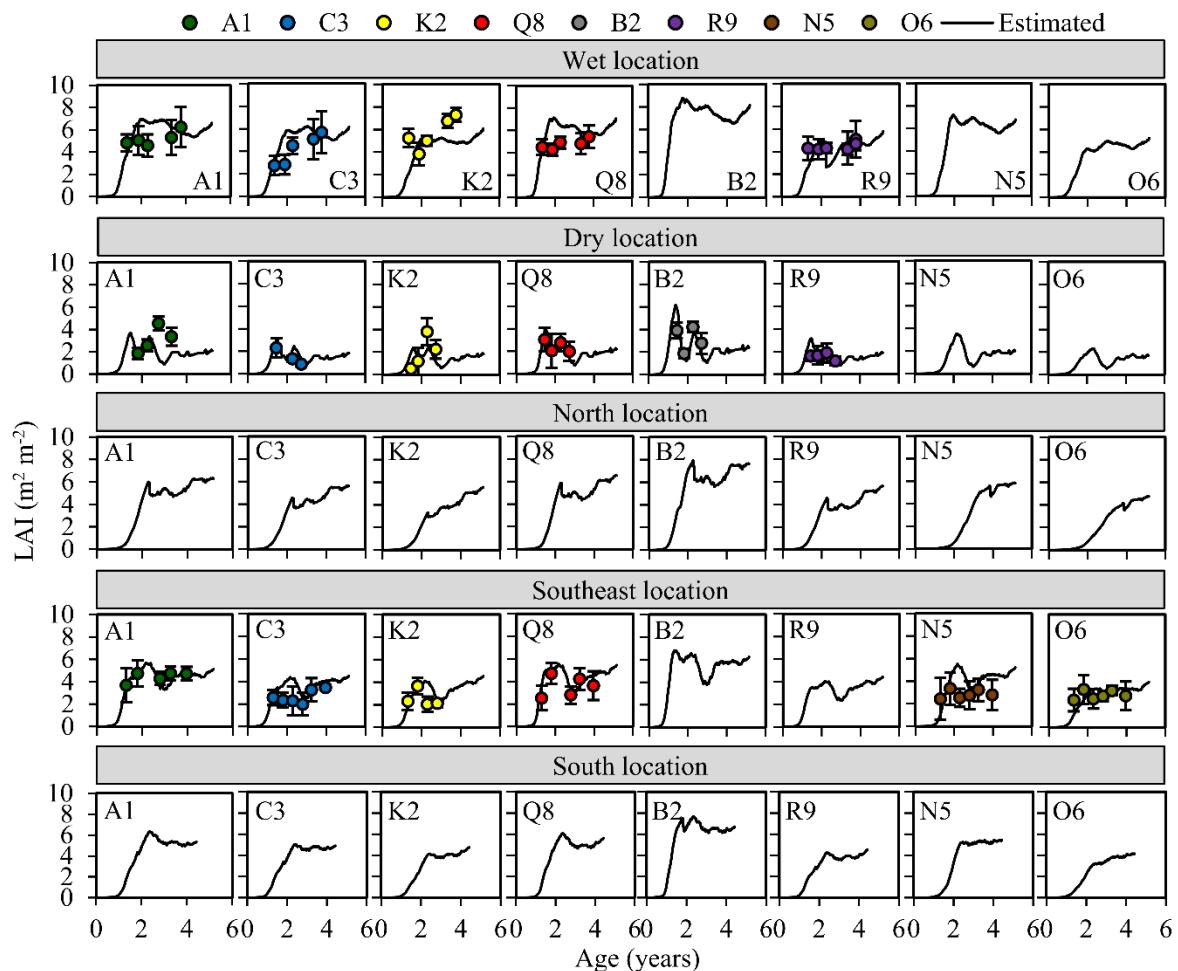


Figure 5. Observed and estimated leaf area index (LAI) by the APSIM Next Generation *Eucalyptus* model throughout the rotation of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6) at locations with contrasting environmental conditions. The wet and dry locations refer to 2 and 9, respectively, while the locations in the North, Southeast and South refer to 19, 10 and 18, respectively. Graphs that present only the estimated values refer to locations where there is no observed data for the respective clone.

4.3.5. *Eucalyptus* ecophysiological growth modifiers affecting modelled traits

Environmental effects were also identified by the changes in growth modifiers by the model for different locations (Figure 6). Parameters that affect growth modifiers for soil water deficit (Fw) and vapour pressure deficit (Fvpd) were the same for all clones due to the lack of genotype-specific information, while those parameters that affect growth modifiers for temperature (Ft) and frost (frost) were differentiated among clones (Tables S2 and S3 in the supplementary material). The Fw and Ft were the ones that most impacted *Eucalyptus* yield across locations within the present study. The effects of rainfall seasonal variations on Fw can be observed at the location 26, classified as dry, and 19, in the north of the country. Locations

in the south of Brazil presented very low effects of soil water deficit. On the other hand, frost events affected the growth at some specific days in these locations. Locations 22 and 33 presented lower effects of frost events and relatively low effects of temperature and water deficit stresses, resulting in the highest stemwood biomass production among those assessed in this study (Figure 6).

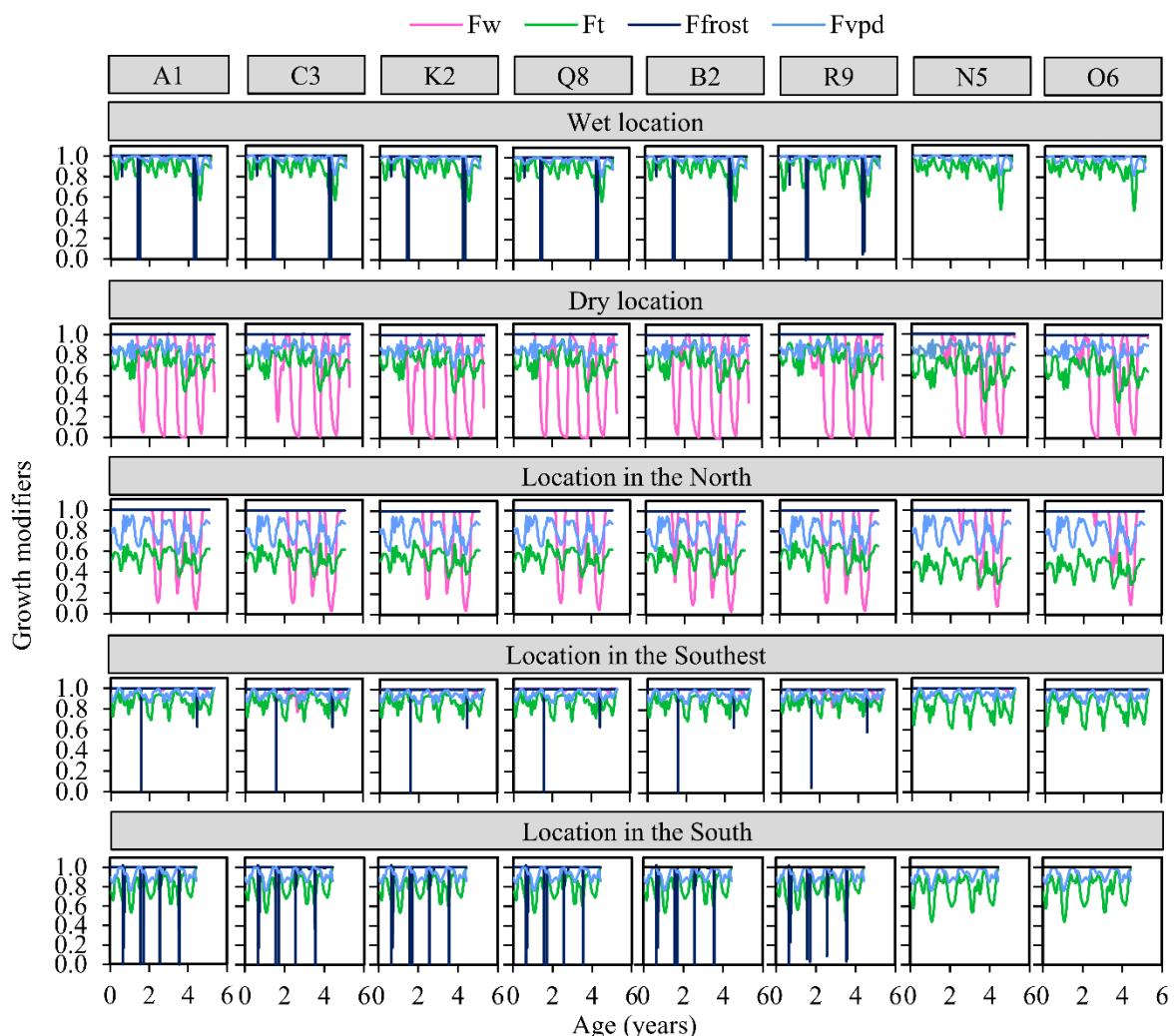


Figure 6. Growth modifiers for soil water deficit (Fw), temperature (Ft), frost (Ffrost) and vapour pressure deficit (Fvpd) simulated by the APSIM Next Generation *Eucalyptus* model throughout the rotation of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6) at locations with contrasting environmental conditions. The wet and dry locations refer to 22 and 26, respectively, while the locations in the North, Southeast and South refer to 19, 33 and 18, respectively. Growth modifiers are presented at a monthly time step, except for Ffrost, which is presented at daily time step. Values range from 0 (no growth) to 1 (growth non-limiting).

4.4. Discussion

The statistical indices and errors found in the present study (Figure 1) are in agreement with other studies involving process-based *Eucalyptus* models in Brazil and around the world. Valadares (2018) used the APSIM Next Generation *Eucalyptus* model to simulate aboveground biomass from 9 locations in Brazil and 3 locations in Australia and found $R^2 = 0.91$ and E index = 0.89. Elli et al. (2019a) assessed the performance of the APSIM-growth, 3PG and FAO models and their multimodel ensemble for estimating *Eucalyptus* stemwood volume under Brazilian conditions and found R^2 from 0.81 to 0.89, d index from 0.94 to 0.96, E index from 0.75 to 0.85 and C index from 0.85 to 0.90 during the model validation. Stape et al. (2004) used the 3PG model for simulating wood production of *Eucalyptus grandis* x *urophylla* grown under different fertilization treatments in the state of São Paulo, Brazil. These authors obtained R^2 from 0.71 to 0.83, E index from 0.61 to 0.75 and RMSE from 5.6 to 7.6 Mg ha⁻¹ year⁻¹. Sands and Landsberg (2002) found $R^2 = 0.71$ for volume MAI simulations from *Eucalyptus globulus* plantations in Australia. Battaglia et al. (2004) evaluated the performance of CABALA model in simulating *Eucalyptus* volume in Tasmania, Australia and found $R^2 = 0.94$ and RMSE = 22 m³ ha⁻¹. González-García et al. (2016) observed $R^2 = 0.84$, E index = 0.79 and RMSE = 29.51 m³ ha⁻¹ for stem volume estimations of *Eucalyptus nitens* in Spain.

From the individual analysis of each location, lesser E index were found at locations 03, 08 and 18 (Figure 2). Sites 03 and 08 are dry environments, especially site 8 where the accumulated annual rainfall was 696 mm year⁻¹ (Table 1). One possible limitation in the present study is the lack of detailed soil data for building APSIM soil profile. Pedotransfer functions fitted for Brazilian soils were used to estimate the soil water holding capacity according to specific characteristics (sand, clay and silt contents) of each site, in addition to RadamBrasil (1974) and Wise (Batjes, 2009) databases. However, soil characteristics may present high horizontal and vertical spatial variability (Motomiya et al., 2011; Siqueira et al., 2015). Besides that, the lack of detailed information on the effective root depth for each clone may be a potential cause of uncertainties in such locations.

Lesser E index at site 18 may be related to the occurrence of soil waterlogging during the rainy season, since the APSIM *Eucalyptus* model does not consider the effects of such event during the simulations. This can explain the APSIM overestimations in such location (Figure 2), which is observed by the positive mean error (10.85 t ha⁻¹), whereas in the other locations in South Brazil, APSIM model slightly underestimated the stem biomass (mean error from -7.5 to 0 t ha⁻¹). Heavy rainfall and poorly drained soils are the main causes of waterlogging events (Davison, 2018), characteristics commonly observed at site 18. Waterlogging events stress

plants primarily by inhibiting the diffusion of atmospheric oxygen to the root zone, and prolonged stress may cause the death of the root system, permanent wilting of leaves, defoliation and hypoxia, constraining respiration (Basak et al., 2015; Clemens et al., 1978).

Increases in both observed and estimated *Eucalyptus* stem biomass were found with increasing annual rainfall and climate moisture index (Figure 3), with a varied responsiveness among clones. Effects of water supply on *Eucalyptus* wood production have been reported by several studies in Brazil and around the world (Christina et al., 2018; Hubbard et al., 2010; Minhas et al., 2015; Prior and Bowman, 2014; Ryan et al., 2010; Stape et al., 2010). Our finds are in agreement with Binkley et al. (2017), who assessed 27 experimental locations in Brazil and found an increase of stemwood production with increasing annual rainfall. These authors found different responsiveness among clones to environmental variations across sites. Similarly, Gonçalves et al. (2017) and Scolforo et al. (2019) found reductions in *Eucalyptus* stem volume with increasing water deficit in the main regions of commercial *Eucalyptus* plantations in Brazil. Stape et al. (2004) assessed *Eucalyptus* traits from 14 locations in north-eastern Brazil and found the water, light and nitrogen use efficiency increased with increasing annual rainfall.

Significant improvement in the accuracy of stem biomass estimations mainly at the beginning of *Eucalyptus* rotation (Figure 4) were obtained after changes to the light extinction coefficient function in the model. Growth rate overestimations at initial stages are commonly found in forest modelling studies (Almeida et al., 2004; Battaglia et al., 2004; Miehle et al., 2009). The frost functions added into the model reduced uncertainties of simulations in Southern Brazil. Two frost functions were added in the model: (i) the photosynthesis modifier for frost (Ffrost) and (ii) senescence rate for frost (SSRF). The current version of the model considers the damages vary according to frost intensity, age of *Eucalyptus* plantation and genetic material (since specific calibrations for each clone were performed). Alvares et al. (2018) modelled monthly frost days in Center-Southern Brazil based on minimum air temperature. They found the highlands of Santa Catarina, Rio Grande do Sul, São Paulo, and Minas Gerais States presented on average more than 13 frosts per year. Thus, modelling frost effects on *Eucalyptus* yield may be of high importance for helping foresters in estimating yield more accurately in such regions.

The observed and estimated LAI variation throughout the *Eucalyptus* rotation was justified by the weather seasonality (Figure 5). LAI decreases occurred mostly after periods of water deficit, which helps to understand the inter-seasonal variability of *Eucalyptus* growth rate. In the wet location, inter-seasonal LAI variations were less evident due to the rainfall relatively

well distributed along the year. Our results are in agreement with Lemos (2012), who used the 3PG model on clonal *Eucalyptus* plantations in São Paulo State, Brazil and observed a maximum LAI at 18 months of age and seasonal oscillations according to weather conditions over the year. Hakamada et al. (2016) found higher LAI at 24 months of age in *Eucalyptus* plantations in the states of Bahia and São Paulo, Brazil.

The growth modifiers of the APSIM *Eucalyptus* model varied among locations and over the *Eucalyptus* rotation (Figure 6). This demonstrates the model was able to simulate effects of both spatial and temporal climate variability on *Eucalyptus* growth. This is an important result, since long-term simulations for assessing effects of weather variability on *Eucalyptus* yield may be a valuable decision support tool in the pursuit of appropriate forest planning and management (Elli et al., 2017). Besides that, Corbeels et al. (2018) and Cooper et al. (2008) highlight that an efficient way to address climate change impacts may be to focus on strategies for coping with climate variability, rather than relying on long-term climate change predictions.

Using modelling to identify genotype differences is a big challenge since literature information and field data are still scarce. Some progresses have been made in this study with the proposed adaptations and a robust calibration of the APSIM Next Generation *Eucalyptus* model for different genotypes. Model evaluation was performed against data of stem biomass, stem volume, basal area, LAI and biomass partitioning. Despite some uncertainties found during the simulations and considering the wide range of environments and genotypes evaluated, APSIM Next Generation *Eucalyptus* model performed very well in simulating *Eucalyptus* complex traits over the main Brazilian producing area and was able to identify environmental and genetic effects. Using APSIM Next Generation *Eucalyptus* model for studying long-term effects of climate variability and change on *Eucalyptus* productivity is a promising future application of that for scientific and practical purposes.

4.5. Conclusions

The APSIM Next Generation *Eucalyptus* model, when properly adapted and calibrated, was successful in simulating environmental and genetic effects on *Eucalyptus* complex traits, such as stem biomass and volume, LAI and basal area, considering the major Brazilian *Eucalyptus* clones and the main Brazilian producing area. In this context, APSIM *Eucalyptus* model may be a valuable decision support tool for helping foresters and companies in matching suitable genotypes to sites and to develop the best management strategies.

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Supplementary material

Table S1. Number of *Eucalyptus* yield data (n) used during the evaluation process of the APSIM Next Generation *Eucalyptus* model for different Brazilian clones (A1, C3, K2, Q8, B2, R9, N5 and O6).

Location ^a	A1 ^b	C3	K2	Q8	B2	R9	N5	O6	Total n per location
1	8	3	4	4	8	8	- ^b	-	35
2	6	12	6	12	6	12	-	-	54
3	5	10	10	10	5	10	-	-	50
4	8	8	8	8	8	8	-	-	48
5	8	16	16	8	8	16	-	-	72
7	8	8	16	15	16	8	-	-	71
8	8	8	8	8	8	8	-	-	48
9	8	8	8	8	8	8	-	-	48
10	8	8	8	8	-	-	8	8	48
11	8	8	16	8	16	16	-	-	72
13	6	6	6	6	6	6	-	-	36
14	7	8	7	7	7	7	-	-	43
18	12	12	6	12	-	-	-	-	42
19	10	10	10	5	6	6	-	-	47
20	8	8	8	8	8	8	-	-	48
22	7	14	7	14	7	7	-	-	56
23	14	14	7	14	-	-	-	-	49
24	9	18	9	18	9	16	-	-	79
26	8	8	16	14	14	8	-	-	68
27	8	16	16	16	-	-	16	16	88
28	16	16	16	16	-	-	16	-	80
30	8	8	8	8	8	8	-	-	48
33	8	8	8	8	8	8	8	8	64
Total n per clone	196	235	224	235	156	168	48	32	1294

^aThe number of data was the same for stem biomass, stem volume and basal area.

^bLocations where the clone was not evaluated.

S1. Documentation of the new functions added to the APSIM Next Generation *Eucalyptus* model

S1.1. Wood density

The *Eucalyptus* wood density may change with age, and the intensity of this change may depend on the genetic material (Almeida and Sands, 2016; Jarbas Silva Borges et al., 2012; Londero et al., 2015; Rocha, 2018). In this context, the following wood density function (Sands and Landsberg, 2002) was added to the model:

$$\rho = \rho_1 + (\rho_0 - \rho_1) e^{-0.69315 \left(\frac{\text{Age}}{t\rho} \right)^{2.99}} \quad (\text{S1})$$

where: ρ is the basic density at a certain age ($t \text{ m}^{-2}$); ρ_0 is the basic density of young trees ($t \text{ m}^{-2}$); ρ_1 the basic density of old trees ($t \text{ m}^{-2}$) and $t\rho$ the age that the trees present intermediate basic density ($t\rho = (\rho_0 + \rho_1)/2$).

As a default, the ρ_0 is 0.40 $t \text{ m}^{-2}$, the ρ_1 is 0.50 and the $t\rho$ is 2.26 years. These values could be changed based on observed data or information existing in the literature. The variation of the wood basic density throughout the *Eucalyptus* rotation is demonstrated in Figure S1.

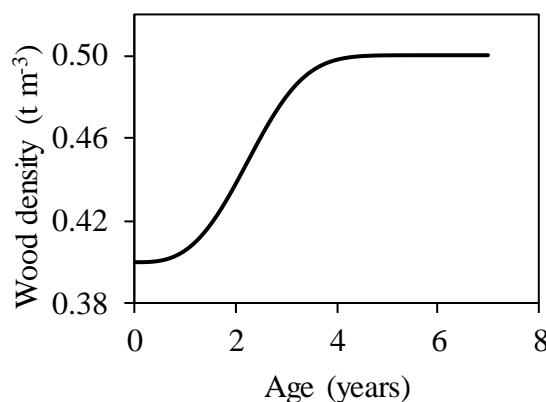


Figure S1. Variation of the wood basic density throughout the *Eucalyptus* rotation. Default values of the model were used.

S1.2. Wood volume as a function of the wood density

Using the wood density curve according to age, the *Eucalyptus* stem volume can be easily calculated using the following equation:

$$\text{Volume} = \sum_{i=1}^n \left(\frac{\text{SDM}_i}{\rho_i} \right) \quad (\text{S2})$$

where: *Volume* is the *Eucalyptus* stem volume ($\text{m}^3 \text{ ha}^{-1}$); *i* the day of the rotation, ranging from the first (1) until the last day of the *Eucalyptus* rotation (n); *SDM* the stem dry matter (excluding branches) according to *Eucalyptus* age (t ha^{-1}); and ρ_i the wood density (t m^{-3}), which varies throughout the *Eucalyptus* rotation.

S1.3. Basal area

From the assumption that the biomass production is correlated with the diameter of trees, an allometric equation was fitted as a function of stem biomass. The coefficients were generated from 1296 data of basal area and stem biomass from several locations and genetic materials. The fitted coefficients are presented as follows:

$$G = 1.6593 \times (SDM^{0.5767}) \quad (\text{S3})$$

where: *G* is the *Eucalyptus* basal area ($\text{m}^2 \text{ ha}^{-1}$) and *SDM* the stem dry matter (excluding branches).

The performance of the allometric equation to estimate the basal area is demonstrated in Figure S2.

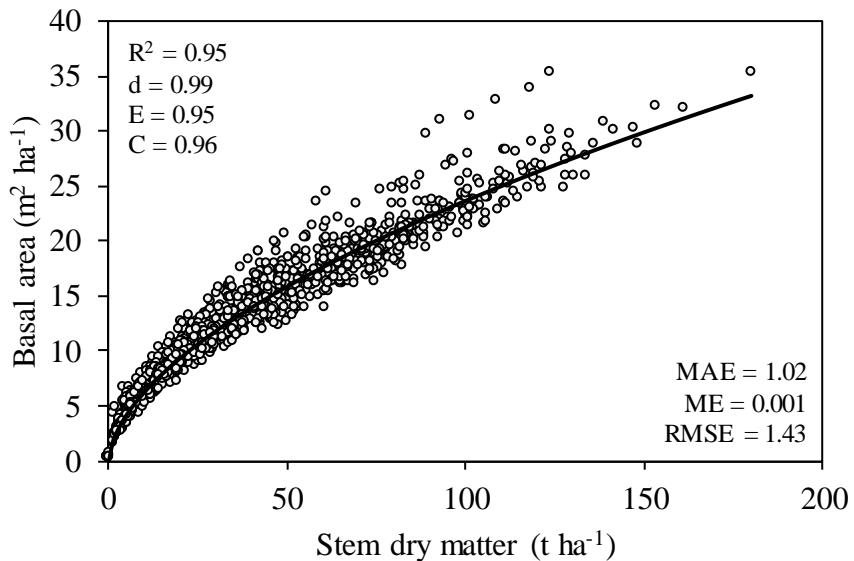


Figure S2. Performance of the allometric equation to estimate the basal area in the APSIM Next Generation *Eucalyptus* model. Statistics given in text are for coefficient of determination (R^2), Willmott agreement index (d), modelling efficiency index (E), confidence index (C), mean absolute error (MAE, t ha^{-1}); mean error (ME, t ha^{-1}) and root mean square error (RMSE, $\text{m}^3 \text{ ha}^{-1}$).

S1.4. Frost functions

S1.4.1. Photosynthesis modifier for frost (Ffrost)

The frost damage on *Eucalyptus* growth may depend on the intensity of frost, as well as the genetic material (Heavilin, 1978; Scarascia-Mugnozza et al., 1989; Tibbits et al., 2006). In this context, our function takes into account the frost intensity is correlated with the daily minimum temperature. The Ffrost ranges from zero to one and is linearly interpolated for different limits in daily minimum temperature. An example of the Ffrost is shown in Figure S3.

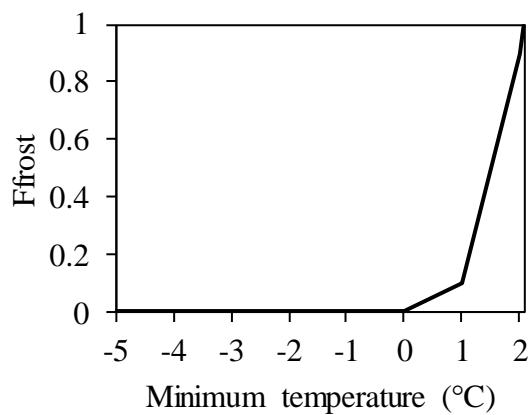


Figure S3. Photosynthesis modifier for frost (Ffrost) for different limits in daily minimum temperature and age. Values in the graphic were obtained from the calibration for the clone A1 (*E. urophylla*).

S1.4.2. Stem senescence rate for frost (SSRF)

A reduction of the tree stand may occur in frost days. The level of tree mortality may depend on the *Eucalyptus* age, in addition to the intensity of frost and genetic material. Frost damages are more intense at the beginning of *Eucalyptus* rotation, since (i) frosts tend to kill mainly young trees (Davidson and Reid, 1987; Leslie et al., 2012) and (ii) the leaves of young trees are closer to ground level, where the minimum temperature is lower (Davidson and Reid, 1987; Freitas, 2018; Sentelhas et al., 1995). In this context, the SSRF can be calculated by the following expression:

$$SSRF = SSFF \times AFF \quad (S4)$$

where: SSRF is the stem senescence rate for frost; SSFF is the stem senescence factor for frost and AFF is the age factor for the occurrence of frost.

The SSFF is linearly interpolated for different limits in daily minimum temperature (°C), and the AFF is and is linearly interpolated for different limits in *Eucalyptus* age (years), as can be seen in Figure S4.

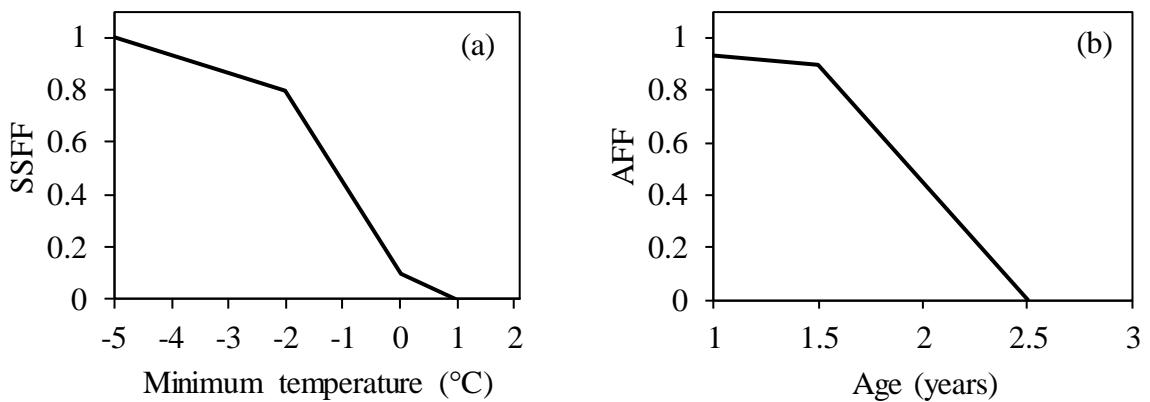


Figure S4. Stem senescence factor for frost (SSFF) and age factor for the occurrence of frost (AFF) for different limits in daily minimum temperature and age, respectively. Values in the graphic were obtained from the calibration for the clone A1 (*E. urophylla*).

S1.5. Light Extinction coefficient throughout *Eucalyptus* rotation

Difficulties are usually found in modelling the development of canopy crown architecture and its effect on radiation absorption before canopy closure (Pury and Farquhar, 1997; Law et al., 2001). Previous studies have shown the yield is overestimated at the beginning of the *Eucalyptus* rotation (Almeida et al., 2004; Battaglia et al., 2004; Miehle et al., 2009). Lower values of extinction coefficient at growth stages with low leaf area index (LAI) have improved the performance of the APSIM model in the present study, reducing yield overestimations at the beginning of the *Eucalyptus* rotation. The new extinction coefficient function (Equation S8) and its variation according to the LAI (Figure S5) are presented as follows:

$$k = k_1 + (k_0 - k_1) e^{-2 \left(\frac{LAI}{ki} \right)^2} \quad (\text{S5})$$

where: k is the extinction coefficient at a certain LAI; k_0 is the extinction coefficient of young trees; k_1 the extinction coefficient of old trees and ki the LAI that the trees present intermediate extinction coefficient ($ki = (k_0 + k_1)/2$; the value assumed in the present study was 0.7).

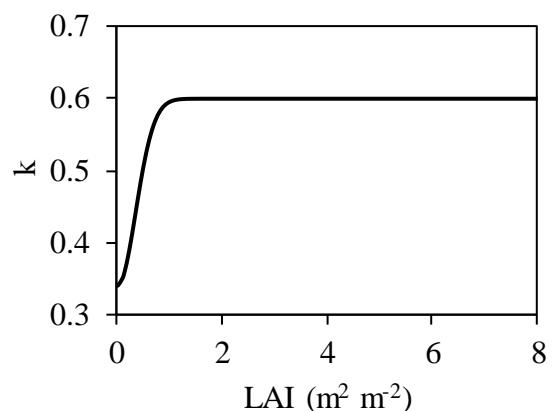


Figure S5. Extinction coefficient (k) as a function of the leaf area index (LAI). Values from the calibration for the clone A1 (*E. urophylla*).

Table S2. APSIM Next Generation *Eucalyptus* model parameters calibrated for the Brazilian clones A1, C3, K2 and Q8.

Parameters ^a	Functions and units ^b	A1 ^c		C3		K2		Q8	
		x	y	x	y	x	y	x	y
Basic wood density of young trees	t m ⁻²	0.39	-	0.39	-	0.39	-	0.39	-
Basic wood density of mature trees	t m ⁻²	0.43	-	0.43	-	0.44	-	0.44	-
Radiation use efficiency	g MJ ⁻²	1.51	-	1.61	-	1.51	-	1.30	-
Light extinction coefficient of seedlings	-	0.34	-	0.36	-	0.35	-	0.25	-
Light extinction coefficient of mature trees	-	0.60	-	0.45	-	0.51	-	0.60	-
Photosynthesis modifier for temperature (FT)	x: temperature (°C)	8	0	8	0	8	0	8	0
	y: FT	18	1	18	1	18	1	18	1
		23	1	23	1	23	1	23	1
		40	0	40	0	40	0	40	0
Photosynthesis modifier for frost (FTF)	x: minimum temperature (°C)	-5	0	-5	0	-5	0	-5	0
	y: FTF	-2	0	-2	0	-2	0	-2	0
		-1	0	-1	0	-1	0	-1	0
		0	0	0	0	0	0	0	0
		1	0	1	0	1	0	1	0
		2	0.9	2	0.9	2	0.9	2	0.9
		2.1	1	2.1	1	2.1	1	2.1	1
Stem senescence rate for frost (SSRF)	x: minimum temperature (°C)	-5	1	-5	1	-5	1	-5	1
	y: SSRF	-2	0.8	-2	1	-2	0.8	-2	0.8
		-1	0.5	-1	0.5	-1	0.5	-1	0.5
		0	0.1	0	0	0	0.1	0	0.2
		1	0	1	0	1	0	1	0
		2	0	2	0	2	0	2	0
		2.1	0	2.1	0	2.1	0	2.1	0
Age factor for occurrence of frost (AFOC)	x: age (years)	0	1	0	1	0	1	0	1
	y: AFOC	1.5	0.9	1.5	0.9	1.5	0.9	1.5	0.9
		2.5	0	2.3	0	2.5	0	2.5	0
Stem partitioning fraction (SPF)	x: individual tree weight (g m ⁻²)	0	0.15	0	0.2	0	0.15	0	0.15
	y: SPF	2000	0.39	2000	0.3	2000	0.33	2000	0.35
		10000	0.61	10000	0.57	10000	0.59	10000	0.58
Branch partitioning fraction (BPF)	x: individual tree weight (g m ⁻²)	0	0.09	0	0.075	0	0.085	0	0.115

	y: BPF	2000	0.09	2000	0.075	2000	0.085	2000	0.115
		10000	0.09	10000	0.075	10000	0.085	10000	0.115
Leaf partitioning fraction (LPF)	x: individual tree weight (g m ⁻²)	0	0.2	0	0.2	0	0.19	0	0.28
	y: LPF	2000	0.17	2000	0.15	2000	0.15	2000	0.24
Coarse root partitioning fraction (CRPF)	x: individual tree weight (g m ⁻²)	0	0.005	0	0.01	0	0.01	0	0.01
	y: CRPF	2000	0.03	2000	0.06	2000	0.04	2000	0.05
		10000	0.04	10000	0.07	10000	0.05	10000	0.06
Fine root partitioning fraction (FRPF)	-	0.26	-	0.29	-	0.26	-	0.3	-
Specific leaf area (SLA)	x: Age (years)	0	0.015	0	0.014	0	0.014	0	0.015
	y: SLA (m ² g ⁻¹)	1	0.011	1	0.011	1	0.011	1	0.012
		2	0.010	2	0.009	2	0.008	2	0.009
		3	0.008	3	0.008	3	0.007	3	0.007
		4	0.007	4	0.007	4	0.007	4	0.007
		80	0.006	80	0.006	80	0.006	80	0.006

^a For the parameters not described here, the default value was considered.

^b For some parameters, x- and y-axis are needed to make the parameter response curve.

^c The calibration process was performed according to observed data, parameter fitting and specific information on the clones already existing in the literature (Christina et al., 2017; Elli et al., 2019a; Lemos, 2012; Mattos, 2015; Valadares, 2018).

Table S3. APSIM Next Generation *Eucalyptus* model parameters calibrated for the Brazilian clones B2, R9, N5 and O6.

Parameters ^a	Functions and units ^b	B2 ^c		R9		N5		O6	
		x	y	x	y	x	y	x	y
Basic wood density of young trees	t m ⁻²	0.39	-	0.39	-	0.39	-	0.39	-
Basic wood density of mature trees	t m ⁻²	0.44	-	0.48	-	0.46	-	0.40	-
Radiation use efficiency	g MJ ⁻²	1.69	-	1.49	-	1.57	-	1.68	-
Light extinction coefficient of seedlings	-	0.30	-	0.38	-	0.26	-	0.35	-
Light extinction coefficient of mature trees	-	0.56	-	0.56	-	0.55	-	0.61	-
Photosynthesis modifier for temperature (FT)	x: temperature (°C) y: FT	8 18 23 40	0 1 1 0	10 19 24 40	0 1 1 0	6 17 22 38	0 1 1 0	6 17 22 38	0 1 1 0
Photosynthesis modifier for frost (FTF)	x: minimum temperature (°C) y: FTF	-5 -2 -1 0 1 2 2.1	0 0 0 0 1 0.9 1	-5 -2 -1 0 1 2 2.1	0 0 0 0 0.1 0.8 1	-5 -2 -1 0 1 2 2.1	0.5 1 1 1 1 2 2.1	-5 -2 -1 0 1 2 2.1	0.5 1 1 0 1 1 1
Stem senescence rate for frost (SSRF)	x: minimum temperature (°C) y: SSRF	-5 -2 -1 0 1 2 2.1	1 0.6 0.4 0 0 2 0	-5 -2 -1 0 1 2 2.1	1 0.9 0.8 0.1 0 0 0	-5 -2 -1 0 1 2 2.1	0.5 0 0 0 0 2 2.1	-5 -2 -1 0 1 2 2.1	0.5 0 0 0 0 0 0
Age factor for occurrence of frost (AFOC)	x: age (years) y: AFOC	0 1.3 1.4	1 0.95 0	0 1.5 2.5	1 0.9 0	0 1.5 2.5	1 0 0	0 1.5 2.5	1 0 0
Stem partitioning fraction (SPF)	x: individual tree weight (g m ⁻²) y: SPF	0 2000 10000	0.15 0.4 0.64	0 2000 10000	0.15 0.3 0.58	0 2000 10000	0.15 0.3 0.57	0 2000 10000	0.15 0.36 0.63
Branch partitioning fraction (BPF)	x: individual tree weight (g m ⁻²)	0	0.08	0	0.09	0	0.09	0	0.11

	y: BPF	2000	0.08	2000	0.09	2000	0.09	2000	0.11
		10000	0.08	10000	0.09	10000	0.09	10000	0.11
Leaf partitioning fraction (LPF)	x: individual tree weight (g m ⁻²)	0	0.19	0	0.19	0	0.2	0	0.14
	y: LPF	2000	0.17	2000	0.16	2000	0.16	2000	0.1
Coarse root partitioning fraction (CRPF)	x: individual tree weight (g m ⁻²)	0	0.03	0	0.03	0	0.02	0	0.02
	y: CRPF	2000	0.1	2000	0.1	2000	0.05	2000	0.06
Fine root partitioning fraction (FRPF)	x: Age (years)	0	0.018	0	0.014	0	0.015	0	0.017
	y: SLA (m ² g ⁻¹)	1	0.014	1	0.011	1	0.013	1	0.013
		2	0.011	2	0.008	2	0.009	2	0.010
		3	0.009	3	0.007	3	0.008	3	0.010
		4	0.008	4	0.007	4	0.007	4	0.009
		80	0.007	80	0.006	80	0.007	80	0.009

^a For the parameters not described here, the default value was considered.

^b For some parameters, x- and y-axis are needed to make the parameter response curve.

^c The calibration process was performed according to observed data, parameter fitting and specific information on the clones already existing in the literature (Christina et al., 2017; Elli et al., 2019a; Lemos, 2012; Mattos, 2015; Valadares, 2018).

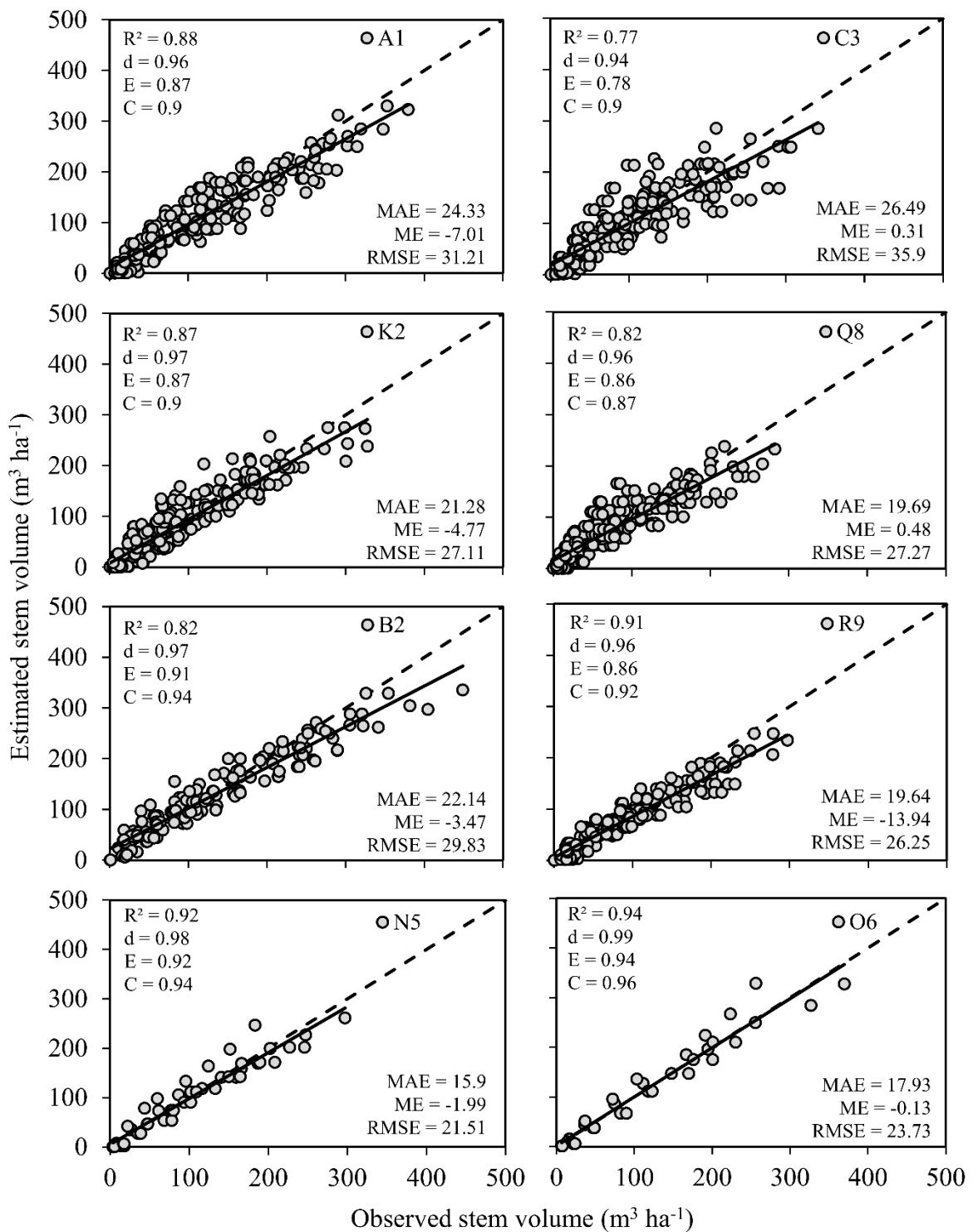


Figure S6. Performance of the APSIM Next Generation *Eucalyptus* model to estimate stem volume of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6). Statistics given in text are for coefficient of determination (R^2), Willmott agreement index (d), modelling efficiency index (E), confidence index (C), mean absolute error (MAE, $\text{m}^3 \text{ ha}^{-1}$); mean error (ME, $\text{m}^3 \text{ ha}^{-1}$) and root mean square error (RMSE, $\text{m}^3 \text{ ha}^{-1}$).

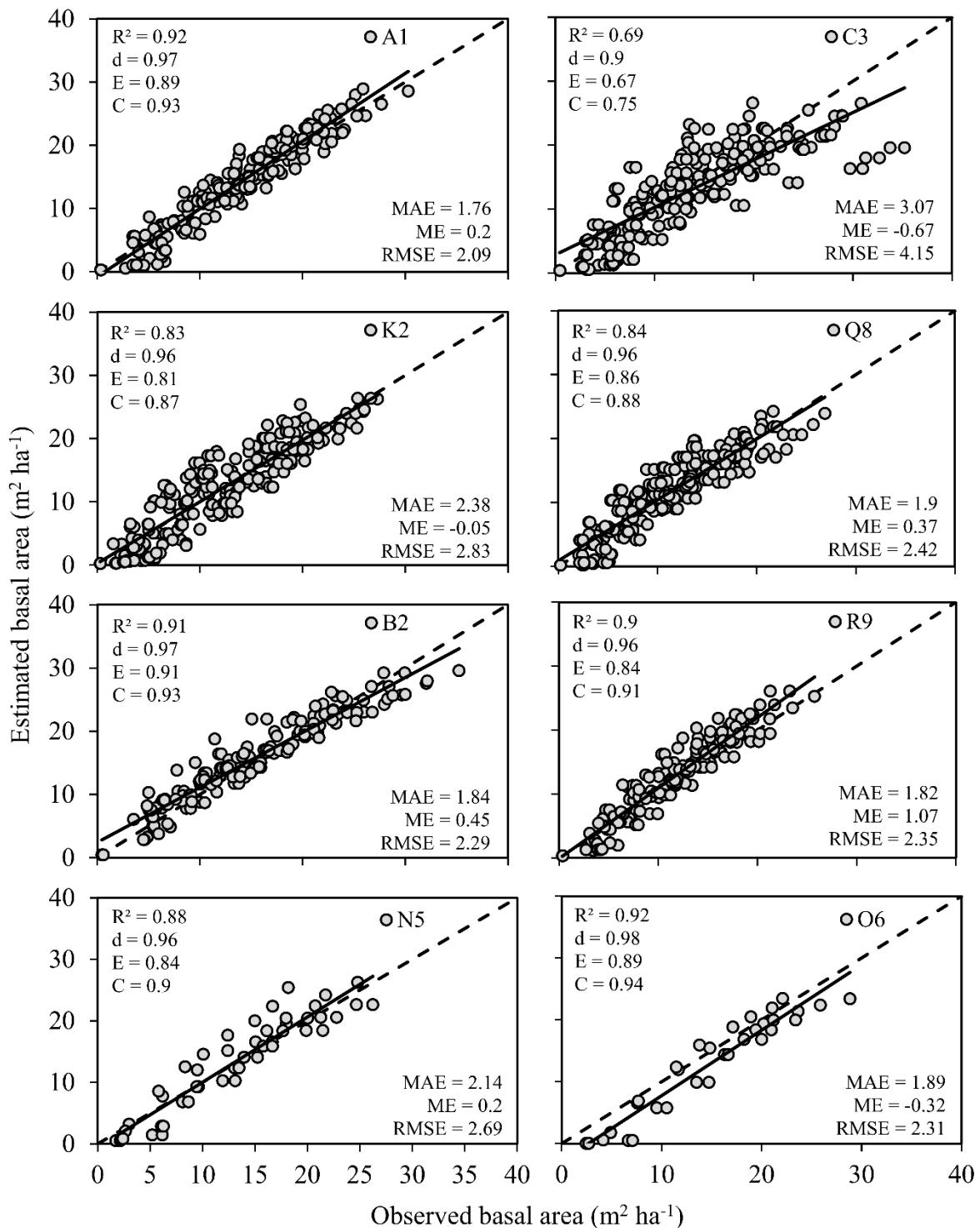


Figure S7. Performance of the APSIM Next Generation *Eucalyptus* model to estimate basal area of different *Eucalyptus* clones (A1, C3, K2, Q8, B2, R9, N5 and O6). Statistics given in text are for coefficient of determination (R^2), Willmott agreement index (d), modelling efficiency index (E), confidence index (C), mean absolute error (MAE, $\text{m}^2 \text{ ha}^{-1}$); mean error (ME, $\text{m}^2 \text{ ha}^{-1}$) and root mean square error (RMSE, $\text{m}^2 \text{ ha}^{-1}$).

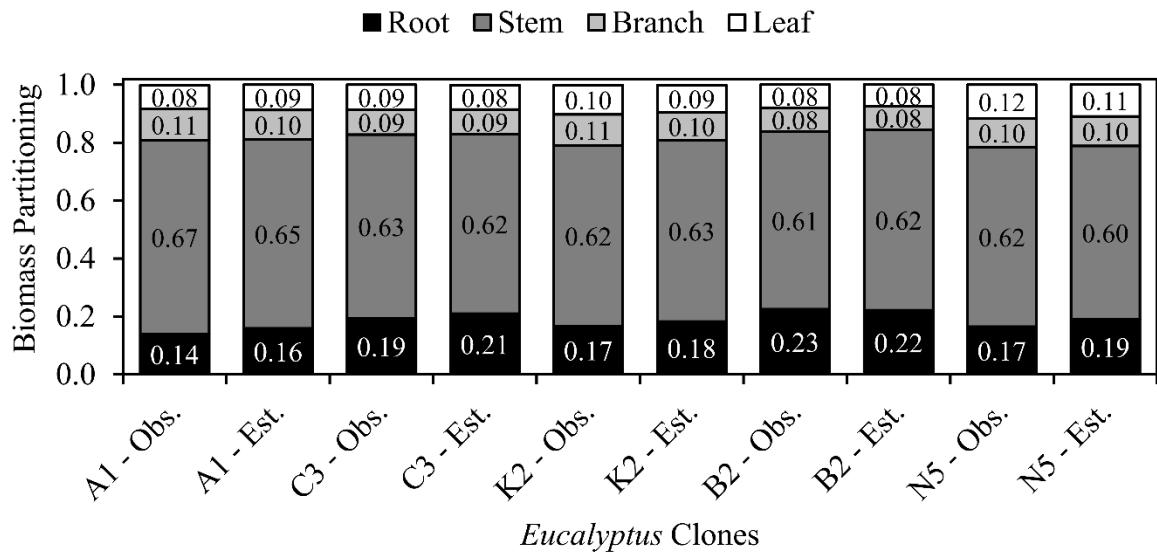


Figure S8. Observed (Obs.) and estimated (Est.) biomass partitioning by the APSIM Next Generation *Eucalyptus* model at 28 months of age of different *Eucalyptus* clones (A1, C3, K2, B2 and N5) at the location of Buri, SP (33-DUR). The dataset used for this calibration was collected from the study of Mattos (2015).

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5. GAUGING THE EFFECTS OF CLIMATE VARIABILITY ON *EUCALYPTUS* PLANTATIONS PRODUCTIVITY ACROSS BRAZIL: A PROCESS-BASED MODELLING APPROACH*

Abstract

Managing climatic variability is essential for dealing with current genotype x environment interactions and for adapting *Eucalyptus* plantations to future climate change. This study uses a process-based modelling approach to assess long-term effects of spatial and temporal climate variability on *Eucalyptus* productivity for 36 sites across Brazil. The attainable stem wood mean annual increment (MAI, $m^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was simulated by the APSIM Next Generation *Eucalyptus* model, considering three soil types (clay, sandy-clay and sandy-loam) and twenty-seven rotations of seven years, using weather data from 1980 to 2013. Spatial and temporal (inter-annual and inter-seasonal) climate variability strongly affected *Eucalyptus* MAI across Brazilian regions. Average *Eucalyptus* MAI ranged from $38 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Imperatriz, MA, Northeast region) to $69 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Borebi, SP, Southeast region), while its coefficient of variation ranged from 3.2% (Antônio Olinto, PR, South region) to 17.2% (Bocaiúva, MG, Southeast region). Our results suggest an average increment of about $0.91 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for each increase of one degree in latitude. *Eucalyptus* growth was mostly driven by water deficit combined with high temperatures at tropical sites, while the tree growth was more affected by low winter temperatures at subtropical sites. The results of the present study have value for understanding how *Eucalyptus* plantations change their growth in response to changing climate. Gauging the effects of climate variability on *Eucalyptus* growth may assist in forest planning by estimating the area to be cultivated, machinery sizing, climate risk, and guiding the tree breeders in choosing appropriate genotypes.

Keywords: APSIM *Eucalyptus* model; water deficit; temperature; latitude; weather seasonality.

5.1. Introduction

Eucalyptus is the most planted hardwood genus in the world, with a total area of about 25 million ha (Borralho et al., 2018). The area cultivated with *Eucalyptus* in Brazil is about 7.5

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million hectares (IBGE, 2019), booming in recent years in tropical agricultural borders (Gonçalves et al., 2013). *Eucalyptus* is well-known for its high growth rate compared to other hardwood species with increases in productivity of approximately 3-fold over the past 40 years to an average mean annual increment (MAI) of around $36 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (IBÁ, 2019; Stape et al., 2010). These advances are a consequence of well-adapted clones and improved management practices for soil preparation, fertilization, row spacing, high-quality seedlings and integrated weed, pest and disease control (Gonçalves et al., 2017; Londero et al., 2012; Melo et al., 2016; Stape et al., 2010, 2001).

In addition to genetic and management factors, *Eucalyptus* productivity is strongly affected by climatic conditions (Binkley et al., 2017; Campoe et al., 2016; Freitas, 2018; Gonçalves et al., 2013; Scolforo et al., 2019a; Stape et al., 2010) and so climatic risk assessments become a very important tool for forest planning. For example, water deficit is the main cause of the *Eucalyptus* yield gap in Brazil (Elli et al., 2019b; Freitas, 2018) and *Eucalyptus* plantations in Brazil continue to expand into less suitable tropical environments, where water deficit is more intense, lasts longer and is accompanied by high temperatures (Binkley et al., 2017; Elli et al., 2019b; Gonçalves et al., 2017). Furthermore, climate change scenarios are projecting an increase on temperatures for Brazil (Bender and Sentelhas, 2018; Venegas-González et al., 2018; Verhage et al., 2017) which may further increase potential evapotranspiration and, consequently, the soil water deficit (Jalota et al., 2018; Pan et al., 2015).

One of the best ways of assessing the effects of climatic conditions on forest growth is by using process-based models combined with long-term climate data. There are several *Eucalyptus* models available for estimating forest growth, such as 3-PG - Physiological Principles in Predicting Growth (Landsberg and Waring, 1997), CABALA – Carbon Balance (Battaglia et al., 2004), Forest-DNDC (Li et al., 2000), FAO - Agroecological Zone (Elli et al., 2019a; Freitas, 2018), G'DAY (Comins and McMurtrie, 1993; Marsden et al., 2013) and APSIM - Agricultural Production Systems Simulator (Holzworth et al., 2014).

The APSIM model has been tested under Brazilian conditions. The APSIM-Growth model (Huth et al., 2001) has been successfully used to simulate *Eucalyptus* yield of several Brazilian genotypes (Elli et al., 2019a). A later version of the APSIM model, known as APSIM Next Generation *Eucalyptus* model, with several improvements related to the execution speed, model construction and visualisation, and manager script flexibility (Holzworth et al., 2018) has also performed well in predicting *Eucalyptus* yield under Brazilian conditions (Valadares, 2018). However, there is a lack of detailed studies on the assessment of temporal and spatial climate variability effects on *Eucalyptus* productivity. Furthermore, coping better with effects

of current climate variability on forest productivity is an essential first step to adapt forest systems to future climate change, given the large uncertainties regarding future climate projections from general circulation models (Cooper et al., 2008; Corbeels et al., 2018; Robertson and Murray-Prior, 2016). For these reasons, this study assesses the long-term effects of climate variability on *Eucalyptus* growth in 36 producing regions across Brazil, using the APSIM Next Generation *Eucalyptus* model.

5.2. Material and methods

5.2.1. Climate and soil data

The present study considered 36 locations (Figure 1), which represent most of the Brazilian *Eucalyptus* production areas. Long-term weather data (maximum, minimum and mean air temperatures, solar radiation, rainfall, relative humidity and wind speed for the period from 1980 to 2013) were obtained from “Xavier” daily gridded weather database (Xavier et al., 2016), which has been found to be suitable for replacing actual data to simulate attainable yield of different species across Brazil (Battisti et al., 2018; Battisti and Sentelhas, 2019; Bender and Sentelhas, 2018; Duarte, 2018; Freitas, 2018). A summary of the climate conditions of the chosen sites is presented in Table 1. Seasonal variations of rainfall, temperature and solar radiation are also presented in the supplementary material (Figures S2, S3 and S4, respectively).

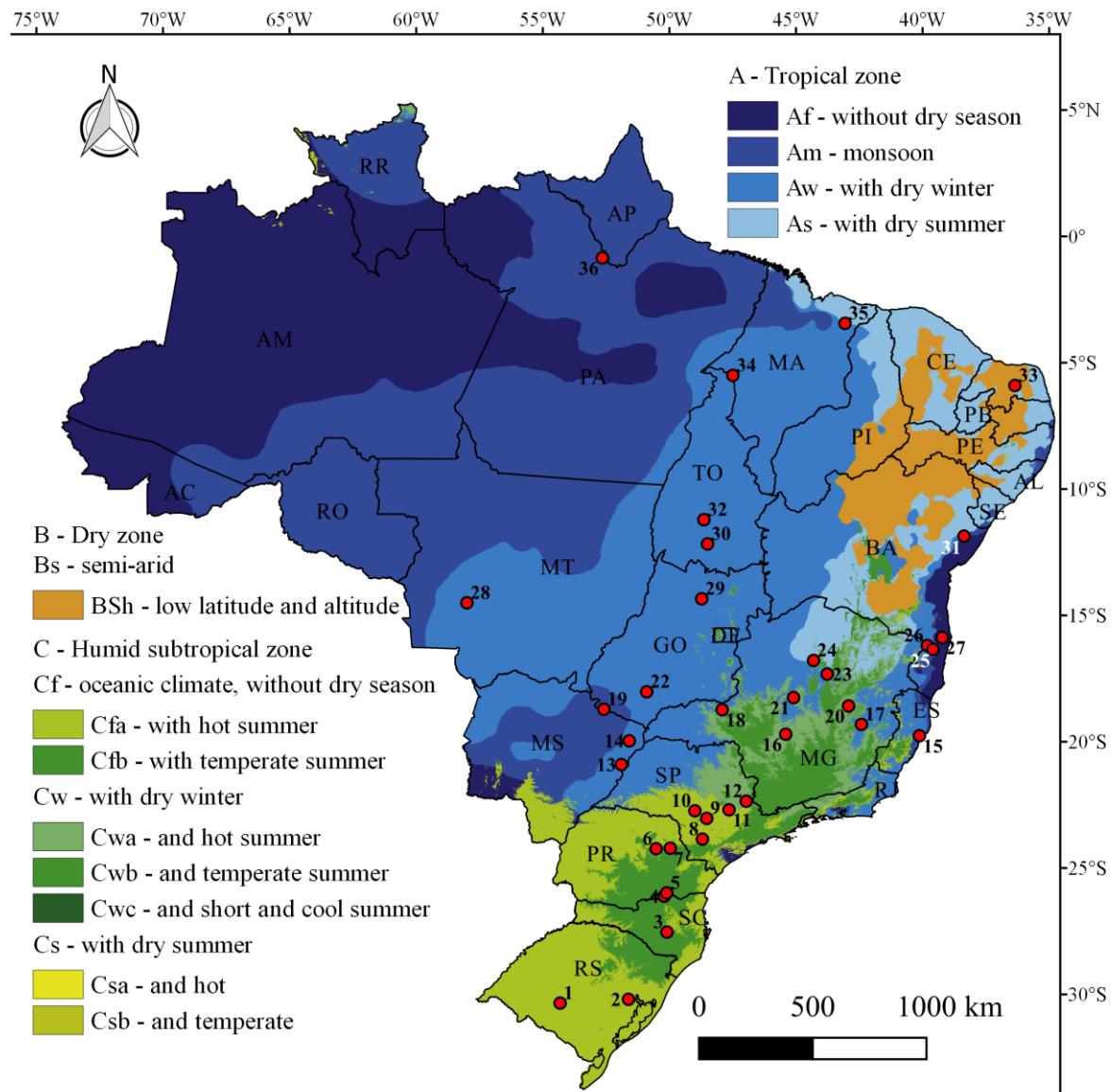


Figure 1. Locations where the long-term stemwood volume simulations were performed and their respective Köppen climate classification in Brazil (map adapted from Alvares et al., 2013). The description of map codes and further information on the characteristics of each location are presented in Table 1.

Table 1. Locations for where the long-term simulations were performed and a summary of their climate conditions during the period from 1980-2013.

Code	Location, State and Region	Lat. ^a	Long.	Alt.	Tm	Rain	ETo
01-SGA ^b	São Gabriel, Rio Grande do Sul (RS), South	30.3 S	54.3 W	102	19.3	1510	1130
02-ELD	Eldorado do Sul, Rio Grande do Sul (RS), South	30.2 S	51.6 W	150	19.7	1477	1078
03-OTA ^b	Otacílio Costa, Santa Catarina (SC), South	27.5 S	50.1 W	870	17.3	1643	990
04-TBA ^b	Três Barras, Santa Catarina (SC), South	26.1 S	50.2 W	812	18.8	1557	996
05-ANT ^b	Antônio Olinto, Paraná (PR), South	26.0 S	50.1 W	916	18.7	1573	995
06-TEL ^b	Telêmaco Borba, Paraná (PR), South	24.2 S	50.5 W	888	20.0	1552	1114
07-ARA ^b	Arapoti, Paraná (PR), South	24.2 S	50.0 W	770	19.4	1524	1065
08-BUR ^b	Buri, São Paulo (SP), Southeast	23.9 S	48.7 W	695	20.5	1368	1104
09-BOT ^b	Botucatu, São Paulo (SP), Southeast	23.0 S	48.5 W	869	21.2	1427	1202
10-BOR ^b	Borebi, São Paulo (SP), Southeast	22.7 S	49.0 W	656	21.7	1402	1246
11-PIR	Piracicaba, São Paulo (SP), Southeast	22.7 S	47.7 W	560	21.5	1397	1201
12-MOG ^b	Mogi Guaçu, São Paulo (SP), Southeast	22.4 S	47.0 W	633	20.6	1540	1131
13-TLA ^b	Três Lagoas, Mato Grosso do Sul (MS), Midwest	20.9 S	51.9 W	361	24.3	1247	1400
14-INO ^b	Inocência, Mato Grosso do Sul (MS), Midwest	20.0 S	51.6 W	480	24.6	1416	1409
15-ARA	Aracruz, Espírito Santo (ES), Southeast	19.8 S	40.1 W	36	24.5	1358	1316
16-BOM ^b	Bom Despacho, Minas Gerais (MG), Southeast	19.7 S	45.4 W	727	22.5	1409	1262
17-BEL ^b	Belo Oriente, Minas Gerais (MG), Southeast	19.3 S	42.4 W	243	22.3	1249	1216
18-EST ^b	Estrela do Sul, Minas Gerais (MG), Southeast	18.7 S	47.9 W	969	23.2	1517	1362
19-CHA ^b	Chapadão do Sul, Mato Grosso do Sul (MS), Midwest	18.7 S	52.6 W	783	24.0	1645	1342
20-GUA ^b	Guanhães, Minas Gerais (MG), Southeast	18.6 S	42.9 W	873	21.2	1257	1199
21-TRE	Três Marias, Minas Gerais (MG), Southeast	18.3 S	45.1 W	806	23.3	1235	1378
22-RIO ^b	Rio Verde, Goiás (GO), Midwest	18.0 S	50.9 W	681	23.9	1543	1338
23-BOC ^b	Bocaiúva, Minas Gerais (MG), Southeast	17.3 S	43.8 W	848	22.6	1059	1354
24-COR ^b	Coração de Jesus, Minas Gerais (MG), Southeast	16.8 S	44.3 W	926	23.7	1057	1448
25-EUN	Eunápolis, Bahia (BA), Northeast	16.3 S	39.6 W	200	24.3	1193	1357
26-ITA	Itagimirim, Bahia (BA), Northeast	16.2 S	39.8 W	276	24.0	1093	1362
27-BEL	Belmonte, Bahia (BA), Northeast	15.9 S	39.2 W	100	24.3	1422	1345
28-TAN	Tangará da Serra, Mato Grosso (MT), Midwest	14.5 S	58 W	572	26.2	1771	1357
29-NIQ ^b	Niquelândia, Goiás (GO), Midwest	14.3 S	48.7 W	545	23.9	1572	1418
30-PEI ^b	Peixe, Tocantins (TO), North	12.2 S	48.5 W	255	27.1	1472	1482
31-INH ^b	Inhambupe, Bahia (BA), Northeast	11.9 S	38.4 W	218	25.1	1041	1493
32-BRE	Brejinho de Nazaré, Tocantins (TO), North	11.2 S	48.6 W	255	27.4	1878	1475
33-NAT	Natal, Rio Grande do Norte (RN), Northeast	5.9 S	36.4 W	60	26.3	1176	1716
34-IMP	Imperatriz, Maranhão (MA), Northeast	5.5 S	47.5 W	121	27.7	1467	1458
35-URB	Urbano Santos, Maranhão (MA), Northeast	3.4 S	43.1 W	81	27.8	1548	1689
36-MON	Monte Dourado, Pará (PA), North	0.9 S	52.7 W	50	27.5	2224	1448

^a Lat. = latitude, in degrees; Long. = longitude, in degrees; Alt. = altitude above sea level, in m; SR = average daily solar radiation, in MJ m⁻² day⁻¹; Tm = mean air temperature, in °C; Rain = accumulated annual rainfall, in mm yr⁻¹ and ETo = accumulated annual reference evapotranspiration, in mm yr⁻¹, which was calculated from Allen et al. (1998) approach. ^b Locations used for model validation.

Given the large number of locations considered in the present study and the lack of detailed soil data required for building the soil profile for the APSIM model, three standard soil

types were considered for all locations, in order to represent different soil water holding capacities (SWHC):

- I) a clay soil with high SWHC (1.52 mm cm^{-1});
- II) a sandy-clay soil with medium SWHC (0.97 mm cm^{-1});
- III) a sandy-loam soil with low SWHC (0.60 mm cm^{-1}).

Similar approaches were used by Battisti and Sentelhas (2017), Dias and Sentelhas (2018) and Battisti and Sentelhas (2019). Standardizing soil conditions is a suitable way of analyzing the climate variability effects on forest growth without confounding signals from variability in soil properties. An effective root depth of 3 m was considered for all locations according to the findings of Christina et al. (2017) and Pinheiro et al. (2019). We recognize that this is a source of uncertainty, but this is justified by the lack of site-specific soil and root information required for building the soil profile in the APSIM *Eucalyptus* model. Further information about the soil profiles can be seen in the supplementary material (Table S1).

5.2.2. The APSIM Next Generation *Eucalyptus* model

The APSIM Next Generation *Eucalyptus* model was used to perform simulations of attainable stemwood volume mean annual increment (MAI) at 7 years-old. This model was validated against measured *Eucalyptus* attainable yield data (optimum or near optimum forest management) from plots situated in 23 of the 36 producing locations described in Table 1. The experimental design of the plots is presented in Binkley et al. (2017). Model parameters for a highly productive and homeostatic Brazilian clone (clone A1 of *Eucalyptus urophylla* presented by Binkley et al. 2017 and Elli et al 2019a) with suitability to a wide range of environments were used. A summary of the statistical indexes from the relationship between observed and estimated *Eucalyptus* stemwood volume is presented in the Supplementary Material (Figure S1).

The APSIM *Eucalyptus* model captures the modelling structure of the APSIM-Growth model (N. I. Huth et al., 2001), but was implemented in the Plant Modelling Framework (PMF), a software platform for creating models in APSIM Next Generation (Brown et al., 2014). Daily biomass production is calculated from daily intercepted solar radiation and a radiation use efficiency (RUE) which is affected by soil and climatic factors. The interception of solar radiation is calculated assuming an exponential light extinction coefficient. Full model documentation is available at <https://www.apsim.info/>. A general approach of this model is presented as follows:

$$\Delta G = R_{\text{int}} \times \varepsilon \times \min(F_T, F_F, F_N, F_{VPD}) \times F_W \quad (1)$$

where: ΔG is the daily growth; R_{int} the daily intercepted solar radiation; ε the radiation use efficiency (g MJ⁻¹ of global solar radiation); and F_T , F_F , F_N , F_{VPD} and F_W are growth modifiers to account for the effects of air temperature, frost, nitrogen, vapor pressure deficit and water supply, respectively.

5.2.3. Long-term growth simulations

Twenty-seven simulations of MAI (m³ ha⁻¹ yr⁻¹) for seven-year rotations were performed using weather data from 1980 to 2013. The first simulation was performed from 15/February/1980 to 14/February/1987, while the last one was performed from 15/February/2006 to 14/February/2013. Soil fertility and management were maintained as non-limiting during the simulations. Therefore, MAI was only affected by determining factors (solar radiation, air temperature, photoperiod, [CO₂], genotype and plant population) and limiting factors (water deficit), and so is referred to here as attainable MAI (Fischer, 2015b; Lobell et al., 2009; Sentelhas et al., 2017, 2015; van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997).

5.2.4. Data analysis

Inter-seasonal variability was analysed for attainable yields and their quartiles representing 25 % (quartile 1) and 75 % (quartile 3) of the probability of occurrence for the growth data throughout the climatic series. The relationships between (i) annual rainfall and attainable MAI, (ii) water deficit stress factor and *Eucalyptus* attainable MAI and (iii) latitude and attainable MAI were also studied. Stress factors for soil water deficit and air temperature were obtained from APSIM *Eucalyptus* model outputs. The functions used to calculate the stress factors are presented in Figure 2. APSIM stress factors for temperature and water deficit vary from 0 (zero growth) to 1 (full growth), and so were inverted (1 - stress factor), in order to attribute low values of factor stress to low effects on growth (0 = full growth; 1 = zero growth). Subsequently, these factors were normalized according to their maximum values in order to facilitate data analysis, here called as relative water deficit stress and relative air temperature stress.

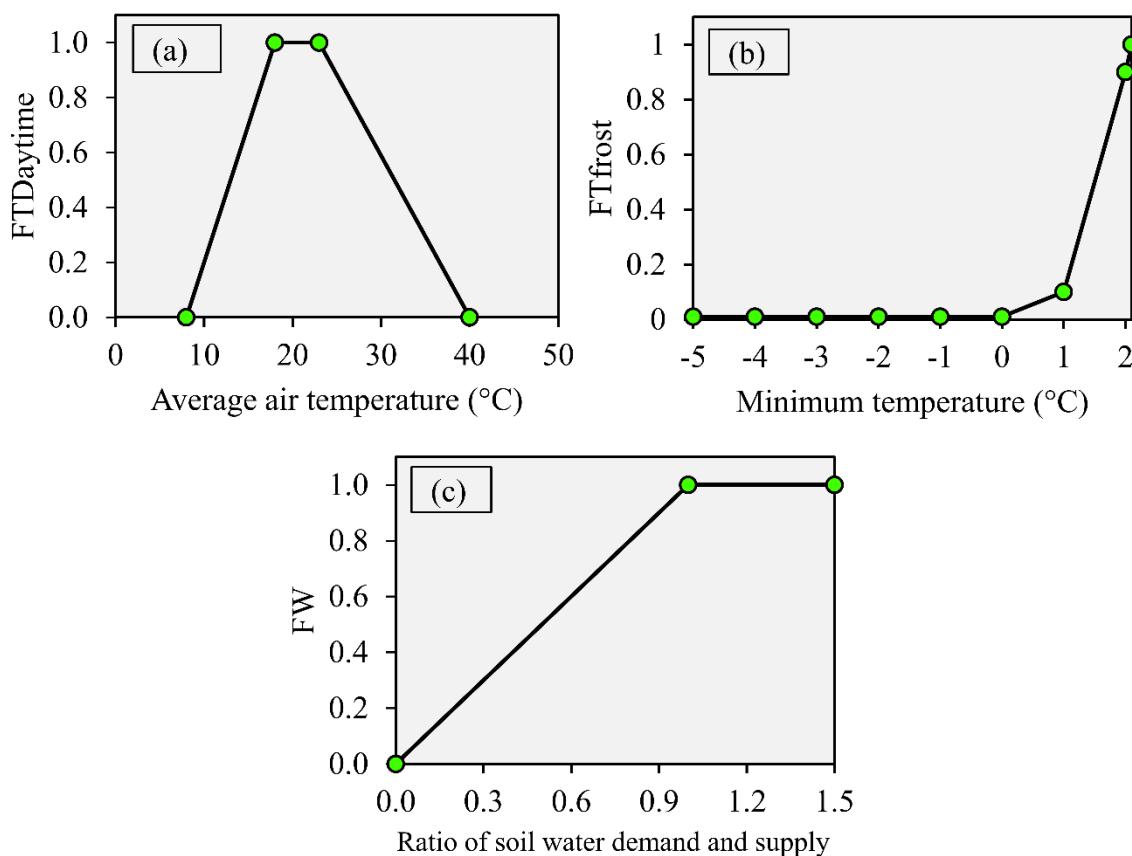


Figure 2. APSIM model functions used to determine temperature (FTDaytime – a and FTfrost – b) and water deficit (FW - c) stress factors. The FTDaytime is linearly interpolated from daily average temperature, while FTfrost is linearly interpolated from daily minimum temperature. The final stress factor for temperature (FT) is calculated using a minimum function for FTDaytime and FTfrost. FW is linearly interpolated for different limits of the ratio of soil water demand and supply.

5.3. Results

5.3.1. Temporal climatic variability and *Eucalyptus* attainable MAI

A large effect of temporal climatic variability on *Eucalyptus* attainable MAI was observed for most locations, with contrasting behaviors according to the location (Figure 3). For site 23-BOC, Southeast Brazil, the attainable MAI at 7-years-old ranged from 36 to 65 m³ ha⁻¹ yr⁻¹, with 20 % of the average values (from three soil types) greater than 45 m³ ha⁻¹ yr⁻¹. In 34-IMP, Northeast Brazil, the attainable MAI ranged from 31 to 47 m³ ha⁻¹ yr⁻¹, with 50% of the average values greater than 38 m³ ha⁻¹ yr⁻¹. On the other hand, low MAI variations were observed in 02-ELD and 36-MON, where the values ranged from 57 to 69 m³ ha⁻¹ yr⁻¹ and from 42 to 48 m³ ha⁻¹ yr⁻¹, respectively (Figure 3). In 02-ELD, 50% of the stemwood average growth

values were greater than $63 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, while in 36-MON, 50% of the MAI values were greater than $46 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Figure 3). Low variations of attainable MAI in response to soil type were observed for sites well-supplied with water, which are mostly located in Southern Brazil and humid coastal region of the country.

*5.3.2. Spatial climatic variability and *Eucalyptus* attainable MAI*

Spatial climatic variability substantially affected *Eucalyptus* stemwood growth (Figure 4). Average stemwood MAI was greater than $56 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in 50% of locations and greater than $65 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in 20% of them. The lowest average values were found at sites 34-IMP ($38 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), 30-PEI ($41 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and 32-BRE ($41 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) in North Brazil. These locations presented average annual temperatures of 27.7 , 27.1 and 27.4 °C respectively (Table 1), above the optimum temperature for growth of major Brazilian *Eucalyptus* clones of 21 °C (Lemos, 2012). Even with high annual rainfall of 1467 , 1472 and 1878 mm for 34-IMP, 30-PEI and 32-BRE, respectively (Table 1), rainfall was not well distributed throughout the year (Figure S2), with very low values accumulated from May to September (139 , 97 and 65 mm, in the same order).

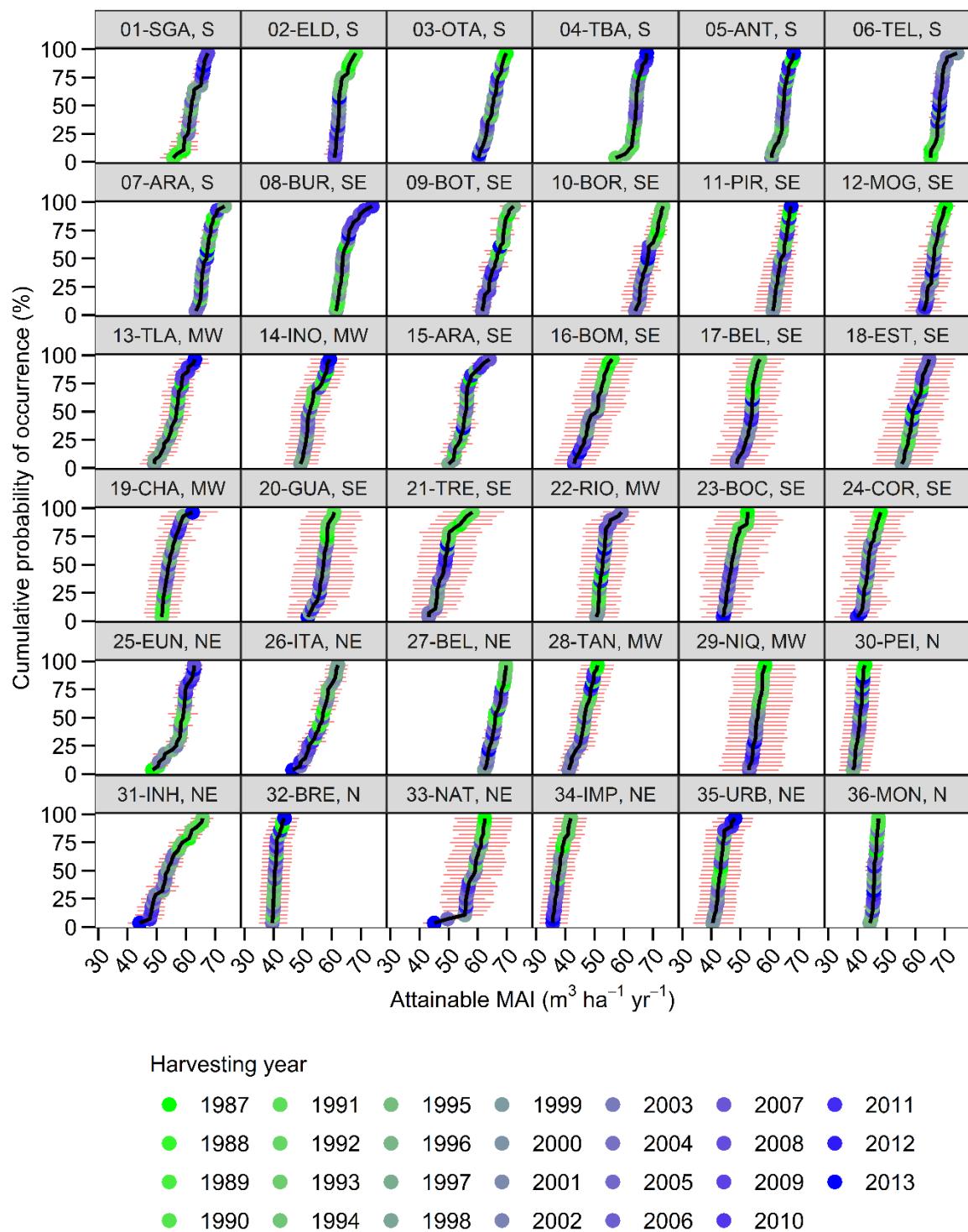


Figure 3. Cumulative probability of occurrence of *Eucalyptus* attainable MAI by assessing 36 Brazilian locations individually, considering twenty-seven rotations of seven years (harvesting years from 1987 to 2013). Horizontal bars represent the range of MAI values for the three soil types (clay, sandy-clay and sandy-loam). Titles given for individual graphs indicate location code (Table 1) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

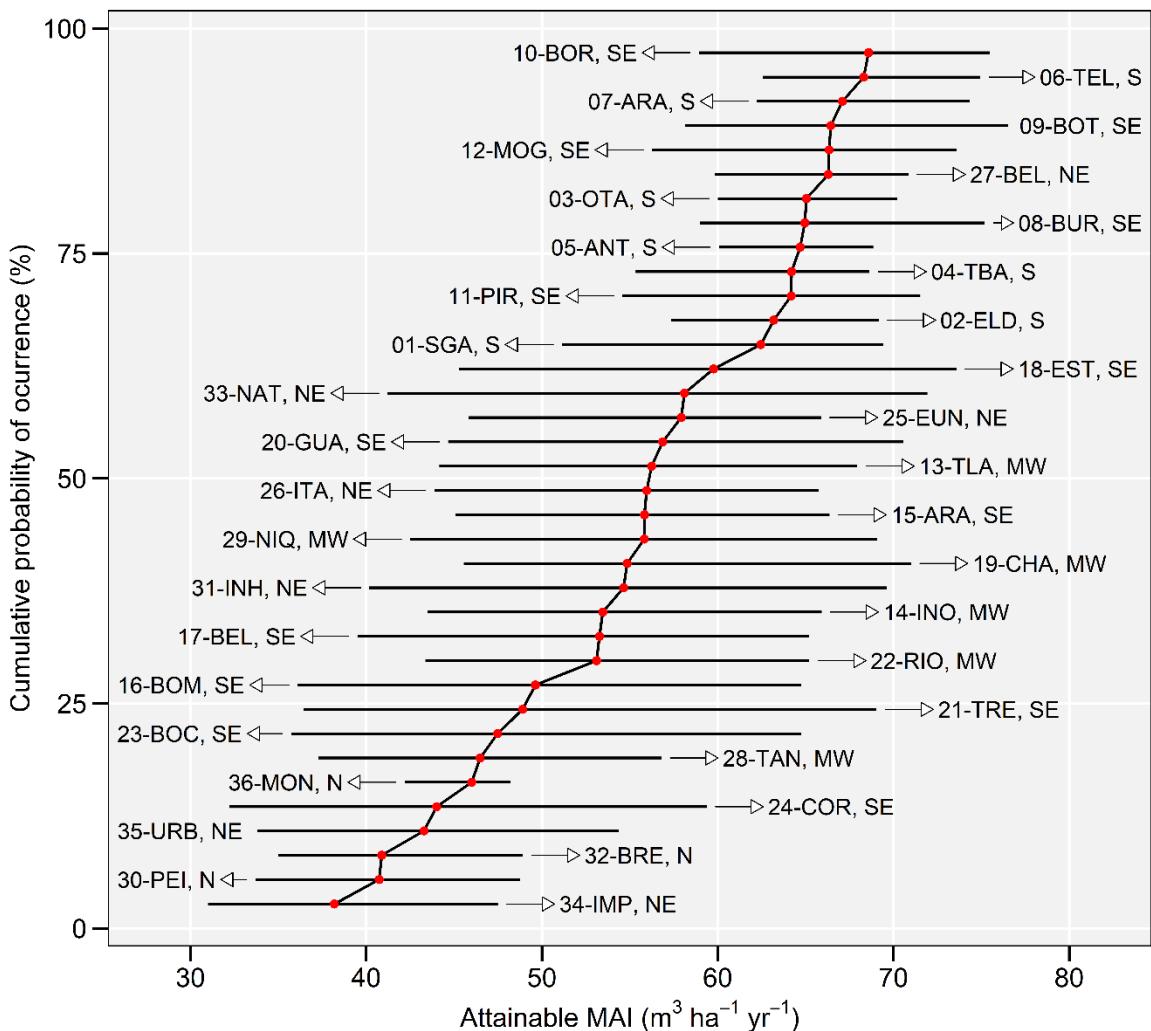


Figure 4. Cumulative probability of occurrence of *Eucalyptus* attainable MAI for 36 Brazilian producing locations, considering the results from a combination of 27 rotations (1980-2013) and three soil types (clay, sandy-clay and sandy-loam). Horizontal bars represent the interval between maximum and minimum MAI values. Labels given for individual data points indicate location code (Table 1) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

Sites 10-BOR, 06-TEL and 07-ARA were the most productive ones, with average productivity values of 69, 68 and 67 $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$, respectively (Figure 4). The average annual temperatures of these sites were 21.7, 20.0 and 19.4 °C respectively and the annual rainfall 1402, 1552 and 1524 mm, relatively well distributed throughout the year, compared to most of the locations in Central North Brazil. A spatial overview of *Eucalyptus* attainable MAI and its coefficient of variation (CV) and relative stresses by water deficit and temperature are presented in the supplementary material (Figure S5). The CV of MAI ranged from 3% (05-ANT) to 17%

(23-BOC). In general, the lowest values of CV were found at locations in Southern Brazil, especially in the Paraná State, and North Brazil, in the Pará state, while the greatest ones were found in Southeast Brazil, in the Minas Gerais state.

5.3.3 Weather seasonality affecting *Eucalyptus* growth

Differences in plant stress and growth patterns were observed in relation to the inter-seasonal climatic variability for 6 sites chosen to span the range of climatic conditions (Figure 5). These effects can be observed by growth reduction at some stages throughout the rotation. In 01-SGA, *Eucalyptus* stands experienced growth rate reductions mainly from May to August, when the average temperature is low. In 06-TEL, the reductions occurred almost in the same period, but with lower intensity than in 01-SGA. However, these locations show low variability between individual plantings due to season. On the other hand, in 24-COR and 28-NIQ, the range in yields for a given age is high, which indicates that these locations have a high growth rate variability as a consequence of their climatic conditions. In these sites, growth was reduced mostly from June to September, influenced by the reduction of rainfall and, consequently, by the intense water deficit. In 34-IMP, rainfall reductions occurred mostly from July to October, which, together with high temperatures, resulted in substantial growth reduction. For site 36-MON, no seasonal variations were identified, and interquartile ranges were very small, with constant growth throughout the seven-year rotation (Figure 5). *Eucalyptus* growth throughout the climatic series for all locations is presented in the supplementary material (Figure S6).

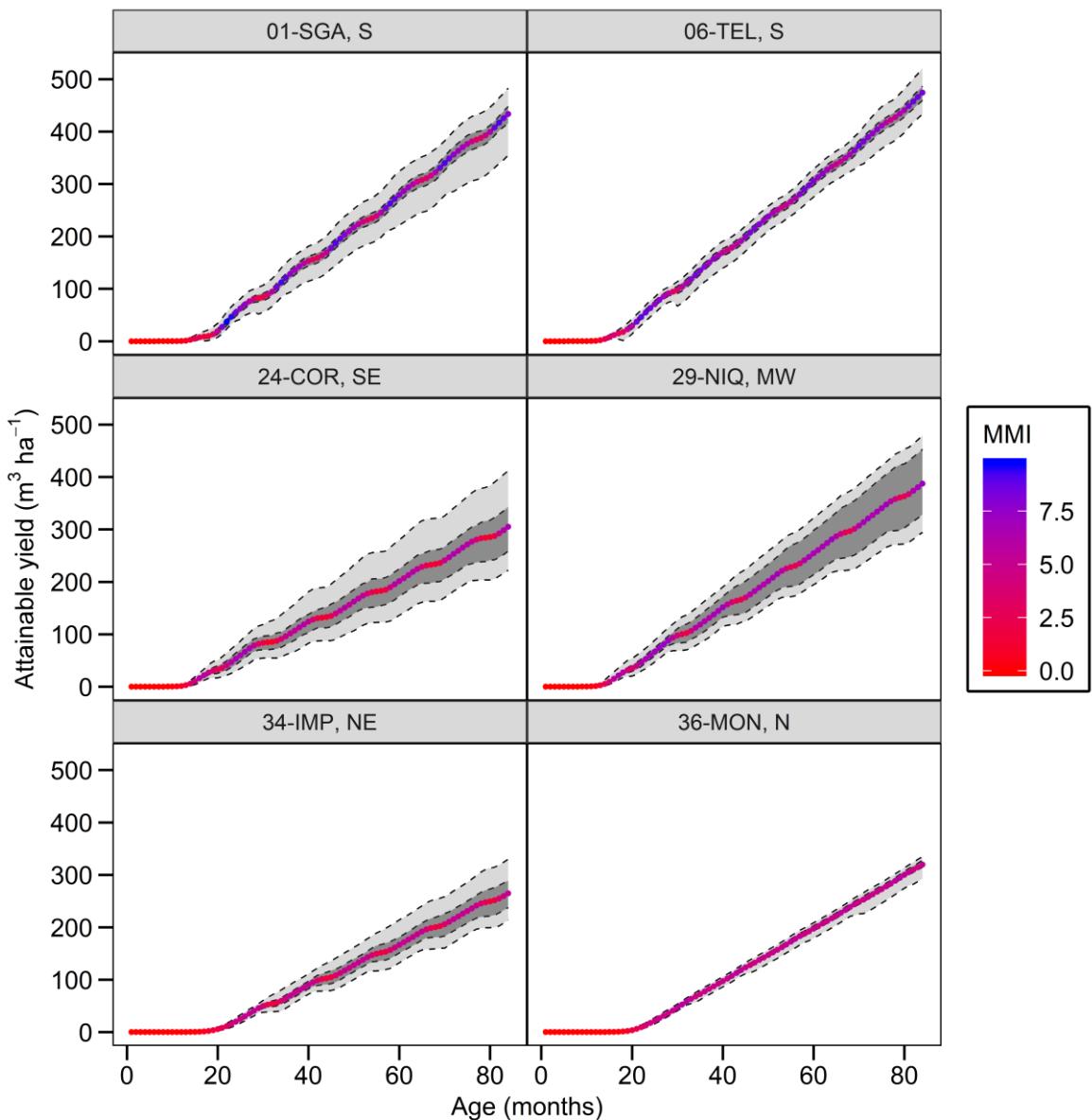


Figure 5. *Eucalyptus* attainable yield for six locations with contrasting climatic conditions in Brazil, considering the results from 27 forest rotations (1980-2013) and three soil types (clay, sandy-clay and sandy-loam). Central lines represent the average *Eucalyptus* attainable yield throughout a seven-year rotation, while color gradients represent the mean monthly volume increment (MMI, $\text{m}^3 \text{ha}^{-1} \text{month}^{-1}$), which was calculated by the difference between the volume of the present and previous month. Internal dashed lines represent the first and third quartiles, while external dashed lines represent the maximum and minimum values. Titles given for individual graphs indicate location code (Table 1) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

5.3.4. Attainable MAI as influenced by climatic conditions and by ecophysiological traits

A positive relationship between *Eucalyptus* MAI and annual rainfall was found (Figure 6a). Some tropical locations in North and Northeast Brazil (28-TAN, 30-PEI, 32-BRE, 34-IMP, 35-URB and 36-MON) did not have the same pattern as the other sites, given their irregular seasonal rainfall distribution. Furthermore, higher values of CV for *Eucalyptus* attainable MAI were found in the driest environments (Figure 6b). Figure 7 shows the relationship between relative water deficit stress factor and *Eucalyptus* attainable MAI, considering soils with different water holding capacities (1.52 , 0.97 and 0.60 mm cm^{-1}). *Eucalyptus* MAI decreased with increasing water deficit. This effect was different for the three soil types ($p < 0.05$) with greater losses in production with lower water holding capacity. Furthermore, MAI showed more pronounced differences with the soil type under drier conditions (i.e. where the relative water deficit stress factor ranged from 0.60 to 1.0).

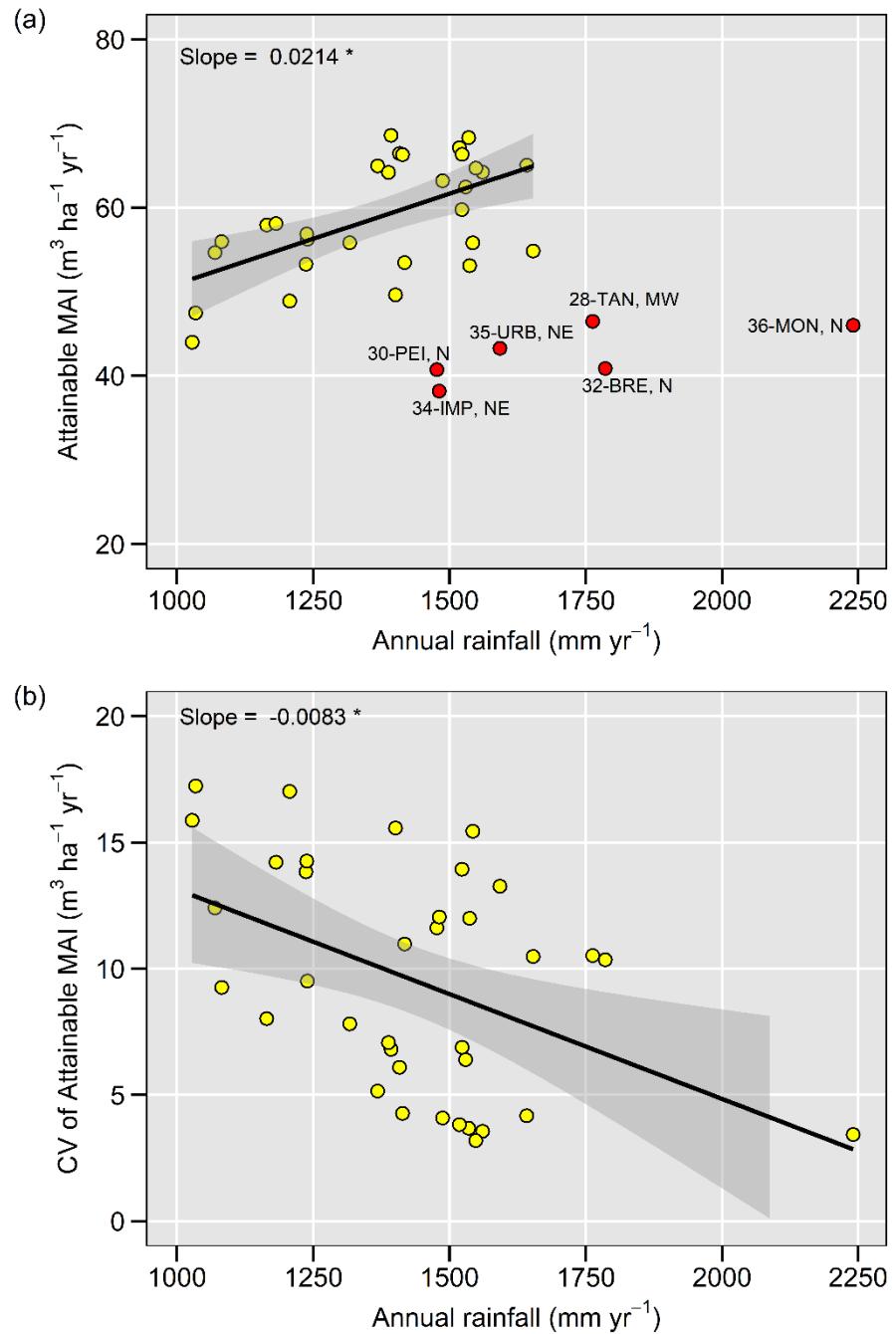


Figure 6. Relationship between *Eucalyptus* attainable MAI and annual rainfall (a) and coefficient of variation (CV) of *Eucalyptus* attainable MAI and annual rainfall (b), considering the data obtained from 27 rotations (1980-2013), three soil types (clay, sandy-clay and sandy-loam) and 36 Brazilian producing locations. Sites highlighted in red were not used for plotting the trend line. *Significant by t test ($p < 0.05$). Labels for individual data points indicate location code (Table 1) + Brazilian region (MW = Midwest, NE = Northeast and N = North).

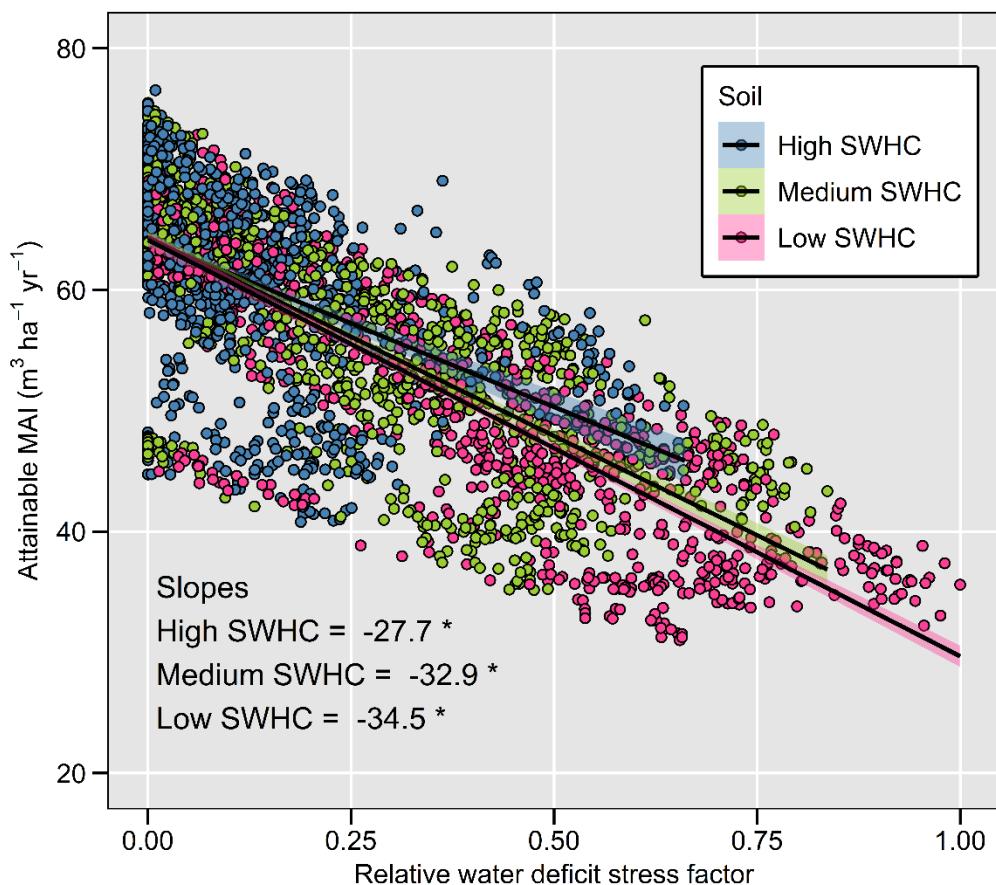


Figure 7. Relationship between the *Eucalyptus* attainable MAI and relative water deficit stress factor from the APSIM *Eucalyptus* model, for three soil types (high, medium and low soil water holding capacity – SWHC), considering 36 locations in Brazil and 27 *Eucalyptus* rotations.

*Significant by t test ($p < 0.05$).

Eucalyptus MAI increased with increasing latitude (Figure 8). Locations with high MAI were mostly placed in latitudes between 22° S and 30° S and, covering Southern Brazil and Central-Southern São Paulo state, where relative water deficit and temperature stress factors were, on average, 0.07 and 0.33, respectively. Temperature stresses in Southern Brazil occurred mostly by low temperatures. Locations at latitudes between 11° S and 21° S presented high water deficit stresses, mainly those in the states of Minas Gerais (average relative water deficit stress of 0.70). Sites 15-ARA and 27-BEL were exceptions, as annual rainfall was relatively high (1358 and 1422 mm yr^{-1} , respectively). The average relative temperature stress for this latitude range (from 11° S to 21° S) was 0.56, predominantly caused by high temperatures. Finally, those locations at latitudes between 0° S and 10° S presented the lowest MAI values, except for site 33-NAT where the simulated average MAI was $58 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ even with an intermediate relative water deficit stress (0.44) and high relative temperature stress (0.69).

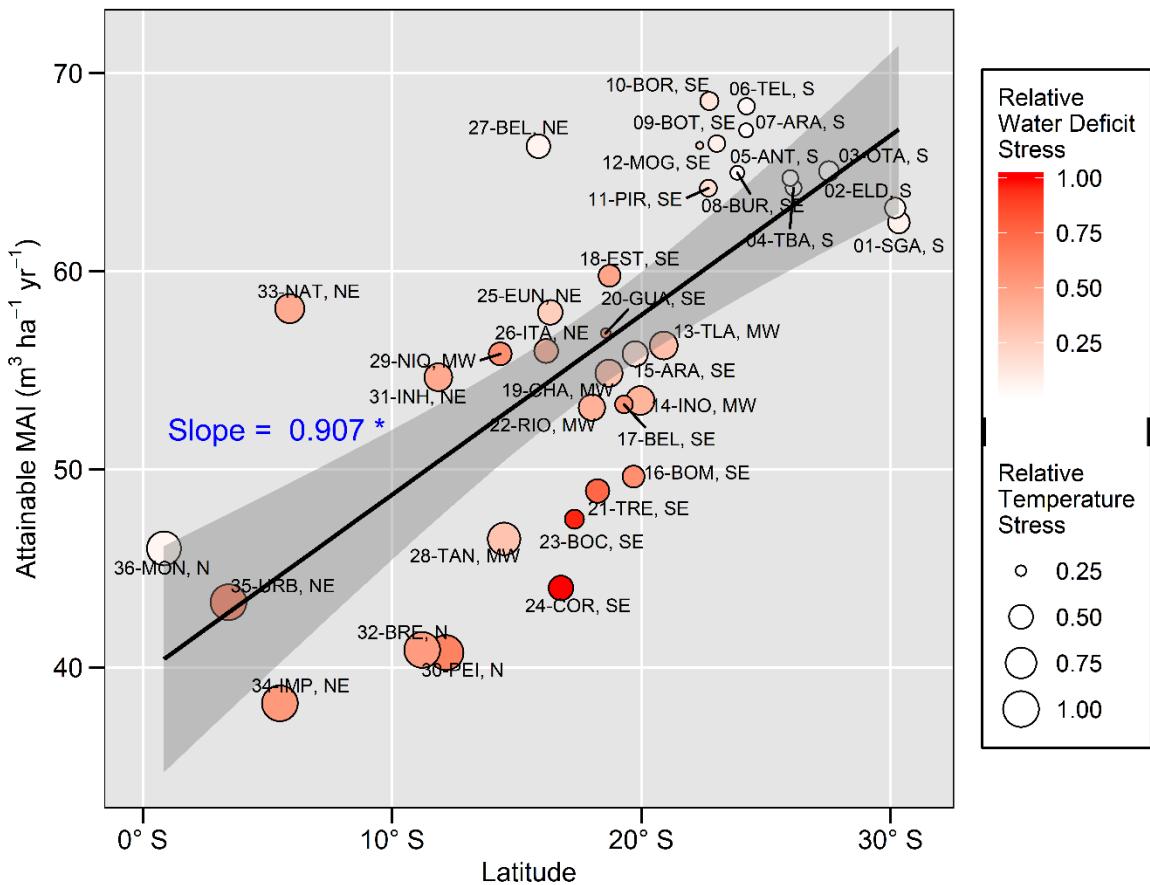


Figure 8. Relationship between the *Eucalyptus* attainable MAI and latitude, considering 36 Brazilian locations, 27 rotations (1980–2013) and three soil types (clay, sandy-clay and sandy-loam). *Significant by t test ($p < 0.05$). The colors in the circles represent the relative water deficit stress, while the size of the circles indicates the relative temperature stress. Labels given to data points indicate location code (Table 1) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

5.4. Discussion

This study characterized the climatic and *Eucalyptus* MAI variability across thirty-six sites in Brazil using a process-based modelling approach coupled with long-term climatic data. *Eucalyptus* growth varied substantially between rotations with the CV for attainable MAI ranging from 3 % (05-ANT) to 17 % (23-BOC). High temporal variability in *Eucalyptus* growth was also found by Freitas (2018), who performed long-term simulations of attainable current annual increment (CAI) in Brazil using the FAO model, and found values ranging from 28.1 to 89.2 $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ in Urbano Santos, MA, and from 61.9 to 103.5 $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ in Borebi, SP. Similarly, Rocha et al. (2016) found differences in *Eucalyptus* stemwood volume at the end of

two rotations (350 and 400 m³ ha⁻¹) in the State of São Paulo, Brazil. Our results are consistent with Rocha et al. (2019) and Campoe et al. (2016), who demonstrated the significant effect of weather conditions on the dynamics of *Eucalyptus* plantations growth.

Gallo et al. (2018) assessed growth traits of various *Eucalyptus* clones under three environments in the state of Rio Grande do Sul, Southern Brazil and obtained MAI of around 62 m³ ha⁻¹ yr⁻¹ for some major clones. The results obtained by Gallo et al. (2018) agree with our findings for the same state (average MAI of 63 m³ ha⁻¹ yr⁻¹). Lemos et al. (2018) used the process-based model 3PG to estimate *Eucalyptus* MAI in the State of São Paulo and found values ranging from 32 to 70 m³ ha⁻¹ yr⁻¹, which agree with the average MAI found in the present study for São Paulo state (66 m³ ha⁻¹ yr⁻¹). Borges et al. (2012) used the 3PG model to simulate *Eucalyptus* MAI in Itacambira, MG, and found MAI of around 40 m³ ha⁻¹ yr⁻¹, lower than the average found for MG state in the present study, which was approximately 56 m³ ha⁻¹ yr⁻¹. This may be explained by the differences in effective root depth and SWHC. Borges et al. (2012) considered a root depth of 2 m and SWHC varying between 200 and 260 mm. In the present study, root depth adopted was 3 m and three soil types were considered: clay (SWHC = 456 mm), sandy-clay (SWHC = 291 mm), and sandy-loam (SWHC = 180 mm), with an average SWHC of 309 mm. Furthermore, such differences may be related to the climate for the chosen study period. Whereas in the present study a daily dataset from 1980 to 2013 was used, Borges et al. (2012) used normal climatic data for the simulation of only one seven-year rotation.

The average *Eucalyptus* attainable MAI found in the present study was around 56 m³ ha⁻¹ yr⁻¹, which is 36% above the national average MAI of 36 m³ ha⁻¹ yr⁻¹, according to IBÁ (2019). Such a difference is likely related to losses caused by sub-optimal management. The present study considers the attainable MAI, which is obtained under optimum forest management. Elli et al. (2019b) assessed the yield gaps, climatic and management efficiencies of *Eucalyptus* plantations across Brazil and found an average forest management efficiency (*Em*) of 64%. *Em* is the relationship between actual and attainable growth and shows how much *Eucalyptus* MAI could be increased by improving forest management (Elli et al., 2019b). Applying the average *Em* obtained by Elli et al. (2019b) to the average attainable MAI of the present study (64% of 56 m³ ha⁻¹ yr⁻¹), the estimated actual MAI would be 36 m³ ha⁻¹ yr⁻¹, the same reported by IBÁ (2019).

Climatic seasonal variability substantially affected forest growth over the rotations and, consequently, the final yield (Figure 5). In tropical sites, the mean monthly volume increment was mostly driven by soil water availability, while in the subtropical locations it was more affected by temperature seasonality. The findings of the present study are consistent with

several other studies in the literature (Brienen and Zuidema, 2005; Campoe et al., 2016; Craven et al., 2011; Granato-Souza et al., 2019; Shimamoto et al., 2016; Venegas-González et al., 2016; Wagner et al., 2014). Campoe et al. (2016) assessed the effects of weather seasonality on individual tree growth of different forest species in Brazil and found that the highest growth rate of *Eucalyptus* in the state of São Paulo occurred in January, during a period of high rainfall, whereas growth almost ceased in November, during a period with very low rainfall. Elli et al. (2017) assessed seasonal effects of weather conditions on the growth of five forest species in Southern Brazil and identified substantial *Eucalyptus* growth reductions due to low temperatures during the winter.

A positive relationship between *Eucalyptus* attainable MAI and annual rainfall was found, with a slope of 0.0216 (Figure 6). It represents an average MAI increase of $2.16 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for each increase of 100 mm yr^{-1} of annual rainfall, which is similar ($\approx 3.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for each increase of 100 mm yr^{-1} of rainfall) to what was presented by Binkley et al. (2017) when assessing 27 experimental sites in Brazil. Stape et al. (2004) found a higher value for the ratio ($\approx 4.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for each increase of 100 mm yr^{-1} of rainfall) when assessing a *E. grandis* × *E. urophylla* clone in North-Eastern Brazil. Sites 28-TAN, 30-PEI, 32-BRE, 34-IMP, 35-URB, and 36-MON, did not present the same pattern as observed for the other assessed sites. The main reason for that, except for 36-MON, was the irregular seasonal rainfall distribution, making the *Eucalyptus* plantations to experience severe droughts, mainly from May to September, even with high annual rainfall. Furthermore, high temperatures, above 27°C , also affected *Eucalyptus* growth in these locations (Table 1).

When *Eucalyptus* attainable MAI was plotted against the relative water deficit stress factor, a negative relationship was observed as expected (Figure 7). Responsiveness of productivity to water deficit varied according to soil type. Soils with clayey texture were more resilient to water deficits due to greater SWHC which reduces water surplus, increases soil water storage and, consequently, reduces water deficit. These results are consistent with those found by the study of Gonçalves et al. (2013), who obtained positive relationships between *Eucalyptus* MAI and soil clay content for three sites in the state of São Paulo, Brazil. They also concluded that soil clay content was directly related to the soil water holding capacity, which was also found by Marsden et al. (2013). Differences in soil type were also more evident for the driest conditions (relative water stress factor ranging from 0.60 to 0.80), which shows that soil type is not an important issue regarding forest growth for sites with adequate water supply in the absence of any nutritional deficit.

Eucalyptus attainable MAI increased with latitude, which clearly shows the effects of climate zones on stemwood growth, as observed by Ellis (2018) and Binkley et al. (2017). The present results suggest an average increase of about $0.91 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for each one degree in latitude. In general, water deficit and temperature stresses decreased with increasing latitude, but no clear trends in annual rainfall according to increasing latitude were observed, given its high temporal and spatial variability (Alvares et al., 2013; Lyra et al., 2014). Air temperature impacts *Eucalyptus* growth (Campoe et al., 2016; Prior and Bowman, 2014) since below or above optimum values affect several physiological processes, such as transpiration and enzymatic dynamics of photosynthesis and respiration (Lin et al., 2015; Atkin et al., 2015). On the other hand, water deficit causes stomatal closure, which reduces CO₂ absorption and, consequently, diminish photosynthesis (Flexas and Medrano, 2002; Martin-StPaul et al., 2017; Medrano et al., 2002). The combined effects of temperature and water deficit stresses explain the lower attainable MAI at locations where latitude is between 0° S and 10° S (Figure 8), where high temperatures and intense water deficit are commonly observed. At site 33-NAT, RN, average *Eucalyptus* attainable MAI was relatively high ($58 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), even with high water deficit and temperatures stresses (Figure 8). This is justified by the higher incidence of solar radiation, with a daily average of $20.6 \text{ MJ m}^{-2} \text{ day}^{-1}$ (Table 1), which increases the potential growth and keeps *Eucalyptus* MAI at high levels even with relatively high environmental stresses (Elli et al., 2019b).

Given the effects that climate variability has on *Eucalyptus* growth, some mitigating strategies may be used to improve forestry resilience and overcome climatic constraints in Brazilian *Eucalyptus* plantations. In tropical regions where water deficit is severe, the following options may be adopted: (i) selection of drought-tolerant genotypes; (ii) maintenance of litter and harvest residues over the soil (minimum cultivation), (iii) use of wider planting spacing, (iv) use of deep soil preparation, and (v) adapt the silvicultural climate-calendar for stand establishment in order to reduce costs and guarantee high seedlings survival (Gonçalves et al., 2017, 2013; Stape et al., 2001). In subtropical regions, where low temperatures are the main problem, the selection of frost-tolerant genotypes is recommended. The knowledge of the frost risk in the region is an important aspect to be considered in the forest planning (Alvares et al., 2018). Therefore, the integration of historical weather data, genotypes, and silvicultural practices are essential for overcoming the abiotic stresses in Brazilian *Eucalyptus* plantations (Elli et al., 2019b; Gonçalves et al., 2013).

5.5. Conclusions

Spatial and temporal (inter-annual and inter-seasonal) climate variability strongly affect attainable growth rates of *Eucalyptus* across Brazil. *Eucalyptus* MAI ranged from 38 m³ ha⁻¹ yr⁻¹ (Imperatriz, MA, Northeast region) to 69 m³ ha⁻¹ yr⁻¹ (Borebi, SP, Southeast region), while its coefficient of variation ranged from 3.2 % (Antônio Olinto, PR, South region) to 17.2% (Bocaiúva, MG, Southeast region). In the tropical sites, *Eucalyptus* growth was mostly driven by water deficit accompanied by high temperatures, while in the subtropical locations it was mainly affected by low air temperature. These findings help to understand how *Eucalyptus* plantations could be managed in order to increase their growth in the present scenario and how the forests will respond to the future climate scenarios, which makes possible to determine the best strategies to mitigate negative impacts. Gauging the effects of climate variability on *Eucalyptus* growth may assist in forest planning by quantifying the area to be cultivated, machinery sizing, climate risk, and guiding the tree breeders in choosing appropriate genotypes.

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Supplementary material

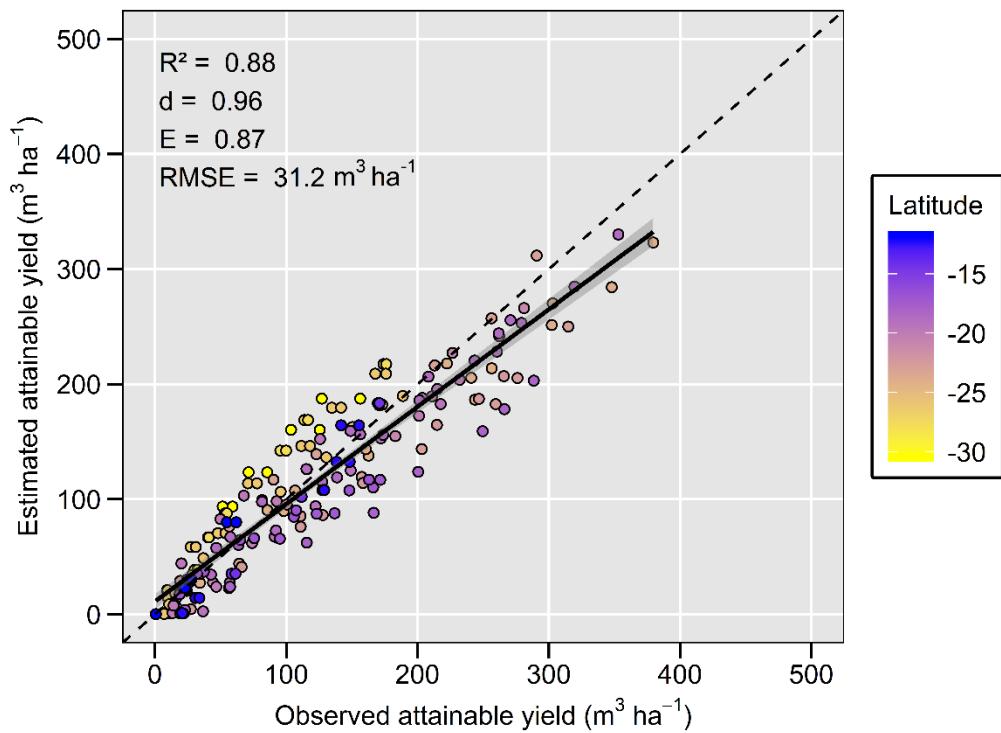


Figure S1. Performance of APSIM Next Generation *Eucalyptus* model to estimate attainable yield at different ages for a six-year rotation across a geographic gradient in Brazil. Statistics in the graph refer to coefficient of determination (R^2), Willmott agreement index (d), modelling efficiency index (E) and root mean square error (RMSE).

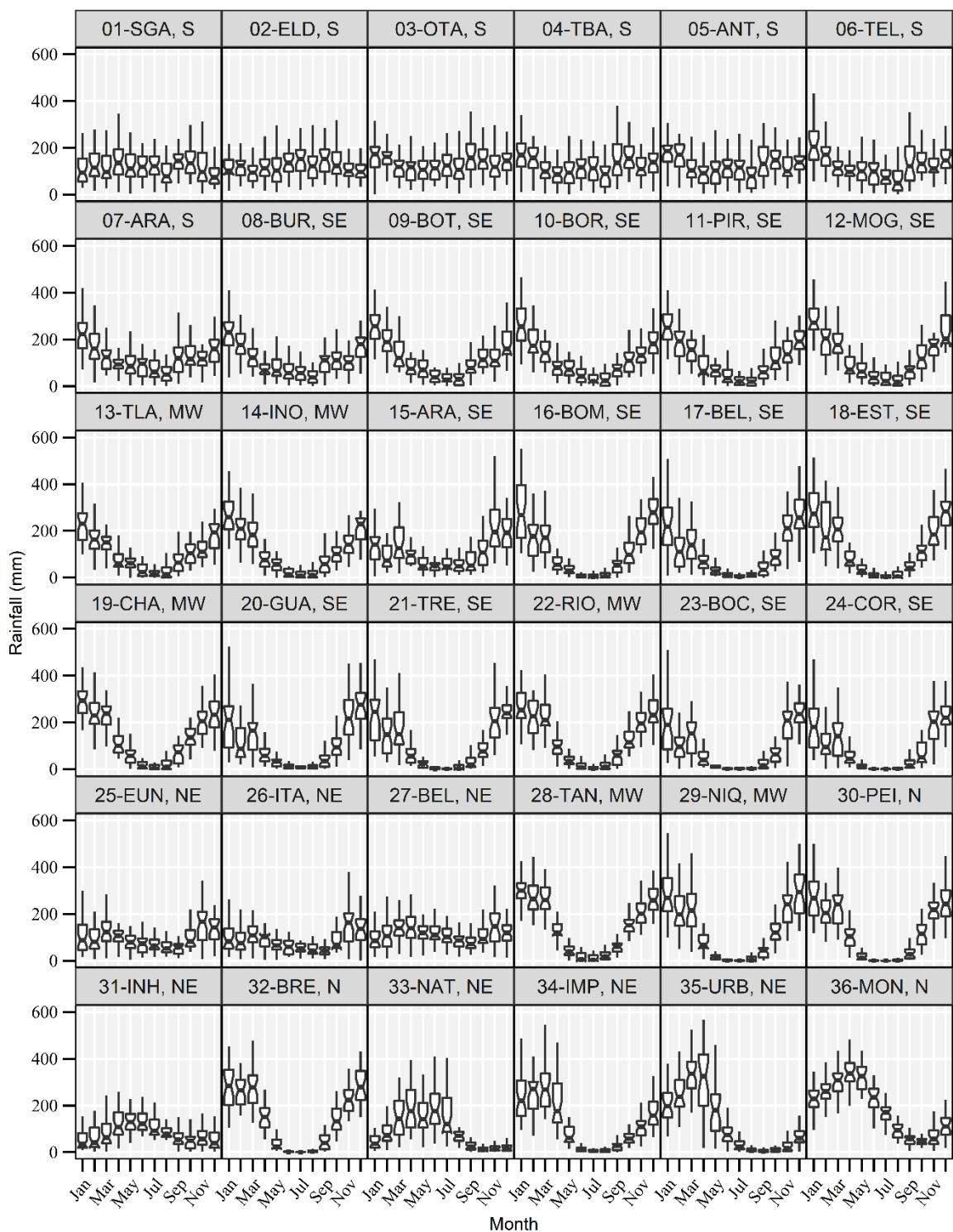


Figure S2. Monthly rainfall variability of 36 *Eucalyptus* production locations in Brazil, for 1980 to 2013. Titles given for individual graphs indicate location code (Table 1 in the manuscript) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

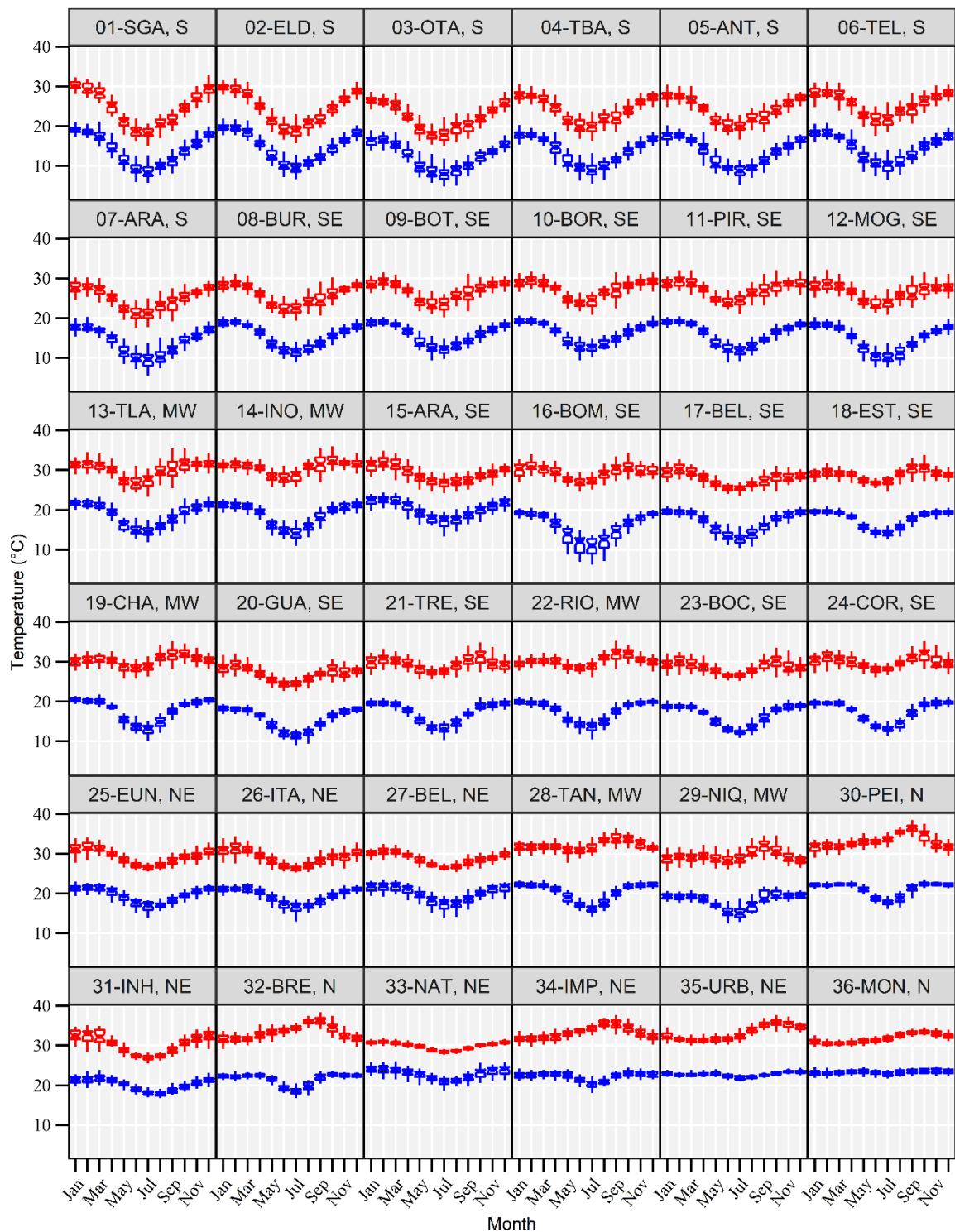


Figure S3. Monthly variability of maximum (red) and minimum (blue) average temperatures of 36 *Eucalyptus* production locations in Brazil for 1980 to 2013. Titles given for individual graphs indicate location code (Table 1 in the manuscript) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

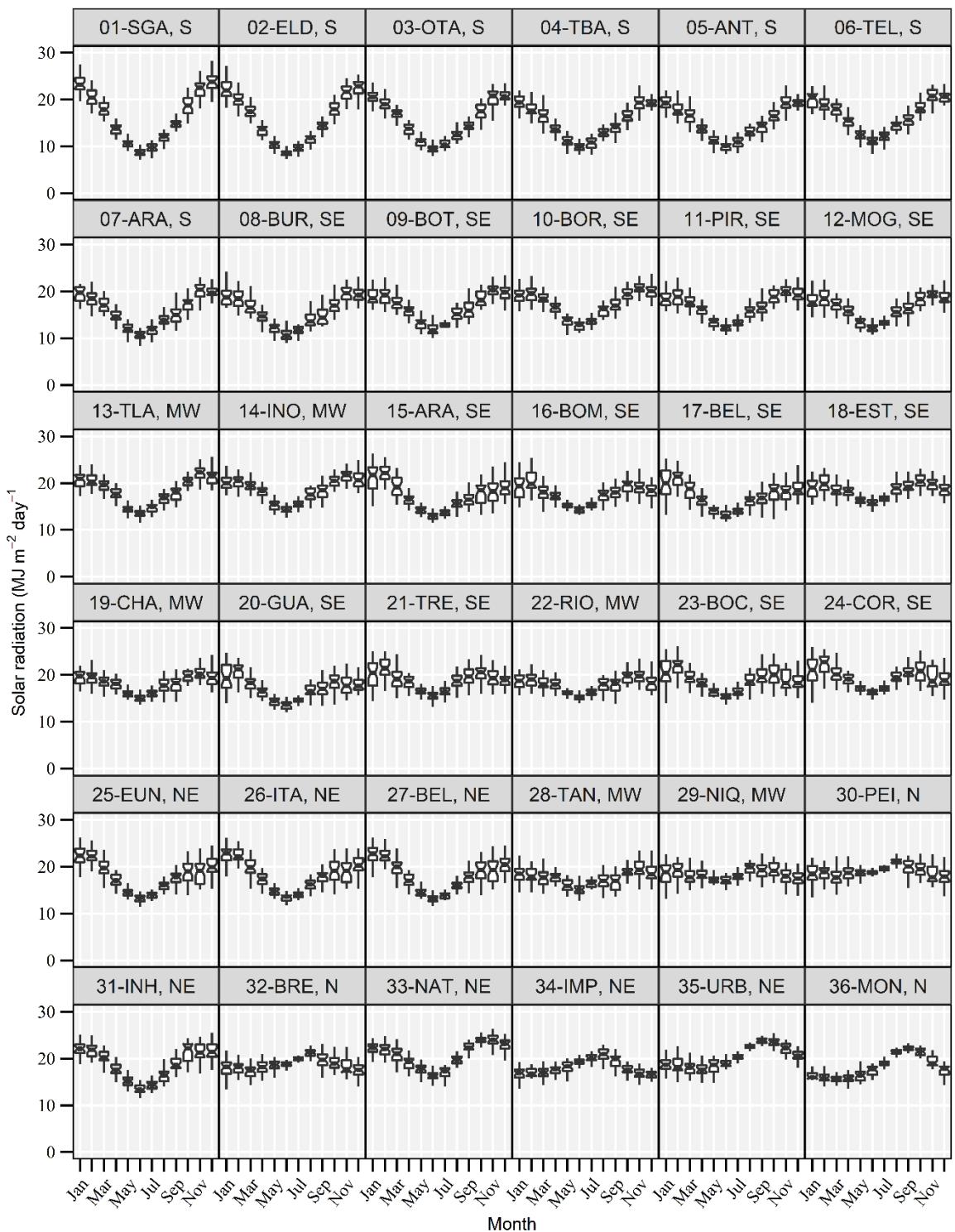


Figure S4. Monthly variability of average daily solar radiation of 36 *Eucalyptus* production locations in Brazil for 1980 to 2013. Titles given for individual graphs indicate location code (Table 1 in the manuscript) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

Table S1. Physical and hydraulic characteristics of the three soil types (clay, sandy-clay, and sandy-loam) used to perform the long-term *Eucalyptus* growth simulations with APSIM model.

Depth ^a	BD ^b	LL ^c	DUL ^d	SAT ^e	SWHC ^f	KL ^g
cm	g cm ⁻³	----- cm ³ cm ⁻³ -----			mm	day ⁻¹
Clay soil with high SWHC (average ^h = 1.52 mm cm ⁻¹)						
0-15	1.440	0.027	0.102	0.420	11.250	0.070
15-30	1.460	0.020	0.070	0.410	7.500	0.070
30-60	1.460	0.020	0.070	0.410	15.000	0.070
60-90	1.530	0.021	0.090	0.394	20.700	0.060
90-120	1.570	0.030	0.080	0.360	15.000	0.040
120-150	1.570	0.030	0.092	0.350	18.600	0.030
150-180	1.570	0.031	0.092	0.350	18.300	0.030
180-210	1.570	0.031	0.092	0.350	18.300	0.030
210-300	1.570	0.031	0.092	0.350	54.900	0.020
Sandy-clay soil with medium SWHC (average = 0.97 mm cm ⁻¹)						
0-15	1.140	0.256	0.405	0.541	22.350	0.070
15-30	1.140	0.256	0.405	0.541	22.350	0.070
30-60	1.260	0.236	0.388	0.519	45.600	0.070
60-90	1.260	0.236	0.388	0.407	45.600	0.060
90-120	1.260	0.236	0.388	0.407	45.600	0.040
120-150	1.260	0.236	0.388	0.407	45.600	0.030
150-180	1.260	0.236	0.388	0.407	45.600	0.030
180-210	1.260	0.236	0.388	0.407	45.600	0.030
210-300	1.260	0.236	0.388	0.407	136.800	0.020
Sandy-loam soil with low SWHC (average = 0.60 mm cm ⁻¹)						
0-15	1.440	0.027	0.102	0.420	11.250	0.070
15-30	1.460	0.020	0.070	0.410	7.500	0.070
30-60	1.460	0.020	0.070	0.410	15.000	0.070
60-90	1.530	0.021	0.090	0.394	20.700	0.060
90-120	1.570	0.030	0.080	0.360	15.000	0.040
120-150	1.570	0.030	0.092	0.350	18.600	0.030
150-180	1.570	0.031	0.092	0.350	18.300	0.030
180-210	1.570	0.031	0.092	0.350	18.300	0.030
210-300	1.570	0.031	0.092	0.350	54.900	0.020

^a Soil profile was built from Assad et al. (2001), Batjes (2009), Battisti and Sentelhas (2017), Christina et al. (2017), Dias and Sentelhas (2018), RadamBrasil (1974) and Reichert et al. (2009). ^b BD = Soil bulk density. ^c LL = Wilting point (-1500 kPa). ^d DUL = Drained Upper Limit (-10 kPa). ^e SAT = Saturated water content. ^f SWHC = Soil water holding capacity. ^g KL = Root extraction factor. ^h Weighted average of SWHC (mm cm⁻¹) considering all depth layers of the soil profile.

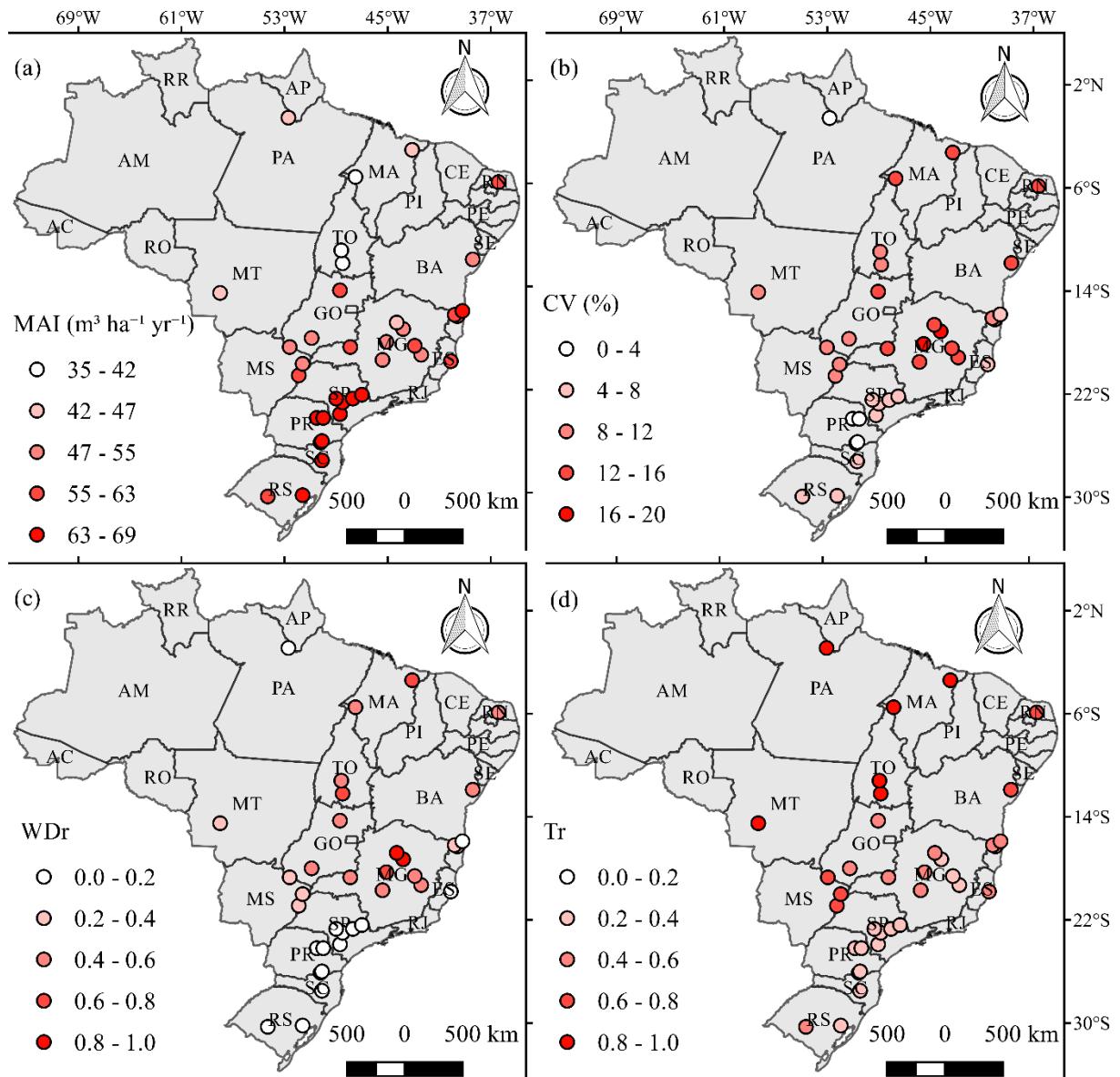


Figure S5. Spatial overview of *Eucalyptus* attainable MAI (MAI – a) and its coefficient of variation (CV – b), relative water deficit (WDr – c) and temperature (Tr – d) stress factors, considering the results of 27 rotations (1980-2013), three soil types (clay, sandy-clay and sandy-loam) and 36 Brazilian production locations.

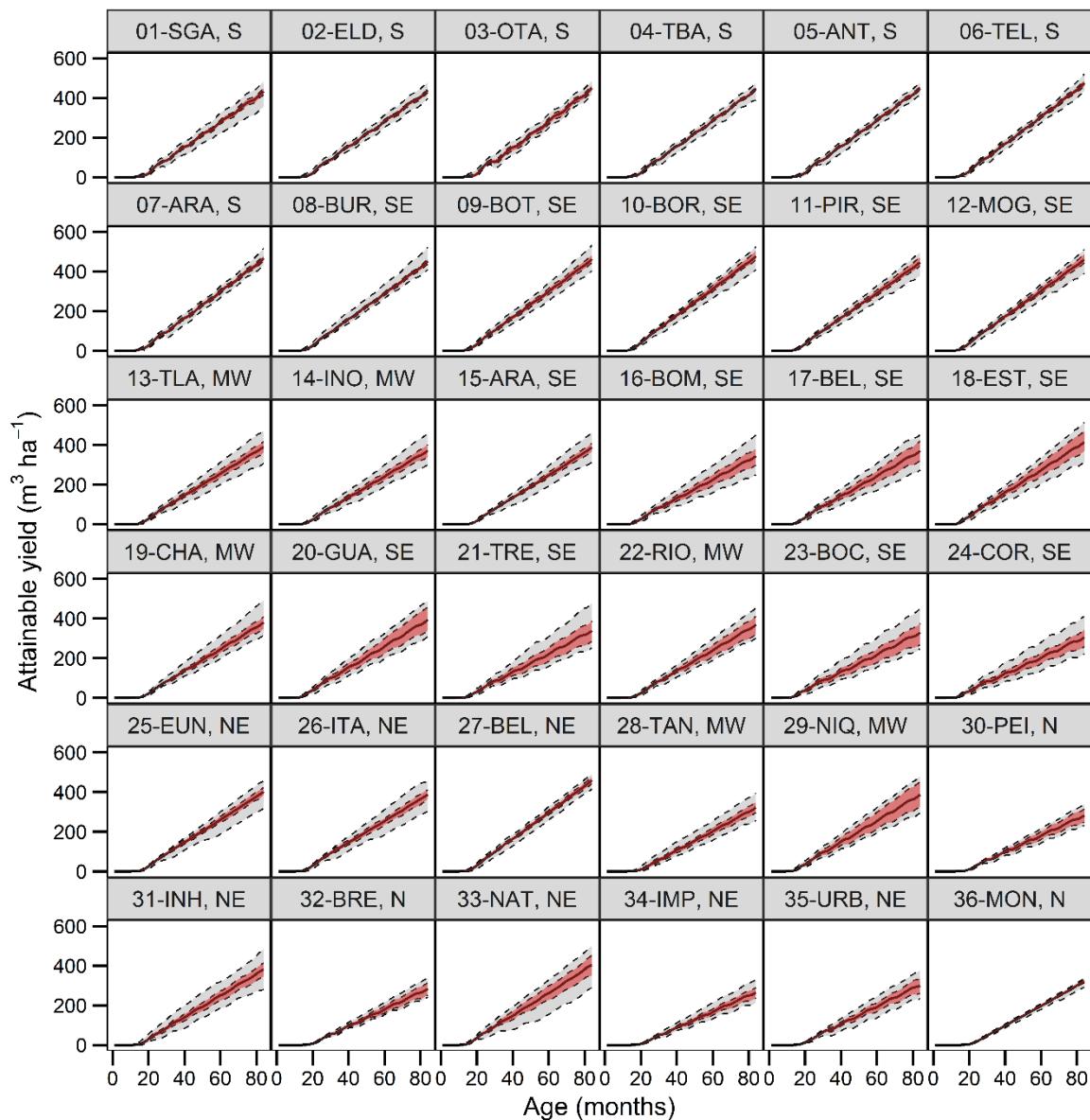


Figure S6. Inter-seasonal climatic variability effect on *Eucalyptus* attainable yield in 36 locations in Brazil, considering the results from 27 forest rotations (1980-2013) and three soil types (clay, sandy-clay and sandy-loam). Solid lines represent the average *Eucalyptus* attainable yield throughout a seven-year rotation. Internal dashed lines represent the first and third quartiles, while external dashed lines represent the maximum and minimum values. Titles given for individual graphs indicate location code (Table 1 in the manuscript) + Brazilian region (S = South, SE = Southeast, MW = Midwest, NE = Northeast and N = North).

References for supplementary material

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6. GLOBAL SENSITIVITY-BASED MODELLING APPROACH TO IDENTIFY SUITABLE *EUCALYPTUS* TRAITS FOR ADAPTATION TO CLIMATE VARIABILITY AND CHANGE

Abstract

Eucalyptus-breeding efforts have been made to identify clones of superior performance in terms of growth and yield and how they will interact with global climate changes. This study performs a global sensitivity analysis for assessing the impact of genetic traits on *Eucalyptus* yield across contrasting environments in Brazil under present and future climate scenarios. The APSIM Next Generation *Eucalyptus* model was used to perform the simulations of stemwood biomass ($t\ ha^{-1}$) for seven-year rotations across 23 locations in Brazil. Projections for the period from 2020 to 2049 using three global circulation models under intermediate (RCP4.5) and high (RCP8.5) greenhouse gas (GHG) emission scenarios were performed. The Morris sensitivity method was used to perform a global sensitivity analysis to identify the influence of plant traits on stemwood biomass. Traits for radiation use efficiency, leaf partitioning, canopy light capture, and fine root partitioning were the most important, impacting the *Eucalyptus* yield substantially in all environments under the present climate. Some of the traits targeted now by breeders for current climate will remain important under future climates. However, breeding should place a greater emphasis on photosynthetic temperature response for *Eucalyptus* in some regions. Global sensitivity analysis was found to be a powerful tool for identifying suitable *Eucalyptus* traits for adaptation to climate variability and change. This approach can improve breeding strategies by better understanding the gene x environment interactions for forest productivity.

Keywords: APSIM *Eucalyptus* model, radiation use efficiency, extinction coefficient, biomass partitioning, photosynthetic temperature response, Morris method.

6.1. Introduction

Eucalyptus is the most planted hardwood genus in the world and its cultivation provides renewable resources for pulp and paper production, lumber industry, beekeeping, firewood and charcoal (Albaugh et al., 2017; IBÁ, 2019). *Eucalyptus* productivity may be affected by spatial and temporal climate variability as well as climate change (Binkley et al., 2017; Campoe et al., 2016; Stape et al., 2010). High yield levels depend on the combined effects of adequate environmental conditions, optimum or near optimum forestry management and the use of highly productive genotypes. *Eucalyptus*-breeding efforts have been made to identify superior

clones in terms of growth and yield (Nunes et al., 2002) and how they interact with the soil, climate and forestry management. In this context, process-based simulation models are promising tools to integrate biophysical and environmental process and then to simulate genotype and management impacts on productivity (Ewert et al., 2015; Landsberg et al., 2003).

Sensitivity analysis (SA) has been applied to process-based simulation models to identify suitable traits that may provide advantages under different climate and soil conditions (Makowski et al., 2006). The SA can be either local or global. In the first, the local response of the outputs is investigated by changes in a single parameter, holding all other parameters fixed. In the global sensitivity analysis (GSA), simultaneous changes in all the studied parameters are considered over their suitable ranges, and interactions between parameters are taken into account (Saltelli et al., 1999). There are different methods to assess GSA, including variance-based methods such as the Fourier amplitude sensitivity test – FAST (Cukier et al., 1973), Sobol' (Sobol', 1993), Extended-FAST (Saltelli et al., 1999) and screening-based methods such as Morris (Morris, 1991). The Morris method calculates the global main effect (elementary effect, μ^*) of a parameter by averaging a number of local based measures for different points in the parameter space (Saltelli et al., 2008). This is a widely used and robust method that require relatively smaller computational costs compared to other methods (Campolongo et al., 2007).

The GSA has been widely applied to various crops, such as wheat (Casadebaig et al., 2016), sugarcane (Sexton et al., 2017) and oil palm (Pardon et al., 2017). Locatelli et al. (2017) sucessfully used the ForestGALES model for assessing wind risk to *Eucalyptus globulus* stands by a Sobol' SA in one environment in North Spain. Nevertheless, there is a lack of studies on the use of GSA to identify suitable *Eucalyptus* genetic traits under contrasting climate conditions, including the effects of spatial and temporal climate variability and change. This approach is of high importance, useful and innovative for *Eucalyptus* breeding and management purposes. In this context, the following hypothesis was raised: a global sensitivity analysis is a useful tool to identify suitable traits for *Eucalyptus* adaptation to climate variability and change. Therefore, the aim of this study was to perform a GSA for assessing the impact of different genetic traits on *Eucalyptus* yield across 23 contrasting environments in Brazil under present and future climate scenarios.

6.2. Materials and methods

6.2.1. Study environments

The simulations were performed for 23 *Eucalyptus* producing locations in Brazil (Figure 1 and Table S1 in the Supplementary Material). The weather data (maximum, minimum and mean temperatures, solar radiation, rainfall, relative humidity and wind speed) were obtained from daily gridded meteorological data (Xavier et al., 2016). The effects of temporal climate variability on *Eucalyptus* yield were assessed from a period from 1980 to 2008, assuming a *Eucalyptus* rotation of seven years. A planting date of 15/Feb was assumed to be indicative for all locations. The soil types (first order) were reported from forestry companies with experimental areas in each studied location. The soil profile required in the APSIM model was built based on pedotransfer functions fitted for Brazilian soils, RadamBrasil (1974) and Wise (Batjes, 2009) databases. Further information on the methodological procedures for building the soil profiles can be found in Elli et al. (2020). No nutrient limitations were considered during the simulations.

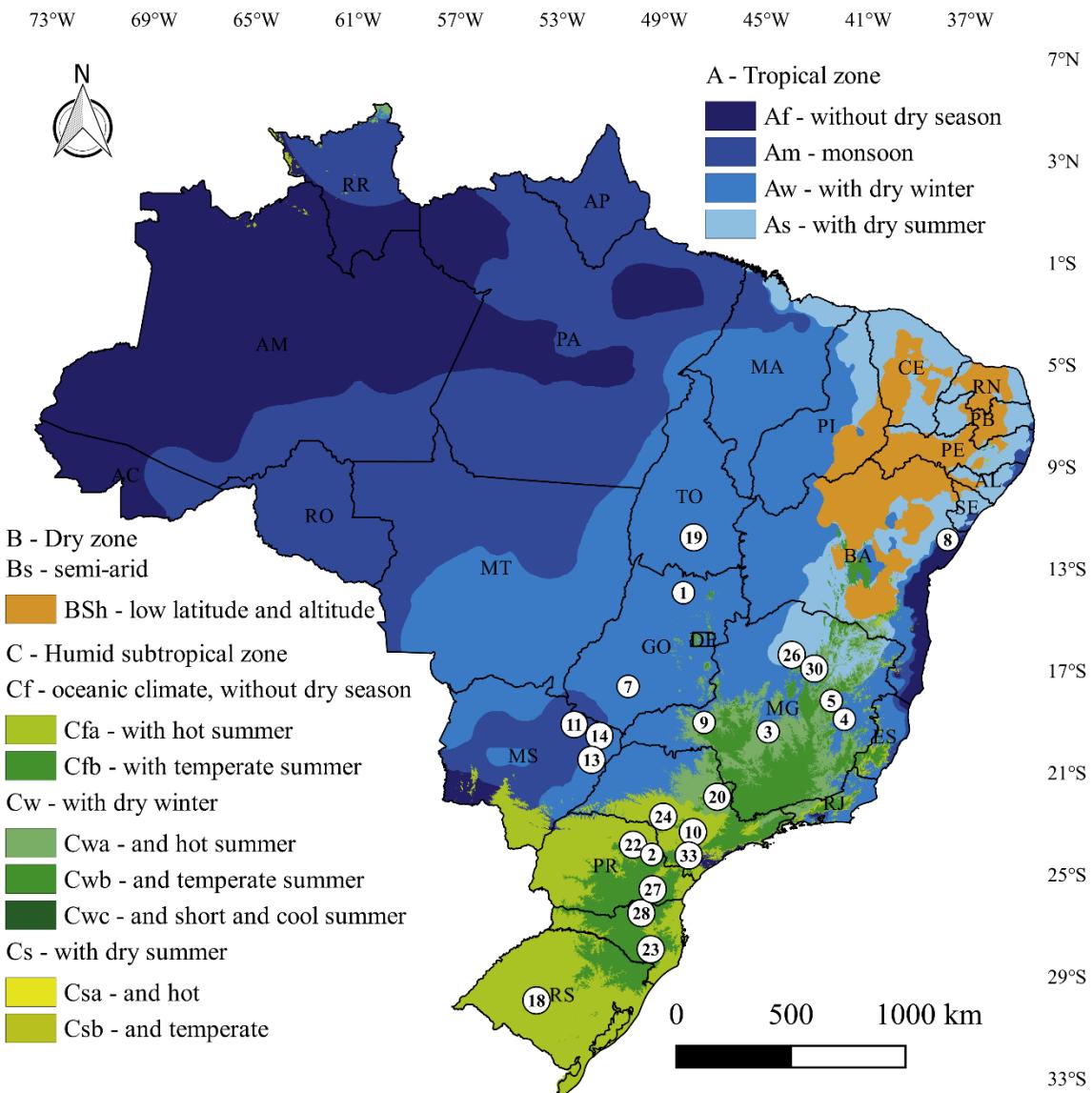


Figure 1. Locations for long-term yield simulations and sensitivity analyses and their respective Köppen climate classification in Brazil (map adapted from Alvares et al., 2013). The description of map codes and further information on the characteristics of each location are presented in Table S1.

6.2.2. Process-based simulation model and CO₂ fertilization functions

The APSIM Next Generation *Eucalyptus* model was used to perform the simulations of stemwood biomass ($t \text{ ha}^{-1}$) at seven years. This model was validated against measured *Eucalyptus* yield data from plots in all sites presented in Figure 1 (Elli et al., 2020), which were conducted under optimum or near optimum forest management. Model parameters for a highly productive and homeostatic Brazilian clone of *Eucalyptus urophylla* with suitability to a wide

range of environments were used. Results of the model performance can be seen in Elli et al. (2020).

The APSIM Next Generation *Eucalyptus* model takes into account the modelling structure from APSIM-Growth model (Huth et al., 2001), but having the possibility of modifications through the Plant Modelling Framework (PMF), a software that allows models to be adjusted and improved in the APSIM platform (Brown et al., 2014). Daily biomass production is calculated from daily intercepted solar radiation and radiation use efficiency (RUE). RUE is affected by soil and climatic factors. Interception of solar radiation is calculated assuming an exponential light extinction coefficient. A general approach of this model is:

$$\Delta G = R_{\text{int}} \times \varepsilon \times \min(F_T, F_F, F_N, F_{VPD}) \times F_W \times F_{CO_2} \quad (1)$$

where: ΔG is the daily growth; R_{int} the daily intercepted solar radiation; ε the radiation use efficiency (g MJ^{-1} of global solar radiation); and F_T , F_F , F_N , F_{VPD} , F_W and F_{CO_2} the growth modifiers to account for the effects of air temperature, frost, nitrogen, vapor pressure deficit, water supply and atmospheric CO₂ concentration.

The APSIM Next Generation *Eucalyptus* model includes five submodels related to different tree components: leaf; branch; stem; coarse root; and fine root. Potential biomass production is modelled by the leaf submodel. Biomass is partitioned to the different organs according to tree size, environmental stresses and species-specific parametrizations. Leaf area growth is obtained from leaf growth and specific leaf area. Similarly, root growth is calculated from a specific root length. Different soil layers are considered to describe the vertical distribution of various soil processes. Available water of each layer depends on the progress of the extraction front to greater depths. The potential water uptake is calculated using the product of the available water in the layer and a factor that controls the rate of extraction (KL). When plant water absorption is lower than the plant demand, reductions in growth rate are considered by water deficit. Full model documentation is available at <https://www.apsim.info/>.

Fertilization effects of CO₂ enrichment were proposed for the APSIM Next Generation *Eucalyptus* model in the present study. Increases in CO₂ concentration impact forest growth by changes in RUE, stomatal conductance (SC) and specific leaf area (SLA). RUE and SC responses to CO₂ enrichment are based on Reyenga et al. (1999) approach for a C₃ plant. To consider the CO₂ effects on RUE and interactions with temperature, APSIM Next Generation *Eucalyptus* model scales RUE by the ratio (Φ_p) of the light-limited photosynthetic response

to increased CO₂ (O’Leary et al., 2015; Reyenga et al., 1999), which is calculated by the following expression:

$$\Phi_p = \frac{(CO_2 - \Gamma)(350 + 2\Gamma)}{(CO_2 + 2\Gamma)(350 - \Gamma)} \quad (2)$$

where Γ is the temperature-dependent CO₂ compensation point, which is calculated by:

$$\Gamma = \frac{(163 - Tmean)}{(5 - 0.1 * Tmean)} \quad (3)$$

where Tmean is the mean daily temperature (°C).

The response of SC to increased CO₂ concentration is obtained by the relationship between the Φ_p and the relative CO₂ gradient (RG), which is calculated by the following equation:

$$RG = \frac{(CO_2 - \Gamma)}{(350 - \Gamma)} \quad (4)$$

Responses of SLA to increased CO₂ are based on findings of Smith et al. (2012) for *Eucalyptus* experimental plots. A linear reduction of about 15% of SLA is considered when CO₂ concentration increases from 350 to 700 ppm.

6.2.3. Climate change scenarios

Climate change scenarios were generated by three Global Circulation Models (GCMs): HadGEM2-ES, GISS-E2-R and CSIRO-Mk3-6-0, which are publicly available from the Coupled Model Intercomparison Project Phase 5 – CMIP5 (Taylor et al., 2012). These models were selected based on its ability to better represent the spatial and temporal distribution of rainfall in different Brazilian regions (Gulizia and Camilloni, 2015; Yin et al., 2013),

The period from 2020 to 2049 (near term) was selected to assess climate change impacts on *Eucalyptus* growth. This period was chosen in order to provide results that may be currently used for the planning of *Eucalyptus* breeding programs for the coming decades, and then to assist in near-term management purposes. Two contrasting greenhouse gases emissions were assessed, which follow distinct representative concentration pathways (RCPs): intermediate emission scenario (RCP4.5) and high emission scenario (RCP8.5). According to Ward et al. (2011), the RCP4.5 scenario offers the best visual match to the recent studies on future fossil fuel production, while the RCP8.5 represents more extreme conditions.

The future climate data were generated from the Climate Scenario Generation Tool for R from the Agricultural Model Intercomparison and Improvement Project – AgMIP, where

changes in maximum and minimum temperature and rainfall were considered (Hudson and Ruane, 2013; Rosenzweig et al., 2014). The other weather variables, such as solar radiation, relative humidity and wind speed (also are required to use in the APSIM *Eucalyptus* model) remained unchanged. Daily weather data from 1980-2009 were used as the baseline. The CO₂ concentrations during the simulations were 360 ppm for the baseline, 450 ppm for RCP4.5 and 480 ppm for RCP8.5. These values represent the concentration referring to the central year of the 30-year period, as recommended by AgMIP (Rosenzweig et al., 2014). Simulations for the baseline were constructed to consist of four consecutive rotations: (i) 15/Feb/1980 to 14/Feb/1987, (ii) 15/Feb/1987 to 14/Feb/1994, (iii) 15/Feb/1994 to 14/Feb/2001, and (iv) 15/Feb/2001 to 14/Feb/2008. Similarly, for climate change assessments, the following rotations were considered: (i) 15/Feb/2020 to 14/Feb/2027, (ii) 15/Feb/2027 to 14/Feb/2034, (iii) 15/Feb/2034 to 14/Feb/2041 and (iv) 15/Feb/2041 to 14/Feb/2048.

6.2.4. Parameters and outputs

The global sensitivity analysis was performed using 25 parameters of the APSIM Next Generation *Eucalyptus* model (Table 1). Ranges for each parameter were selected from a robust calibration of the model for different Brazilian *Eucalyptus* clones and environments to ensure realistic changes in magnitude. These parameters were chosen due to their ability of predicting *Eucalyptus* genotypes differences (Elli et al., 2020). The effects of parameters were analysed in terms of impacts on the stemwood biomass at the seventh year of the *Eucalyptus* rotation.

Table 1. Description and ranges of the parameters used to perform the global sensitivity analysis of the APSIM Next Generation *Eucalyptus* model.

Parameters	Functions and units ^a	x or y axis used in the SA ^b	Abbreviation	Lower Limit	Upper Limit
Radiation use efficiency	g MJ ⁻²	-	RUE	1.30	1.69
Light extinction coefficient of seedlings	-	-	Ky	0.25	0.38
Light extinction coefficient of mature trees	-	-	Km	0.45	0.61
Photosynthesis modifier for temperature (FT)	x: temperature (°C) y: FT	x x x x	FT_1 FT_2 FT_3 FT_4	6.00 17.00 22.00 38.00	10.00 19.00 24.00 40.00
Photosynthesis modifier for frost (FF)	x: minimum temperature (°C) y: FF	y y	FFrost_1 FFrost_2	0.80 0.00	1.00 0.50
Stem senescence rate for frost (SSRF)	x: minimum temperature (°C) y: SSRF	y y y	MFrost_1 MFrost_2 MFrost_3	0.00 0.00 0.50	0.20 1.00 1.00
Age factor for occurrence of frost (AFOC)	x: age (years)	x	AgeFrost	0.80	1.20
Stem partitioning fraction (SPF)	x: individual tree weight (g m ⁻²) y: SPF	y y y	Stem_Part_1 Stem_Part_2 Stem_Part_3	0.15 0.30 0.57	0.20 0.40 0.64
Branch partitioning fraction	-	y	Branch_Part	0.08	0.12
Leaf partitioning fraction (LPF)	x: individual tree weight (g m ⁻²) y: LPF	y y y	Leaf_Part_1 Leaf_Part_2 Leaf_Part_3	0.14 0.10 0.09	0.28 0.24 0.20
Coarse root partitioning fraction (CRPF)	x: individual tree weight (g m ⁻²) y: CRPF	y y y	CRoot_Part_1 CRoot_Part_2 CRoot_Part_3	0.01 0.03 0.04	0.03 0.10 0.10
Fine root partitioning fraction	-	y	FRoot_Part	0.24	0.35
Specific leaf area (SLA)	x: Age (years) y: SLA (m ² g ⁻¹)	x	SLA	0.80	1.20

^a For some of the parameters presented, x and y axis are required to make the parameter response curve. ^b SA = sensitivity analysis.

For some age-related parameters (such as the age factor for occurrence of frost and specific leaf area), a new approach was proposed in order to consider the effects of the whole function by changing only one delta (Δ) coefficient in each case as described below (Figure 2). For this, some structural changes were made to the APSIM Next Generation *Eucalyptus* model. A delta coefficient was added as a multiplier to the x-axis of a given age-related function

throughout the whole *Eucalyptus* rotation. Savings in execution time were gained from a reduction in the number of parameters required to evaluate any given interpolated function. For instance, the original function for specific leaf area includes 12 parameters ($x = 0, 1, 2, 3, 4, 8$ and $y = 0.015, 0.011, 0.010, 0.008, 0.007$ and 0.006). The sensitivity of the model to changes in x was evaluated using one parameter (Δ), saving approximately 106,000 seven-year simulations in the present study, given the large number of environments, *Eucalyptus* rotations and climate scenarios assessed.

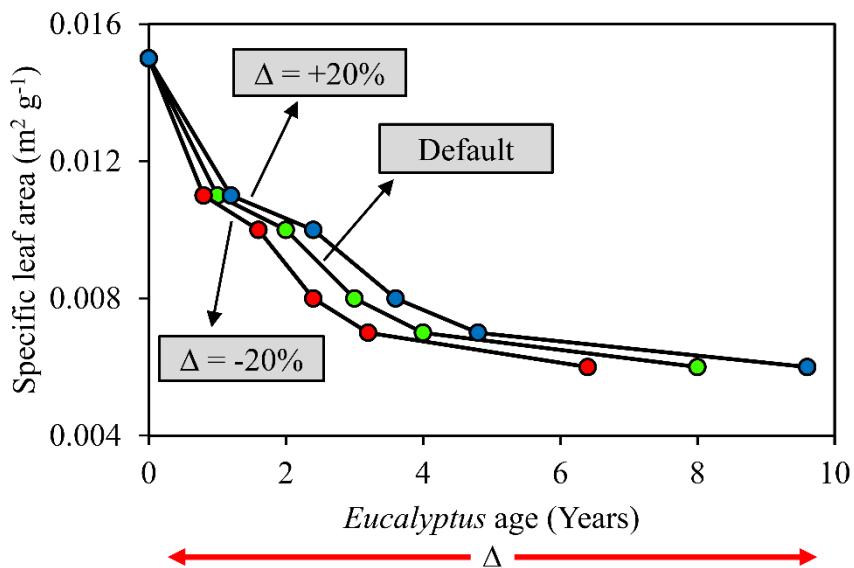


Figure 2. Schematic representation of the Δ coefficient applied to the specific leaf area function of the APSIM Next Generation *Eucalyptus* model. Δ values of -20% and +20% of the default values represent the lower and upper limits, respectively, to perform the sensitivity analysis. In Table 1, delta values are presented as 0.8 (-20%) and 1.2 (+20%).

6.2.5. Global sensitivity analysis

The Morris sensitivity method (Morris, 1991) was used to perform the global sensitivity analysis. This method is based on the calculation of the elementary effects of each input parameter on a given model output. The Morris method can be conceptualised as a randomised one-at-a-time (OAT) design, as it varies one factor at a time independently of the others, recording at each time the effect of this variation on the output. This procedure is repeated “r” times, where r is the number of trajectories to explore the variability in elementary effect across the parameter space, and generally ranges from 10 to 50 (Campolongo et al., 2007). In the present study, 15 trajectories were considered sufficient after preliminary tests for contrasting

locations using up to 30 trajectories showed stable results for mean of absolute values of the elementary effects with $r = 15$.

The total number of model simulations is given by $r(n+1)$, where n is the total number of studied parameters. In the present study, 25 genetic parameters were considered, then $15(25+1) = 390$ seven-year simulations were performed in each environment and considering only one seven-year *Eucalyptus* rotation. As spatial and temporal climate variability were considered, 23 environments and four *Eucalyptus* rotations in each location were used. Then, $390 * 23$ (environments) * 4 (rotations) = 35,880 seven-year simulations on a daily time-step were performed for present climate assessments. During the future climate simulations, the same number of trajectories and parameters were used, therefore $15(25+1) = 390$ seven-year simulations were performed in each environment, considering one *Eucalyptus* rotation. These simulations were reproduced for 23 locations, four *Eucalyptus* rotations and six climate future scenarios (three GCM x two RCP). Then, $390 * 23 * 4 * 6 = 215,280$ seven-year simulations were performed. Therefore, a total number of 251,160 seven-year simulations were performed during the global sensitivity analysis.

As result of Morris's method, two sensitivity indexes were calculated for each of the 25 parameters: the mean of absolute values of the elementary effects (μ^*) and the standard deviation (σ) of the elementary effects. The μ^* is used to rank the importance of each parameter, i.e. the higher μ^* is, the more influential is the parameter on *Eucalyptus* stemwood biomass at the seventh year of the rotation. The σ indicates the level of interaction between the parameters and/or non-linearity effects, i.e. the higher σ is, the higher are the interactions between parameters and/or non-linearity effects. The Morris method is implemented in the APSIM Next Generation modelling framework to provide μ^* and σ as well as graphical analysis of the results. This APSIM framework uses the “morris” function from the “sensitivity” package (version 1.11.1) available in the R statistical software (R Development Core Team, 2010). This version also includes a space-filling optimisation of the experimental design (Campolongo et al., 2007). Ranges for each parameter are normalised in order to allow a better comparison of elementary effects between parameters with different magnitudes.

6.3. Results

6.3.1. Influential traits under present climates

RUE, Km, Ky, FT_3 and parameters related to biomass partitioning (Leaf_Part_1, Leaf_Part_3 and FRoot_Part) were the most influential parameters in most locations under the present climate conditions (Figure 3), indicating that these parameters substantially affect stemwood biomass regardless of the environmental conditions. Parameters related to frost effects (mainly AgeFrost and MFrost_2) were influential for predicted yield only at locations in Southern Brazil where night-time temperatures are lower. In general, traits related to leaf partitioning (Leaf_Part_1 and Leaf_Part_3) presented the highest levels of interaction with other parameters and/or non-linearity effects for most locations as shown by the highest values of σ .

6.3.2. Temporal climate variability affecting the level of influence of *Eucalyptus* traits

The value of μ^* was affected by the temporal climate variability as indicated by its variation across the different seven-year *Eucalyptus* rotations (Figure 4). For instance, the μ^* for RUE in Otacílio Costa, SC (23-KLO) was higher during the first two rotations (75.9 and 76.4 t ha⁻¹ for 1980-1987 and 1987-1994, respectively), compared to the results found for subsequent rotations (63.7 and 64.4, respectively). On the other hand, effects of AgeFrost were lower during the first two rotations (0 and 2.0 t ha⁻¹ for 1980-1987 and 1987-1994, respectively) compared to the next rotations (1994-2001 and 2001-2008), when the parameter values were respectively 23.8 and 33.4 t ha⁻¹. Temporal variations were also observed for Leaf_Part_1 at Inhambupe, BA (08-COP), Botucatu, SP (10-DUB), Mogi Guaçu, SP (20-IPB) and Telêmaco Borba, PR (22-KLT) and for Leaf_Part_3 at Botucatu, SP (10-DUB), Chapadão do Sul, MS (11-FCB), and Buri, SP (33-DUR).

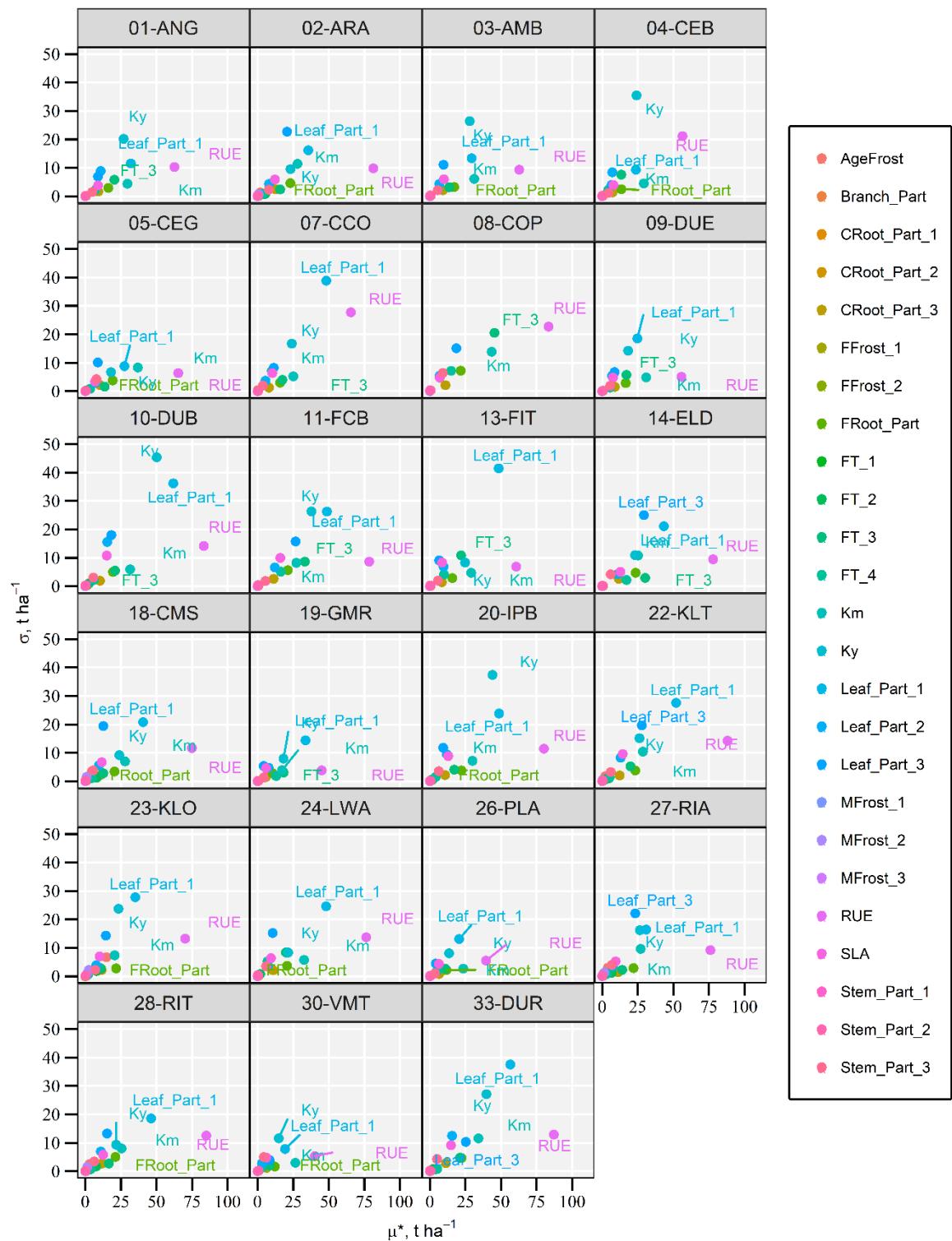


Figure 3. Level of influence (μ^*) and level of interaction and/or non-linearity (σ) of 25 parameters of the APSIM Next Generation *Eucalyptus* model to estimate stem biomass for 23 producing locations in Brazil, considering the period from 1980 to 2008.

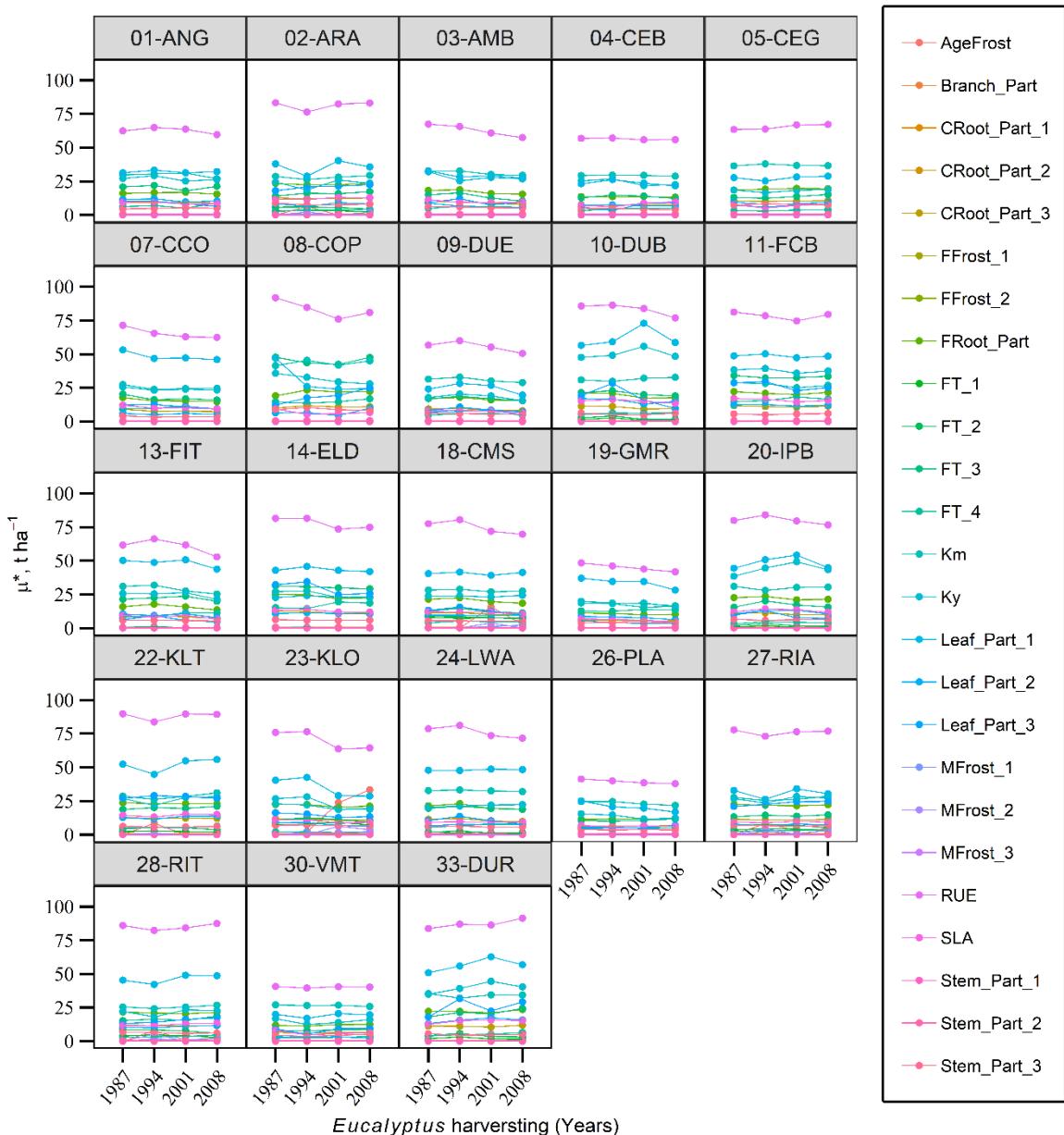


Figure 4. Effects of temporal climate variability on the level of influence (μ^*) of 25 parameters of the APSIM Next Generation *Eucalyptus* model to estimate stem biomass for 23 locations in Brazil.

6.3.3. Climate change projections and their impacts on *Eucalyptus* yield

According to the climate change projections from three global circulation models for the period from 2020 to 2049, the annual mean air temperature is expected to increase at all assessed locations (Table 2). The overall increases in air temperature for RCP4.5 and RCP8.5 will be respectively 1.3 °C and 1.6 °C, in relation to the baseline period from 1980 to 2009. Annual rainfall projections vary according to the region. In general, North and Northeast Brazil are predicted to experience decreases in annual rainfall, while the South region may have annual

rainfall increase. The Midwest and Southeast regions showed no clear trends for annual rainfall. *Eucalyptus* yield forecasts indicate a likely increase at most locations evaluated, except at Peixe, TO, for RCP8.5 and Inocência, MS, for both RCPs 4.5 and 8.5, where current mean annual temperatures are higher (24.6 °C and 27.1 °C, respectively). The average yield increment obtained for future climates was 8% for RCP4.5, ranging from -3% to 21%, and 9% for RCP8.5, ranging from -3% to 24%.

Table 2. Annual mean air temperature (Tmean), annual rainfall, and *Eucalyptus* yield (stem biomass at 7 years) changes for the future climate (2020-2049), according to the average of three global circulation models, for 23 locations in Brazil, considering intermediate (RCP4.5) and high (RCP8.5) emission scenarios. The period from 1980 to 2009 was used as baseline (Base).

Location	Tmean			Annual Rainfall			Yield	
	Base ^a	RCP 4.5	RCP 8.5	Base	RCP 4.5	RCP 8.5	Base	RCP 4.5
	----- °C -----	mm	----- % -----	t ha ⁻¹	----- % -----		RCP 8.5	
Niquelândia, GO	23.7	1.6	2.0	1569	-2	-7	158	7
Arapoti, PR	19.5	1.2	1.3	1528	3	4	203	6
Bom Despacho, MG	22.5	1.3	1.6	1417	3	-2	162	10
Belo Oriente, MG	22.3	1.2	1.5	1248	2	-3	135	20
Guanhães, MG	21.3	1.3	1.6	1259	0	-3	182	15
Rio Verde, GO	24.0	1.6	1.9	1540	3	-2	149	7
Inhambupe, BA	25.1	0.9	1.1	1068	-8	-14	144	9
Estrela do Sul, MG	23.2	1.5	1.8	1523	2	-2	153	9
Botucatu, SP	21.3	1.3	1.5	1418	1	4	197	6
Chapadão do Sul, MS	24.1	1.7	1.9	1676	1	0	184	0
Três Lagoas, MS	24.2	1.5	1.8	1245	1	0	166	4
Inocência, MS	24.6	1.6	1.9	1421	-1	-3	187	-3
São Gabriel, RS	19.2	0.9	1.1	1534	7	6	187	12
Peixe, TO	27.1	1.5	1.9	1486	-4	-12	119	2
Mogi Guaçu, SP	20.5	1.3	1.6	1537	4	1	199	7
Telêmaco Borba, PR	20.2	1.4	1.5	1554	3	5	208	4
Otacílio Costa, SC	17.4	1.1	1.2	1648	7	9	197	10
Borebi, SP	21.7	1.3	1.5	1402	1	4	195	9
Coração de Jesus, MG	23.7	1.3	1.6	1062	0	-6	110	17
Antônio Olinto, PR	18.9	1.2	1.3	1551	5	9	196	6
Três Barras, SC	19.0	1.1	1.3	1574	5	9	195	6
Bocaiúva, MG	22.5	1.3	1.5	1063	0	-4	115	21
Buri, SP	20.6	1.3	1.4	1370	2	6	194	5
South	19.0	1.1	1.3	1565	5	7	198	7
Southeast	22.0	1.3	1.6	1330	1	0	164	12
Midwest	24.1	1.6	1.9	1490	0	-2	169	3
Northeast	25.1	0.9	1.1	1068	-8	-14	144	9
North	27.1	1.5	1.9	1486	-4	-12	119	-2
Average	22.0	1.3	1.6	1421	1	0	171	8
								9

^aBaseline (base) values are given in terms of the mean values of temperature, annual rainfall and *Eucalyptus* yield (stemwood biomass) at the seventh year, while RCP4.5 and RCP8.5 are given in terms of mean increment (°C for mean air temperature and % for annual rainfall and *Eucalyptus* yield) from the baseline.

6.3.4. Influential traits under future climate scenarios

RUE, Km, Ky, FT_3 and parameters related to biomass partitioning remained the most influential parameters in most locations under climate change scenarios (Figure 5). An increased influence was observed for parameters related to the effect of temperature on photosynthesis. FT_4 became one of the five most important parameters in tropical locations such as Bom Despacho, MG (03-AMB), Chapadão do Sul, MS (11-FCB), Inocência, MS (14-ELD), Peixe, TO (19-GMR) and Coração de Jesus, MG (26-PLA). FT_3 increased its relative level of importance under climate change scenarios. For instance, in the present climate (Figure 3), FT_3 was the fifth most influential trait in Três Lagoas, MS (13-FIT), with a μ^* of 21.9 t ha⁻¹, while under the RCP8.5 (Figure 5), it was the second most important, with a μ^* of 57.0 t ha⁻¹. Similar patterns were obtained when RCP4.5 was assessed (Figure S1 in the supplementary material).

6.3.5. General ranking of influential traits under present and future climate scenarios

Considering all locations and seven-year rotations for *Eucalyptus* production, RUE, Leaf_Part_1, Km, Ky and FRoot_Part were the five most influential traits (median of μ^* above 20 t ha⁻¹) for the present climate (Figure 6). About half of the assessed parameters (13 of the 25) had little impact on yield (median of μ^* below 1 t ha⁻¹). Leaf_Part_1, Ky, Leaf_Part_3, RUE and Km were the five parameters with the highest interaction and/or non-linearity effects, with a median of σ above 6.0 t ha⁻¹. Again, 13 of the 25 parameters presented low levels of interaction and/or non-linearity effects (median of σ below 1 t ha⁻¹). When the future climate scenarios were assessed (RCP4.5 and 8.5), RUE, Leaf_Part_1, FT_3, Km and Ky were the five most influential parameters for both RCPs, with a median of μ^* above 30 t ha⁻¹ (Figure 6). Leaf_Part_1, Ky, RUE, Leaf_Part_3, Km and FT_3 were the parameters with the highest interaction level with other parameters and/or non-linearity effects (median of σ above 10.0 t ha⁻¹) for both RCPs.

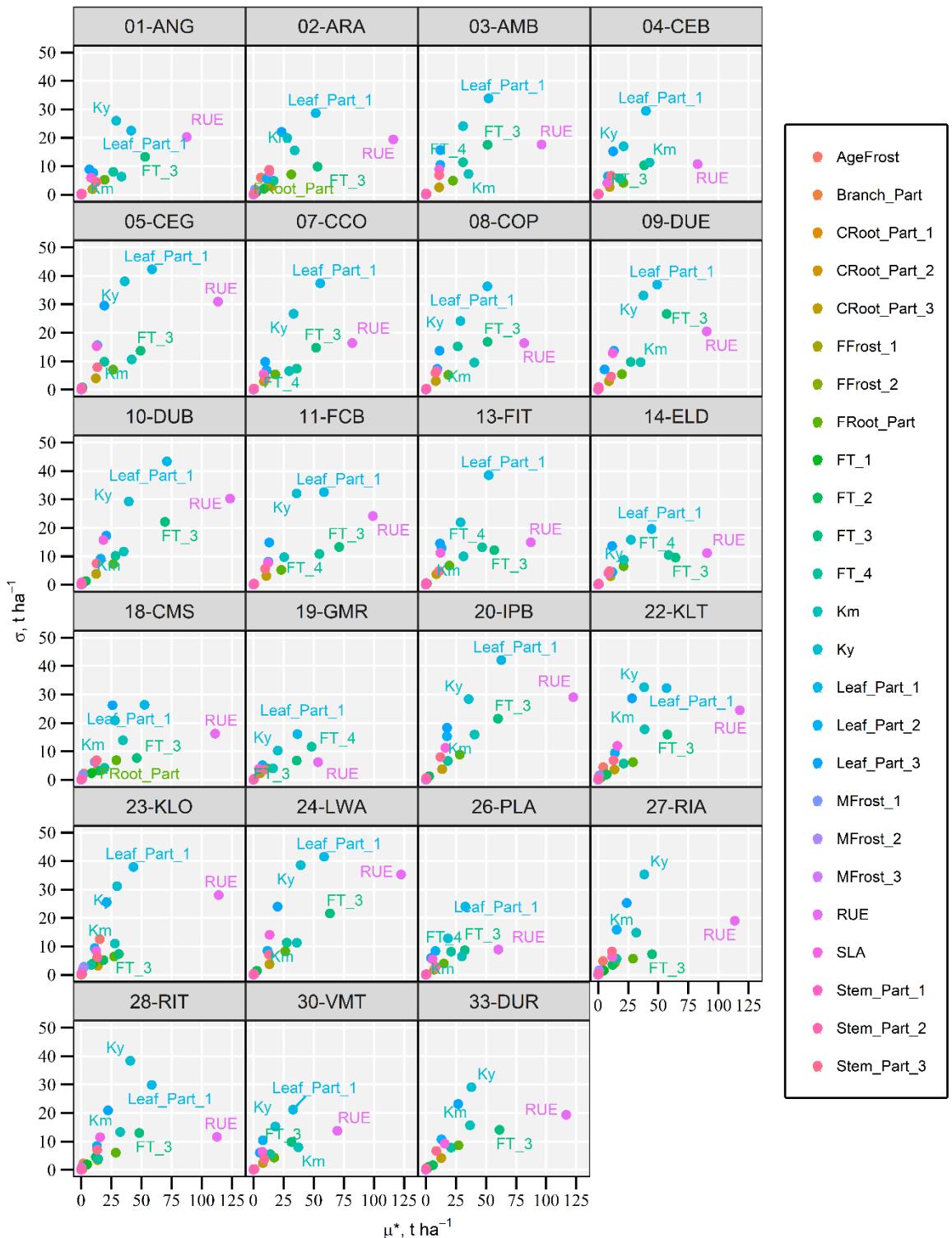


Figure 5. Level of influence (μ^*) and level of interaction and/or non-linearity (σ) of 25 parameters of the APSIM Next Generation *Eucalyptus* model to estimate stem biomass for 23 locations in Brazil, for the future climate (2020-2049), considering the average of three global circulation models, under a high emission scenario (RCP8.5).

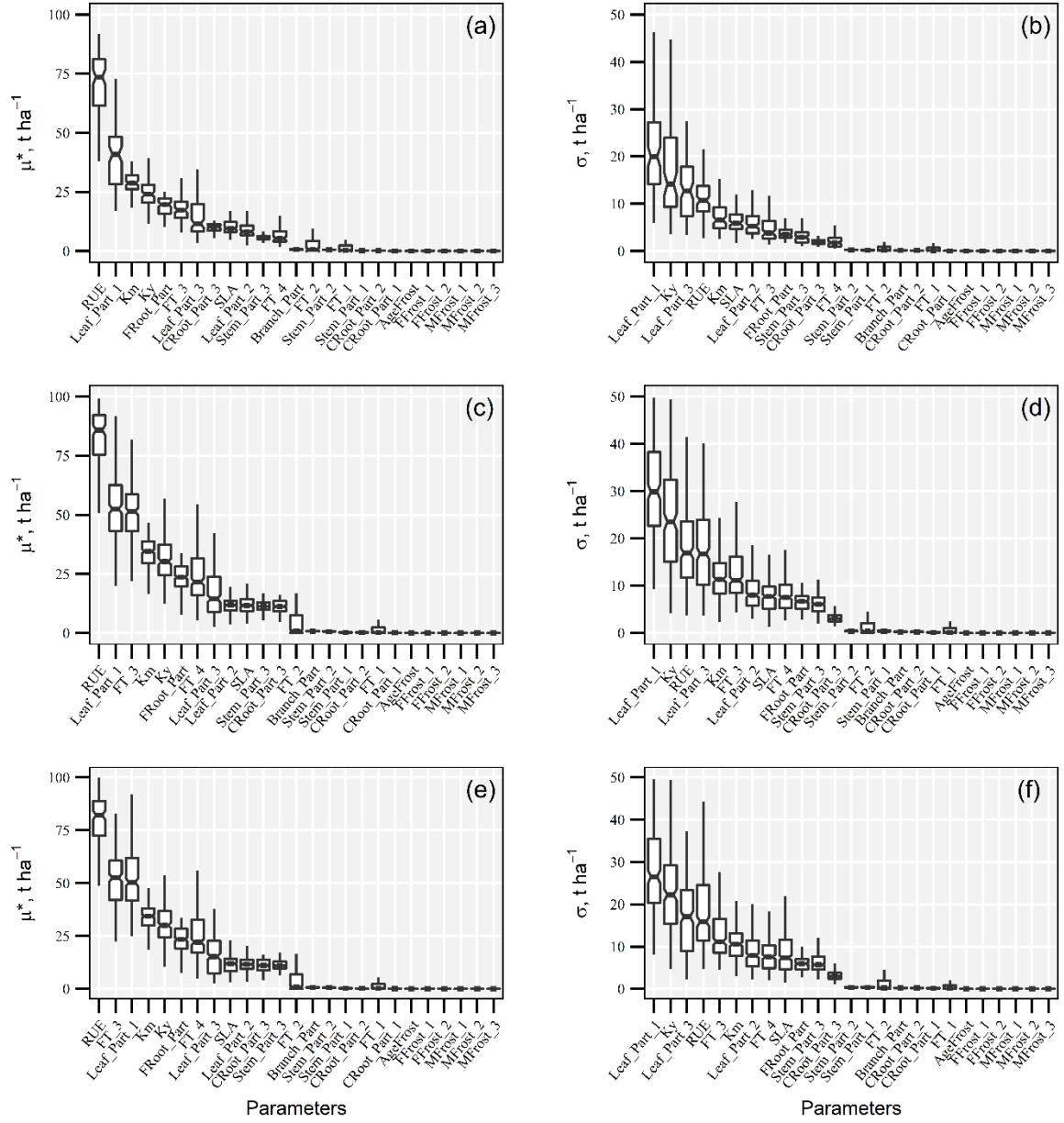


Figure 6. Level of influence (μ^*) and level of interaction and/or non-linearity (σ) of 25 parameters of the APSIM Next Generation *Eucalyptus* model to estimate stem biomass for the baseline period (a and b), and from the average of three global circulation models, considering the future period from 2020 to 2049, under intermediate (RCP4.5 – c and d) and high (RCP8.5 – e and f) emission scenarios. All *Eucalyptus* rotations and environments were considered. Parameters were sorted in descending order according to the median.

6.3.6. Spatial climate variability, climate change and their interaction with influential traits

Existing spatial climate variability in Brazil affected the level of influence of some *Eucalyptus* traits (Figure 7). In the present analysis, μ^* was divided by the stemwood biomass of each location (normalized μ^*), in order to better compare sites and climate scenarios. For

present climate conditions, no clear regional trends were observed, mainly for RUE and FRoot_Part. On average, the normalized μ^* for FT_3 was higher in Northeast (0.31), North (0.15) and Midwest (0.14) regions, than in the South (0.08) and Southeast (0.09) regions. Km presented the highest values of normalized μ^* (> 0.2) at Inhambupe, BA (08-COP), and Bom Despacho (04-CEB), Coração de Jesus (26-PLA) and Bocaiuva (30-VMT), all in the state of Minas Gerais.

The level of influence of RUE, FT_3, Km and FRoot_Part on *Eucalyptus* yield showed a tendency to increase under future climates (Figure 7). Relative increments in the level of influence for such parameters was higher in South and Southeast than in the other regions of the country. At a national level, the normalized μ^* of FT_3, RUE, FRoot_Part and Km respectively increases by 127%, 21%, 8% and 3%, under the RCP8.5, in relation to the baseline. On the other hand, frost-related traits were less influential on *Eucalyptus* yield in the subtropical sites under future climate scenarios. On average, the normalized μ^* of AgeFrost was 50% and 11% lower in the states of RS and SC, respectively, under the RCP8.5. For MFrost_2, the normalized μ^* decreased 50% in the state of Santa Catarina and become null in the states of RS and PR, under the RCP8.5 (data not presented in the spatial overview in Figure 7).

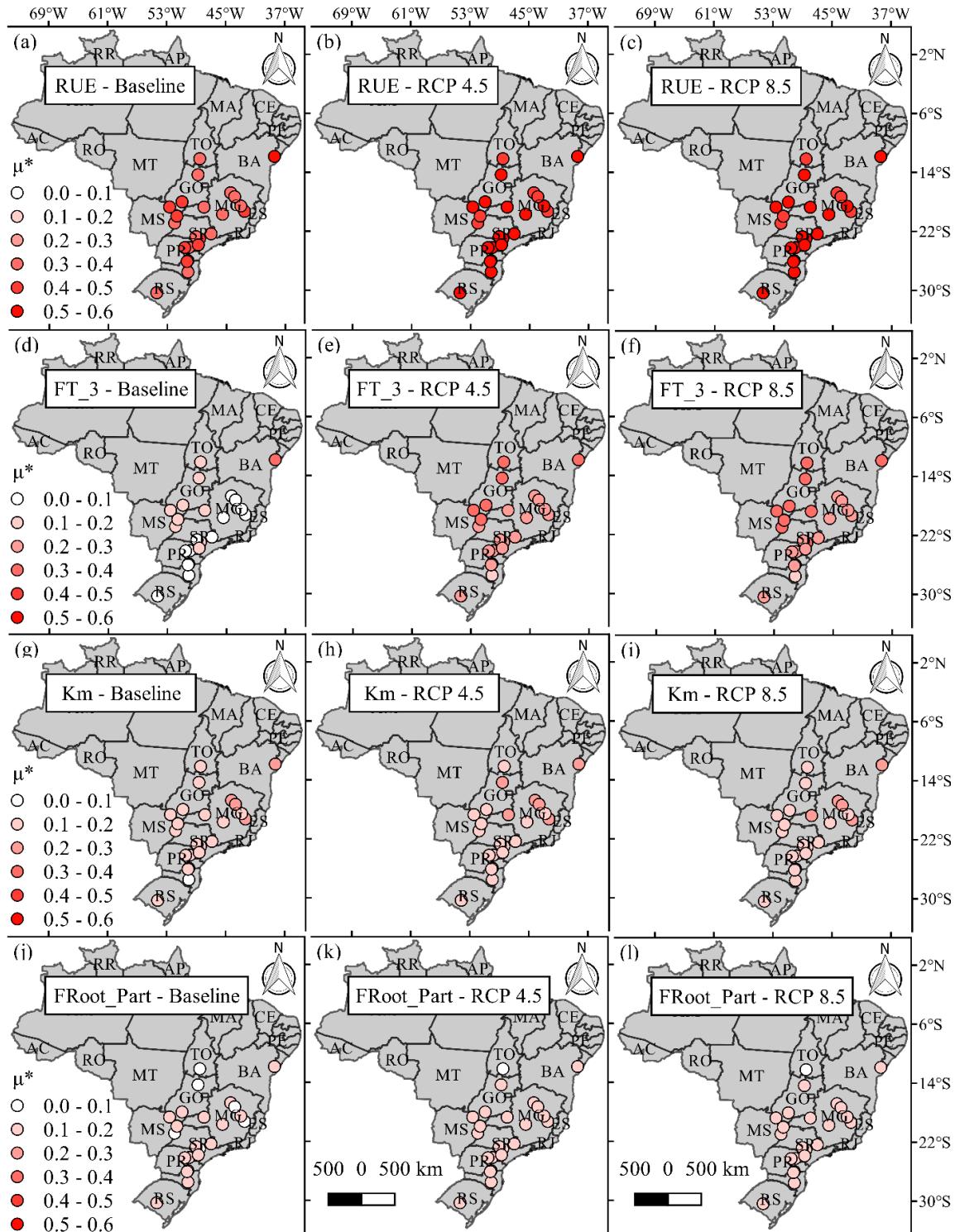


Figure 7. Effects of spatial climate variability on the level of influence (normalized μ^*) of the following parameters: RUE (a to c); FT_3 (b); Km (d to f); Km (g to i); and FRoot_Part (j to l), to estimate *Eucalyptus* stem biomass for the present (baseline) and future climates, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios.

6.4. Discussion

RUE and traits relating to canopy light interception (K_m , K_y), temperature effects on photosynthesis (FT_3) and biomass partitioning (Leaf_Part_1, Leaf_Part_3 and FRoot_Part) were the most influential in most Brazilian locations under present climate (Figure 3). Whilst this is the first application of global sensitivity analysis for the simulation of *Eucalyptus* traits under present and future climate scenarios, previous studies in other crops have found similar results. Casadebaig et al. (2016) performed a global sensitivity analysis using the APSIM-wheat model and the Morris method in four environments in Australia and found that radiation use efficiency (y_{rue}), extinction coefficient ($y_{extinct_coef}$), thermal time ($tt_{end_of_juvenile}$) and traits related to biomass partitioning (y_{frac_leaf} , and y_{frac_pod}) were among the most influential traits to this crop. Sexton et al. (2017) used the APSIM-Sugar model to perform a global sensitivity analysis in two Australian environments, and found that RUE, number of green leaves (green_leaf_no) and root conductance (K_L) were the most influential traits in both environments.

The results of the present study are also supported by other studies in the literature, showing that RUE is an important trait affecting *Eucalyptus* yield (Binkley et al., 2010; le Maire et al., 2013), which indicates that special attention should be given to such trait in the breeding programs. Plant architecture and leaf area distribution are also important features affecting the amount of light absorbed (Larsen and Kershaw, 1996) and therefore *Eucalyptus* productivity, which justifies the high levels of influence of K_m and K_y on *Eucalyptus* stemwood biomass found in the present study. Similarly, Mattos et al. (2020) evaluated the wood growth, canopy structure and light use efficiency in 18 *Eucalyptus* clones in Brazil and found that leaf angle distribution may be an important factor that affects the amount of intercepted solar radiation and, consequently, *Eucalyptus* productivity.

FT_3 was among the most influential parameters in all assessed locations in the present study (Figure 3). This parameter defines photosynthetic responses to temperature in the APSIM Next Generation *Eucalyptus* model. Our results suggest the use of genotypes with suitable cardinal temperatures for a given environment may substantially increase stem wood yield. This is supported by findings of Binkley et al. (2017), who evaluated the yield of 18 *Eucalyptus* clones across 27 locations in Brazil and found different patterns of yield response among the clones to mean annual temperature and annual rainfall. These authors also concluded that overall patterns of stem production varied strongly among clones within sites and across them.

Leaf_Part_1 was the most influential parameter related to biomass partitioning and presented the highest levels of parameter interaction for most locations (Figure 3). The results

in the present study agree with those of Campoe et al. (2012), who evaluated stand-level patterns of carbon fluxes and partitioning in *Eucalyptus grandis* plantations in Brazil, and found that carbon partitioning to the leaf was significantly correlated with gross primary production. Similarly, Forrester et al. (2012) found that periodic annual volume increment was strongly correlated with leaf area index (LAI) in *Eucalyptus nitens* plantations in Australia. Whilst a reduction of the leaf partitioning may increase the amount of biomass partitioned to the stem, it may also decrease the forest growth rate due to reduced photosynthesis. However, partitioning patterns also may be affected by biotic and abiotic factors, silvicultural management practices as well as the responsiveness of a given genotype to environmental stresses.

Variations in μ^* among the different simulated rotations were found (Figure 4). This suggests the temporal climate variability affects the influence of some traits on *Eucalyptus* yield. This highlights the need to consider not only large-scale spatial variability when evaluating potential traits, but also the impact of seasonal climate variability at each location and the need for repeated sampling of climate records when undertaking sensitivity analyses. These results are supported by Sexton et al. (2017), who identified an inter-annual variability in sensitivity indexes on sugarcane biomass and sucrose yield using the APSIM-Sugar model. These authors also found the level of inter-annual variability varied according to the environment. The effects of temporal climate variability on μ^* of some traits found in the present study are mostly related to the inter-annual and inter-seasonal rainfall variability, mainly in the center-north region of the country. In Southern Brazil, where meteorological frost days are frequent (Alvares et al., 2018), frost-related parameters became more important compared to the other regions. Clear differences in such parameters were found among the rotations, as can be observed in Otacílio Costa, SC, for AgeFrost (Figure 4).

According to the climate change projections for the period 2020-2049, the annual mean air temperature will increase at all assessed locations, while the future annual rainfall change will vary according to the region (Table 2). These results agree with those found by Bender and Sentelhas, (2018) for Brazilian conditions. These authors used seven GCMs to project climate change scenarios for 31 locations in Brazil. They found that South region will mostly experience increases in annual rainfall and the North and Northeast regions will experience decreases. These authors projected mean temperature increments of 1.9 °C and 2.63 °C for RCP4.5 and 8.5, respectively, considering the future period from 2040-2069. These values are slightly higher than those found in the present study (1.60 °C and 1.90 °C for RCP4.5 and 8.5), which are justified by the different future periods evaluated, since we used the period from 2020-2049.

The *Eucalyptus* plantations in Brazil will experience increases in stemwood biomass in most of the locations evaluated in center-south Brazil under future climates (Table 2), which is mostly explained by the increased atmospheric CO₂ concentration (Almeida et al., 2009). The average yield increments for RCP4.5 were 8%, ranging from -3% to 21%, while for RCP8.5 it was 9%, ranging from -3% to 24%. Similarly, Pinkard et al. (2010) assessed the *Eucalyptus* productivity (stemwood volume) under current and future climates from six locations in Australia, using two GCM (CSIRO-Mk3 and Hadley-Mk2) for period from 2015 to 2044, and the process-based model CABALA (Battaglia et al., 2004). Pinkard et al. (2010) applied the A2 emission scenario to the CSIRO-Mk3 GCM, and the A1FI emission scenario to the Hadley-Mk2 GCM. The CO₂ concentration of 450 ppm was used for both scenarios. These authors found that average yield will increment by 20.6%, ranging from 11.2% to 30.4% for the scenario generated by GCM CSIRO-Mk3-A2, and 6.9%, ranging from -5.5 to 23.9% when using GCM Hadley-Mk2-AiFI. On average, the yield increment found by these authors was 13.8%, similar to the results found in the present study.

Similar results were found by Almeida et al. (2009), who used the 3PG process-based model to quantify the spatial variation of *Eucalyptus* productivity under climate change scenarios across about 32 million ha located near the Atlantic coast of Brazil (covering parts of the states of Espírito Santo, Bahia, Rio de Janeiro, and Minas Gerais). The GCM CSIRO Mark 3.0 climate model was used to project climate changes for the 30-year period centred on 2030. The A1B emission scenario was considered, using a CO₂ concentration of 450 ppm. These authors suggested an average increase of 17% in mean annual stem biomass increment, a similar result compared to our findings from the same region, which was about 15% for RCP4.5 and 16% for RCP8.5, considering the average of the results from Belo Oriente, MG, Guanhães, MG, and Inhambupe, BA. *Eucalyptus* yield forecasts indicate a likely slight decrease at the tropical locations of Peixe, TO, and Inocência, MS. The reason is that positive effects of CO₂ fertilization will not be able to offset the negative impacts of high temperatures and water deficit, which is consistent with the findings of Booth (2013).

RUE, Km, Ky and parameters related to biomass partitioning (Leaf_Part_1, Leaf_Part_3 and FRoot_Part) remained among the most influential parameters under climate change scenarios (Figures 5 and 6). On the other hand, traits related to cardinal temperatures became more important when future climates were assessed, mainly the traits FT_3 and FT_4. The use of genotypes adapted to higher temperatures may be a potential strategy to mitigate climate change impacts, mainly for *Eucalyptus* plantations in tropical sites. In Brazil, the expansion of planted forests to tropical states such as Mato Grosso do Sul (MS) and Tocantins, and even in

the equatorial states of Maranhão and Piauí (Gonçalves et al., 2017), make the choice of genetic materials with tolerance to higher temperatures and water deficit an important challenge, since the *Eucalyptus* yield in such regions is lower than in the subtropical traditional regions, as presented in Table 2.

Effects of the spatial climate variability on the influential level of some traits are shown in Figure 7. No clear regional trends were observed, mainly for RUE and FRoot_Part. Besides that, no well-defined relationships between the normalized μ^* and climate variables (e.g., annual rainfall, temperature, reference evapotranspiration, CMI) were found (data not shown). This may be related, in part, to the site-specific physical and hydraulic soil properties used during the process-based simulations with soil water holding capacity highly variable among the sites (0.70 mm cm^{-1} to 1.25 mm cm^{-1}). Our results provide directions of important traits that may offer strategies for *Eucalyptus* adaptation to climate variability and change. Therefore, *Eucalyptus* straightforward research programs, dealing together with breeding, management and ecophysiology, could give special attention to such traits in order to select superior clones and matching them with better sites for obtaining higher sustainable productivities at the present and in the future climates.

6.5. Conclusions

Global sensitivity analysis was found to be a powerful tool for identifying suitable *Eucalyptus* traits for adaptation to climate variability and change. This approach can improve breeding strategies by better understanding the gene x environment interactions for yield. Traits for radiation use efficiency, leaf partitioning, canopy light capture, and fine root partitioning were the most important, impacting the *Eucalyptus* yield substantially in all environments under the present climate. The *Eucalyptus* yield under climate change scenarios showed results in agreement with those found in the literature, which make the APSIM Next Generation *Eucalyptus* model able to perform future climate assessments to different approaches. Some of the traits targeted now by breeders for current climate will remain important under future climates. However, breeding should place a greater emphasis on temperature response for *Eucalyptus* in some regions.

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Supplementary material

Table S1. Locations for long-term yield simulations and sensitivity analyses and their respective soil order and summary of the weather conditions (1980 to 2009).

Code	Location, State	Soil order ^a	Tmea	Rain	RET	CMI
01-ANG	Niquelândia, GO	Oxisol	23.7	1569	1411	0.10
02-ARA	Arapoti, PR	Oxisol	19.5	1528	1059	0.31
03-AMB	Bom Despacho, MG	Oxisol	22.5	1417	1255	0.11
04-CEB	Belo Oriente, MG	Oxisol	22.3	1248	1219	0.02
05-CEG	Guanhães, MG	Oxisol	21.3	1259	1199	0.05
07-CCO	Rio Verde, GO	Entisol	24.0	1540	1335	0.13
08-COP	Inhambupe, BA	Ultisol	25.1	1068	1495	-0.29
09-DUE	Estrela do Sul, MG	Oxisol	23.2	1523	1365	0.10
10-DUB	Botucatu, SP	Oxisol	21.3	1418	1195	0.16
11-FCB	Chapadão do Sul, MS	Oxisol	24.1	1676	1331	0.21
13-FIT	Três Lagoas, MS	Oxisol	24.2	1245	1399	-0.11
14-ELD	Inocência, MS	Entisol	24.6	1421	1405	0.01
18-CMS	São Gabriel, RS	Oxisol	19.2	1534	1119	0.27
19-GMR	Peixe, TO	Entisol	27.1	1486	1475	0.01
20-IPB	Mogi Guaçu, SP	Oxisol	20.5	1537	1123	0.27
22-KLT	Telêmaco Borba, PR	Oxisol	20.2	1554	1111	0.29
23-KLO	Otacílio Costa, SC	Incept.	17.4	1648	987	0.40
24-LWA	Borebi, SP	Entisol	21.7	1402	1249	0.11
26-PLA	Coração de Jesus, MG	Oxisol	23.7	1062	1446	-0.27
27-RIA	Antônio Olinto, PR	Ultisol	18.9	1551	1004	0.35
28-RIT	Três Barras, SC	Oxisol	19.0	1574	1003	0.36
30-VMT	Bocaiúva, MG	Oxisol	22.5	1063	1343	-0.21
33-DUR	Buri, SP	Oxisol	20.6	1370	1098	0.20

^a Soil order was reported by forestry companies, classified from US Soil Taxonomy (Soil Survey Staff, 2014); Tmea = mean air temperature, in °C; Rain = accumulated annual rainfall, in mm; RET = accumulated annual reference evapotranspiration, which is calculated from Allen et al. (1998) approach and CMI = climate moisture index (Willmott and Feddema, 1992), which is calculated as follows: when Rain < RET, CMI = (Rain/RET) - 1; when Rain ≥ RET, CMI = 1 - (RET/Rain). Positive values of CMI represent wetter climates, while negative values represent drier climates.

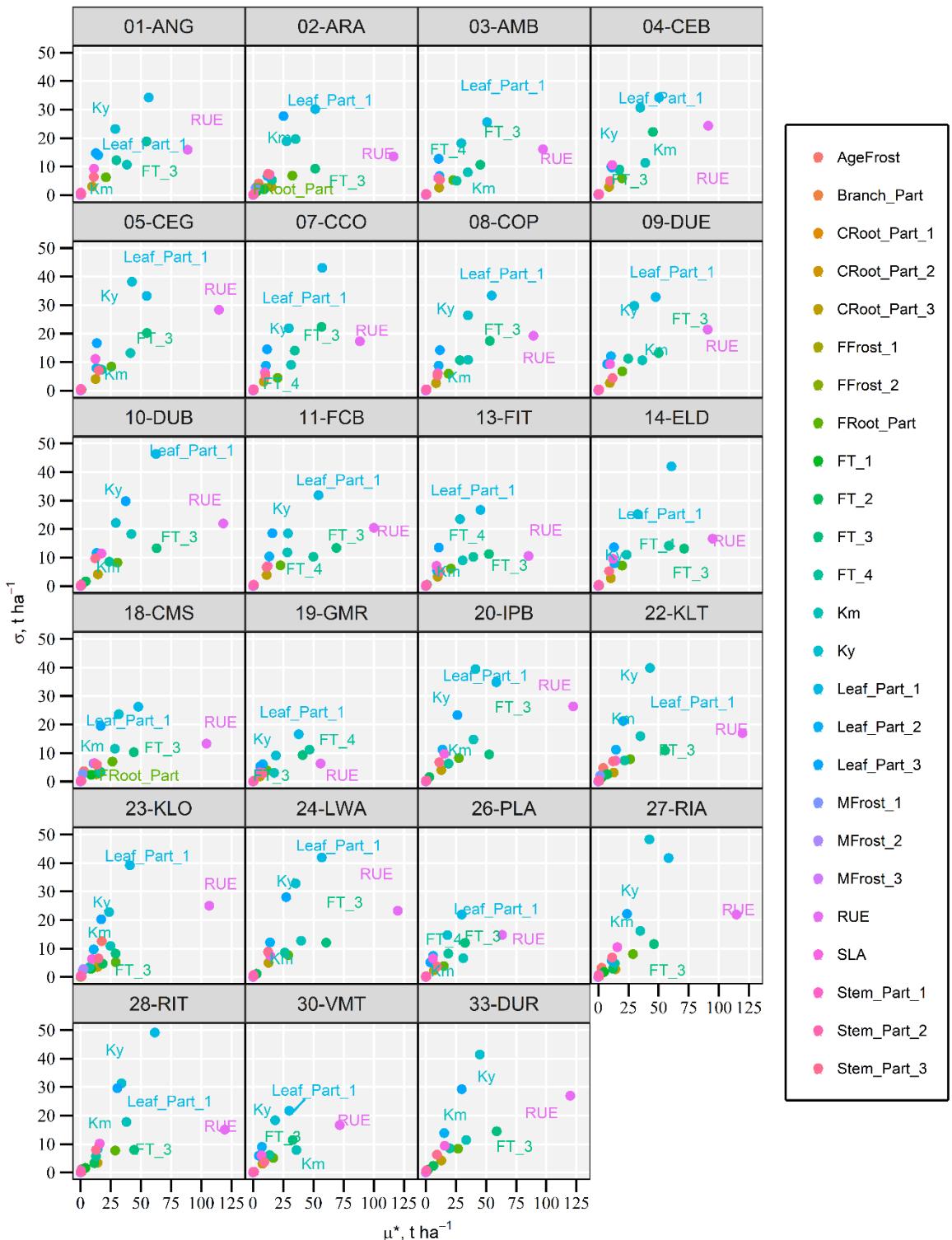


Figure S1. Level of influence (μ^*) and level of interaction and/or non-linearity (σ) of 25 parameters of the APSIM Next Generation *Eucalyptus* model to estimate stem biomass for 23 locations in Brazil, for the future climate (2020-2049), considering the average of three global circulation models, under a high emission scenario (RCP4.5).

References for supplementary material

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7. SUSCEPTIBILITY OF *EUCALYPTUS* PLANTATIONS TO FUTURE CLIMATE SCENARIOS ACROSS A GEOGRAPHIC GRADIENT IN BRAZIL

Abstract

Eucalyptus is the world's most planted hardwood tree. Concerns about potential impacts and uncertainties of climate change on *Eucalyptus* plantations productivity are arising and studies about that are still scarce. This study assesses the effects of climate change on *Eucalyptus* plantations productivity across a geographic gradient in Brazil by mid- and end-century and quantifies the uncertainty of climate and productivity projections. Ten global circulation models (GCM) under intermediate (RCP4.5) and high (RCP8.5) greenhouse gas emission scenarios, for the 2040-2069 and 2070-2099 periods were used for future climate projections. The APSIM Next Generation *Eucalyptus* model was used to simulate the *Eucalyptus* mean annual increment (MAI, $m^3 \text{ ha}^{-1} \text{ yr}^{-1}$) at seven years for eight locations in Brazil. The response of *Eucalyptus* productivity is expected to be site-specific and will mostly depend on the balance between the possible negative effects of increasing temperatures and the potential productivity increments caused by higher CO₂ concentration. Plantations located in South and Southeast Brazil are expected to experience increases in MAI, while those located in Center-North Brazil will experience more pronounced MAI reductions. Uncertainties in projections are higher under RCP8.5 and for the end-of-century, especially for annual rainfall and MAI. Future climate projections from GCMs coupled with a *Eucalyptus* simulation model provide valuable information to facilitate the exploration of potential strategies and guidance of policy decision-making for forestry adaptation to climate change on a regional or national scale. However, forest companies and foresters should be cautious when using projected information for local-scale adaptation options, as the uncertainties in climate (especially in rainfall) and productivity projections are substantially large.

Keywords: APSIM *Eucalyptus* model, climate change uncertainties, temperature stresses, global circulation models, *Eucalyptus* productivity.

7.1. Introduction

Brazil is the world's largest *Eucalyptus* producer, with a cultivated area of about 7.5 million hectares (IBGE, 2018) and an average stemwood mean annual increment (MAI) of around 36 $m^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (IBÁ, 2019). *Eucalyptus* MAI is affected by climate, genetic and management factors (Binkley et al., 2017; Elli et al., 2019a, 2017; Gonçalves et al., 2004; Ryan et al., 2010;

Scolforo et al., 2019b, 2017; Sentelhas et al., 2017; Stape et al., 2010); however, the climate is the only factor that foresters have little or no control. Thus, concerns about climate change impacts and their uncertainties on *Eucalyptus* productivity have been raised (Almeida et al., 2009; Booth, 2013). Atmospheric CO₂ concentration has increased from pre-industrial levels of 280 ppm to a current level of about 408 ppm and is continuing to rise at about 2 ppm yr⁻¹ (NOAA, 2019). Increases of 1 °C in global average temperature have been observed compared to pre-industrial levels, with a projection to reach 1.5 °C between 2030 and 2052 if the current rate remains (IPCC, 2018).

One of the best ways to assess the effects of future climates on forest productivity is by combining process-based simulation models with future climate projections generated by global circulation models – GCMs (Almeida et al., 2009; Battaglia et al., 2009; Pinkard et al., 2010). GCMs from the Coupled Model Intercomparison Project, Phase 5 - CMIP5 (Taylor et al., 2012) are currently the most used for projecting future climates. As GCMs are highly complex and present many uncertainties in the predicted climate variables due to their structural differences (Corbeels et al., 2018; Mearns, 2010; Torres and Marengo, 2013), studies using multi-GCM ensembles have been used to cover the range of possible outcomes and then to address and quantify the potential uncertainties in future climate projections (Bender and Sentelhas, 2018; Torres and Marengo, 2013; Zhang et al., 2019).

Studies about climate change impacts on *Eucalyptus* plantations productivity are still scarce. Almeida et al. (2009) assessed the spatial variation of *Eucalyptus* MAI under future climates across an area close to the Atlantic coast of Brazil, covering parts of Espírito Santo, Bahia, Rio de Janeiro, and Minas Gerais states, and obtained an average increase of 17% in stemwood biomass production. Pinkard et al. (2010) assessed the *Eucalyptus* stemwood volume under future climates for six locations in Australia and observed average yield changes ranging from -5.5% to +30.4%, depending on the location and climate scenario. While, Ellsworth et al. (2017), in a study also conducted in Australia, found that elevated CO₂ concentration does not increase *Eucalyptus* productivity on soils where phosphorus is limited.

Increased CO₂ tends to rise the photosynthetic rate, especially in C3 plants (Ainsworth and Long, 2004; Ainsworth and Rogers, 2007), such as *Eucalyptus*. Furthermore, higher CO₂ concentration may cause a partial stomatal closure and, consequently, a reduction of stomatal conductance and transpiration, resulting in higher water use efficiency by plants (Ainsworth and Long, 2004; Ainsworth and Rogers, 2007). On the other hand, higher temperatures may increase physiological stresses on *Eucalyptus* plantations (Battaglia et al., 1996), mainly in tropical regions, where rising temperatures increase the vapour pressure deficit (VPD), leading

to increments on potential evapotranspiration and, consequently, water deficit (Jalota et al., 2018; Pan et al., 2015). Booth (2013) highlighted that impacts of climate change on *Eucalyptus* productivity may be site-specific and depend, in part, on the balance between the possible negative effects of increased temperatures and rainfall declines and the potential productivity increments caused by elevated CO₂ concentration.

In this context, the following hypothesis was established: Brazilian *Eucalyptus* plantations will experience regional impacts on productivity as a response to climate change, and the uncertainties associated to climate and productivity projections may be substantially high. Based on that, the aim of this study was to assess the effects of climate change on *Eucalyptus* plantations productivity, as well as the uncertainties associated to the climate projections, by using the APSIM Next Generation *Eucalyptus* model, in eight Brazilian producing sites, considering an ensemble of ten GCMs on mid- and end-of-century periods, under high and intermediate emission scenarios.

7.2. Material and methods

7.2.1. Process-based *Eucalyptus* model

The APSIM Next Generation *Eucalyptus* model was used to perform simulations of stemwood mean annual increment (MAI, m³ ha⁻¹ yr⁻¹) at 7 years-old. APSIM *Eucalyptus* model calculates daily biomass production from intercepted solar radiation and radiation use efficiency (RUE). The interception of solar radiation is calculated assuming an exponential light extinction coefficient. RUE is affected by growth modifiers that account for the effects of air temperature, frost, nitrogen, vapor pressure deficit, water supply, and CO₂ concentration. CO₂ concentration also affects stomatal conductance and specific leaf area. Full model documentation is available at <https://www.apsim.info/>.

APSIM *Eucalyptus* model was adapted, calibrated and validated against measured *Eucalyptus* yield data from 23 locations in Brazil (Elli et al., 2020), covering the main Brazilian producing area, in which the plots were conducted under optimum or near optimum forest management. Model parameters for a highly productive and homeostatic Brazilian clone of *Eucalyptus urophylla* with suitability to a wide range of environments were used. Results of the model performance can be seen in Elli et al. (2020).

7.2.2. Studied environments

The simulations were performed for eight sites located in both traditional and expanding *Eucalyptus* plantation areas in Brazil, covering a latitude gradient of about 30 degrees (Figure

1 and Table S1 in the Supplementary Material). Long-term weather data (maximum, minimum and mean air temperatures, solar radiation, rainfall, relative humidity and wind speed) at a daily time-step were obtained from “Xavier” high-resolution daily gridded weather database (Xavier et al., 2016), which has been found to be suitable for replacing actual weather data for process-based modelling purposes (Battisti et al., 2018; Battisti and Sentelhas, 2019; Bender and Sentelhas, 2018; Freitas, 2018). Three standard soil types were considered for all locations, in order to take into account the effects of different soil water holding capacities (SWHC), as recommended by Battisti and Sentelhas (2019) and Dias and Sentelhas (2018): I) clay soil with high SWHC (1.52 mm cm^{-1}); II) sandy-clay soil with medium SWHC (0.97 mm cm^{-1}) and III) sandy-loam soil with low SWHC (0.60 mm cm^{-1}). An effective root depth of 3 m was considered for all locations, according to the findings of Christina et al. (2017) and Pinheiro et al. (2019). Further information about the soil profiles can be seen in the Supplementary Material (Table S2).

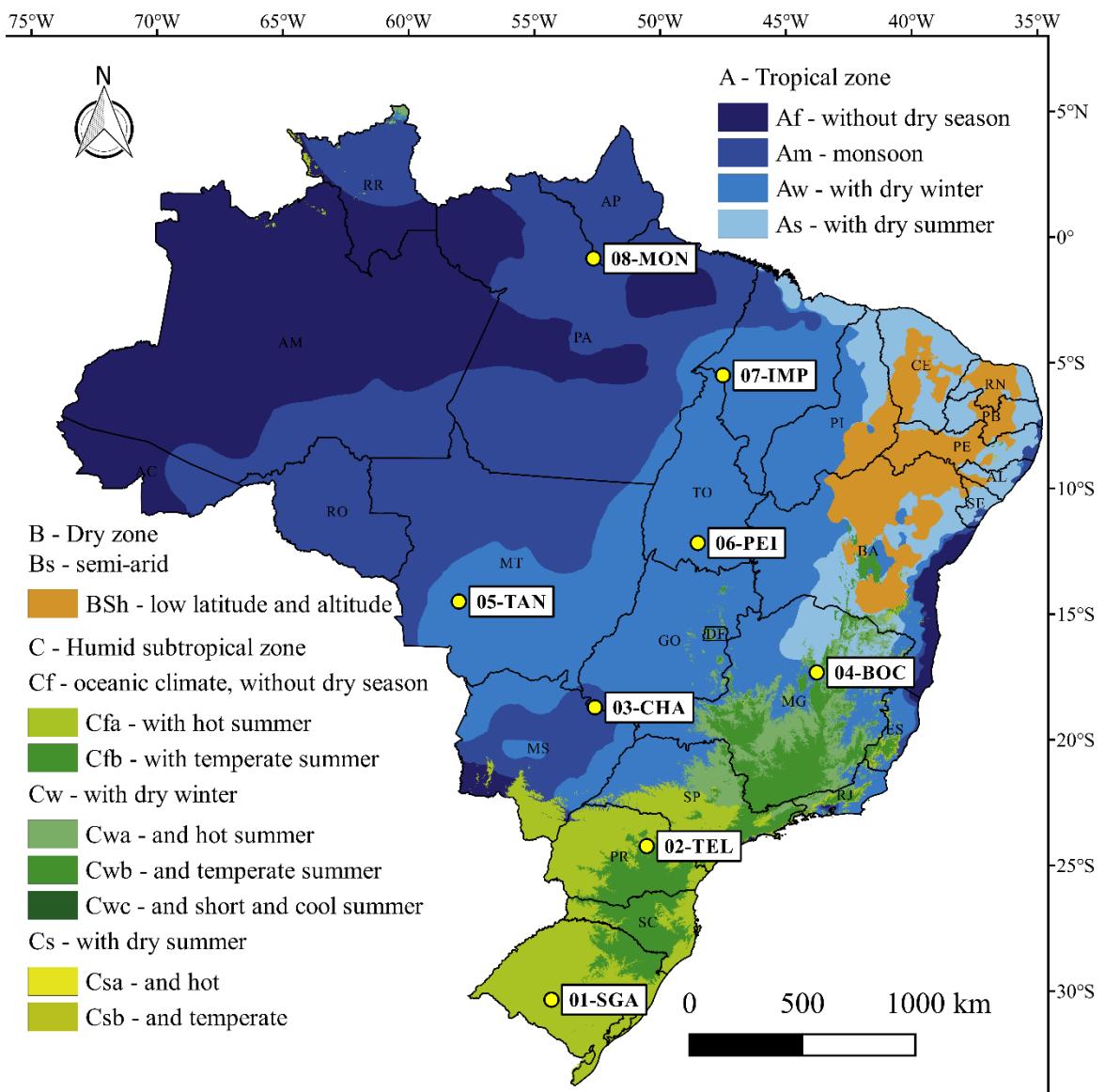


Figure 1. Locations where the long-term stemwood mean annual increment (MAI) simulations were performed and their respective Köppen climate classification in Brazil (map adapted from Alvares et al., 2013).

7.2.3. Climate change impacts

Daily weather data from 1980-2009 were used to represent the present climate (baseline). Future climates were projected using the Climate Scenario Generation Tool for R from the Agricultural Model Intercomparison and Improvement Project – AgMIP, in which mean monthly changes in maximum and minimum air temperature and rainfall were added to the baseline (Hudson and Ruane, 2013; Rosenzweig et al., 2014; Wilby et al., 2004). Solar radiation, relative humidity, and wind speed, also used by the APSIM Next Generation *Eucalyptus* model, remained unchanged. Ten global climate models (GCMs) were used to

project future climate scenarios, as follows: GISS-E2-R; CanESM2; CSIRO-Mk3-6-0; HadGEM2-CC; HadGEM2-ES; inmcm4; MIROC5; MIROC-ESM; MPI-ESM-LR; and CNRM-CM5. These models are publicly available from the Coupled Model Intercomparison Project Phase 5 – CMIP5 (Taylor et al., 2012) and were selected based on their ability to represent the spatial and temporal distribution of rainfall in different Brazilian regions (Gulizia and Camilloni, 2015; Pinheiro et al., 2014; Silveira et al., 2013; Yin et al., 2013).

Two future periods to assess climate change impacts were considered: 2040 to 2069 (mid-century) and 2070 to 2099 (end-of-century). Furthermore, two contrasting greenhouse gases emission scenarios were assessed, which follow distinct representative concentration pathways (RCPs): intermediate emission scenario (RCP4.5) and high emission scenario (RCP8.5). According to Ward et al. (2011), the RCP4.5 scenario offers the best visual match to the recent studies on future fossil fuel production, while the RCP8.5 represents more extreme conditions. The CO₂ concentrations during the simulations were set at 360 ppm for the baseline, 499 and 532 ppm for the RCP4.5, and 571 and 801 ppm for the RCP8.5 emission scenarios, respectively for mid and end-of-century. These values represent the concentration referring to the central year of the 30-year period, as recommended by AgMIP (Rosenzweig et al., 2014).

Model simulations for the baseline considered twenty-four consecutive rotations of seven-year cycles. The first simulation was performed from 15/Feb/1980 to 14/Feb/1987; the second simulation was performed from 15/Feb/1981 to 14/Feb/1988, while the last one was performed from 15/Feb/2003 to 14/Feb/2010. Similarly, for the mid-of-century, the first simulation was performed from 15/Feb/2040 to 14/Feb/2047; the second simulation was performed from 15/Feb/2041 to 14/Feb/2048, while the last one was performed from 15/Feb/2063 to 14/Feb/2070. Finally, for the end-of-century, the first simulation was performed from 15/Feb/2070 to 14/Feb/2077, the second simulation was performed from 15/Feb/2071 to 14/Feb/2078 and the last simulation was performed from 15/Feb/2093 to 14/Feb/2100. For the baseline, the total number of seven-year simulations was 192 (24 rotations × 8 sites), while for the future climate scenarios it was 7,680 (24 rotations × 8 sites × 10 GCMs × 2 future periods × 2 RCPs).

No nutrient limitations were considered during the simulations. Therefore, MAI was only affected by solar radiation, air temperature, photoperiod, [CO₂], genotype and plant population (determining factors) and water deficit (limiting factor), being referred as attainable MAI (Elli et al., 2019a; Fischer, 2015b; Lobell et al., 2009; van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997). Annual average temperature, accumulated rainfall and attainable MAI changes in relation to the baseline (1980-2009) were analysed for the different future

periods (mid- and end-of-century) and emission scenarios (RCP4.5 and RCP8.5). The coefficients of variation from the ten GCMs were calculated in order to quantify the uncertainties in climate change projections (Asseng et al., 2013; Corbeels et al., 2018).

7.3. Results

7.3.1. Climate change projections

Projected changes in annual rainfall were highly variable depending on the GCM and the study environment (Figure 2). Variations from the different GCMs were more evident for the period 2070-2099 and for RCP8.5. Projected annual rainfall presented higher variation among GCMs than projected annual average temperature (Figure 2). Even with large variation depending on the GCM, all of them projected temperature increases under future climates. Average annual temperature increases of 8% (1.9 °C) and 10% (2.4 °C) under RCP4.5 and RCP8.5, respectively, are expected for the period 2040-2069 (Table 1). For the end-of-century (2070-2099), increases of 10% (2.4 °C) and 18% (4.4 °C) under RCP4.5 and RCP8.5, respectively, were projected.

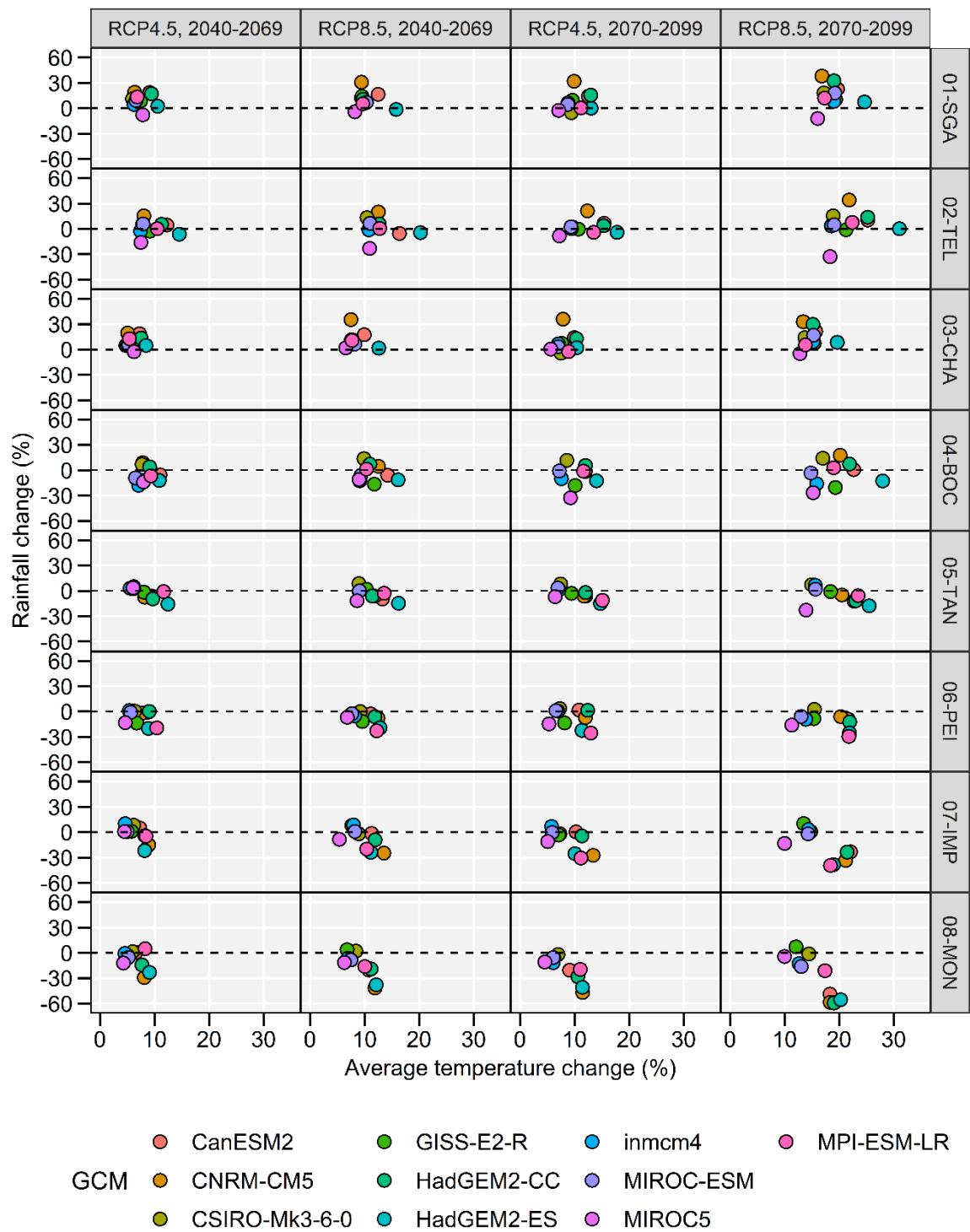


Figure 2. Annual average temperature and accumulated rainfall changes (%) in relation to the baseline (1980-2009), as an average from ten global circulation models (GCMs) for eight locations in Brazil, considering the future periods from 2040 to 2069 and from 2070 to 2099, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios.

Table 1. Changes in annual average temperature, annual rainfall, *Eucalyptus* attainable mean annual increment (MAI) at seven-years in relation to the baseline (1980-2009) and their coefficient of variation (CV) from ten global circulation models (GCMs) for eight locations in Brazil, considering the future periods from 2040 to 2069 and from 2070 to 2099, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios.

Location	Baseline	Period: 2040 - 2069				Period: 2070 - 2099				
		RCP4.5		RCP8.5		RCP4.5		RCP8.5		
		Change	CV	Change	CV	Change	CV	Change	CV	
%										
°C		Annual average temperature								
01-SGA	19.2	7.6	1.5	10.5	2.0	10.3	1.8	18.9	2.0	
02-TEL	20.2	9.6	2.2	12.9	2.7	12.1	3.0	22.2	3.3	
03-CHA	24.1	6.1	1.2	8.4	1.6	8.2	1.5	15.0	1.7	
04-BOC	22.5	8.5	1.4	11.3	2.1	10.4	2.0	19.4	3.4	
05-TAN	26.2	8.4	2.3	11.2	2.3	10.3	3.0	19.4	3.5	
06-PEI	27.1	7.4	1.8	10.2	2.0	9.4	2.6	17.7	3.6	
07-IMP	27.7	6.7	1.6	9.7	2.2	8.7	2.6	16.9	3.5	
08-MON	27.5	6.5	1.6	9.2	2.1	8.4	2.5	15.6	3.1	
Average	24.3	8	2	10	2	10	2	18	3	
mm		Annual rainfall								
01-SGA	1535	10	8	10	9	7	10	16	12	
02-TEL	1555	1	8	2	12	2	8	6	16	
03-CHA	1677	9	7	11	9	8	11	14	10	
04-BOC	1064	-6	10	-4	10	-6	14	-4	15	
05-TAN	1773	-3	7	-4	7	-4	7	-6	11	
06-PEI	1487	-7	9	-9	8	-7	12	-12	11	
07-IMP	1477	-2	10	-7	13	-10	15	-16	22	
08-MON	2229	-8	12	-16	18	-19	19	-27	35	
Average	1599	-1	9	-2	11	-4	12	-4	17	
$m^3 \text{ ha}^{-1} \text{ yr}^{-1}$		Attainable MAI at seven years								
01-SGA	63	10	2	13	3	10	2	9	5	
02-TEL	68	4	4	3	6	3	5	-5	8	
03-CHA	54	8	3	9	5	6	3	2	7	
04-BOC	47	8	6	15	8	10	9	17	11	
05-TAN	46	-6	11	-12	13	-11	15	-44	44	
06-PEI	41	-5	8	-10	11	-10	13	-44	50	
07-IMP	38	-1	10	-8	15	-9	16	-44	55	
08-MON	46	1	6	-4	10	-4	12	-27	29	
Average	50	2	6	1	9	-1	9	-17	26	

Locations 01-SGA and 02-TEL, both in Southern Brazil, and 03-CHA, in the Midwest, are expected to experience increases in annual rainfall under both RCP4.5 (from 1 to 10%) and RCP8.5 (from 2 to 11%) for the period 2040-2069 (Table 1). For the end-of-century (2070-

2099), changes are expected to range from 2% (02-TEL) to 8% (03-CHA) under RCP4.5 and from -6% (02-TEL) to 16% (01-SGA) under RCP8.5. Locations 04-BOC (Southeast), 05-TAN (Midwest), 06-PEI and 08-MON (North) and 07-IMP (Northeast) are expected to experience annual rainfall reductions. For the period 2040-2069, these reductions will range from -2% (07-IMP) to -8% (08-MON) under RCP4.5 and from -4% (04-BOC and 05-TAN) to -16% (08-MON) under RCP8.5, while for the period 2070-2099, reductions will range from -4% (05-TAN) to -19% (08-MON) under RCP4.5 and from -4% (04-BOC) to -27% (08-MON) under RCP8.5.

7.3.2. Climate change impacts on Eucalyptus plantations productivity

Simulated *Eucalyptus* plantations productivity responses to climate change strongly depends on the Brazilian region, as a result of their contrasting current climates (Table 1 and Figure 3). For the period 2040-2069, locations 01-SGA, 02-TEL, 03-CHA, 04-BOC and 08-MON are expected to experience increases of 4 to 10% and of 3 to 15% in attainable MAI under RCP4.5 and RCP8.5, respectively. For the location 08-MON, almost no changes will occur under RCP4.5 (1%) and a slight MAI reduction (-4%) is projected under RCP8.5. Locations 05-TAN, 06-PEI and 07-IMP will experience reductions in attainable MAI of -1 to -6% and of -8 to -12% under RCP4.5 and RCP8.5, respectively. For the period 2070-2099, 01-SGA, 03-CHA and 04-BOC will experience MAI increases, while 05-TAN, 06-PEI, 07-IMP and 08-MON are expected to have attainable MAI reduced under both RCP4.5 and RCP8.5. Projections for 02-TEL indicate a slight MAI increase (3%) under RCP4.5 and a slight reduction (-5%) under RCP8.5. Specific attainable MAI for the ten assessed GCMs and a spatial overview of simulated attainable MAI changes and their CVs are presented in the Supplementary Material (Figures S1 to S3).

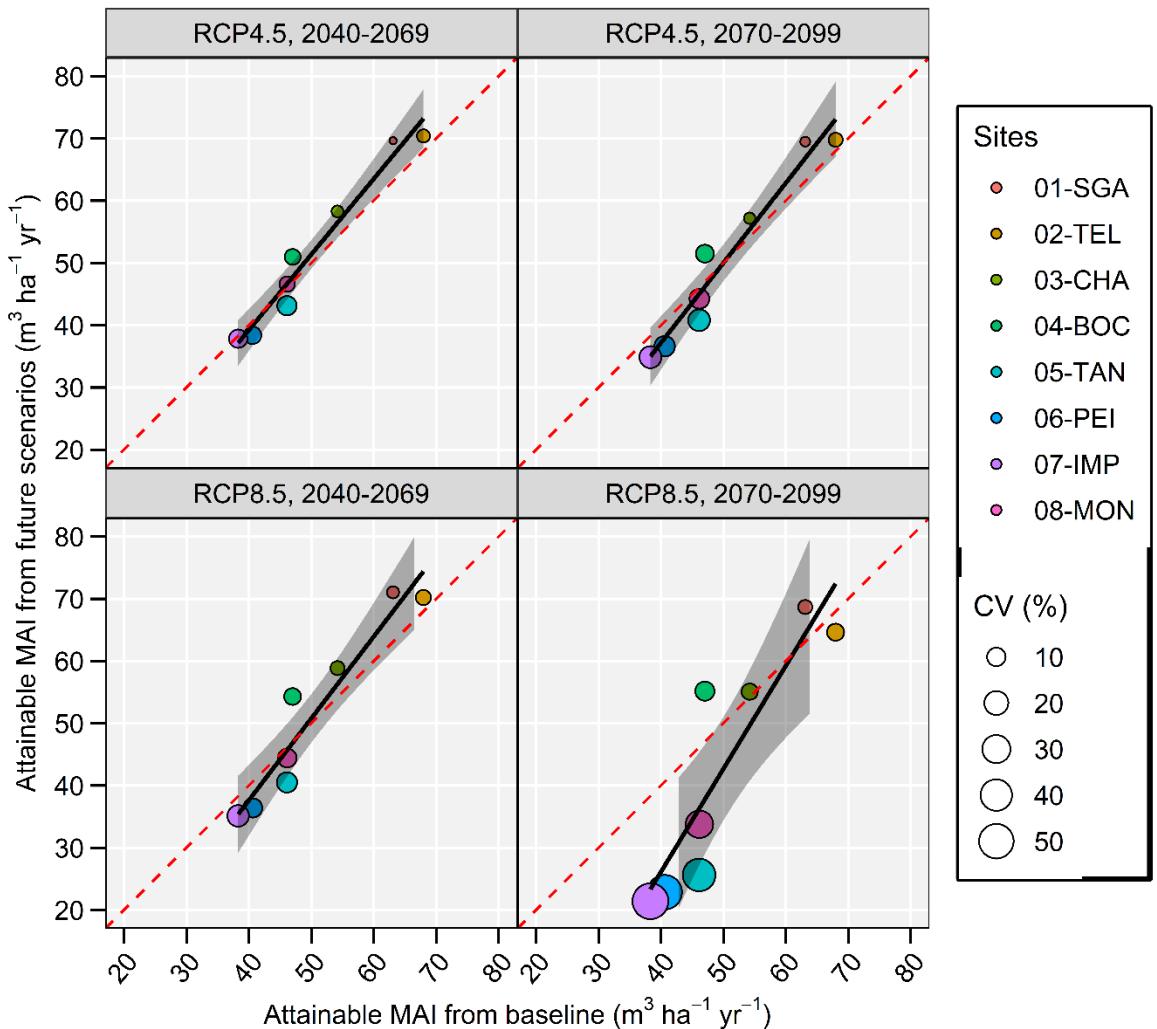


Figure 3. Relationship between the simulated attainable mean annual increment (MAI) from the baseline period and projected by an ensemble of ten global circulation models (GCMs), under RCP4.5 and RCP8.5. The colors in the circles represent the Brazilian sites evaluated, while the size of the circles indicates the coefficient of variation (CV).

7.3.3. Uncertainties in climate change projections

On average, the CVs of air temperature, rainfall and attainable MAI obtained from the ten GCMs assessed was higher under RCP8.5 and for end-of-century (Table 1 and Figure 3), especially for annual rainfall and attainable MAI, than for RCP4.5. The average CV for annual rainfall was 9% (ranging from 7 to 12%) and 11% (ranging from 7 to 18%) under RCP4.5 and RCP8.5, respectively, for the mid-century, and 12% (ranging from 7 to 19%) and 17% (ranging from 11 to 35%), in the same sequence, for the end-of-century. The CV for attainable MAI projections varied from 2% to 55%, with the average CV for 2070-2099 under RCP8.5 being

26%, almost three times the average CV for attainable MAI found under RCP4.5 (9%) for the same period.

7.3.4. Productivity x climate x ecophysiology relationships

The responses of *Eucalyptus* productivity to changes in air temperature and rainfall in the future scenarios are highly dependent on the location (Figure 4). The highest rates of change in attainable MAI in response to increasing temperature were observed for locations 05-TAN, 06-PEI, IMP-07 and 08-MON, which are expressed by the slopes of the fitted regressions of -3.55, -3.96, -4.31 and -3.16, respectively. For the sites 02-TEL, 03-CHA and 04-BOC, intermediate rates of change in attainable MAI with temperature alterations were found, with the slopes of the fitted regressions reaching -0.75, -0.72 and 0.74. Finally, location 01-SGA expressed almost no changes in attainable MAI with increasing temperature, since the regression slopes was only -0.16. Inverse trends were found for the relationship between changes in annual rainfall and attainable MAI, but with a similar pattern. Locations 05-TAN and 06-PEI presented the highest rates of change in attainable MAI with changing rainfall, while sites 01-SGA and 03-CHA had the lowest variations.

Temperature projections under high emission scenario (RCP8.5) suggest average values above 30 °C for the tropical locations, represented by 05-TAN, 06-PEI, 07-IMP and 08-MON, during the period 2070-2099, coinciding with the highest attainable MAI reductions (Figure 5). Positive MAI increments generally will occur under scenarios where the projected average temperature was lower than 27 °C. Even for the baseline, most of thermal stresses in *Eucalyptus* plantations were caused by temperatures above the optimal range for *Eucalyptus* growth, and they will become more severe in the future, especially in tropical regions (Figure 6). In addition to heat stresses, *Eucalyptus* trees will experience slight increases in VPD stresses under future climates, which is justified by the lower APSIM growth modifier for VPD (Figure S4 in Supplementary Material). The growth modifier for water deficit showed no clear trends and varied according to the environment (Figure S4 in Supplementary Material).

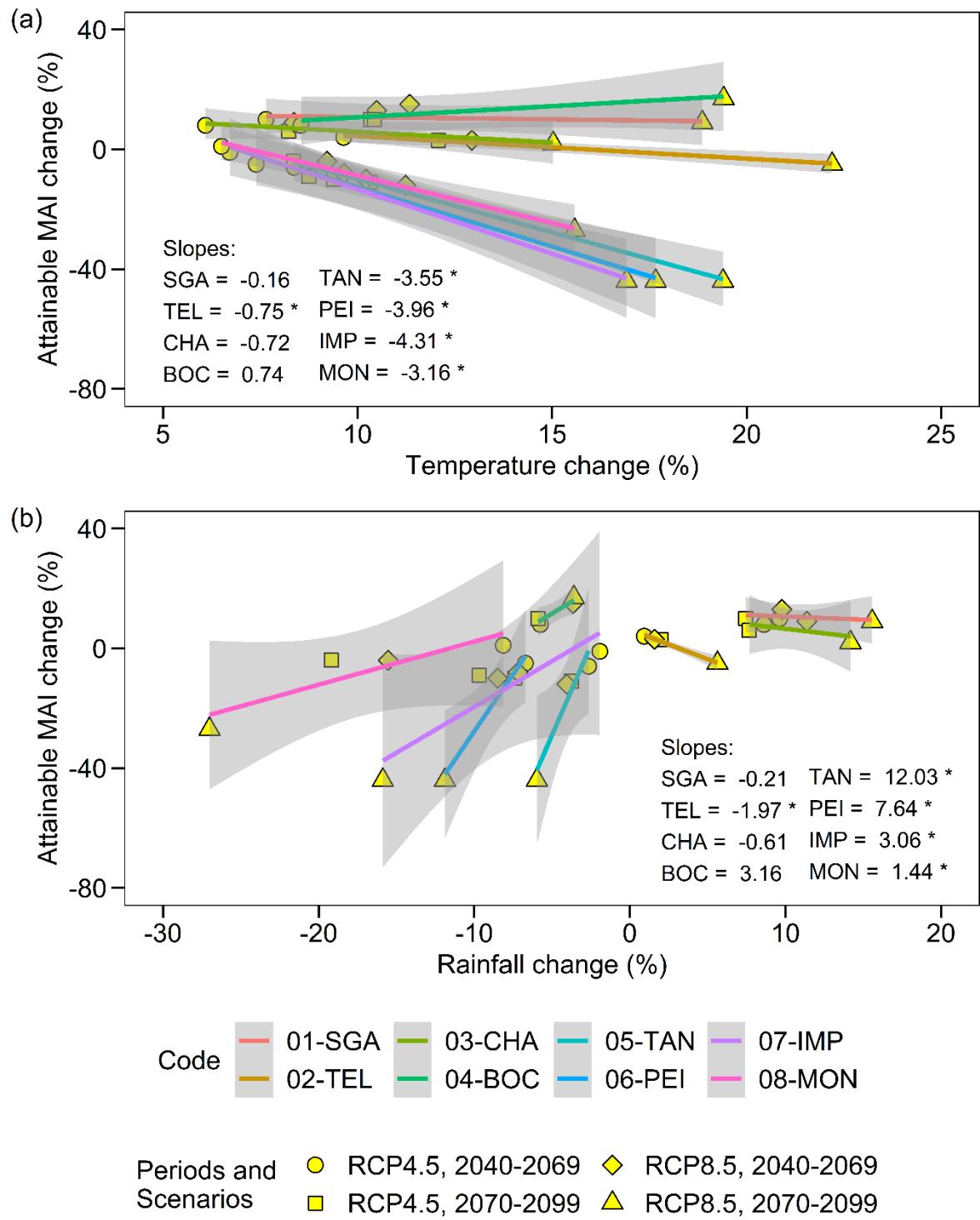


Figure 4. Relationships between changes in simulated attainable MAI and annual average temperature (a) and annual rainfall (b) for eight contrasting Brazilian locations averaged from ten global circulation models (GCMs) under two emission scenarios (RCP4.5 and RCP8.5) and two future periods (2040-2069 and 2070-2099). *Significant by t-test ($p < 0.05$).

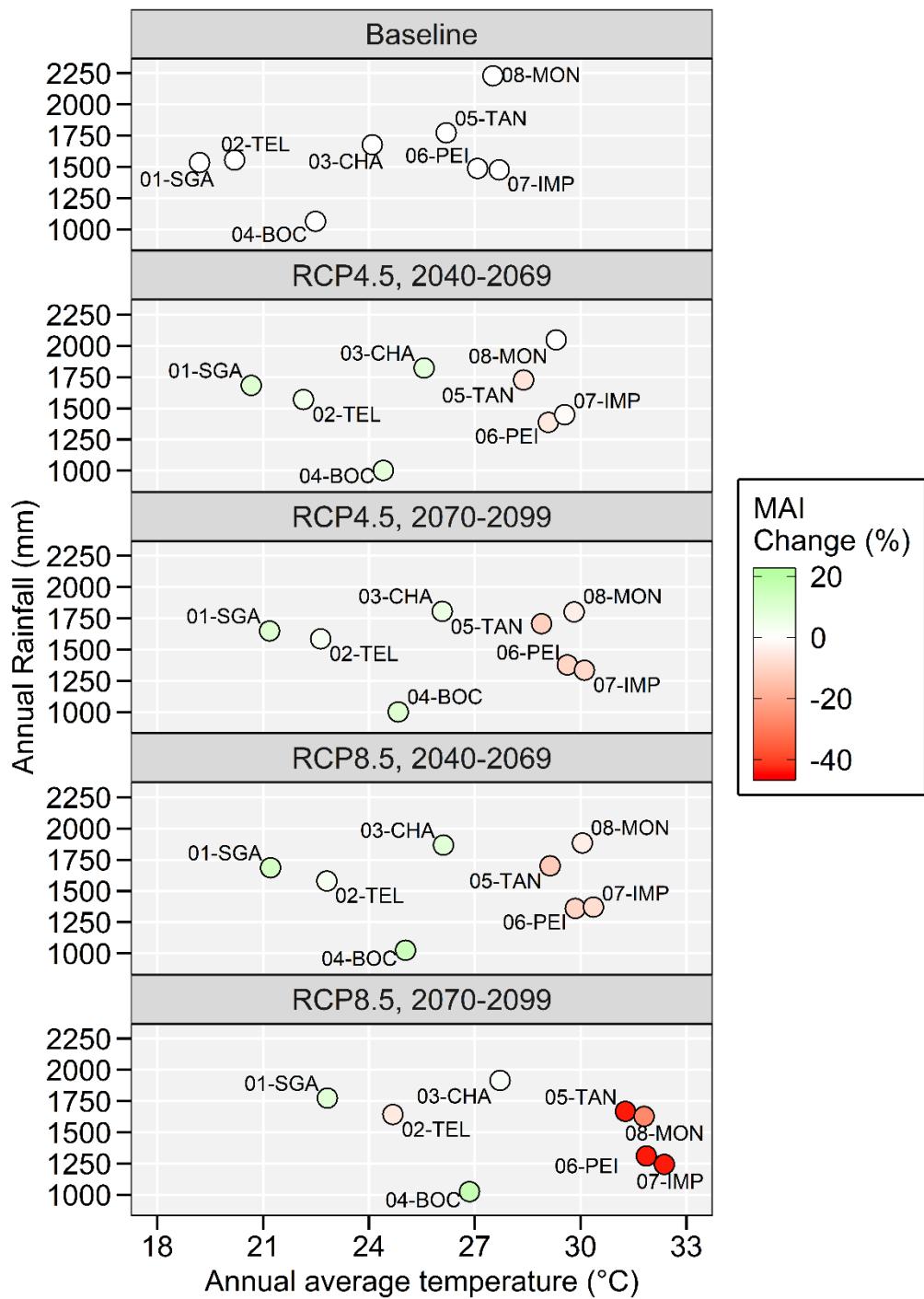


Figure 5. Annual average temperature, accumulated annual rainfall and simulated attainable mean annual increment (MAI) changes from the average of ten GCMs for eight locations in Brazil, considering the future periods from 2040 to 2069 and from 2070 to 2099, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios, considering the baseline period from 1980 to 2009.

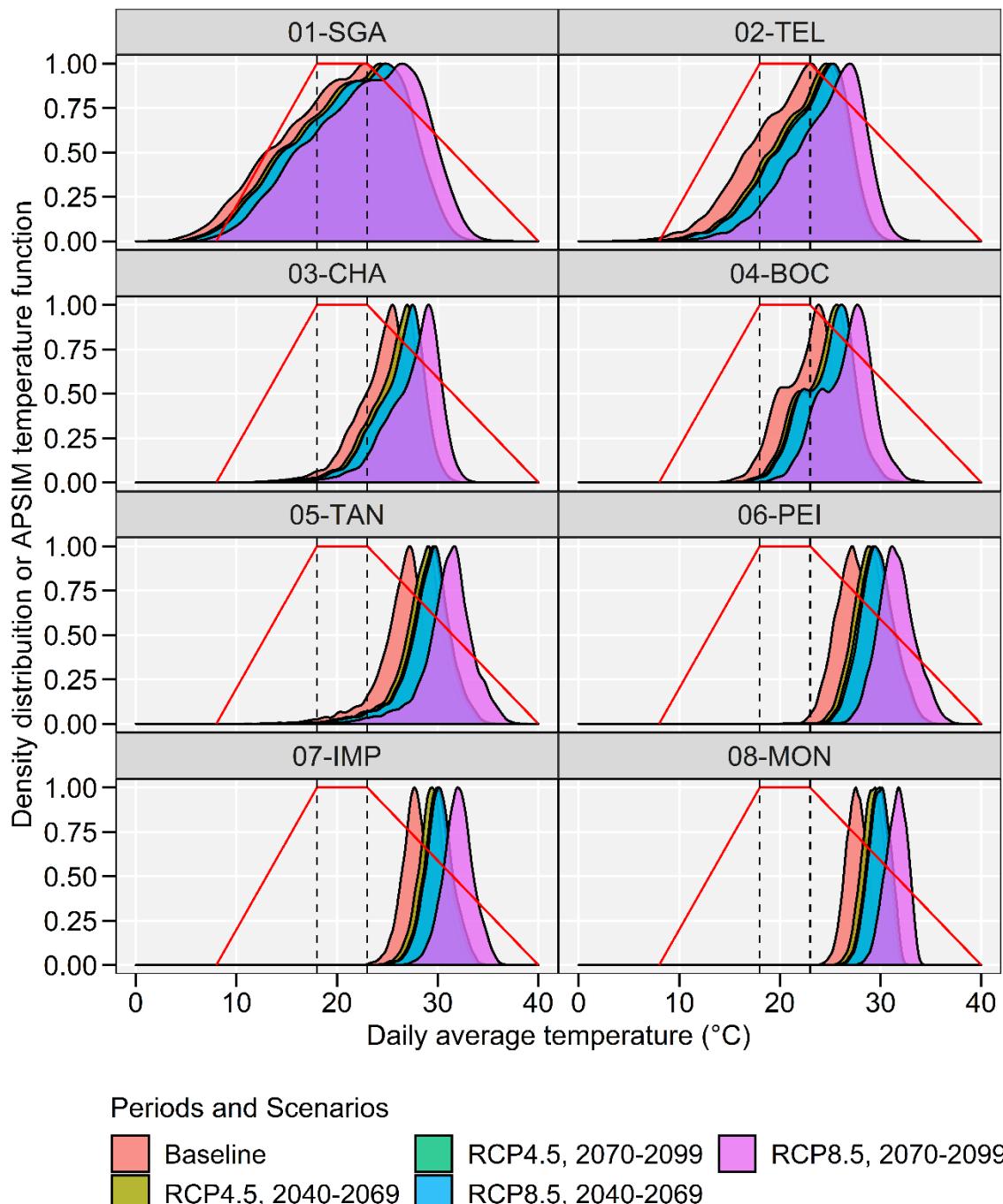


Figure 6. Density distribution (Kernel method) of daily average temperature for 30-year climatic series, considering the baseline (1980-2009) and the future periods from 2040 to 2069 and from 2070 to 2099, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios from ten global circulation models (GCMs) for eight Brazilian locations. Solid red lines indicate the growth modifier to account for the effects of air temperature on *Eucalyptus* productivity in the APSIM *Eucalyptus* model, which varies from 0 (null growth) to 1 (full growth). Dashed black lines indicate the optimum temperature range considered by the model.

7.4. Discussion

Projected changes in annual rainfall and average air temperature found in the present study (Table 1 and Figure 2) are consistent with the results found by Bender and Sentelhas (2018). These authors used seven GCMs to project climate change scenarios for thirty-one locations in Brazil and obtained average increases in annual rainfall in South region, and rainfall reductions in the North and Northeast regions. For average temperature, Bender and Sentelhas (2018) found increases ranging from 1.9 °C to 2.6 °C for the period 2040-2069, and from 2.4 °C to 4.5 °C, for the period 2070-2099, under RCP4.5 and RCP8.5, respectively, similar to what was found in the present study with ten GCMs. Moreover, the projected changes in annual rainfall and average temperature found here also agree with the results obtained by Torres and Marengo (2013), Reboita et al. (2014) and Verhage et al. (2017) for Brazilian conditions.

Simulated future *Eucalyptus* plantations productivity varied widely depending on the region (Table 1 and Figure 3). In general, sites located in South and Southeast Brazil will experience increases in *Eucalyptus* attainable MAI, while North Brazil will experience more pronounced MAI reductions. The current average temperatures in South and Southeast Brazil are relatively lower compared to other Brazilian regions; thus, future temperature rises will not strongly affect *Eucalyptus* growth, as the mean annual temperature will remain close to the optimum temperature range considered by the APSIM *Eucalyptus* model, which is from 18 to 23 °C (Figure 6). On the other hand, plantations in center-north Brazil will experience higher average temperatures in the future climates and heat stresses are expected to be higher. For these locations, potential productivity increments caused by CO₂ fertilization will be not able to offset the negative impacts of increased temperatures, which is consistent with the findings of Booth (2013).

Our results agree with those obtained by Pinkard et al. (2010), who assessed climate change impacts on *Eucalyptus* plantations productivity in six sites in Australia for the future periods of 2015-2044 and 2055-2084, using the CABALA model (Battaglia et al., 2004). These authors projected future climates by two GCMs (CSIRO-Mk3 and Hadley-Mk2). For the period 2015-2044, they obtained average yield increments of 21%, ranging from 11% to 30% according to the location when the GCM CSIRO-Mk3 was used, and of 7%, ranging from -6 to 24% when the GCM Hadley-Mk2 was considered. For the period 2055-2084, MAI increments ranged from 17 to 63% (average of 42%) using the CSIRO-Mk3 model and from 25 to 63% (average of 41%) using the Hadley-Mk2 Model. Similarly, Almeida et al. (2009) used the 3PG process-based model to assess climate change impacts on *Eucalyptus* productivity close to the Brazilian Atlantic coast, covering parts of the states of Espírito Santo, Bahia, Rio de Janeiro,

and Minas Gerais. The GCM CSIRO Mark 3.0 was used to project climate changes for the 30-year period centered on 2030. They found average increases of 17% in stem biomass increment, similar to what was found in the present study for the location 04-BOC, in the Minas Gerais state.

Large uncertainties in simulated *Eucalyptus* productivity under future climate scenarios were observed in the present study. The CVs of the attainable MAI ranged from 2% to 55% depending on the location and future scenario adopted (Table 1 and Figure 3). This is justified by the high variation of climate predictions by the GCMs (Corbeels et al., 2018; Mearns, 2010; Torres and Marengo, 2013). Rainfall projections showed a greater uncertainty compared to the temperature, and in many instances, do not even agree on whether changes will be positive or negative, which is consistent with the findings of Cooper et al. (2008). Considering that no clear positive or negative trends in projected rainfall were observed in most of the cases, productivity changes could be mostly explained by the rising temperatures (Corbeels et al., 2018).

Eucalyptus productivity responses to temperature changes for the future climate projections were highly site-specific (Figure 4a), as highlighted by Booth (2013). The rate of changes in attainable MAI were most pronounced in tropical environments, where the current Köppen climate type is As (Alvares et al., 2013), i.e. tropical with dry summer. On the other hand, the lower rates of changes in attainable MAI were obtained for locations in Southern Brazil, which comprises a subtropical zone (climates Cfa and Cfb, according to Köppen's climate classification). Temperature and vapour pressure deficit (VPD) stresses are expected to increase under future climates (Figure S4 in the Supplementary Material), which is consistent with the findings of Eamus et al. (1995), Battaglia et al. (1996) and Dong et al. (2019). In this context, *Eucalyptus* genotypes with some heat tolerance may offer improved adaptation to climate change.

Although MAI responses to rainfall changes were also significant (Figure 4b), we believe that these responses are mostly related to temperature effects, as there was no significant increase in water deficit in future climates (Figure S4 in the Supplementary Material). The MAI responses to rainfall occurred because rainfall and temperature are correlated, i.e., regions with higher temperatures commonly experience low rainfall regimes. Even in environments where rainfall reductions are expected, no increases in water deficit stresses were observed. There are some potential explanations for that: the uncertainty in projected rainfall arising from using different GCMs is large, and in many cases, no clear positive or negative trends are observed; some studied locations (e.g., 05-TAN and 08-MON) will still have good levels of annual rainfall as their current amounts are high ($>1700 \text{ mm yr}^{-1}$), and may not experience severe water deficits

in the future; despite the increased potential evapotranspiration caused by rising temperature, APSIM *Eucalyptus* model considers reductions in stomatal conductance and in specific leaf area with increasing CO₂ concentration, reducing the tree demand for water. Therefore, water deficit effects in future scenarios will depend on the balance among site-specific changes in rainfall, temperature (affecting potential evapotranspiration and VPD) and ecophysiological processes altered by future CO₂ concentration.

In addition to the uncertainties related to future climate projections, process-based models also may present sources of uncertainties with regard to the structural features, parameters, input data and CO₂ fertilization functions (Asseng et al., 2013; Corbeels et al., 2018; Tao et al., 2018). Furthermore, *Eucalyptus* genotypes may have different physiological responses to increasing atmospheric CO₂ and temperature (Battaglia et al., 1996). Despite the high uncertainty in the rainfall projections, extended periods of drought are likely to become more frequent in future climates (Marengo et al., 2007). APSIM model does not simulate the mortality processes of *Eucalyptus* plantations caused by severe drought periods, which is already observed in some tropical Brazilian regions (Scolforo et al., 2019a). Booth (2013) found that high temperatures combined with increasing water deficit may increase *Eucalyptus* drought deaths. Thus, APSIM model may be overestimating *Eucalyptus* productivity in the locations with severe water deficit (Elli et al., 2019b).

7.5. Conclusions

The present study provides some directions on how *Eucalyptus* plantations productivity may respond to climate change across contrasting environments in Brazil. The response of *Eucalyptus* productivity will be site-specific and will mostly depend on the balance between the possible negative effects of increased temperatures and the potential productivity increments caused by elevated CO₂ concentration. In general, *Eucalyptus* plantations located in South and Southeast Brazil are expected to experience increases in attainable MAI in the simulated future scenarios, while those located in Center-North Brazil will experience more pronounced MAI reductions. Future climate projections from GCMs coupled with *Eucalyptus* simulation models may provide valuable information that may facilitate the investigation of potential strategies and guidance of policy decision-making for forestry adaptation to climate change on a regional or national scale. However, forest companies and foresters should be cautious when using projected information for local-scale adaptation options, as the uncertainties in projected climate (especially in rainfall) and productivity are substantially large.

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Supplementary material

Table S1. Brazilian locations used for the long-term mean annual increment (MAI) simulations with APSIM Next Generation *Eucalyptus* model, for present and future climate scenarios.

Code	Location and State	Latitude (°)	Longitude (°)	Altitude (m)
01-SGA	São Gabriel, Rio Grande do Sul (RS)	30.3 S	54.3 W	102
02-TEL	Telêmaco Borba, Paraná (PR)	24.2 S	50.5 W	888
03-CHA	Chapadão do Sul, Mato Grosso do Sul (MS)	18.7 S	52.6 W	783
04-BOC	Bocaiúva, Minas Gerais (MG)	17.3 S	43.8 W	848
05-TAN	Tangará da Serra, Mato Grosso (MT)	14.5 S	58 W	572
06-PEI	Peixe, Tocantins (TO)	12.2 S	48.5 W	255
07-IMP	Imperatriz, Maranhão (MA)	5.5 S	47.5 W	121
08-MON	Monte Dourado, Pará (PA)	0.9 S	52.7 W	50

Table S2. Physical and hydraulic characteristics of the three soil types (clay, sandy-clay, and sandy-loam) used to perform the long-term *Eucalyptus* MAI simulations with the APSIM Next Generation model, for the present and future climate scenarios.

Depth ^a	BD ^b	LL ^c	DUL ^d	SAT ^e	SWHC ^f	KL ^g
cm	g cm ⁻³	-----	cm ³ cm ⁻³ -----	-----	mm	day ⁻¹
Clay soil with high SWHC (average ^h = 1.52 mm cm ⁻¹)						
0-15	1.440	0.027	0.102	0.420	11.250	0.070
15-30	1.460	0.020	0.070	0.410	7.500	0.070
30-60	1.460	0.020	0.070	0.410	15.000	0.070
60-90	1.530	0.021	0.090	0.394	20.700	0.060
90-120	1.570	0.030	0.080	0.360	15.000	0.040
120-150	1.570	0.030	0.092	0.350	18.600	0.030
150-180	1.570	0.031	0.092	0.350	18.300	0.030
180-210	1.570	0.031	0.092	0.350	18.300	0.030
210-300	1.570	0.031	0.092	0.350	54.900	0.020
Sandy-clay soil with medium SWHC (average = 0.97 mm cm ⁻¹)						
0-15	1.140	0.256	0.405	0.541	22.350	0.070
15-30	1.140	0.256	0.405	0.541	22.350	0.070
30-60	1.260	0.236	0.388	0.519	45.600	0.070
60-90	1.260	0.236	0.388	0.407	45.600	0.060
90-120	1.260	0.236	0.388	0.407	45.600	0.040
120-150	1.260	0.236	0.388	0.407	45.600	0.030
150-180	1.260	0.236	0.388	0.407	45.600	0.030
180-210	1.260	0.236	0.388	0.407	45.600	0.030
210-300	1.260	0.236	0.388	0.407	136.800	0.020
Sandy-loam soil with low SWHC (average = 0.60 mm cm ⁻¹)						
0-15	1.440	0.027	0.102	0.420	11.250	0.070
15-30	1.460	0.020	0.070	0.410	7.500	0.070
30-60	1.460	0.020	0.070	0.410	15.000	0.070
60-90	1.530	0.021	0.090	0.394	20.700	0.060
90-120	1.570	0.030	0.080	0.360	15.000	0.040
120-150	1.570	0.030	0.092	0.350	18.600	0.030
150-180	1.570	0.031	0.092	0.350	18.300	0.030
180-210	1.570	0.031	0.092	0.350	18.300	0.030
210-300	1.570	0.031	0.092	0.350	54.900	0.020

^a Soil profile was built from Assad et al. (2001), Batjes (2009), Battisti and Sentelhas (2017), Christina et al. (2017), Dias and Sentelhas (2018), RadamBrasil (1974) and Reichert et al. (2009). ^b BD = Soil bulk density. ^c LL = Wilting point (-1500 kPa). ^d DUL = Drained Upper Limit (-10 kPa). ^e SAT = Saturated water content. ^f SWHC = Soil water holding capacity. ^g KL = Root extraction factor. ^h Weighted average of SWHC (mm cm⁻¹) considering all depth layers of the soil profile.

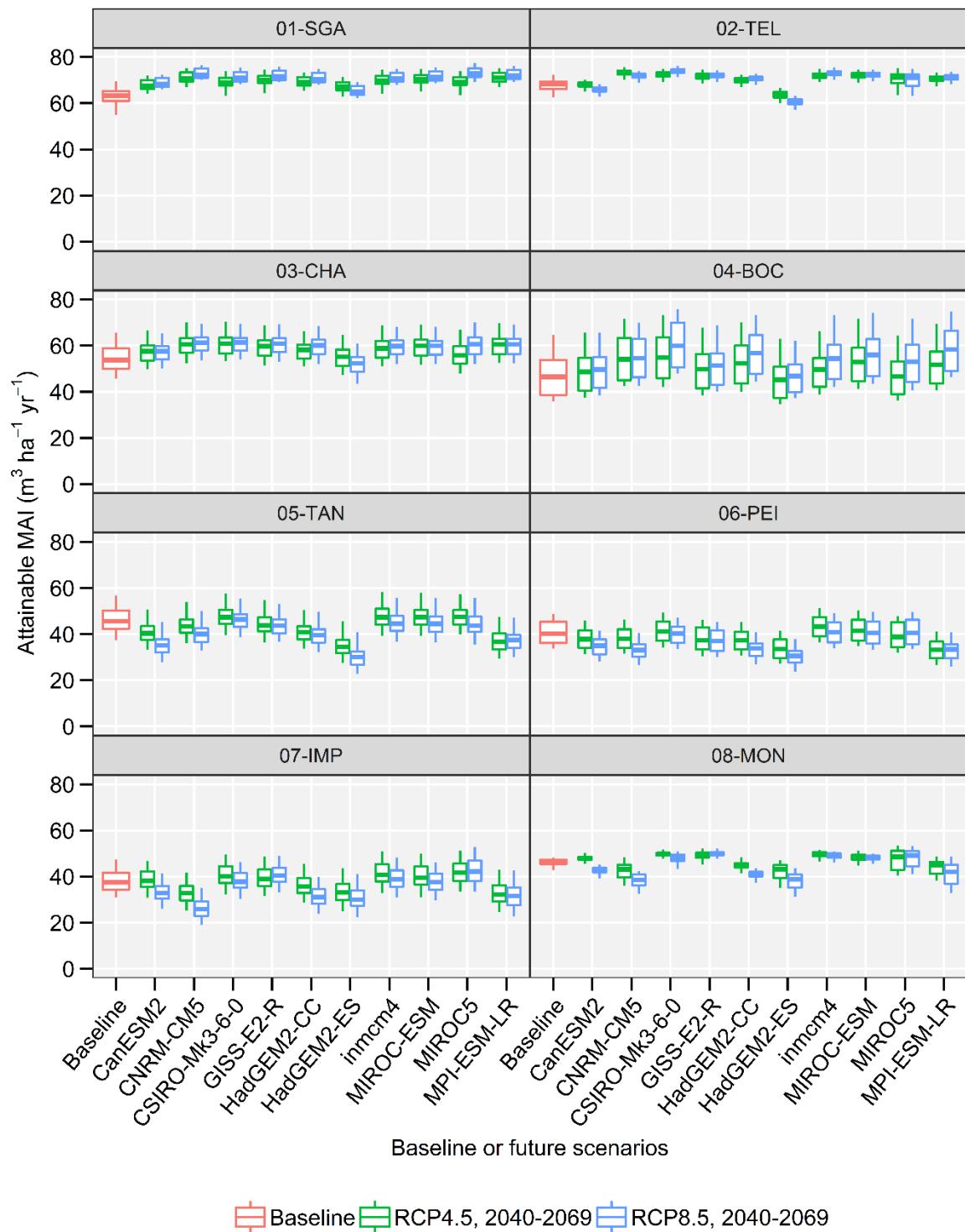


Figure S1. *Eucalyptus* attainable mean annual increment (MAI) simulated with data from the baseline (1980 to 2009) and from the ten global circulation models (GCMs) for eight Brazilian locations, considering the future period from 2040 to 2069, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios.

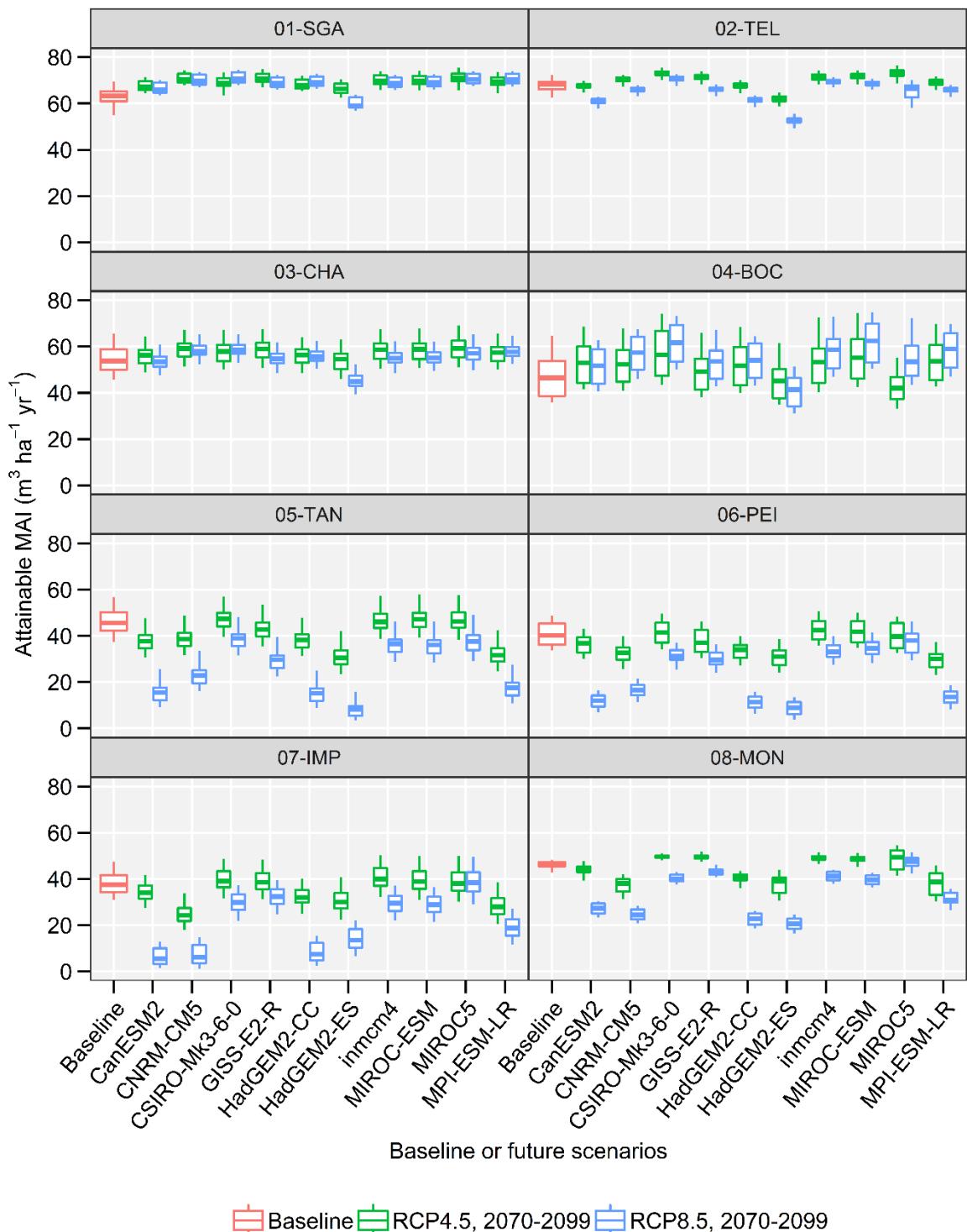


Figure S2. *Eucalyptus* attainable mean annual increment (MAI) simulated with data from the baseline (1980 to 2009) and from the ten global circulation models (GCMs) for eight Brazilian locations, considering the future period from 2070 to 2099, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios.

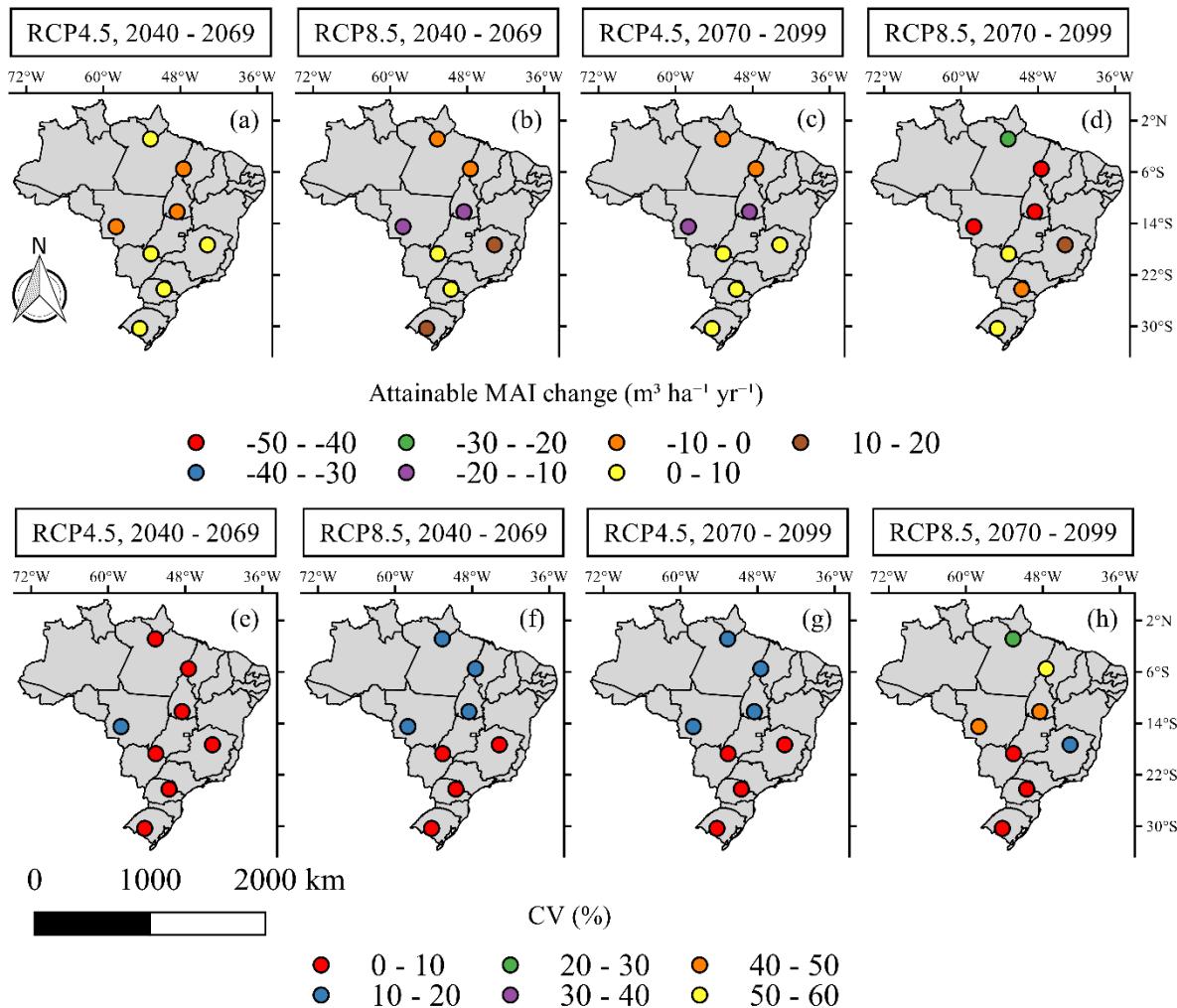


Figure S3. *Eucalyptus* attainable mean annual increment (MAI, a – d) changes and coefficient of variation (CV, e – h) simulated from ten global circulation models (GCMs) for eight Brazilian locations, considering the future periods from 2040 to 2069 and from 2070 to 2099, under intermediate (RCP4.5) and high (RCP8.5) emission scenarios.

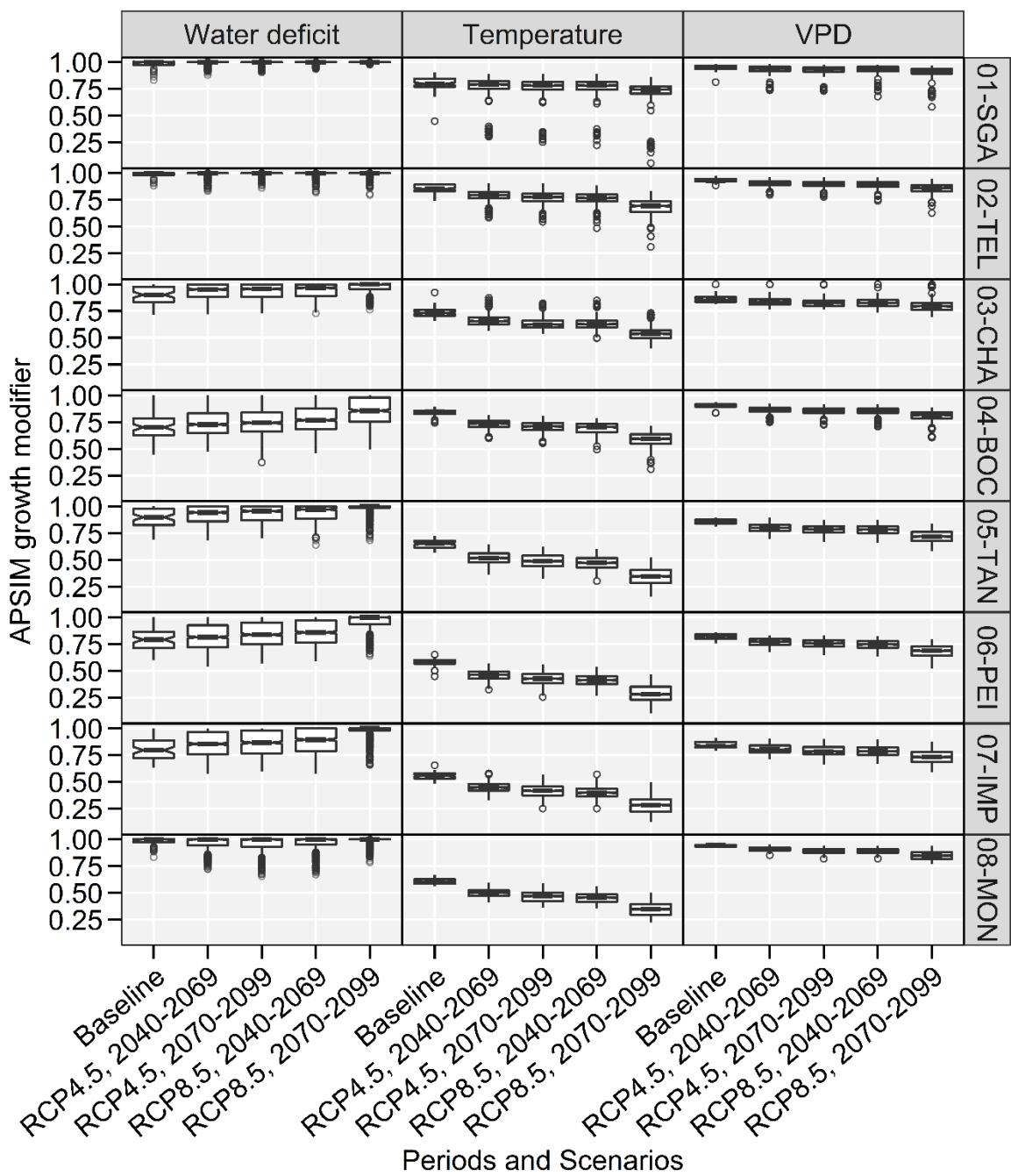


Figure S4. Simulated APSIM growth modifiers to account for the effects of water deficit, air temperature and vapor pressure deficit (VPD) for eight Brazilian locations, considering the baseline (1980-2009), and an ensemble of ten global circulation models (GCMs) projected for two emission scenarios (RCP4.5 and RCP8.5) and two future periods (2040-2069 and 2070-2099). Growth modifier functions vary from 0 (null growth) to 1 (full growth).

References for supplementary material

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8. FINAL REMARKS

All the *Eucalyptus* simulation models assessed in the present study were able to predict *Eucalyptus* growth and yield across a wide range of climates and soil types in Brazil, after properly adapted, calibrated and evaluated. The use of a multimodel ensemble approach slightly reduced the errors in yield predictions compared to the individual performance of the models, and it should be prioritized whenever possible. However, the time required for parameterizing and running several models and the availability of information on model parameters should be considered when choosing to use an ensemble approach. The choice of the appropriate model should be made according to the model's capacity for better addressing a given objective. The availability of model inputs (e.g. weather and soil data) and information on genetic parameters should be also considered. For these reasons, knowing the main structural features, advantages and limitations of different simulation models is important for choosing the best one for a given purpose.

A multimodel approach was found to be powerful in assessing the *Eucalyptus* growth gaps in Brazil. The water deficit was the main cause of *Eucalyptus* growth gaps in Central Northern Brazil, while the sub-optimal forest management was the main cause in Southern Brazil. The growth gap analysis, commonly referred to as yield gap analysis, provides a basis for identifying the main sources of losses in the forest systems, caused by water or management deficiencies. The growth gaps caused by sub-optimal forestry management are relatively easier to exploit, compared to those caused by water deficit. Future studies could focus on decomposing the growth gaps by sub-optimal management, e.g. quantifying the relative contribution of different causes, such as sub-optimal fertilization, the occurrence of weeds, pests and diseases, to the total growth gap caused by management, in order to make decisions and field interventions more efficiently.

Performing genotype-specific calibrations in the forest modelling area is a big challenge due to the lack of information available or even the lack of model predictive skills. Some progress has been made in the present study, especially with the APSIM Next Generation *Eucalyptus* model, which was successful in simulating environmental and some genetic effects on *Eucalyptus* complex traits, such as stem biomass and volume, leaf area index and basal area. In this context, process-based modelling may be a valuable decision support tool for helping foresters and companies in matching suitable genotypes to sites and to develop the best management strategies. However, environmental effects are commonly better simulated than genetic effects by the simulation models. Future studies could focus on collecting highly-detailed information, especially related to physiological traits, to improve the models' abilities

to predict genotypes differences and allow a better understanding of gene x environment x management interactions for *Eucalyptus* productivity.

Spatial and temporal climate variabilities strongly affect *Eucalyptus* growth rates across Brazil. In general, for tropical sites, *Eucalyptus* growth was mostly driven by water deficit accompanied by high temperatures, while in the subtropical locations it was mainly affected by low air temperatures. Approaches using long-term climate information combined with process-based productivity models may generate important information to foresters, assisting in planning and decision making and giving some directions on climate risk. Despite that, such approaches are currently little explored, so we strongly encourage their use in future forestry studies.

Process-based modelling approaches have been increasingly used by breeders to identify target traits that provide advantages in given environments. Global sensitivity analysis was found to be a powerful tool for identifying suitable *Eucalyptus* traits for adaptation to climate variability and change. This approach gives some directions by better understanding the gene x environment interactions for forest productivity. Some of the traits targeted now by breeders under the current climate, such as those for radiation use efficiency, biomass partitioning and canopy light capture will remain important under future climates. However, breeding should give a greater emphasis on traits for photosynthetic temperature response, since they will be more important for *Eucalyptus* productivity in a near-future climate.

The responses of *Eucalyptus* plantations to climate change are still highly uncertain. First, no clear positive or negative trends in projected rainfall by GCMs are observed in some regions. Secondly, uncertainties arising from process-based models are also high. These uncertainties may be related to the model structure, parameters, input data, CO₂ fertilization functions and differences among genotypes in sensitivity to CO₂ and climate variations. One of the reasons for that is the high cost and labor to conduct experiments to validate climate change responses, such as Free-Air CO₂ Enrichment (FACE) experiments. Future climate projections from GCMs coupled with *Eucalyptus* simulation models may provide information to “facilitate the investigation” of potential strategies for forestry adaptation. Analysing in more detail the effects of current climate variability on *Eucalyptus* productivity using high-quality historical weather data could be a good option to explore options for climate change adaptation.

From the results obtained in the present study, we conclude that *Eucalyptus* simulation models are powerful tools to assess alternatives for increasing resilience and productivity of *Eucalyptus* plantations to climate variability and change. Developing a yield forecasting system based on a process-based multimodel approach may be a promising future study in this research

area. Adding structural features to account for the impacts of pests and diseases on forest growth is also a big challenge, and future efforts are necessary. Further studies aiming at increasing models' performance are always welcome since it increases the accuracy of forestry decision making and planning. This study fits the scope of the Agricultural Model Intercomparison and Improvement Project – AgMIP (Rosenzweig et al., 2013), and it may be a good starting point to perform a broader model intercomparison project for *Eucalyptus* forests.

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