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Foreword

Climate change may mean significant changes in crop productivity, including for planted forests, due to changes in climatic parameters. These impacts may be more intense in some regions of the country. Scientific investigation based on field data obtained over the long term and projected scenarios are important tools for planning and decision making that can help decrease vulnerability and risk for the forest sector in the near future. Along these lines, this study (which was conducted with support from Klabin S.A., a forest-based company) indicates changes that may be on the horizon, discusses climatic behavior in some regions of Brazil which are important centers for eucalyptus production, and projects impacts on productivity and carbon emissions/removal capacity in eucalyptus forests within the scenario of climate change.

A highlight of this study is the use of the HadGEM2-ES model to predict rainfall, average temperature, evapotranspiration, water deficit, frost events, and minimum temperature at 10-year intervals until 2040. This is a differential, since other studies consider longer intervals.

The study indicates climatic risk and the resulting impact on eucalyptus production in southern Brazil. However, detailed investigation in the municipalities of Itapetininga, Telêmaco Borba, and Otacílio Costa points to variations in the vulnerability of these environments. The study also examines the potential of these eucalyptus forests to accumulate carbon, indicating how and to what extent this function may be affected.

Predicting potential changes is an intelligent way to prepare for and even ameliorate the impacts of climate change, thus making it possible to maintain the potential for the region and eucalyptus forests to make significant contributions to environmental quality and reaffirm the opportunities that are present for the forest sector within the context of the green economy and decarbonization of the economy.

Marcílio José Thomazini

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Sumário

Introduction

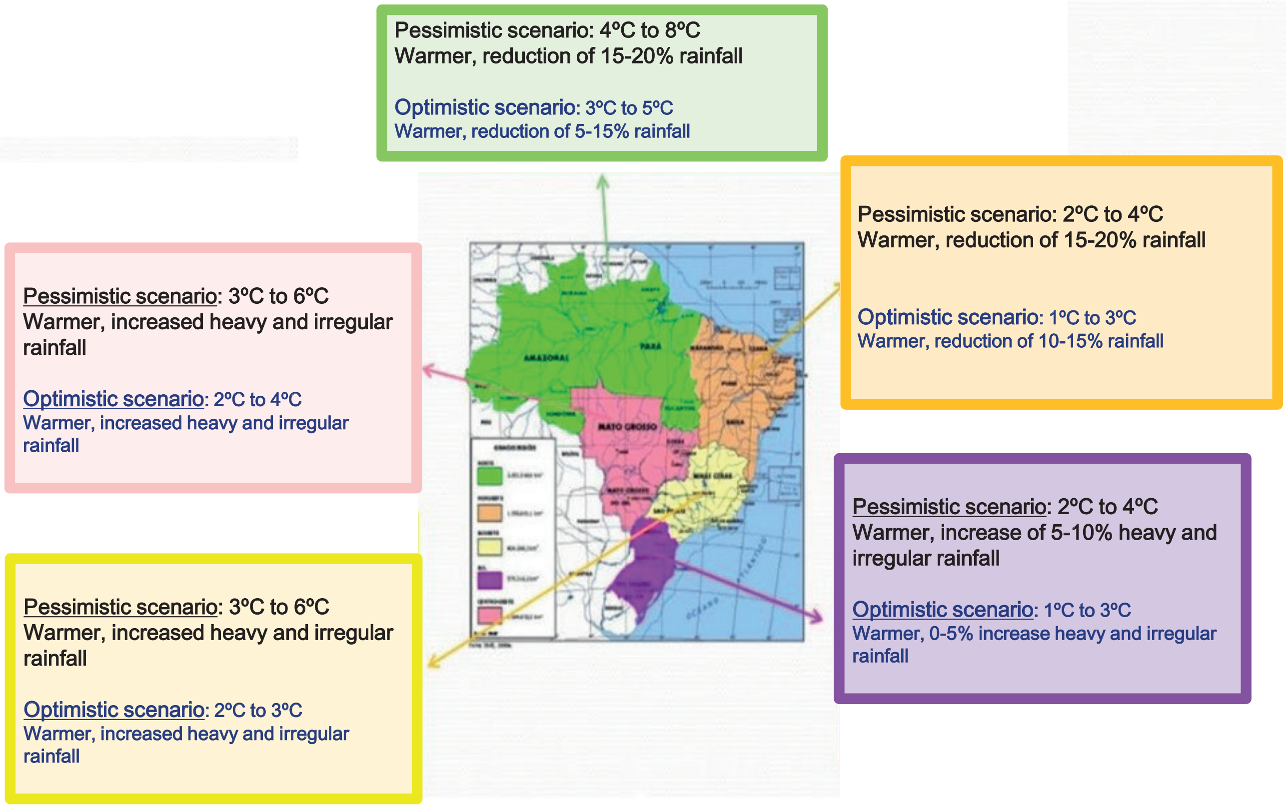
Earth is roughly 4.6 billion years old, and *Homo sapiens* emerged only approximately 300,000 years ago (Press et al., 2008). Over these billions of years there have been drastic changes to the planet's surface and atmosphere, with various warming and cooling episodes. When the planet was first formed, the atmosphere was dense and rich in nitrogen, water vapor, and carbon dioxide (CO_2) from volcanic eruptions and cosmic collisions. Nitrogen is currently the main gas comprising the atmosphere (78%), and oxygen accounts for 21% (Marin et al., 2008). The remaining 1% is made up of CO_2 and other gases.

The presence of life on Earth was only made viable with the formation of water in a liquid state as the planet cooled and the lithosphere and atmosphere were formed. The first ocean basins date from 3.6 to 3.9 billion years ago (Press et al., 2008). There is still major controversy about the oldest living beings; some scientists believe that the first organisms were primitive bacteria that emerged 3.5 million years ago, with simple cellular characteristics such as rudimentary cell walls, few enzymes, and the absence of cytochromes. Recently, scientists have discovered miniscule filaments, pieces, and tubes in rocks in Canada that are up to 4.28 billion years old. If the estimated age of these micro-fossils is correct, life emerged relatively soon after the planet was formed.

There have always been temperature variations on the planet's surface and, in turn, its atmosphere over these millions of years of life on Earth, and there is evidence indicating that these temperatures were much higher than they are today, mainly reflecting the concentration of CO_2. For example, today it is known that Earth and Venus have the same quantity of CO_2. On Venus, where the gas traps the sun's rays in the atmosphere, the temperature can reach 400 °C; on Earth, the CO_2 is present in the atmosphere, the soil, and in living beings.

Temperatures on Earth will continue to fluctuate. Studies indicate that over its 4.6 billion years, Earth experienced climate changes on a global scale that lasted from 100,000 to 1,000,000 years and caused mass extinctions of many species. Other research shows that the Earth's core, which is roughly 3,500 km thick with temperatures varying from 3,700 °C to 6,000 °C in its center, is cooling. This temperature used to be in the millions of degrees Celsius, and some scientists estimate that total cooling may occur in 4 billion years. So if this process is geological, why are we talking about global warming and human influence? Because hundreds of measurements indicate this phenomenon is real. One source is the Intergovernmental Panel on Climate Change (IPCC); its fifth report to the United Nations in September 2013 (Stocker et al., 2013) stated that human activity was responsible for global warming, and that this process was accelerating, with 95% certainty. Climate analyses indicate that since 1850 (the start of the industrial era) there has been a mean temperature increase of approximately 0.9 °C, with more than 66% of this heating occurring over the past 60 years. Over the past three decades, this increase was 0.2 ºC per decade. The rate of CO_2 increase has also accelerated since continuous monitoring of the atmosphere's composition began in 1958. This increase has evolved from 0.7 parts per million (ppm) per year to an average of 22 ppm per year in recent decades. Because of the progressive increases in the concentration of greenhouse gases (GHG), in May 2013 CO_2 levels reached 400 ppm for the first time in the recent history of humankind. Data from March 25, 2018 taken at the Mauna Loa Observatory in Hawaii showed a CO_2 concentration of 410.16 ppm. In 2017, the record was reached on April 26, when the concentration of CO_2 reached 412.63 ppm (IPMA, 2018). According to the IPCC, by the end of the twenty-first century the concentration of CO_2 could reach twice the current level, approximately 800 ppm.

The main causes of this increase are associated with the current development model and the use of the planet's available natural resources leading to gas emissions as a result of burning fossil fuels and changes in land use, such as converting native forests for agricultural uses or into urban areas. In practice, this increase, which according to the IPCC (Stocker et al., 2013) exceeds 1 °C in some locations, causes serious direct impacts, affecting a variety of areas such as biodiversity, agriculture, water resources, and coastal zones. It also provokes indirect impacts in cities, energy, industry, and infrastructure, transport, and healthcare. Figure 1 shows potential impacts from climate change that could be seen regionally in Brazil until the end of the twenty-first century.



Pessimistic scenario: 4ºC to 8ºC
Warmer, reduction of 15-20% rainfall

Optimistic scenario: 3ºC to 5ºC
Warmer, reduction of 5-15% rainfall

Pessimistic scenario: 3ºC to 6ºC
Warmer, increased heavy and irregular rainfall

Optimistic scenario: 2ºC to 4ºC
Warmer, increased heavy and irregular rainfall

Pessimistic scenario: 2ºC to 4ºC
Warmer, reduction of 15-20% rainfall

Optimistic scenario: 1ºC to 3ºC
Warmer, reduction of 10-15% rainfall

Pessimistic scenario: 3ºC to 6ºC
Warmer, increased heavy and irregular rainfall

Optimistic scenario: 2ºC to 3ºC
Warmer, increased heavy and irregular rainfall

Pessimistic scenario: 2ºC to 4ºC
Warmer, increase of 5-10% heavy and irregular rainfall

Optimistic scenario: 1ºC to 3ºC
Warmer, 0-5% increase heavy and irregular rainfall

Figure 1. Future climate scenarios for Brazil until the end of the twenty-first century.

Adapted from Souza et al. (2014).

Various measures are being taken in an attempt to mitigate GHG emissions. Since 2007, Brazil has been making major efforts in deploying its National Policy on Climate Change (Law nº 12.187/2009) (Brasil, 2009). The 2009 Copenhagen climate accord was signed to reduce emissions, and ten sectoral plans were created in an initial attempt to mitigate GHG. Strong strides were made to reduce deforestation in the Amazon, and as a result agriculture is more notable in Brazil's global emissions. In response, the country encouraged agricultural practices and integrated production systems with low carbon emissions. An important example is the National Policy on Climate Change (*Politica Nacional sobre Mudança do Clima*, PNMC), which finances practices such as sowing directly into untilled post-harvest fields, integrated crop-livestock, crop-livestock-forest, and forest-livestock systems, agroforestry systems, planted forests, and biological nitrogen fixation. All these systems offer a positive impact for carbon flows; in other words, they act as sinks for GHG or avoid GHG emissions, and are consequently important measures for mitigating GHGs. In most of these systems, the forest component is highlighted as an important practice to reduce carbon emissions.

Another pathway is intensification of genetic research. Climate change impacts various biological levels. Little is known about how it affects the molecular, biochemical, and physiological processes that determine how each chain responds, from individuals up to global ecosystems. For this reason, genomic sciences must be incorporated into ecological studies.

In terms of adaptation, research and development on the following topics should be emphasized:

- Identifying varieties that are better adapted (resistant/tolerant) to abiotic stress resulting from climate change such as high CO_2 concentrations, drought, and heat, under controlled conditions.
- Discovering molecular, biochemical, and physiological mechanisms that mediate responses and adaptation to this stress.
- Developing molecular markers (genetic and biochemical) to assist in selecting the best-adapted varieties in genetic improvement programs.
- Discovering genes involved in adaptation (resistance/tolerance) with biotechnological value.
- Other more detailed studies should be conducted to assess how crops adapt to new pests or diseases that result from climatic imbalance. Identification, systematization of data, analysis of vulnerabilities, and mapping the growth of new pests and diseases should be priorities in investigating how crops will adapt to global warming.
- In this sense, this text investigates regional vulnerabilities and potential impacts of climate change scenarios for eucalyptus cultivation in the areas of Brazil that contain large areas of planted forests. An emissions balance assessment was also conducted for eucalyptus plantations, mainly considering carbon storage in the soil where this crop grows.

Eucalyptus cultivation in Brazil and the main climate risks

According to a report from the Brazilian Tree Industry (IBÁ, 2020), the forest sector drives the national economy, with a sectorial gross domestic product (GDP) of R$ 86.6 billion, representing 1.3% of Brazilian GDP and 6.9% of industrial GDP. In 2019, the trade balance reached a record US$ 11.4 billion. The same report indicates that climate change brings with it risks and opportunities for the forest-based sector. The challenges facing the sector include discussions of carbon pricing and the solidification of a global market concerned with the bioeconomy. In 2018, the industry’s stocks of CO_2 equivalent totaled 4.2 billion tons.

The total area of planted trees in Brazil in 2019 was 9.0 million hectares, a 2.4% increase over 2018. Eucalyptus plantations occupy 6.97 million hectares, while areas of pine total 1.64 million hectares; other species including rubber, acacia, teak, and *paricá* account for approximately 390,000 hectares (IBÁ, 2020). Meanwhile, the Brazilian Institute of Geography and Statistics (IBGE) indicates that an even larger area is planted with eucalyptus, totaling 7.5 million hectares, and 1.9 million hectares of pine (IBGE, 2018). It should be noted that the IBGE data are self-declared and include industrial plantations as well as forests planted on small and medium-sized properties.

The eucalyptus plantations are mainly located in the states of Minas Gerais (28%), São Paulo (17%), and Mato Grosso do Sul (16%) (IBÁ, 2020). In recent years, the area planted with eucalyptus grew an average of 1.1% per year. Mato Grosso do Sul led this expansion with an average increase of

7.4% per year in this state alone (IBÁ, 2020). Pine plantations were concentrated in Paraná (44%) and Santa Catarina (26%), followed by Rio Grande do Sul (17%) and São Paulo (9%) (IBÁ, 2020).

The productive potential of eucalyptus plantations in tropical regions, especially in Brazil, is much higher than in other regions of the world, with few exceptions. Brazilian competitiveness in the forest sector is based on the favorable environmental conditions and efficient technology used, and is the result of consistent investments in research and development by companies in the sector along with universities and other research institutions (Ribeiro et al., 2009).

Understanding the relationships between physical conditions in the environment, particularly soils and the atmosphere, and the various species cultivated makes it possible to obtain more precise data on how weather and the climate affect growth, development, and productivity in the forest stands. In general, the main meteorological variables that affect growth, development, and productivity of forest plantations are rainfall (volume, intensity, regime, and distribution), air temperature, and solar radiation (Hoogenboom, 2000); the photoperiod, air and soil humidity, and wind direction also have an effect (Pereira et al., 2002; Mavi; Tupper, 2004).

Temperature

The high temperatures in the tropics are favorable for eucalyptus production. During winter, plants do not go dormant as they do at higher latitudes, since average daily values below the basal temperature for eucalyptus are rarely reached.

Within the temperature range where photosynthesis occurs, three variables can be defined: minimum or lower basal temperature (Tbi), optimal temperature (Tot), and maximum or upper basal temperature (Tbs). According to Almeida et al. (2004), for the eucalyptus crop in northern Espírito Santo the optimal temperature for photosynthesis is 25 °C, with a lower limit of 8 °C and upper limit of 36 °C. Silva (2006) considered 25 °C to be the optimal temperature, 8 °C the lower limit, and 40 °C the upper limit for eucalyptus production in the center-east region of Minas Gerais. Besides these limits, critical low and high temperatures (Tci and Tcs, respectively) should also be considered.

In many species of vegetation, the critical low temperature is the point at which freezing occurs, with consequent cell death. However, the freezing point varies according to species, depending on its capacity to produce antifreeze proteins and cryoprotective sugars. Woody plants in particular are more resistant to freezing, due to protective mechanisms such as dehydration.

Floriani et al. (2013), in an assessment of the effects of acclimatization on cold tolerance in eucalyptus species, observed that for unacclimatized seedlings TL50 (the lethal temperature at which 50% of cell death occurs) occurred at -4.5 °C for *Eucalyptus benthamii*, -3.9 °C for *E. dunnii,* and -2.0 °C for *E. grandis* and *E. saligna*. In investigating the impact of global warming on eucalyptus cultivation, it is important to know the minimal temperature to see how extreme events (such as heat waves or cold fronts) can affect the crop.

Depending on the species, the lowest critical temperature may vary. In studies on the occurrence of low temperatures, the reference temperature considered is usually the grass temperature; in other words, the temperature closest to the soil. At the soil level, or at crop level for low annual crops, this temperature generally tends to be 2 °C lower than the screen temperature levels recorded in the weather station. However, this is not the reality for eucalyptus, except for recently planted seedlings that are still small and closer to ground level.

According to Dibax (2007), eucalyptus trees affected by freezing temperatures exhibit a variety of damage, and when seen from a distance exhibit burning or bronzing of the foliage. Higa and Higa (1997) stated that aside from direct damage such as total or partial crown death or even complete death of the plant, indirect damage is more frequent, and may not only restrict growth potential in the plants but also make them more susceptible to infection by pathogens or even make the establishment of commercial populations of eucalyptus trees unfeasible.

As the area planted with eucalyptus trees expands across southern Brazil, selection of frost-resistant genetic material represents a major challenge. Higa and Higa (1997), in a study conducted in Campo do Tenente, Paraná, classified *E. dunnii* as one of the best species in this genus in terms of growth and resistance to frost injury, with performance similar to *E. viminalis* tested in these conditions.

Within this context, the reference limits for assessing climatic risk to eucalyptus from temperature are detailed in Table 1.

Table 1. Cardinal temperature considered for assessing the potential and climate risk in plantations of *Eucalyptus grandis*. *Eucalyptus urophylla.* or *Eucalyptus urograndis* hybrids.

Plant size	Cardinal temperature (°C)				
	Tci	Tbi	Tot	Tbs	Tcs
Seedlings and young plants <50 cm	0	8	25	36	40
Plants >50cm tall	-2	8	25	36	40

Note: Tci: critical low temperature or lethal minimal temperature; Tbi: minimal or lower basal temperature; Tot: optimal temperature; Tbs: maximum or upper basal temperature; Tcs: critical high temperature or lethal maximum temperature.

Source: Adapted from Almeida et al. (2004), Silva (2006) and Floriani et al. (2013).

Rainfall: maximum, minimum, and average

In the tropics, water availability in a region is one of the most important climatic characteristics for plant growth. Unlike other meteorological elements, rain is much more variable, and is the main factor that determines productivity. Table 2 presents the reference values for eucalyptus.

Table 2. Established reference values for establishing productive eucalyptus populations of *Eucalyptus grandis* and *Eucalyptus urophylla*.

Species	Favorable annual rainfall		Extreme rain event daily maximum (mm)
	Minimum (mm)	Maximum (mm)	
*Eucalyptus grandi*s	1.000	1.800	100
Eucalyptus urophylla	1.000	1.500	100

Source: Adapted from Ribeiro et al. (2009).

Both scarcity and excess of rain can be harmful. Eucalyptus trees subjected to excess water from heavy rain can exhibit anomalies such as leaf necrosis, tip dieback in the branches and main stem, adventitious sprouting along the main stem and the branches, leaves with narrowed limbus, deformations, or signs of nutritional deficiency in adult trees, as well as obstructions of the xylem in the wood and roots caused by tyloses. Tip dieback disease, for example, has been related to both scarcity and excess of water, indicating that there is a relationship between this disease and the local hydric regime (Maschio et al., 2000).

The most suitable way to assess water availability for a crop is via the water balance, the approach which will be utilized in this study. However, even without developing a more elaborate water balance, some simpler and more direct indicators can be established based on the precipitation in a location.

Reference evapotranspiration

Evapotranspiration is the process of simultaneously transferring water to the atmosphere through evaporation from the soil and transpiration by the plants. Reference evapotranspiration (ETo) is the quantity of water that will be evaporated and transpired by a certain kind of vegetation under standard conditions and without water restriction. In this way, ETo is limited to only the vertical energy balance, in other words, local environmental conditions (Pereira et al., 2002).

Therefore, ETo indicates the evapotranspirative demand of the atmosphere in a certain location during a certain period.

While rain is the main source of water for agricultural crops, evapotranspiration represents their consumption, or water demand. It is the difference between supply and demand that will define water availability for the crop, an essential factor in defining productivity.

In large areas or during periods in the past (such as in meteorological data series), the most practical means of estimating water availability or water deficit for a crop is by calculating the water balance for the soil. But because of uncertainties or potential difficulties surveying the parameters needed to determine a precise water balance, evapotranspiration is a much simpler and practical indicator to identify critical periods of water demand or consumption. In critical periods when ETo is already high or rising with little to no rain, a sufficient water reserve in the soil is necessary. In young eucalyptus seedlings with root systems that are still not very developed, the water reserve in the soil is quickly used when demand is high due to lack of rain, and supplemental or “rescue” irrigation is needed to ensure that they survive this period. As a result, ETo is an important, simple, and practical indicator to assess the impact of climate change on water demand in a specific location.

For the analyses in this study, which involve quantifying the plant stress conditions and production risk in present and future scenarios, “high” and “very high” evapotranspiration categories will be considered, as described in Table 3.

Table 3. Classification of reference evapotranspiration intervals (ETP) for frequency and risk analyses.

ETP	ETo (mm/day)	Expected impact
Low	0-3	- Low water demand. normally associated with cloudy days and/or low temperatures. The plant's needs are met even with low storage. No immediate risk.
Intermediate	3-5	- Little or no impact. Optimal conditions for water consumption.
High	5-7	- High water demand. normally associated with sunny days and high temperatures. This high demand is unfavorable for most crops. As a species with excellent stomatal control. eucalyptus is less affected and its water needs are met in soils with elevated storage. Plants can exhibit symptoms of deficit during the hottest hours of the day. even when storage is high. particularly young plants. This intense ETo normally occurs after several days without rain. and intensifies as humidity in the environment decreases and temperatures rise progressively. There is more respiration with less photosynthesis. resulting in reduction or temporary stoppage of growth. Risk is high for recently planted young trees.
Very high	>7	- Very unfavorable for agriculture in general. even crops that are more resistant to high temperatures. - High water demand. normally associated with sunny days. high temperatures. and low air humidity levels and/or strong winds. - As a species with excellent stomatal control. eucalyptus is less affected and will lose less water. Its water needs are not met. even in water with elevated storage. Plants exhibit evident symptoms of deficit during the hottest hours of the day. even when storage is high. particularly young plants. This intense ETo only occurs after a series of days without rain. resulting in a process of aggravation as humidity decreases in the environment and temperatures rise progressively. There is more respiration with less photosynthesis. resulting in reduction or temporary stoppage of growth. It is common for tender tips on young trees to dry up and die. Risk is extremely high for recently planted young trees.

Adapted from Caldato et al. (2013) 507-516, and Liu et al. (2017).

Water availability and deficit for eucalyptus

Close to 80% of agricultural variability in the world results from varying meteorological conditions during the cultivation cycle, especially for dry farming crops, since producers have no control over these natural phenomena (Petr, 1991; Fageria, 1992; Hoogenboom, 2000; Sentelhas; Monteiro, 2009).

In Brazil, most agricultural land is located in areas that are subject to differing degrees of water deficit, and this is the main cause of variability in national agricultural production, which includes eucalyptus forests. Even the direct and deleterious effects caused by high temperatures are still normally associated with long periods of drought. Within this context, drought is the principal risk factor for eucalyptus production in Brazil.

To characterize and quantify this risk, some specific characteristics of eucalyptus must be considered which make it better adapted to drought, particularly *E. grandis* x *E. urophylla* hybrids compared to the other cultivated species.

One such characteristic is efficient stomatal control (Almeida; Soares, 2003), which allows eucalyptus to minimize water loss due to transpiration during periods of deficit or very high atmospheric demand. Carneiro (2004), in an experiment in the region of Belo Oriente, Minas Gerais, Brazil, quantified the water needs of young eucalyptus trees and the effect of seasonality on water use in 2-year-old irrigated and unirrigated clones of *E. grandis* x *E. urophylla* hybrids. Stomatal conductance was measured during wet and dry periods, and mean values varied from 0.41 mol m^{-2} s^{-1} to 0.22 mol m^{-2} s^{-1} for irrigated trees and from 0.38 mol m^{-2} s^{-1} to 0.24 mol m_{-2} s_{-1} for the non-irrigated trees. Essentially, stomatal control was found to depend on the product of the meteorological variables vapor pressure deficit and temperature, and was inversely related to overall solar radiation.

Another important characteristic is the root system, which in favorable soils can reach great depths. Almeida and Soares (2003) compared water use in *E. grandis* plantations in an area of dense ombrophile forest (in the Atlantic Forest biome) and concluded that for a seven-year growth cycle, eucalyptus can consume less water than the native forest in the region. In years when rainfall was close to the historical average, evapotranspiration was in balance for both ecosystems, and in years when rainfall was lower than the historical average, the Atlantic Forest had higher evapotranspiration rates than eucalyptus forests. However, this phenomenon does not always fully manifest due to soil limitations; soils with physical or chemical impediments can severely limit root development at greater depths.

These aspects condition how eucalyptus responds to situations with high and low evapotranspirative demand and greater or less water supply, and define its water consumption. For one- and two-year-old plantations, Sacramento Neto (2000) obtained approximately equal average real evapotranspiration rates (ETr of 5.0 mm d^{-1} and 1.4 mm d^{-1}) for the wet and dry periods of the year, respectively. For ten-year-old adult plantations, Neves (2000) found an approximate ETr value of 5.7 mm d^{-1} and 2.3 mm d^{-1} during the wet and dry periods of the year, respectively.

These responses can be adequately represented by the water balance, making it possible to produce objective indicators of environmental favorability or disadvantage in the present as well as future scenarios. One indicator most commonly used to determine water status for a certain site and crop is water deficit (WD), since it can be easily related to borderline or critical conditions. For example, the WD value derived from the climatological water balance has been used as an indicator to select eucalyptus genetic materials. In regions where WD is high (annual deficit 100-200 mm/year), species or hybrids with medium to high drought tolerance are recommended. In regions with a deficit of 200-400 mm/year, considered very high WD, only species or hybrids with high drought tolerance are recommended (Gonçalves, 2014).

Methodology

This study is based on the concept of climate, which describes changes in atmospheric conditions over a certain period. Climatology specifically quantifies climatological conditions over a period of time. Climatological normals are the values obtained for climatic conditions over at least 30 years.

Characteristics of the region of study

Considering the distribution of eucalyptus plantations in Brazil, and in order to perform an initial assessment of vulnerability, this study focused on the southern region of Brazil, which spans the states of Paraná and Santa Catarina as well as part of the productive region in the state of São Paulo.

Criteria for data selection

The ideal period for a study of climatological normals should cover series of observations with at least 30 years of data that is updated to the present. Considering the spatial heterogeneity of the regions under study and differences in data availability, it makes more sense to invest time in a more rigorous selection process that results in good data series than include a large number of weather stations and have to manage complex quality control and error-filling algorithms that can add uncertainty to the results.

Initially, all the meteorological stations located in the south of the country (the states of Rio Grande do Sul, Santa Catarina, and Paraná) and part of the region in the São Paulo were identified. This pre-selection comprised all the stations with error rates below 30% and a time series greater than 15 years. However, many stations identified in these regions did not meet these criteria and were consequently discarded. The most recent year with complete data was 2010.

As a result, for selection of the weather stations a maximum error rate of 4% was permitted. This percentage was determined based on the spatial distribution of the stations that meet this criterion, since a lower number would not leave a sufficient number of stations in some parts of the indicated regions. The data were analyzed for consistency, eliminating discrepant values or anomalous data sequences.

All available temperature series from 1980 to 2010 were selected, thus completing the 30-year data series. This set of data was also analyzed for consistency, eliminating inconsistent data, values beyond the normal range for the region, or systematic deviations from neighboring stations.

The temperature data for the weather stations located within the indicated regions (which represent an area with a 10-13 km radius) were used to reconstruct the series at the same points as the pluviometric stations by interpolation with altitude correction.

Selected stations

Climatologic normal conditions were defined considering the period 1980-2010. In this way, all the selected stations have a historical series of rainfall and temperature for this period or beyond, which made it possible to **define the climatology of the regions and characterize climatically homogeneous zones** with series of at least 30 years of complete data.

In the south region and in part of the region in the state of São Paulo, all existing pluviometric stations and a set of pre-selected stations from several institutions already integrated into the Brazilian National Water Agency (ANA) database were identified.

In the region under study and the surroundings, the location of all available temperature data series from satellite data series and ground stations was identified, with a resolution of 0.5 x 0.5 degrees latitude. The data were provided by the Agricultural Model Intercomparison and Improvement Project (AGMIP) coordinated by the United States Department of Agriculture (USDA), the National Aeronautics and Space Administration (NASA), and Columbia University. A total of 143 stations were selected for a total of 372 municipalities.

Tabulating the series and replacing errors

By applying the selection criteria described, 143 pluviometric stations were selected; their locations are presented in Figure 2. The average frequency of data error at the selected stations was 1%. In these cases, the errors were filled with values from the nearest neighboring station.

At the same points as the pluviometric stations, the temperature series were generated by interpolation and altitude correction.

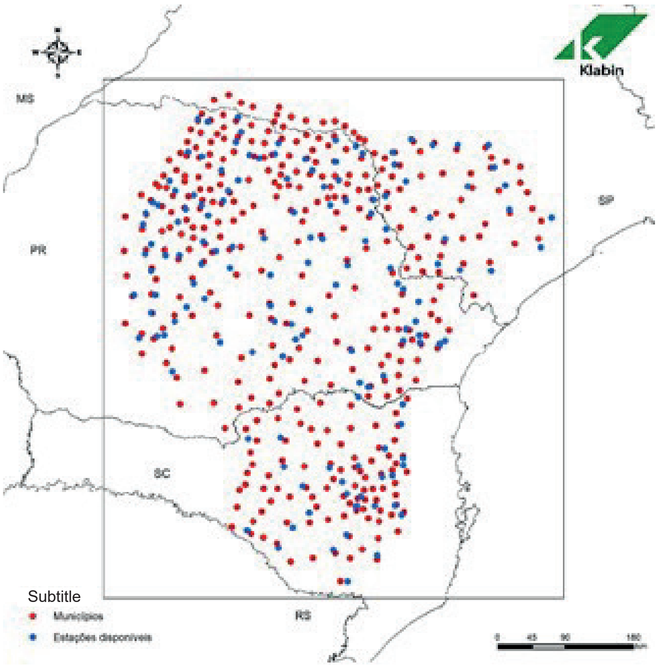


Figure 2. Pluviometric stations identified in the study region. Red dots indicate municipalities. while blue dots indicate the selected stations with at least 30 years of daily data.

Collection and organization of soil maps

Existing soil maps were identified, at a 1:250,000 scale following the standard established in *Zoneamento Agroecológico da Cana de Açúcar no Brasil*, published by Embrapa (Manzatto et al., 2010).

To organize spatial distribution of the soils, data is needed to assess their water retaining behavior. The soil's capacity to store water is affected by many factors, but reasonable estimates can be made based on depth, levels of clay, sand, and silt, and assessment of the textural gradient. Soil depth is one aspect that appears in soil maps, from small-scale efforts to large-scale surveys of entire properties. It can also be easily measured in the field by rural producers, extension agents, and technicians from various backgrounds. The textural gradient is evaluated based on the relationship between the clay levels of two horizons or consecutive layers of soils.

It is important to emphasize that soil fertility parameters were not used in this study, because: i) soil fertility can be modified using fertilizers and corrective measures; ii) although some fertility attributes such as cation exchange capacity (CEC) and organic matter content may affect the soil's capacity to store water, this influence is not considered in the models that predict soil water retention.

Standardizing soil indications in agricultural zoning

Considering that estimating soil water storage capacity depends on soil depth and its capacity to retain water, as well as the need to standardize criteria via attributes that are easy to use by various groups of readers who will utilize the information provided here, the following soil categories were adopted to assess climate risk for eucalyptus cultivation:

Type 1 soils: These are soils: i) with clay content greater than 10% but less than 15% in the top 50 cm of soil; and ii) soils with clay content of 15-35% and sand content <70% that exhibit abrupt variation of texture in the top 50 cm of soil, in other words, the top 50 centimeters have a horizon or soil layer with 15% or more clay (absolute value) than another.

Type 2 soils: These soils have clay content of 15-35% and sand content <70% in the top 50 cm of soil (without an abrupt variation in clay content).

Type 3 soils: These are: i) soils with clay content >35% in the top 50 cm of soil; and ii) soils with <35% clay and <15% sand (silty texture) in the top 50 cm.

Soil mapping as a function of water retention capacity

After applying the soil type classifications, the final mapping for the states of São Paulo, Paraná and Santa Catarina is illustrated in Figure 3.

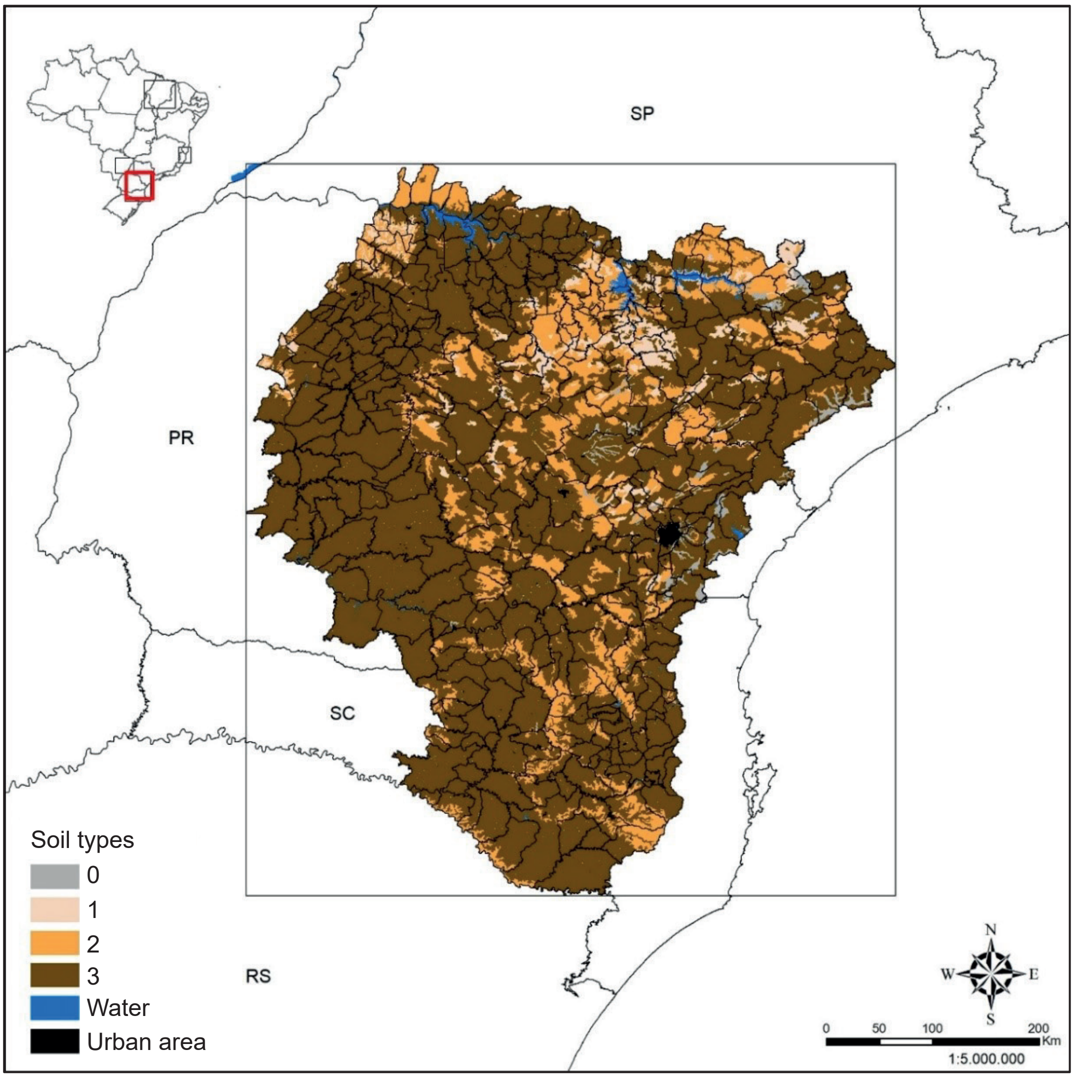


Figure 3. Soil mapping for the study region. according to the Zoneamento Agricola de Riscos Climáticos criteria.

Note: Soil types: 0: not classified; 1: soils with >10% but <15% clay in the top 50 cm. and soils with 15-35% clay and <70% sand that exhibit abrupt texture variation in the top 50 cm of soil (one horizon/soil layer in the top 50 cm with 15% or more clay [absolute value] than another; 2: i) soils with 15-35% clay and <70% sand in the top 50 cm; 3: soils with >35% clay in the top 50 cm; and ii) soils with <35% clay and <15% sand (silty texture) in the top 50 cm.

Rainfall and temperature data: present and future

After the stages of obtaining and preparing the meteorological data series and defining critical limits for the main meteorological variables in order to analyze the potential and climatic risk of eucalyptus cultivation, this step consisted of analyzing the temperature and rainfall data during the reference period and in future projections.

The future scenarios used in this study were generated by the RCP 8.5 scenario of the HadGEM2-ES simulation, which is the most extreme scenario indicated by the IPCC (Stocker et al., 2013). But at this time, considering the flow of CO_2 emissions, this is the most realistic scenario in terms of global warming. This is because emissions measured since 2010 by GHG inventories indicate values greater than or equal to those predicted in the RCP 8.5 scenario curves indicated in the IPCC (Stocker et al., 2013).

The data series used in this study were generated by the method of applying the deviations (D) according to Assad et al. (2016), estimated by the model for the different time windows. The deviations between the reference period adopted by the climate model and the model projections for 2011-2020, 2021-2030, and 2031-2040 were calculated. The deviations were applied to the actual observed data series to reconstruct series in the future scenarios up to 2040.

The technique of applying the deviations to the observed series is used to maintain the original structure and natural variability of the temporal series of meteorological variables as they actually occur. This minimizes any biases introduced by the models in the distribution of the variables, which is particularly sensitive for analysis of extreme events.

With the finalized data set, values for rainfall and temperature during the reference period 1981-2010 (climatological normal) and the HadGEM2-ES scenarios for 2011-2020, 2021-2030, and 2031-2040 were generated. The time series for each of the four regions evaluated (Figure 8) were summarized by the mean or total with monthly, four-monthly, and annual aggregation.

Based on the monthly results, for each variable the four-month periods of interest were defined as a function of the seasonability characteristics (summer/winter) in the areas of study. For rainfall, the rainiest four-month period (Quad.+) and least rainy four-month period (Quad.-) were defined, and the hottest four-month period (Quad.+) and least hot four-month period (Quad.-) were also defined, along with the coldest and least cold periods.

From the 30-year series of observed data (1981-2010), the observed trend was adjusted by linear regression for the monthly totals or means for the regions of study.

Interpolated maps were generated from the climatology in the four-month periods of interest for each variable, for the reference period and the projected climate scenarios.

A frequency distribution model was adjusted to the minimum temperature time series. A normal distribution model was used for the maximum temperature series. The adjusted models were utilized to estimate the occurrence of low and high temperature adverse events. For extreme rain events, a direct frequency analysis was used.

Estimating productivity

In the estimation and analysis of productivity, the impacts of global warming on eucalyptus productivity were considered for São Paulo, Paraná, and Santa Catarina. The regions covered by the municipalities of Itapetininga (SP), Telêmaco Borba (PR), and Otacílio Costa (SC) were considered as references because they have temporal productivity series data extending from 1980 to 2015. As a result, the climate series used in the local analyses for Itapetininga (SP), Telêmaco Borba, and Otacílio Costa were extended until 2015.

During this stage, the spatial analysis mainly considered the water requirement satisfaction index (WRSI), which is an indicator of productivity and climate risk adopted in agricultural zoning of climate risk. A relative impact study was carried out on wood productivity, using productivity of 57 m^3 wood/ha/year for calculation purposes.

In the local reference areas, the following mean annual increments (MAI) recommended by Klabin S/A were utilized:

- Itapetininga, SP: MAI= 50 m^3/ha/year.
- Telêmaco Borba, PR: MAI= 57 m^3/ha/year.
- Otacílio Costa, SC: MAI= 37 m^3/ha/year.

In all cases, the 2010-2020, 2020-2030, and 2030-2040 projections were used, with 1980-2010 as the base year. To do so, it was necessary to identify the climatic risks associated with eucalyptus productivity in the areas of Itapetininga, Telêmaco Borba, and Otacílio Costa, considering the period 1980-2015.

- The main climatic risks assessed were:
- Amount and frequency of intense drought.
- Minimum temperature (considering frost).
- Average temperature.
- Evapotranspiration potential.
- Water deficit.

Soil texture was estimated according to the guidelines of the Brazilian Ministry of Agriculture, Livestock and Supply's Climate Risk Zoning guidelines (ZARC). The soil texture map was generated and used to determine the available water capacity (AWC) of the soil to calculate the water balance and determine water deficit. Next, the local/regional water balance map was created.

After the stages of obtaining and preparing the meteorological data series and defining critical limits for the main meteorological variables in order to analyze the potential and climatic risk to the crop, the impacts of the climate indicators for eucalyptus productivity were analyzed.

Because no reliable historical series on relative humidity, radiation balance, and wind speed are available, reference evapotranspiration (ETo) could not be estimated by the Penman Monteith method, considered by the Food and Agriculture Organization of the United Nations (FAO) as the preferred method due to its precision (Allen et al., 1998). Of the existing methods that use only maximum and minimum temperature, the Hargreaves and Samani model performed best when calibrated for local conditions. For this reason, the ETo data were estimated from the daily minimum and maximum temperatures using the Hargreaves and Samani equation (1985), with optimized parameterization for climatic conditions in the regions indicated for this study (Eq. 1).

$$ETo = 0.0018 * Qo * ((Tmax - Tmin)^{\wedge}0.83) * (Tmed) - 0.5 \quad \text{[Equation 1]}$$

Where:

ETo = reference evapotranspiration
Qo = radiation at the top of the atmosphere
Tmax = maximum temperature
Tmin = minimum temperature
Tmed = mean temperature.

From the data on evapotranspiration potential, rainfall, and the physiological parameters of eucalyptus, the water balance for this crop was calculated using Thornthwaite and Mather's climatological method, which makes it possible to quantify water variations in the soil as a function of water supply and demand in the cultivation environment.

The water balance was calculated for when the crop has a **completely formed canopy**, which occurs from 12 months of age. The crop parameters necessary to calculate the water balance are the crop coefficient curve (Kc) throughout the year and the AWC, assumed as a function of a soil with medium water storage capacity and eucalyptus's deep root system.

Assessing water availability and demand during the initial phase of eucalyptus development, the following mean values were determined: soil water evaporation coefficient (Ke) = 0.57; basal coefficient for the crop (Kcb) = 0.13; and single-crop coefficient (Kc) = 0.70. In the intermediate phase of crop development, the values were, Ke = 0.01, Kcb = 0.81, and Kc = 0.82, respectively (Alves, 2013).

In one- and two-year-old plantations, Sacramento Neto (2000) obtained approximately equal average rates of actual evapotranspiration (ETr): 5.0 mm d^{-1} in wet periods and 1.4 mm d^{-1} in dry periods of the year. In 10-year-old adult plantations, Neves (2000) determined ETr values of approximately 5.7 mm d^{-1} and 2.3 mm d^{-1} during the wet and dry periods of the year, respectively.

Considering these results and the efficient stomatic control of eucalyptus (Almeida; Soares, 2003), an average Kc value of 0.8-0.9 is appropriate for eucalyptus plantations with a fully formed canopy. A value of 0.9 was adopted for the most favorable period of the year when active growth occurs, and 0.8 during the driest months of the year with reduced growth. For months with intermediate growth, a value of 0.85 was adopted for Kc.

Another fundamental parameter to estimate is AWC, considering the soil type and the depth of the root system. Almeida and Soares (2003) evaluated the amount of water available in the soil in an adult eucalyptus plantation up to a depth of 2.5 m. In this layer, the variation curve for available water in the soil rarely exceeded 160 mm, indicating a probable reference for maximum soil storage capacity.

Although eucalyptus roots can reach depths of over two meters, the quantity of roots and volume of soil utilized decreases drastically with depth. Total soil porosity, the depth to be aerated, and the level of oxygen consumption significantly influence the minimum aeration porosity required for complete oxygenation of a root system (Van Lier, 2001). In this way, a direct correspondence between root depth and the volume of soil effectively utilized by the roots and, in turn, with AWC cannot be assumed. Although it reaches greater depths, the root system does not grow as profusely as on the surface, and therefore cannot utilized the entire volume of soil. For this reason, in crops with very deep root systems AWC is not expected to vary as significantly as a function of soil texture as it does in crops with shallow root systems. For example, sandy soils store less water than clay soils, but the greater aeration of the sandy soil permits plants to develop a denser root system in the deep layers, unlike in clay soils which are less aerated (Costello et al., 1991; Bartholomeus et al., 2008).

Viable soil depth is a preponderant factor, as is distribution of root density along the soil profile. Eucalyptus has a high root density in the surface layers of the soil. Therefore, measuring viable soil depths (i.e. without physical or chemical impediments) is fundamental to correctly estimate AWC for eucalyptus. To determine this value for this species, besides considering that 80% of the active roots are situated up to 30 cm deep, AWC was determined for 1.5-2.0 m.

To determine water deficiency by soil type according to the characterizations established above, the following retention capacities were considered:

- Sandy soils (type 1) = 0.7 mm water/cm of soil.
- Medium texture soils (type 2) = 0.9 mm water/cm of soil.
- Clay soils (type 3) = 1.0 mm water/cm of soil.

These results were based on several retention curves obtained over the past 30 years to develop the Climate Risk Zoning in Brazil guidelines, which have been officially adopted by the Brazilian Ministry of Agriculture for the last 24 years.

From root distribution in the soil profile and root density present in each layer, the useful fraction of stored water can be estimated to calculate the effective available water capacity (Yu et al., 2007; Besharat et al., 2010). In this way, a weighting factor can be adjusted for the useful fraction of water in the soil as a function of eucalyptus's root distribution in the soil depth. A total of 100% was used for root density exceeding 0.30 g/dm^3, with a proportional reduction for lower densities.

Therefore, to determine water deficit for each region, the water balances were calculated with the following values for AWC:

- Soil type 1 = 105 mm.
- Soil type 2 = 135 mm.
- Soil type 3 = 150 mm.

From these references, the reference evapotranspiration (ETo) that defines atmospheric demand could be estimated, along with the crop's evapotranspiration potential (ETc), its real evapotranspiration (ETr), the water requirement satisfaction index (WRSI) obtained by the ETr/ETc ratio, and the crop's water deficit (DEF). These values were calculated for all the complete series for the reference period 1981-2010, and for the HadGEM2-ES scenarios for 2011-2020, 2021-2030, and 2031-2040. In general, the HadGEM-ES model is more realistic and captures seasonal and spatial distributions, as well as distribution of the precipitation rate in all regions of South America (Yin et al., 2013), which allows this model to be used safely for future projections.

Water deficit occurs whenever ETr<ETc, and implies stomatal closure and reduced biomass production. Equation 2 is used to calculate the effect of water deficit on eucalyptus productivity,

$$PR = [1 - Ky\,(1 - ETr / Eto * Kc)] * PPf \qquad \text{[Equation 2]}$$

where:

PR = actual productivity
Ky = adjustment coefficient

ETr = actual evapotranspiration of the crop
ETo = reference evapotranspiration
Kc = crop coefficient
PPf = final potential productivity

The value for Ky varies according to the crop and its phenological phase. Normally, the flowering and production formation phases are most sensitive to water stress. This is a well-known coefficient for annual crops (Doorenbos; Kassan, 1994).

For perennial crops, where real productivity is obtained via the mean annual increment (MAI), the climatological indicator can be simplified to seek a direct relationship between PPr and the WRSI, which are also annual.

From the monthly results for each variable, the water balances were defined for the areas of study, and the corresponding WRSI values were determined.

Interpolated maps with the WRSI values were generated for the study region using the climatology of interest for each variable in the reference period and in the four climatic scenarios.

The time series of daily ETo for each location in the study region were used to calculate the frequency of occurrence for the following classes of atmospheric water demand: low (<3 mm/day), medium (3-5 mm/day), high (5-7 mm/day), and very high (>7 mm/day), as described above. The annual WRSI time series for each site in the study region were used to calculate the frequency of occurrence in WRSI classes ranging from very low to very high, in nondimensional intervals of two-tenths.

Results

Climate characteristics in the region of study

Climatology and future climate projections for the study region are presented considering variations in rainfall (Figures 4 and 5; Table 4), temperature (Figures 6 and 7; Table 5), evapotranspiration (Figure 8), and water deficit (Figure 9). It should be noted that there is a decadal oscillation of climatic events in all regions which generates phenomena such as El Niño and La Niña; according to the simulation model, these may be more accentuated in the period 2021-2030. The variation in minimum temperature indicates a reduction in frost risk (temperature <2 degrees centigrade), which is indicated in Figure 10.

The results obtained for the study region indicate that rainfall is not a limiting factor for the growth of eucalyptus. At the end of the HadGEM2-ES model for the 2021-2030 scenario there is an indication of a reduction in rainfall, but it is close to the lower limit for crop growth. This fact, which is repeated in all regions, reflects the decadal oscillation, mainly in the Pacific Ocean.

The results observed in the study region indicate that there may be growth limitation due to lower critical temperature. It should be noted that minimum temperatures below 2 °C are recorded in the study region (Table 6). The optimum temperature (Tot), at its lower limit, is below acceptable values, leading to a reduction in the rate of growth during the winter. The upper basal temperatures are below the upper limits for the four scenarios analyzed (Tables 5 and 7), which means that the maximum temperature will not be a limiting factor for the growth of eucalyptus in the study region.

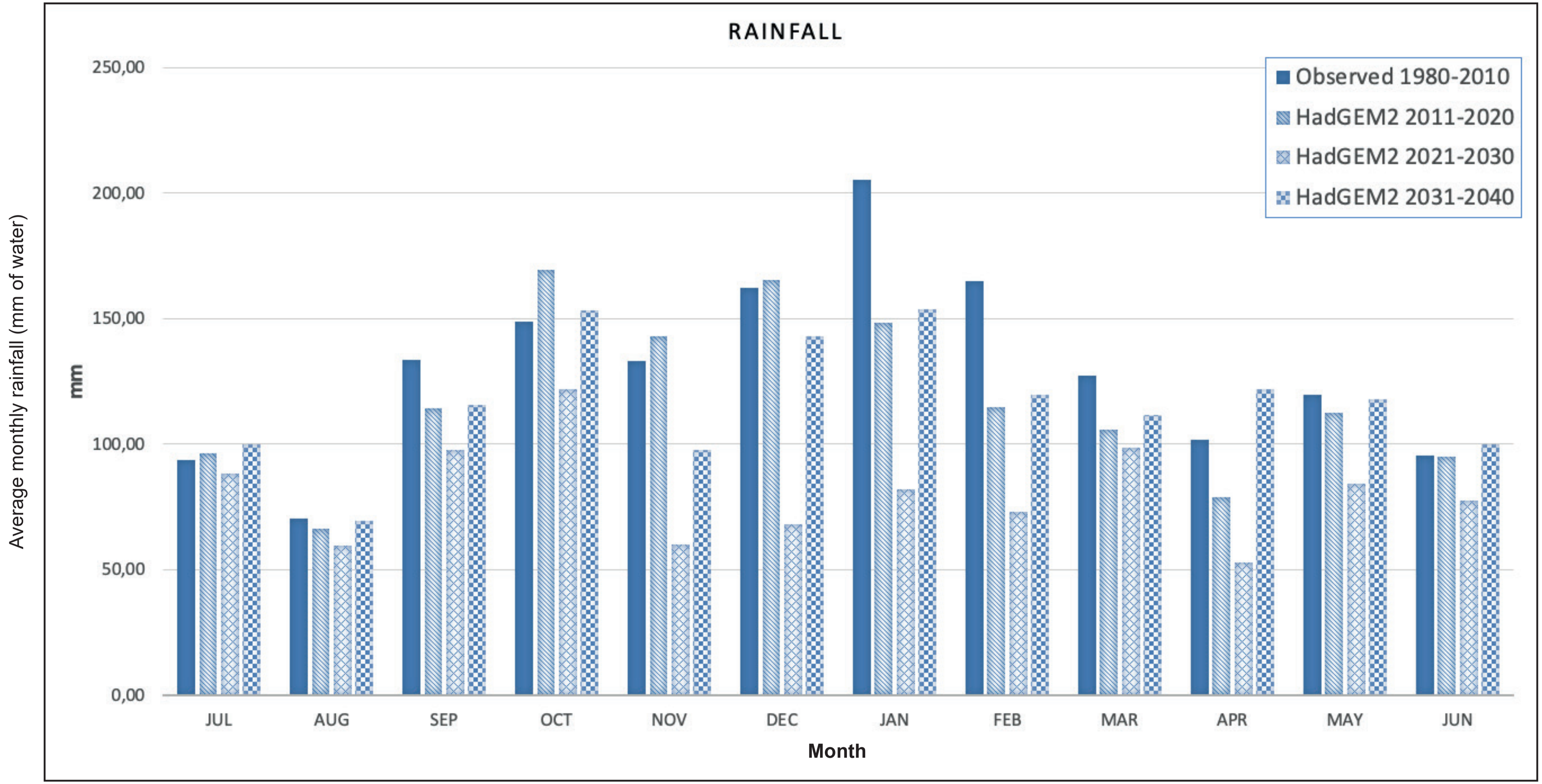
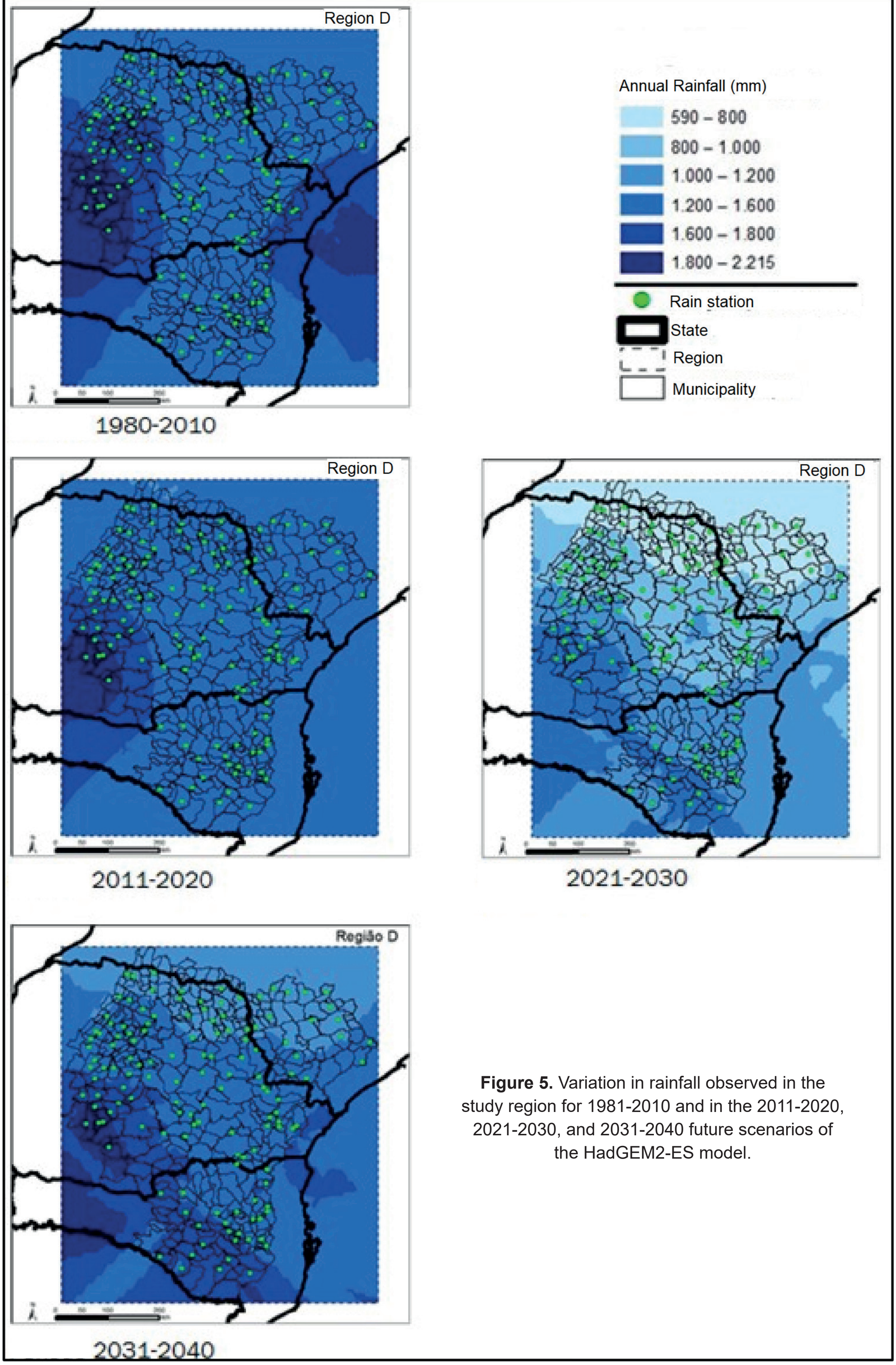


Figure 4. Average monthly rainfall observed in the study region for 1981-2010 and in the HadGEM2-ES scenarios for 2011-2020, 2021-2030, and 2031-2040.



1980-2010

2011-2020

2021-2030

2031-2040

Figure 5. Variation in rainfall observed in the study region for 1981-2010 and in the 2011-2020, 2021-2030, and 2031-2040 future scenarios of the HadGEM2-ES model.

Table 4. Average monthly rainfall during the rainiest four-month period (Quad.+). during the least rainy four-month period (Quad.-). average annual total. and percentage of annual total during the rainiest and least rainy four-month periods observed in the study region for 1981-2010 and in the future scenarios generated by the HadGEM2-ES model for 2011-2020, 2021-2030, and 2031-2041.

Month	Observed 1980-2010	HadGEM2-ES 2011-2020	HadGEM2-ES 2021-2030	HadGEM2-ES 2031-2040
Jul	93.79	96.48	88.41	99.90
Aug	70.58	66.54	59.49	69.44
Set	133.74	114.20	97.63	115.83
Oct	149.07	169.32	121.97	153.48
Nov	133.19	143.26	60.22	97.87
Dec	162.38	165.57	68.17	142.95
Jan	205.18	148.37	81.86	153.72
Feb	165.14	114.97	73.07	119.61
Mar	127.25	105.81	98.49	111.83
Apr	101.77	78.99	52.85	121.87
May	119.83	112.62	84.15	118.02
Jun	95.39	94.85	77.43	99.93
Quad.+	665.90	626.52	332.24	548.03
Quad.-	379.59	370.49	309.49	385.10
Annual Total	1,557.31	1,410.98	963.76	1,404.46
Quad.+ (%)	43	44	34	39
Quad.- (%)	24	26	32	27

▨ Rainy months 🟧 Dry months

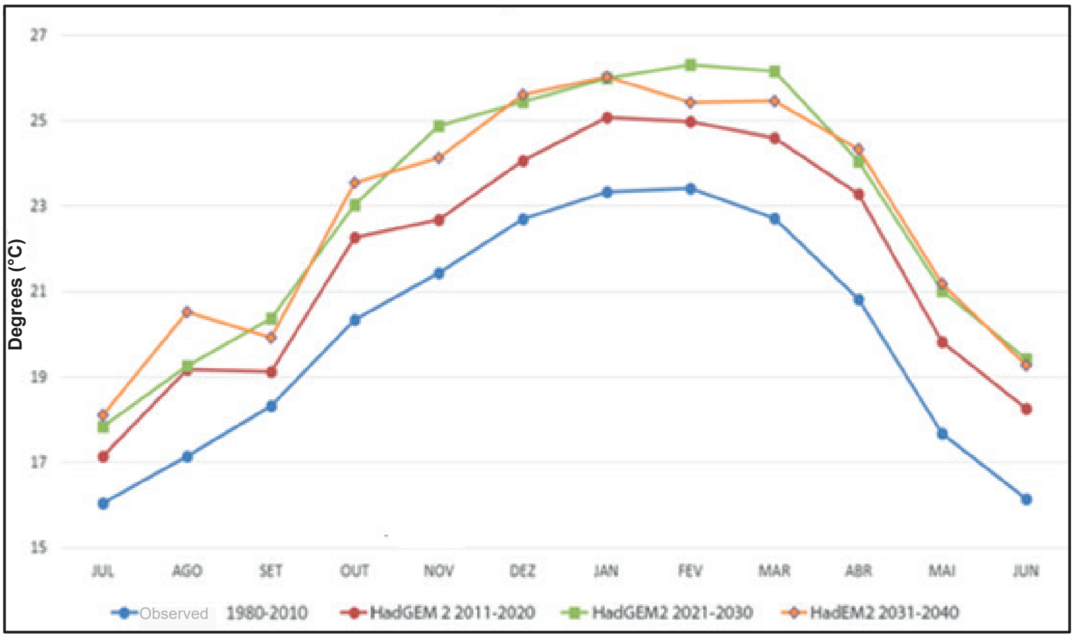
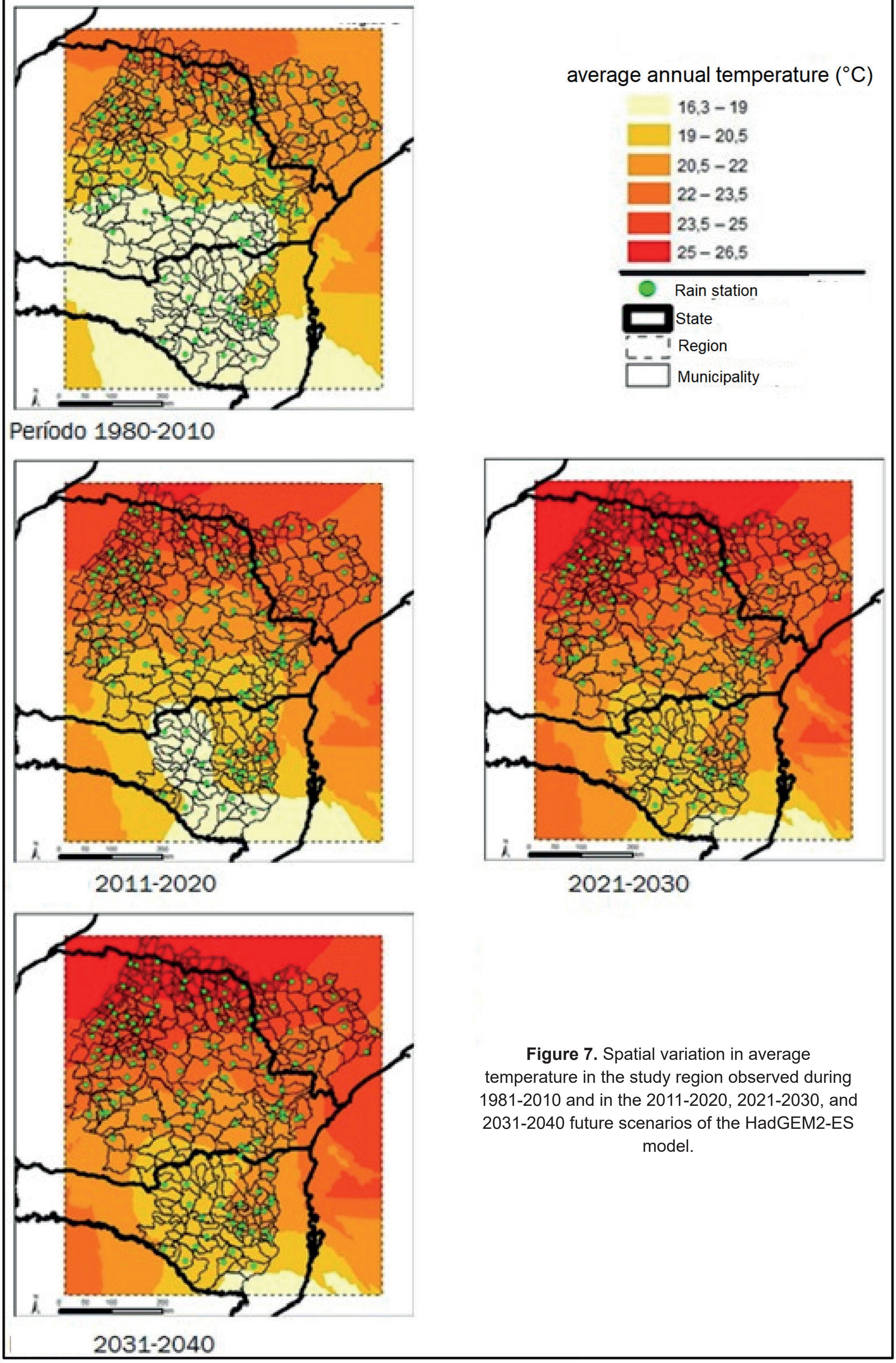


Figure 6. Monthly averages for mean daily temperatures in the study region observed during 1981-2010 and In the 2011-2020, 2021-2030, and 2031-2040 future scenarios of the HadGEM2-ES model.



Período 1980-2010

2011-2020

2021-2030

2031-2040

Figure 7. Spatial variation in average temperature in the study region observed during 1981-2010 and in the 2011-2020, 2021-2030, and 2031-2040 future scenarios of the HadGEM2-ES model.

Table 5. Monthly averages for daily average temperatures (°C) in the study region observed during 1981-2010 and in the 2011-2020, 2021-2030, and 2031-2040 future scenarios of the HadGEM2-ES model.

Month	Observed 1980-2010	HadGEM2-ES 2011-2020	HadGEM2-ES 2021-2030	HadGEM2-ES 2031-2040
Jul	16.04	17.15	17.85	18.11
Aug	17.14	19.18	19.26	20.52
Sep	18.33	19.13	20.37	19.92
Oct	20.33	22.26	23.02	23.55
Nov	21.43	22.67	24.87	24.13
Dec	22.70	24.05	25.44	25.61
Jan	23.32	25.07	25.99	26.02
Feb	23.41	24.98	26.31	25.43
Mar	22.71	24.60	26.15	25.45
Apr	20.82	23.29	24.05	24.32
May	17.68	19.82	21.02	21.19
Jun	16.16	18.26	19.43	19.27

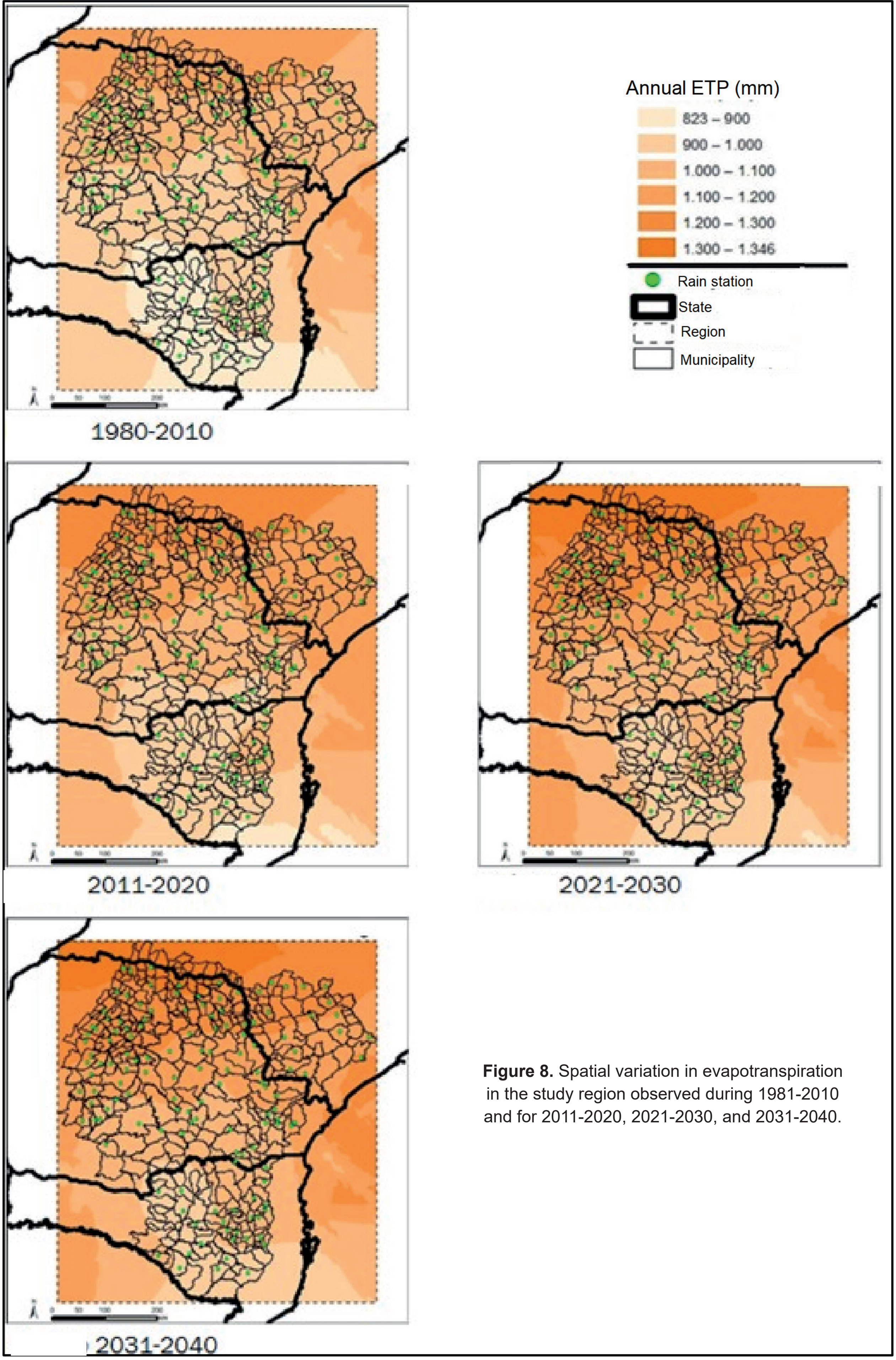


Figure 8. Spatial variation in evapotranspiration in the study region observed during 1981-2010 and for 2011-2020, 2021-2030, and 2031-2040.

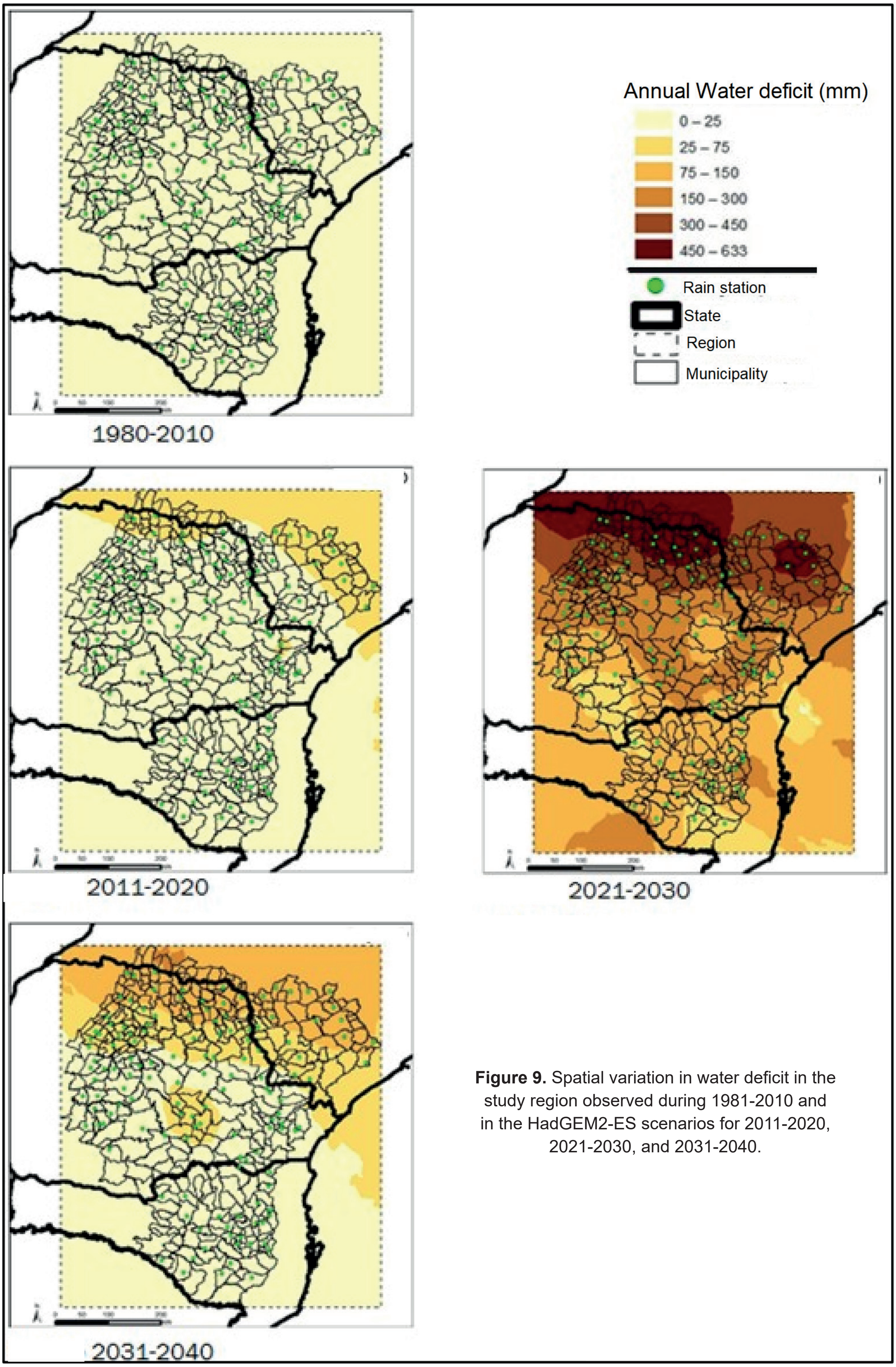


Figure 9. Spatial variation in water deficit in the study region observed during 1981-2010 and in the HadGEM2-ES scenarios for 2011-2020, 2021-2030, and 2031-2040.

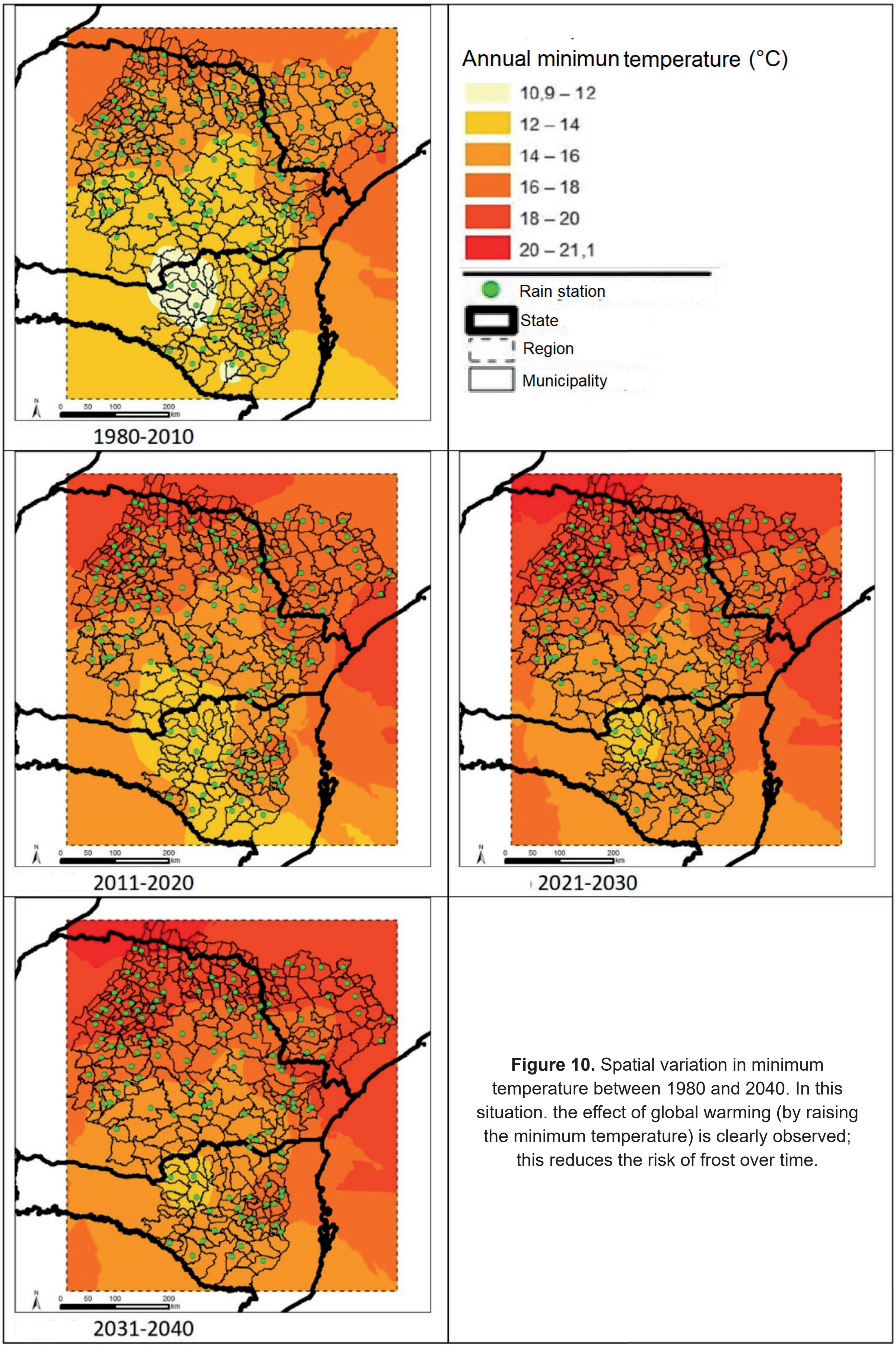


Figure 10. Spatial variation in minimum temperature between 1980 and 2040. In this situation. the effect of global warming (by raising the minimum temperature) is clearly observed; this reduces the risk of frost over time.

Table 6. Temperatures observed in relation to reference cardinal temperatures in the study region (Tci >2 °C; Tbi >10 °C; Tot 16-26 °C; Tbs 21-31 °C; Tcs <31 °C).

Plant size	Temperature cardinal (ºC)				
	Tci	Tbi	Tot	Tbs	Tcs
Seedlings and young plants <50 cm	0	8	25	36	40
Plants >50cm tall	-2	8	25	36	40

Note: Tci: critical low temperature or lethal minimal temperature; Tbi: minimal or inferior base temperature; Tot: optimal temperature; Tbs: maximum or upper base temperature; Tcs: critical high temperature or lethal maximum temperature.

Table 7. Probability of temperatures >34 °C in the study regions. as a percentage.

Year	2010	2015	2025	2035
Study region	1.74	6.14	13.75	11.74

The daily average evapotranspiration values in the study region are not limiting for production of this crop (Figure 8). They are at the lower average limit for water demand, usually associated with partially cloudy days and/or moderate temperatures, indicating water requirements for plants that can be supplied with medium and high storage. The evapotranspiration values obtained do not represent immediate or future risk.

Water deficiency **is not a limiting factor for eucalyptus production**, except for the regions that straddle the border between the states of Paraná and São Paulo, which during 2021-2040 may exceed 300 mm/year (Figure 9). Among the states analyzed, Paraná and Santa Catarina present the best present and future climatic conditions for production of eucalyptus.

Table 8 shows the probability of frost. Note that as the minimum temperature increases over the study periods, the risk of frost decreases from 73% during 1980-2010 to 22% in 2031-2040.

Table 8. Probability of frost.

	Probability of frost occurrence (%)			
	1980-2010	2011-2020	2021- 2030	2031-2040
Study region	0.73	0.36	0.25	0.22

From the climatology, the results indicate differing degrees of vulnerability from either low temperatures or severe water deficit.

Water deficit by soil type

In order to determine water deficit by soil type, retention capacities were considered to be 0.7 mm H_2O/cm for sandy soils, 0.9 mm H_2O/cm for medium soils, and 1.0 mm H_2O/cm for clay soils. Only the results obtained for type 2 soils are presented in this study (Figure 11).

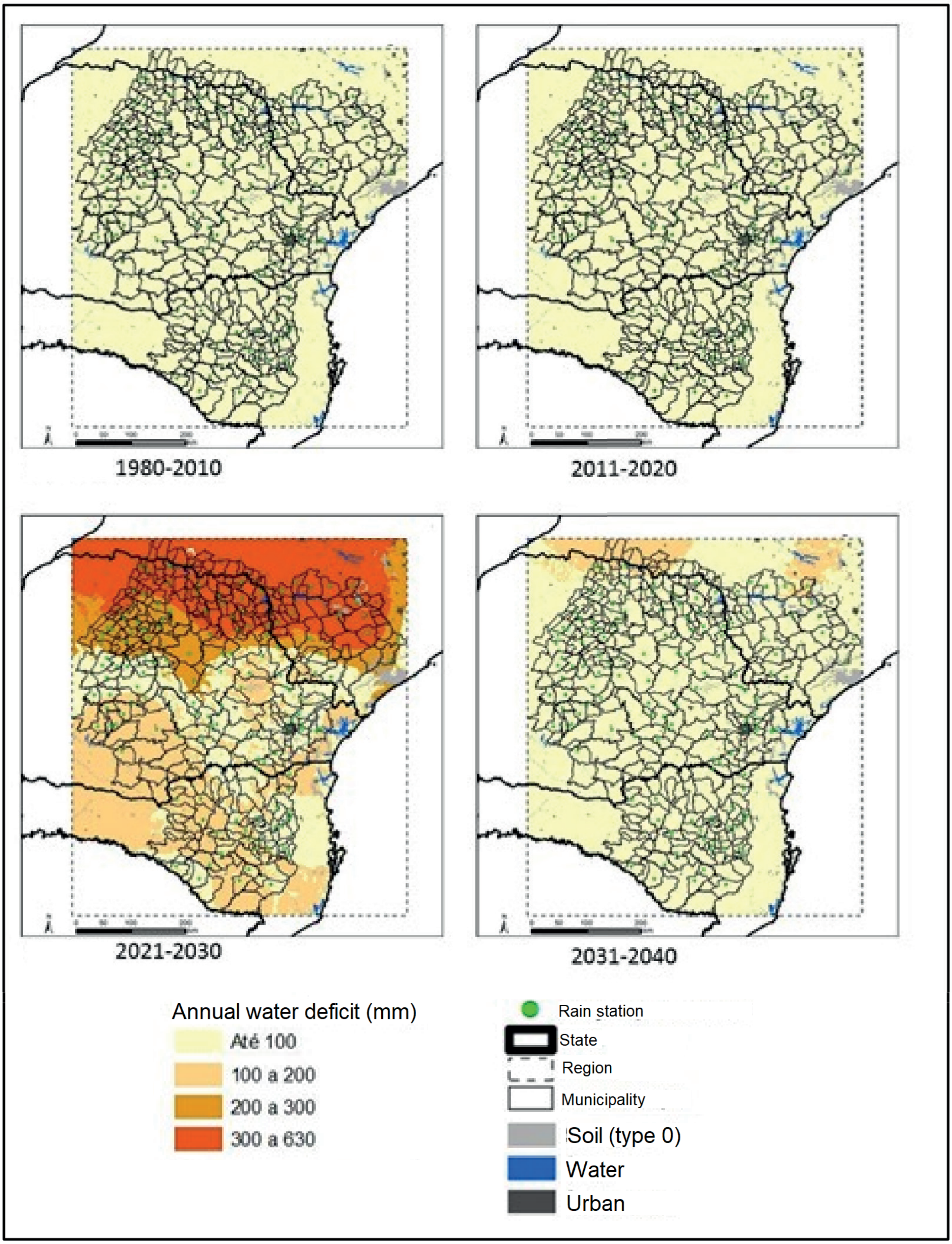


Figure 11. Water deficit in the study region for type 2 soils in 2010 and in the decades 2011-2020, 2021-2030, and 2031-2040.

Productivity analysis

For the productivity analysis, WRSI values were estimated as established in the methodology. For demonstration purposes, the mappings will only be presented for soil type 2.

Table 9 presents the WRSI values for the study region, for all soil types. Due to the increase in temperatures and variation in rainfall over time and in the future (2025 and 2035), the results indicate almost no impact on the WRSI in the study region.

Table 9. Annual variation in water requirement satisfaction index (WRSI) including future projection of global warming for the study region.

Year	Soil		
	Type 1	Type 2	Type 3
1980	0.86	0.86	0.86
1981	0.73	0.74	0.75
1982	0.80	0.81	0.82
1983	0.85	0.85	0.85
1984	0.82	0.83	0.83
1985	0.65	0.67	0.68
1986	0.81	0.82	0.83
1987	0.82	0.83	0.83
1988	0.72	0.74	0.75
1989	0.86	0.86	0.86
1990	0.86	0.86	0.86
1991	0.80	0.81	0.81
1992	0.84	0.84	0.85
1993	0.84	0.85	0.85
1994	0.80	0.81	0.81
1995	0.82	0.83	0.83
1996	0.82	0.83	0.83
1997	0.80	0.81	0.82
1998	0.84	0.85	0.85
1999	0.80	0.81	0.81
2000	0.82	0.83	0.83
2001	0.86	0.86	0.86
2002	0.81	0.82	0.83
2003	0.80	0.81	0.81
2004	0.82	0.82	0.83
2005	0.80	0.81	0.81
2006	0.72	0.74	0.74
2007	0.77	0.78	0.79
2008	0.83	0.83	0.84
2009	0.82	0.83	0.83
2010	0.84	0.84	0.84
2015	0.83	0.84	0.84
2025	0.84	0.84	0.84
2035	0.83	0.83	0.83

For the purpose of indicating the variations, the central value of the WRSI values for the series was used. For example, for the 2011-2020 series the central WRSI value of 2015 was used; this was done for the other series. The closer the WRSI is to the 1.0, the lower the impact on productivity.

Figure 12 shows the variability in WRSI as a function of time for the periods 1980-2010, 2011-2020, 2021-2030, and 2031-2040. The results achieved for soil type 2 are shown here.

For type 2 soils, WRSI will become increasingly restrictive as time passes. In the northwest of Paraná and southwestern São Paulo, the WRSI may be below 50%, meaning that plantations will have half the volume of water they need to attain their potential productivity. A loss of productivity is consequently expected in this region, with climatic restriction due to more frequent warm spells in winter and longer dry periods.

In the overall average for the study region, when the WRSI is related to the potential mean annual increment of 57 m^3/ha/year, the impact on eucalyptus productivity was less than 5% for type 2 soils (Table 10).

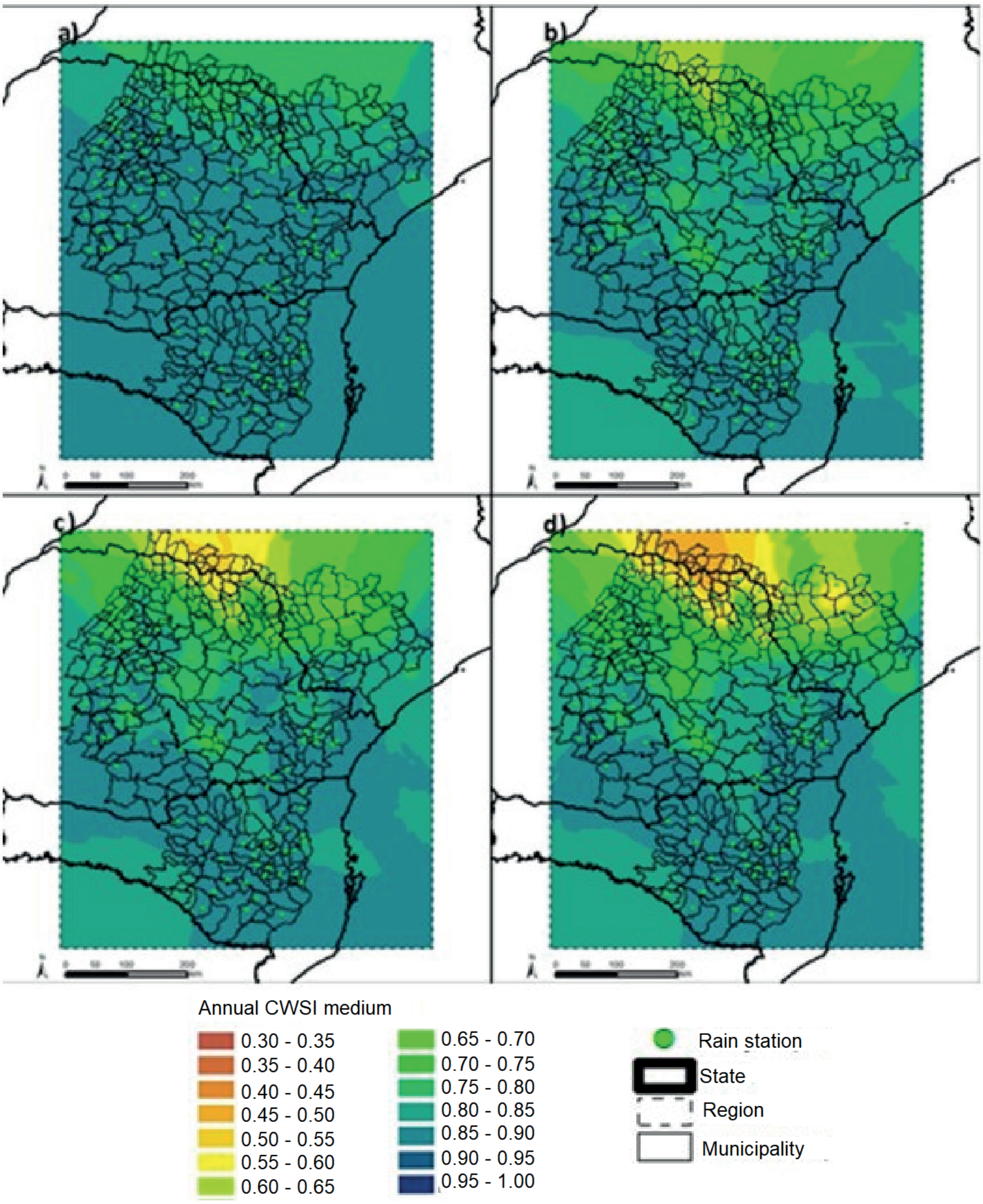


Figure 12. Spatial and temporal variation of WRSI values for type 2 soils in the study region for the following years: a) 2010; b) 2015; c) 2025; d) 2035.

Table 10. Mean annual increment (MAI) value adjusted according to variation in water requirement satisfaction index (WRSI) in type 2 soils. considering a potential MAI of 57 m^3/ha/year for the region analyzed.

Year	Study region
1980	57.0
1981	49.0
1982	53.8
1983	56.5
1984	55.0
1985	44.5
1986	54.6
1987	55.0
1988	49.2
1989	56.9
1990	57.1
1991	53.6
1992	55.9
1993	56.1
1994	53.4
1995	54.9
1996	55.1
1997	53.9
1998	56.1
1999	53.6
2000	54.9
2001	56.9
2002	54.5
2003	53.5
2004	54.6
2005	53.7
2006	48.8
2007	51.9
2008	55.3
2009	55.0
2010	55.7
2015	55.5
2025	55.7
2035	55.2
Mean	54.2
Maximum	57.1
Minimum	44.5

The temporal variation in MAI for the period 1980-2040, considering impact on eucalyptus productivity due to increased temperature and rainfall variation, was determined by the HadGEM2-ES model for the periods 1981-2010, 2011-2020, 2021-2030, and 2031-2040 for type 2 soils (Figure 13).

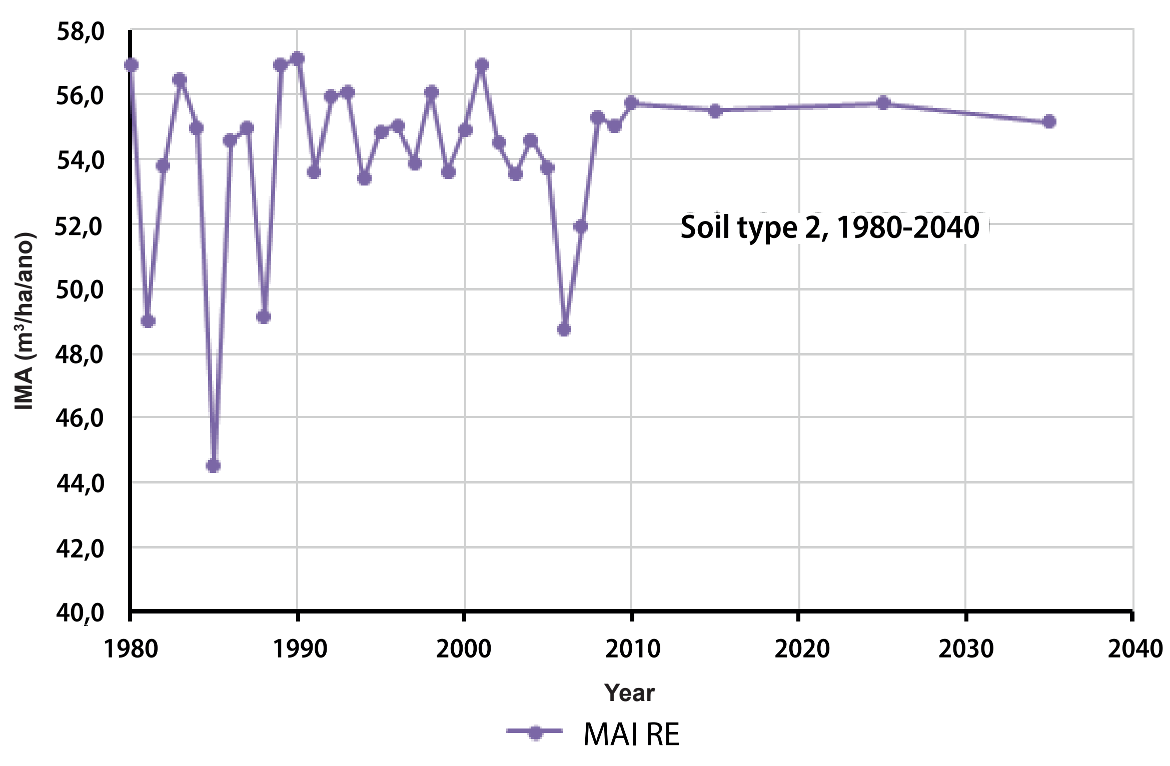


Figure 13. Temporal variation in adjusted mean annual increment values (MAI RE). considering the impact of increased temperature and rainfall variation on eucalyptus productivity determined by the HadGEM2-ES2 model for the periods 1981-2010, 2011-2020, 2021-2030, and 2031-2040, for type 2 soils (texture).

Tables 11, 12, and 13 show the probability of occurrence for annual WRSI and future average WRSI values in the region for the three soil types, considering the annual averages and the least rainy and rainiest four-month periods.

Table 11. Probability of occurrence for annual and mean water requirement satisfaction index (WRSI) at present (2015) and in the future in the study region according to soil type. considering mean annual rainfall values.

Indicator		Soil 1	Soil 2	Soil 3
		Probability (%)		
WRSI	>0.5	0.0	0.0	0.0
	0.5-6.0	0.0	0.0	0.0
	6.1-7.0	3.2	3.2	3.2
	7.1-8.0	25.8	12.9	12.9
	>8.1	71.0	83.9	83.9
		WRSI		
Years	2015	0.83	0.84	0.84
	2025	0.84	0.84	0.84
	2035	0.83	0.83	0.83

Table 12. Probability of occurrence for annual and mean water requirement satisfaction index (WRSI) in the future in the study region according to soil type. considering the least rainy four-month period.

Indicator		Soil 1	Soil 2	Soil 3
		Probability (%)		
WRSI	>0.5	3.2	3.2	3.2
	0.5-6.0	9.7	3.2	3.2
	6.1-7.0	19.4	16.1	12.9
	7.1-8.0	67.7	77.4	80.6
	>8.1	0.0	0.0	0.0
		WRSI		
Years	2015	0.77	0.78	0.78
	2025	0.78	0.79	0.79
	2035	0.75	0.76	0.76

Table 13. Probability of occurrence for annual and mean water requirement satisfaction index (WRSI) at present (2015) and in the future in the study region according to soil type. considering the rainiest four-month period.

Indicator		Soil 1	Soil 2	Soil 3
		Probability (%)		
WRSI	>0.5	0.0	0.0	0.0
	0.5-6.0	0.0	0.0	0.0
	6.1-7.0	3.2	3.2	0.0
	7.1-8.0	3.2	0.0	3.2
	>8.1	93.5	96.8	96.8
		WRSI		
Years	2015	0.90	0.90	0.90
	2025	0.90	0.90	0.90
	2035	0.86	0.86	0.87

Impact on eucalyptus productivity in Klabin’s forest production units

Itapetininga (SP)

In order to analyze the critical conditions in Itapetininga, in São Paulo, the water balance was initially established for the years 1980-2015 using daily weather data.[1] As a climatic water balance, the standard AWC of 100 mm was established. Table 14 presents the input parameters for the water balance, and Table 15 shows the monthly mean parameters for establishing the water balance.

Table 14. Input parameters for the Thornthwaite water balance for eucalyptus cultivation in Itapetininga. SP. 1980-2015.

Location	
Latitude (degrees)	-23.63 S
Altitude (meters)	650
Soils and climate	
Available water capacity (mm)	100
Estimated temperature (°C)	Mean temperature
I index*	106.88
A index*	2.28

* The I and A indexes are adjustment indexes for the Thornthwaite water balance.

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[1] The period was extended until 2015. due to the productivity curves that will be analyzed later.

Table 15. Monthly average climate data for establishing the water balance In Itapetininga. SP.

Month	Rainfall (mm)	Temperature (°C)		
		Maximum	Minimum	Mean
January	230	28.70	19.15	23.92
February	175	29.26	19.28	24.27
March	138	28.41	18.52	23.46
April	73	26.79	16.84	21.82
May	78	23.99	13.93	18.96
June	64	22.98	12.29	17.63
July	58	23.10	11.85	17.48
August	36	24.93	12.70	18.81
September	89	25.46	14.13	19.80
October	116	26.93	16.06	21.49
November	121	27.79	17.10	22.44
December	180	28.51	18.36	23.44

Table 16 presents the probability of ETR occurrence in the city of Itapetininga (SP) from the months of January to December, considering soil types 2 and 3 (since type 1 soils are very uncommon in this municipality). In general, no unfavorable conditions for forestry were observed, and the possibility of ETR >5 mm is low, indicating that eucalyptus is a crop that resists high temperatures. But during the months of May to July, it is almost certain that ETR will be up to 3 mm, regardless of soil type.

Table 16. Probability of ETR occurrence in Itapetininga. SP. 1980-2015. as a percentage.

Month	ETR (mm)							
	0-3	3-5	5-7	> 7	0-3	3-5	5-7	> 7
	Soil type 2				Soil type 3			
	Probability of ETR occurrence (%)							
January	3	69	28	0	0	75	25	0
February	3	91	6	0	3	91	6	0
March	3	97	0	0	3	97	0	0
April	94	6	0	0	94	6	0	0
May	100	0	0	0	100	0	0	0
June	100	0	0	0	100	0	0	0
July	100	0	0	0	100	0	0	0
August	94	6	0	0	94	6	0	0
September	47	53	0	0	44	56	0	0
October	22	75	3	0	22	75	3	0
November	22	70	8	0	22	70	8	0
December	0	69	31	0	0	69	31	0

Table 17 shows the future ETR values in millimeters from January-December for the years 2015, 2025 and 2035, considering soil types 2 and 3 (because, as mentioned, type 1 soils are uncommon in the region). The projected water demand for the future reaches its highest values in December and January, when it can exceed 5 mm. In the following months, ETR demand is reduced until May/

June and gradually begins to rise again in the following months. The lowest ETR was projected for April to August, when it is 2-3 mm regardless of soil type.

Table 17. Future ETR from January-December 2015, 2025, and 2035 in Itapetininga, SP, in millimeters. considering soil types 2 and 3.

Month	Type 2			Type 3		
	2015	2025	2035	2015	2025	2035
	Future ETR (mm)					
January	5.11	5.29	5.47	5.11	5.29	5.47
February	4.90	4.84	4.48	4.90	4.86	4.53
March	4.01	3.85	3.69	4.02	3.88	3.73
April	2.96	2.85	2.72	2.99	2.88	2.76
May	2.37	2.32	2.21	2.37	2.33	2.23
June	2.27	2.38	2.49	2.27	2.38	2.49
July	2.56	2.66	2.76	2.56	2.66	2.76
August	2.86	2.86	2.86	2.92	2.94	2.94
September	2.99	3.14	3.30	3.05	3.20	3.36
October	4.19	3.78	3.33	4.23	3.85	3.43
November	4.04	3.45	2.81	4.10	3.53	2.90
December	5.37	5.18	4.45	5.37	5.20	4.48

Table 18 shows the normal annual water balance for the period 1980-2015. Notably, the water deficit is zero or very low all year round, and there is a water surplus from January to March. This illustrates the importance of ensuring that eucalyptus is cultivated in well-drained soils.

Table 18. Normal annual water balance for 1980-2015 in the municipality of Itapetininga. SP.

Month	Rainfall	Deficit	Storage	Surplus
	mm water			
January	230	0	100	26
February	175	0	100	46
March	138	0	100	21
April	73	-1	87	0
May	78	0	99	0
June	64	0	100	2
July	58	-1	85	0
August	36	-26	43	0
September	89	-18	33	0
October	116	-19	25	0
November	121	-22	19	0
December	180	0	42	0

With these results, the graph of the variation in water balance at the Itapetininga production unit can be generated (Figure 13). As shown in Figure 14, no marked water deficiency was observed. Because the calculation utilized the AWC value of 100 mm, which is the normal climatic water balance, the results will be even better for the 105 mm, 135 mm, and 150 mm AWC values that correspond to soil types 1, 2, and 3, respectively.

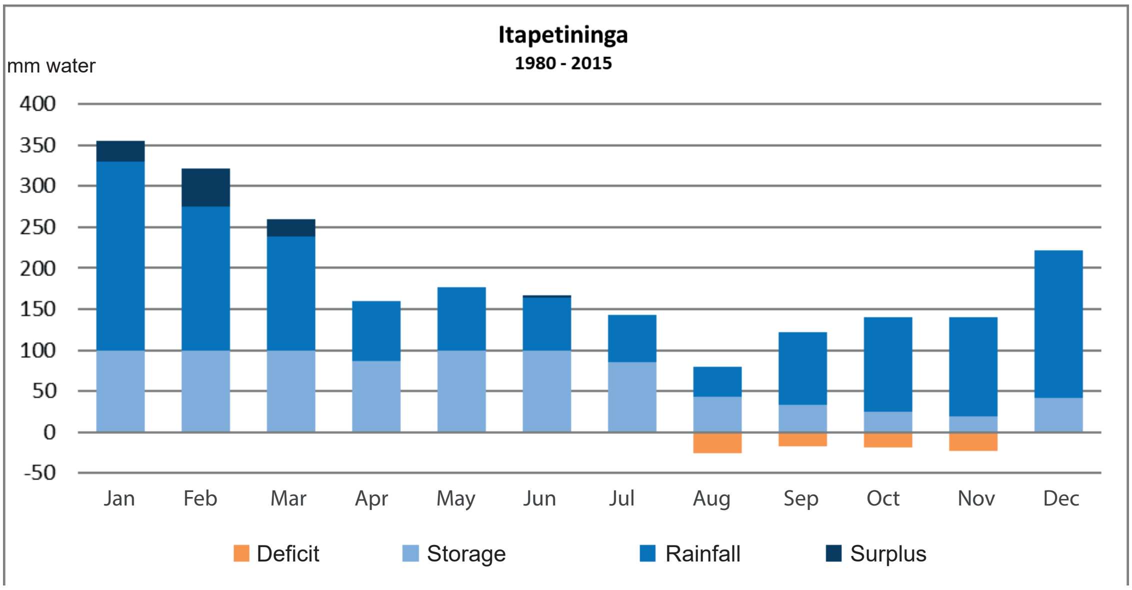

Figure 14. Normal water balance for Itapetininga (SP), 1980-2015.

To verify the impact of global warming in future years over the 2010-2020, 2020-2030, and 2030-2040 periods, the water balances were calculated for these years, considering the central year of each series. The results are shown in Figures 15, 16, and 17.

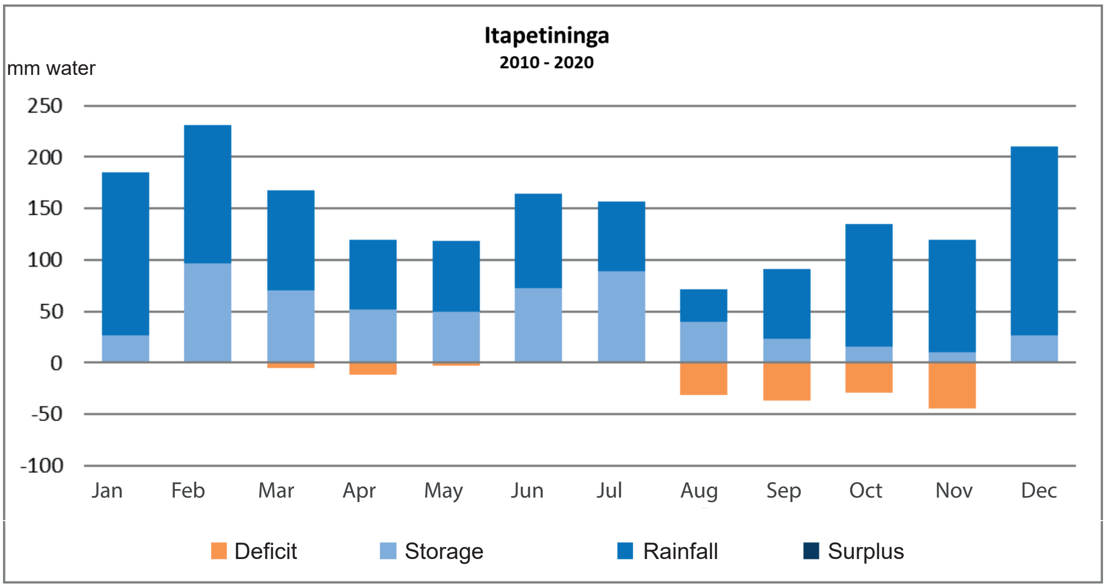

Figura 15. Balanço hídrico em Itapetininga (SP), para o período de 2011 a 2020.

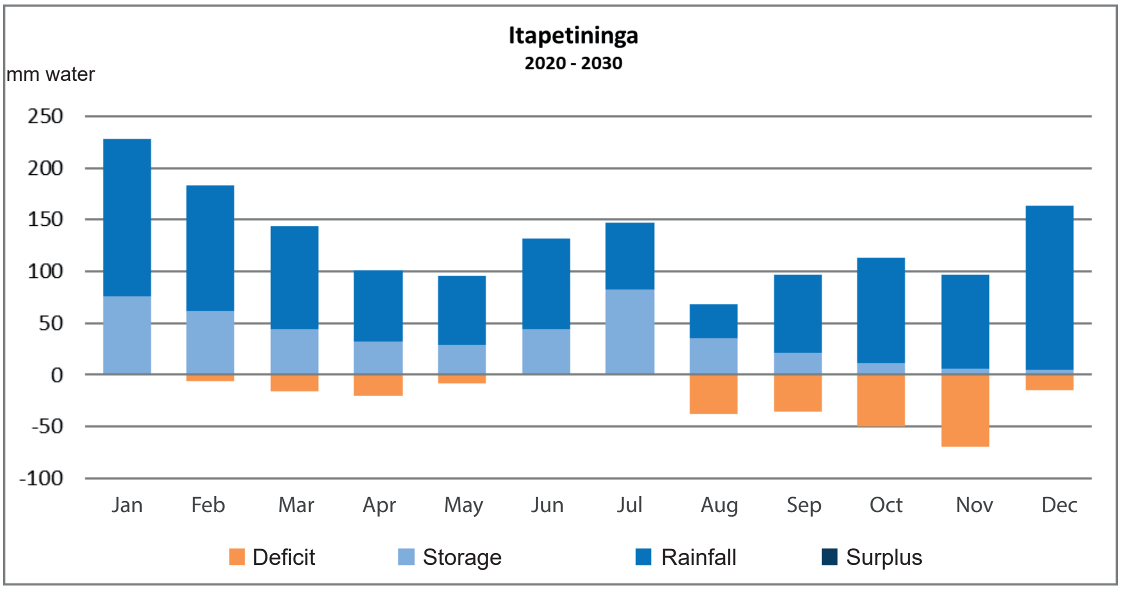

Figure 16. Water balance in Itapetininga (SP), 2020-2030.

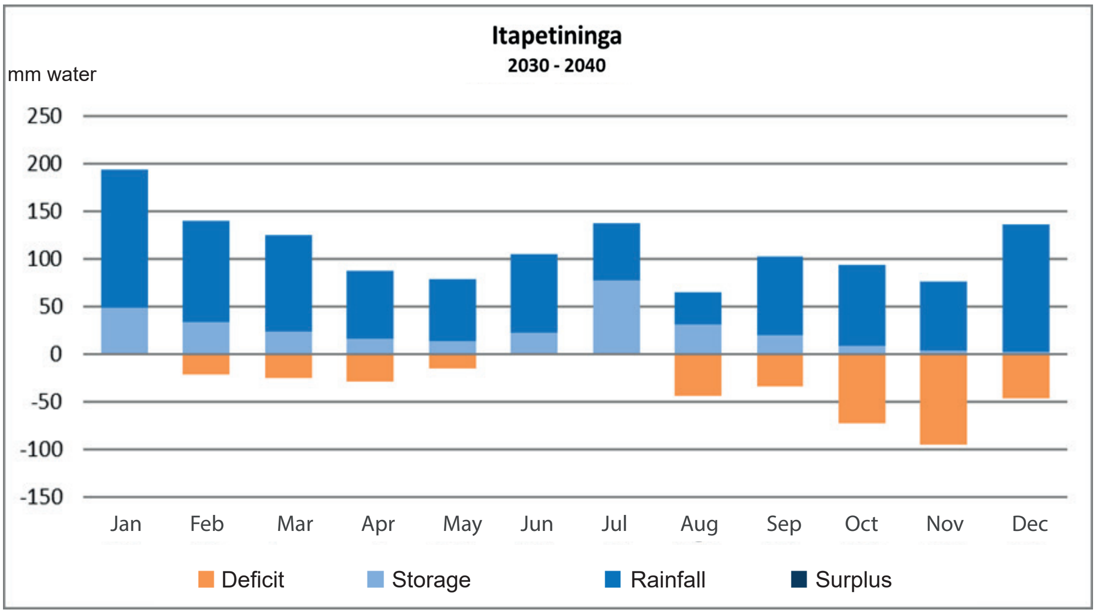

Figure 17. Water balance in Itapetininga (SP), 2030-2040.

With the increase in temperature as a function of the estimate obtained from the HadGEM2 model, **the water deficit exceeds the critical value of 200 mm/year.** Productivity may be negatively impacted as a result of this deficit.

In the analysis of extreme phenomena during the 1980-2015 period, 19, 26, 13, and 12 occurrences of temperatures exceeding 34 °C were observed in the months of September, October, November, December, and January, respectively. There is no marked tendency toward increased extreme heat wave phenomena in the region. The same can be said for frost risk. Among the 13,601 minimum temperature values analyzed, 16 were screen temperatures below 2 °C, which means -1.34 °C on the surface of the plant (frost). As for maximum rainfall, only one event was observed in 35 years with rain exceeding 100 mm, and as a result there was no flooding of the soil that could damage the crop.

Table 19 shows the frequencies of consecutive days without rainfall during the 1980-2015 period. These periods without rain can occur in any month. When they occur during a dry period, accompanied by intense heat (25-35 °C), strong sun, and low relative humidity in the rainy season or even in winter, this meteorological phenomenon is considered a warm dry spell (known locally as a *veranico*). These are critical periods that can be harmful to agriculture. Over 35 years of analysis in Itapetininga (SP), occurrence frequencies of at least 43% for these warm dry spells lasting over 30 days were seen in the months of January, March, and December (Table 19). These can cause damage to eucalyptus.

Table 19. Frequencies of days without rain observed during 1980-2015 in Itapetininga (SP). highlighting warm spells (*veranicos*). expressed as a percentage.

Month	Length of period without rain (days)						
	Up to 5	6-10	11-15	16-20	21-25	26-30	31-35
January	26	63	6	3	0	0	43*
February	23	43	20	0	0	43	0
March	23	63	26	3	3	0	43*
April	11	43	29	9	3	49	0
May	11	26	20	20	3	3	46
June	14	40	23	3	3	49	0
July	6	20	17	11	6	0	51
August	14	23	23	11	6	3	46
September	11	37	17	6	6	51	0
October	20	31	9	9	3	3	43
November	11	49	11	3	6	49	0
December	29	71	3	3	0	0	43*

* Warm dry spell (*veranico*).

From the MAI, CAI, and commercial production data provided by Klabin, growth curves and relations with WRSI could be constructed for the municipality of Itapetininga. As illustrated in Figure 18 maximum CAI growth occurs in Itapetininga in the third year after planting, and maximum MAI occurs in the fourth year after planting.

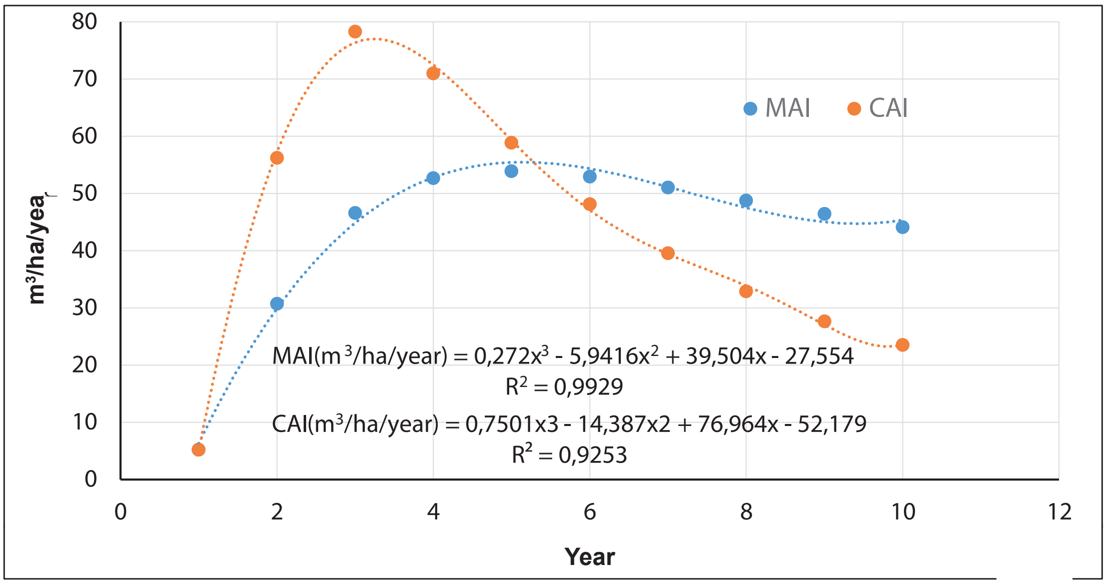

Figure 18. Adjusted growth curves for MAI and CAI of *Eucalyptus grandis* and *Eucalyptus urophylla* in Itapetininga (SP), 2005-2015.

Using meteorological parameters and field data provided by Klabin, MAI and WRSI could be calculated for the first seven years of eucalyptus culture in Itapetininga (SP) (Table 20).

With the WRSI for this period, the growth curve was then adjusted correspondingly (i.e. estimating the MAI from a given WRSI value). The calculation to determine the maximum MAI extended up to year seven, which was considered the main harvest year.

The relationship between WRSI and MAI is shown in Figure 19. The WRSI accounts for 93% of the MAI variation, which is a good relationship between observed MAI and estimated WRSI. The temporal variation in MAI for the period 1980-2040 is shown in Figure 20.

Table 20. Variation in MAI and WRSI after adjusting the curves, for the first seven years of eucalyptus cultivation in Itapetininga (SP).

Year	MAI (m^3/ha/year)	WRSI
1st	5	0.13
2nd	31	0.30
3rd	47	0.38
4th	53	0.52
5th	54	0.73
6th	53	0.73
7th	51	0.69

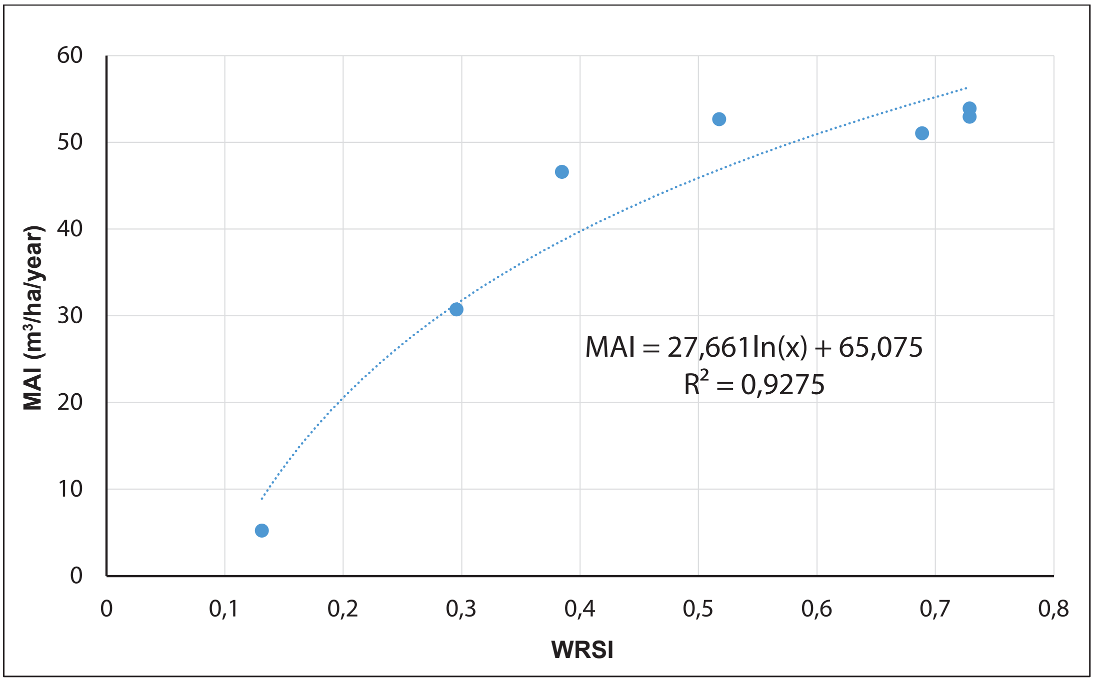

Figure 19. MAI value adjusted according to WRSI in Itapetininga (SP), 2005-2015.

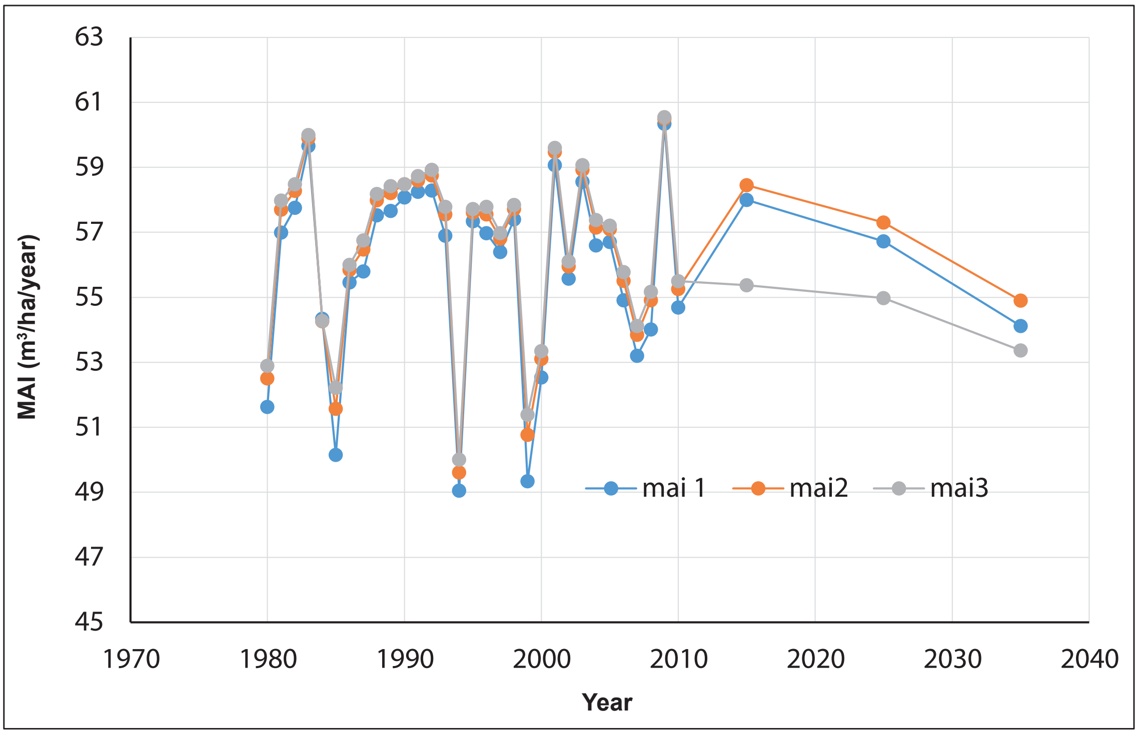

Figure 20. Temporal variation in mean annual increment (MAI) in Itapetininga (SP) 1980-2040, considering soil types 1 (MAI1), 2 (MAI2), and 3 (MAI3).

Annual variations in WRSI are more evident in the years 1980, 1985, 1994, and 1999, when the MAI value is lower (Table 21). In this case the annual rainfall is 1357 mm, and the difference in rainfall for the drier years is approximately 400 mm. This reduction can be explained by the reduction in rainfall (supply) observed in the region, as seen in the data in Table 22. Note that the HadGEM2 model indicates a very slight scenario of reduced productivity (by 1-5 m^3/ha/year) in the 30-year interval.

Table 21. Annual variation in WRSI and MAI (m^3/ha/year) for soil types 1. 2. and 3 in Itapetininga (SP) during the 1980-2035 period. with years with less rainfall highlighted in yellow.

Year	WRSI1	WRSI2	WRSI3	MAI 1	MAI 2	MAI 3
1980	0.61	0.63	0.64	51.63	52.50	52.90
1981	0.74	0.76	0.77	57.00	57.70	57.97
1982	0.76	0.78	0.79	57.76	58.28	58.48
1983	0.82	0.83	0.83	59.65	59.90	59.99
1984	0.67	0.67	0.67	54.34	54.26	54.28
1985	0.58	0.61	0.62	50.16	51.57	52.21
1986	0.70	0.71	0.72	55.46	55.85	56.00
1987	0.71	0.73	0.74	55.80	56.47	56.75
1988	0.76	0.77	0.78	57.52	57.99	58.19
1989	0.76	0.78	0.78	57.66	58.21	58.43
1990	0.77	0.79	0.79	58.07	58.48	58.48
1991	0.78	0.79	0.79	58.25	58.59	58.73
1992	0.78	0.79	0.80	58.29	58.75	58.93
1993	0.74	0.76	0.77	56.89	57.55	57.78
1994	0.55	0.57	0.57	49.05	49.61	50.01
1995	0.75	0.76	0.76	57.35	57.61	57.72
1996	0.74	0.76	0.77	56.98	57.55	57.79
1997	0.73	0.74	0.74	56.40	56.81	56.98
1998	0.75	0.76	0.77	57.40	57.72	57.84
1999	0.56	0.59	0.60	49.34	50.77	51.39
2000	0.63	0.64	0.65	52.54	53.10	53.34
2001	0.80	0.82	0.82	59.07	59.48	59.60
2002	0.71	0.72	0.72	55.58	55.95	56.10
2003	0.79	0.80	0.80	58.56	58.93	59.07
2004	0.73	0.75	0.75	56.60	57.15	57.38
2005	0.74	0.75	0.75	56.71	57.10	57.20
2006	0.69	0.70	0.71	54.91	55.51	55.78
2007	0.65	0.66	0.67	53.20	53.85	54.12
2008	0.67	0.69	0.69	54.01	54.91	55.17
2009	0.84	0.85	0.85	60.34	60.49	60.55
2010	0.68	0.70	0.70	54.69	55.26	55.50
2015*	0.77	0.78	0.70	58.00	58.45	55.37
2025*	0.74	0.75	0.69	56.72	57.31	54.98
2035*	0.67	0.69	0.65	54.12	54.90	53.37

*Values estimated by the HadGEM2 model.

Table 22. Total annual rainfall values for the Itapetininga region (SP) during the years in which the model estimated lower MAI values. in millimeters.

Year	Annual rainfall (mm)	Year characterized as
1980	1,156	Dry
1985	968	Dry
1994	927	Dry
1999	932	Dry

Telêmaco Borba (PR)

In order to analyze the critical conditions for the city of Telêmaco Borba, in Paraná, the water balance was initially established for the years 1980-2015 using daily weather data.[2] As a climatic water balance, AWC of 100 mm was established. Table 23 lists the input parameters.

Table 23. Input parameters for the Thornthwaite water balance for eucalyptus cultivation in Telêmaco Borba (PR). 1980-2015.

Location	
Latitude (degrees)	-24.13 S
Altitude (meters)	741
Solo e clima	
Available water capacity (mm)	100
Estimated temperature (°C)	Mean temperature
I index*	99.83
A index*	2.12

*A and I indexes are part of the adjustment for the Thornthwaite water balance.

Table 24 lists the average monthly parameters to establish the water balance.

Table 24. Monthly average climate data for establishing the water balance in Telêmaco Borba (PR).

Month	Rainfall (mm)	Temperature (ºC)		
		Maximum	Minimum	Mean
January	215	28.70	19.15	23.92
February	166	29.26	19.28	24.27
March	121	28.41	18.52	23.46
April	102	26.79	16.84	21.82
May	123	23.99	13.93	18.96
June	114	22.98	12.29	17.63
July	92	23.10	11.85	17.48
August	66	24.93	12.70	18.81
September	138	25.46	14.13	19.80
October	154	26.93	16.06	21.49
November	136	27.79	17.10	22.44
December	174	28.51	18.36	23.44

Table 25 presents the probability of occurrence for ETR in the city of Telêmaco Borba (PR) from the months of January to December, considering soil types 2 and 3 (since type 1 soils are very uncommon in this region). Note that in general, there are no conditions unfavorable for forestry in this region, even for crops that are more resistant to high temperatures.

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[2] The period was extended until 2015 as a function of the productivity curves, which will be analyzed later.

Table 25. Probability of ETR occurrence in Telêmaco Borba (PR) during 1980-2015. as a percentage.

Month	ETR (mm)							
	0-3	3-5	5-7	> 7	0-3	3-5	5-7	> 7
	Soil type 2				Soil type 3			
	Probability of ETR occurrence (%)							
January	6	69	25	0	6	69	25	0
February	0	100	0	0	0	100	0	0
March	3	97	0	0	3	97	0	0
April	94	6	0	0	94	6	0	0
May	100	0	0	0	100	0	0	0
June	100	0	0	0	100	0	0	0
July	100	0	0	0	100	0	0	0
August	92	8	0	0	92	8	0	0
September	31	69	0	0	31	69	0	0
October	8	92	0	0	8	92	0	0
November	6	86	8	0	6	86	8	0
December	3	67	31	0	3	67	31	0

Table 26 shows the future ETR values in millimeters from January-December of the years 2015, 2025 and 2035, considering soil types 2 and 3 (because, as mentioned, type 1 soils are uncommon).

Table 26. Future evapotranspiration (ETR) from January-December 2015. 2025. and 2035. in Telêmaco Borba (PR). considering soil types 2 and 3. in millimeters.

Month	Type 2			Type 3		
	2015	2025	2035	2015	2025	2035
	Future ETR (mm)					
January	4.98	5.63	5.41	4.98	5.63	5.58
February	4.82	4.51	4.10	4.83	4.56	4.16
March	3.97	3.70	3.42	4.00	3.75	3.48
April	2.94	3.08	3.37	2.96	3.10	3.37
May	2.35	2.46	2.57	2.35	2.46	2.57
June	2.14	2.23	2.32	2.14	2.23	2.32
July	2.36	2.45	2.54	2.36	2.45	2.54
August	3.33	3.45	3.13	3.36	3.33	2.93
September	3.91	4.00	4.01	3.91	4.01	4.02
October	4.97	5.12	4.94	4.97	5.13	4.98
November	5.27	4.85	3.97	5.30	4.91	4.08
December	5.56	5.07	4.35	5.56	5.12	4.42

Table 27 shows the normal annual water balance for the period 1980-2015 in Telêmaco Borba (PR). Notably, the water deficit is zero or very low throughout the year, and there is a water surplus.

Table 27. Normal annual water balance for 1980-2015 in the municipality of Telêmaco Borba (PR).

Month	Rainfall	Deficit	Storage	Surplus
	mm			
January	215	0	100	66
February	166	0	100	43
March	121	0	100	4
April	102	0	100	16
May	123	0	100	61
June	114	0	100	59
July	92	0	100	25
August	66	-5	72	0
September	138	0	99	0
October	154	0	100	14
November	136	-1	87	0
December	174	0	100	3

With these results, the situation is favorable for cultivation, with climatic restrictions in the dry period when the ETR is 2.0-3.0 mm, indicating low water demand. No water deficit was observed.

Finally, Figure 21 presents a complete summary of the water balance for Telêmaco Borba from 1980 to 2015. Because the calculation considered an AWC value of 100 mm, which is the normal water balance, the results will be even better for the 105 mm, 135 mm, and 150 mm AWC values that correspond to soil types 1, 2, and 3.

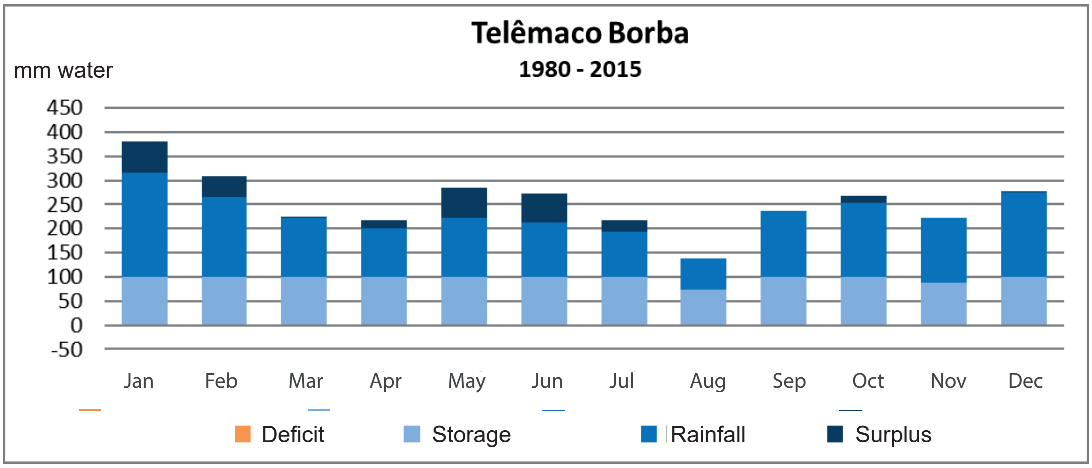

Figure 21. Normal water balance for Telêmaco Borba (PR). 1980-2015.

To verify the impact of global warming in future years over the 2010-2020, 2020-2030, and 2030-2040 periods, the water balances were calculated for these years, considering the central year of each series. The results are shown in Figures 22, 23, and 24.

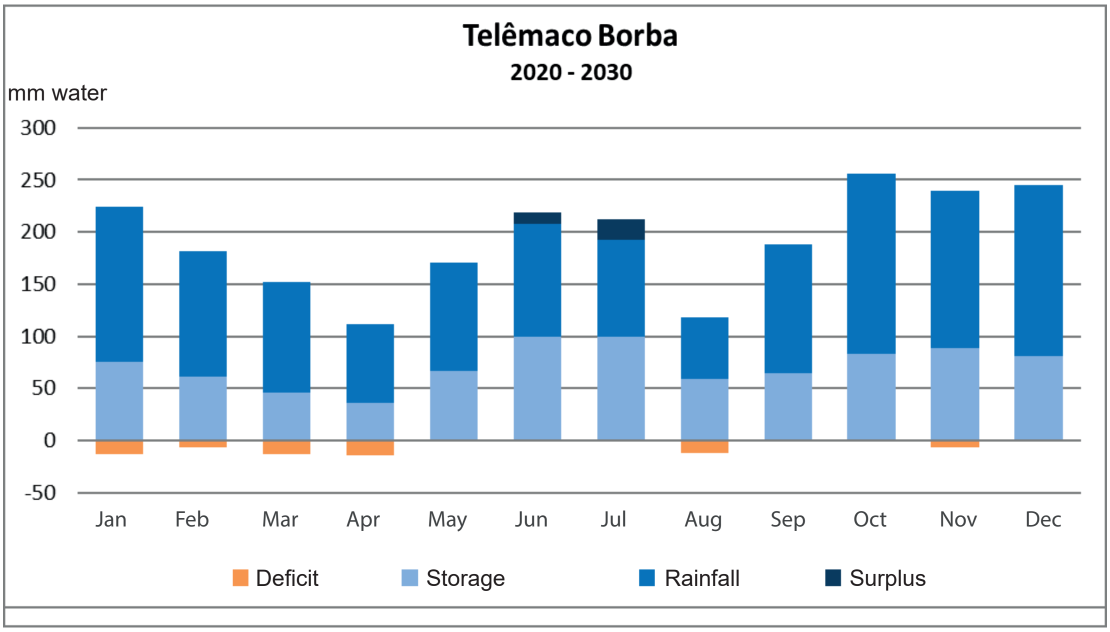

Figure 22. Water balance in Telêmaco Borba (PR), 2010-2020.

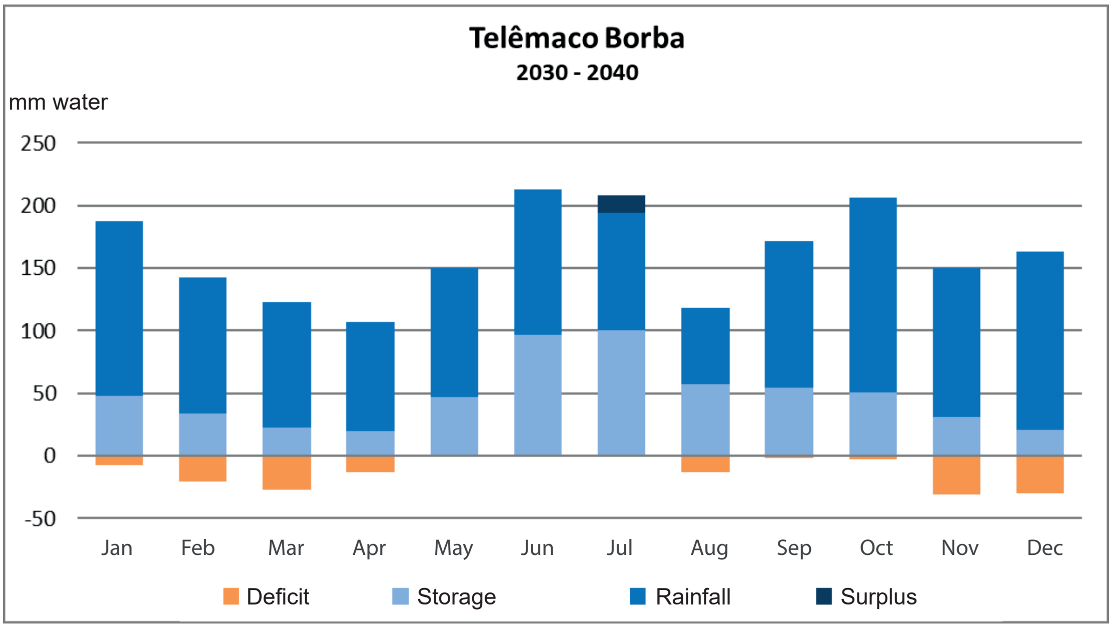

Figure 23. Water balance in Telêmaco Borba (PR), 2020-2030.

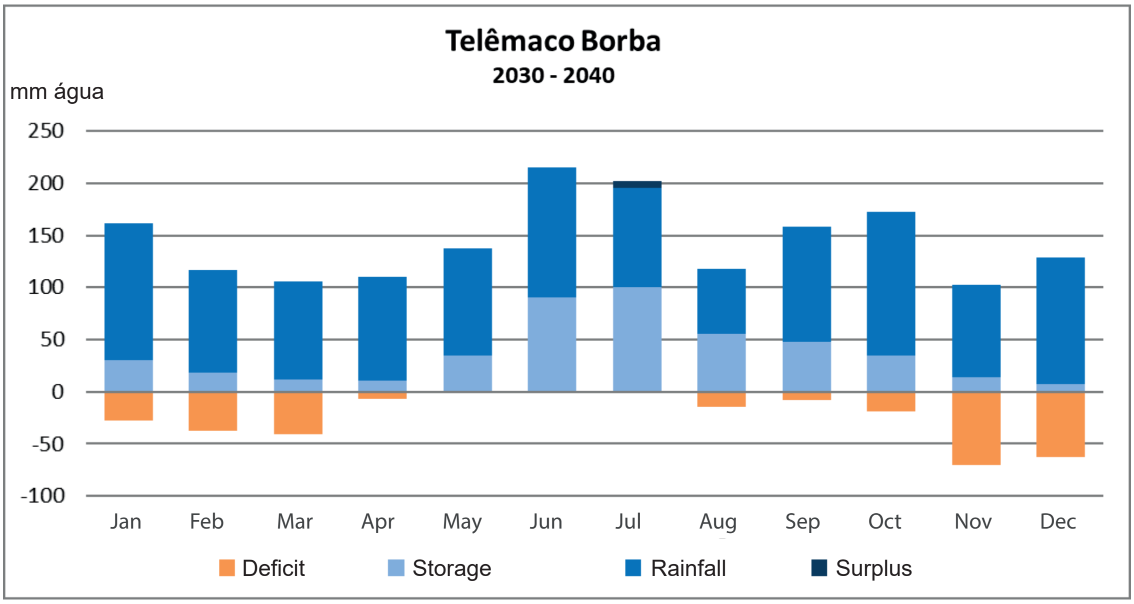

Figure 24. Water balance in Telêmaco Borba (PR), 2030-2040.

With the increase in temperature as a function of the estimate obtained from the HadGEM2-ES model, the water deficit exceeds the critical value of 200 mm/year for the 2030-2040 period. The maximum estimated value was approximately 287 mm/year. Productivity may be negatively impacted as a result of this deficit.

In the analysis of extreme phenomena during the 1980-2015 period, 19, 26, 13, and 12 occurrences of temperatures exceeding 34 °C were observed in the months of September, October, November, December, and January, respectively. There is no marked tendency toward increased extreme heat wave phenomena in the region. The same can be said for frost risk. Among the 13,011 minimum temperature values analyzed, 54 registered screen temperature values lower than 2 ºC, which means at -1.34 ºC on the surface of the plant (frost). In other words, the chance of frost in this region is less than 1%. As for maximum rainfall, three events were observed in 35 years with precipitation exceeding 100 mm/day, but there was no flooding of the soil that could damage the eucalyptus crop.

Table 28 shows the frequencies of days without rainfall during the 1980-2015 period. As mentioned above, periods without rain may occur during each month, as shown in Table 28, but these may be part of a warm dry spells of summer-like weather (*veranicos*) when they occur in periods of drought with intense heat. In this case they are harmful to agriculture. In Telêmaco Borba, over 35 years of analysis, the frequency of occurrence for these warm dry spells lasting more than 30 days was at least 12-14% during January and December (Table 28); in other words, a low frequency of this phenomenon was observed.

Table 28. Frequencies of days without rain observed during 1980-2015 in Telêmaco Borba (PR). highlighting warm dry spells (*veranicos*). expressed as a percentage.

Month	Duration of period without rain (days)						
	Up to 5	6-10	11-15	16-20	21-25	26-30	31-35
January	40	57	10	2	0	0	12*
February	38	48	10	2	0	12	0
March	26	86	19	5	0	0	17
April	24	71	36	7	0	24	0
May	24	86	24	10	10	0	17
June	24	86	24	10	3	21	0
July	29	62	36	14	10	2	14
August	26	60	29	5	10	7	24
September	43	60	19	10	2	14	0
October	21	100	10	0	0	0	14
November	26	86	17	2	0	14	0
December	45	64	7	7	0	0	14*

*Warm spell (*veranico*).

Growth curves and impact on productivity in Telêmaco Borba

From the MAI, CAI, and commercial production data, growth curves and relations with the WRSI could be constructed for the municipality of Telêmaco Borba. Figure 25 shows the adjusted growth curves for MAI and CAI in the Telêmaco Borba region, from 2005 to 2015. These curves were adjusted for ten years of data from *E. saligna* and *E. grandis* x *E. urophylla*. The MAI and CAI curves were adjusted with both datasets. Figure 25 shows that maximum growth occurs in the fourth year after planting in this region, and MAI reaches its highest value in the fifth year.

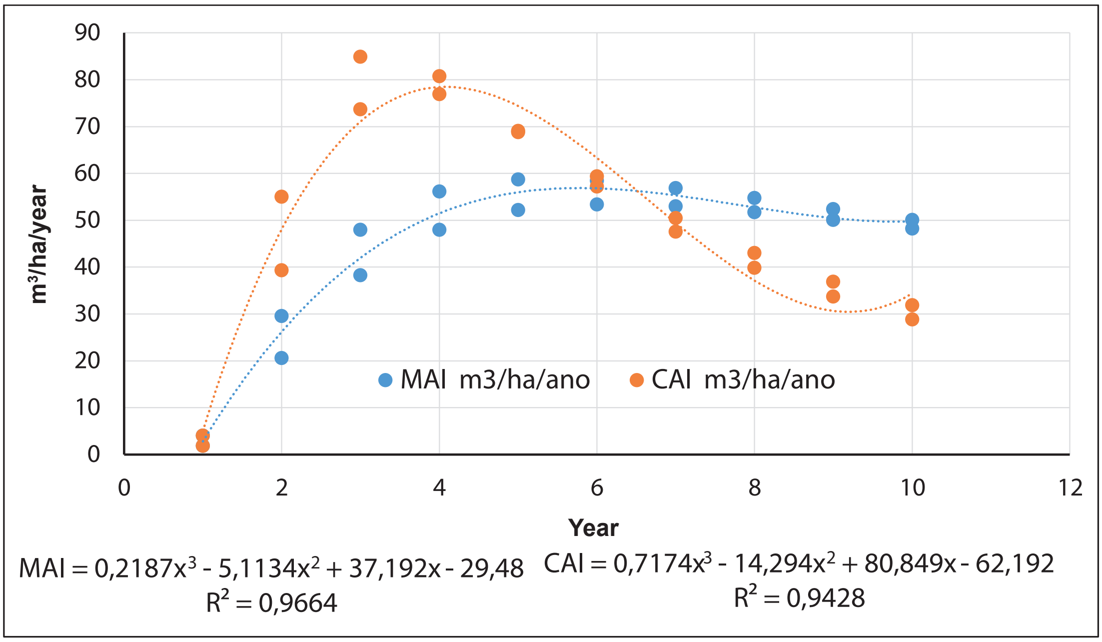

Figure 25. Adjusted growth curves for mean annual increment (MAI) and current annual increment (CAI) for *Eucalyptus grandis* x *Eucalyptus urophylla* and *Eucalyptus saligna* in Telêmaco Borba (PR), from 2005 to 2015.

Using meteorological parameters and field data, MAI and WRSI could be calculated for the first seven years in cultivated forests of *E. grandis* x *E. urophylla* and *E. saligna* in Telêmaco Borba (PR) (Table 29). With the WRSI for this period, the growth curve was then adjusted correspondingly (i.e. with a certain WRSI, the MAI can be estimated by the model). The calculation to determine the maximum MAI extended up to year seven, considered the main harvest year for *E. grandis* x *E. urophylla* and *E. saligna*.

Table 29. Variation in mean annual increment (MAI) and water requirement satisfaction index (WRSI) after adjusting the curves. for the first seven years of eucalyptus cultivation in Telêmaco Borba (PR).

Year	MAI (m³/ha/year)	WRSI	Year	MAI (m³/ha/year)	WRSI
	Eucalyptus saligna			*E. grandis* x *E. urophylla*	
1st	2	0.13	1º	4	0.13
2nd	21	0.28	2º	30	0.28
3rd	38	0.43	3º	48	0.43
4th	48	0.56	4º	56	0.56
5th	52	0.72	5º	59	0.72
6th	53	0.79	6º	58	0.79
7th	53	0.83	7º	57	0.83

The relationship between WRSI and MAI is shown in Figure 26. Note that the WRSI accounts for 94% of the MAI variation, which is a good relationship between observed MAI and estimated WRSI.

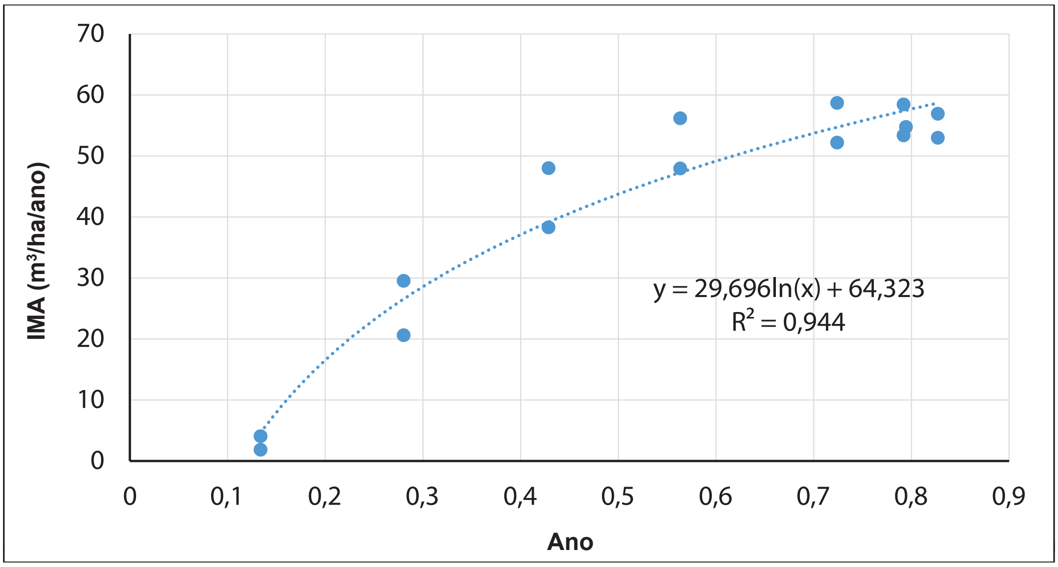

Figure 26. Mean annual increment (MAI) adjusted according to water requirement satisfaction index (WRSI) in Telêmaco Borba, PR, for the period 2005-2015.

The temporal variation in MAI for the period 1980-2040 is found in Figure 27.

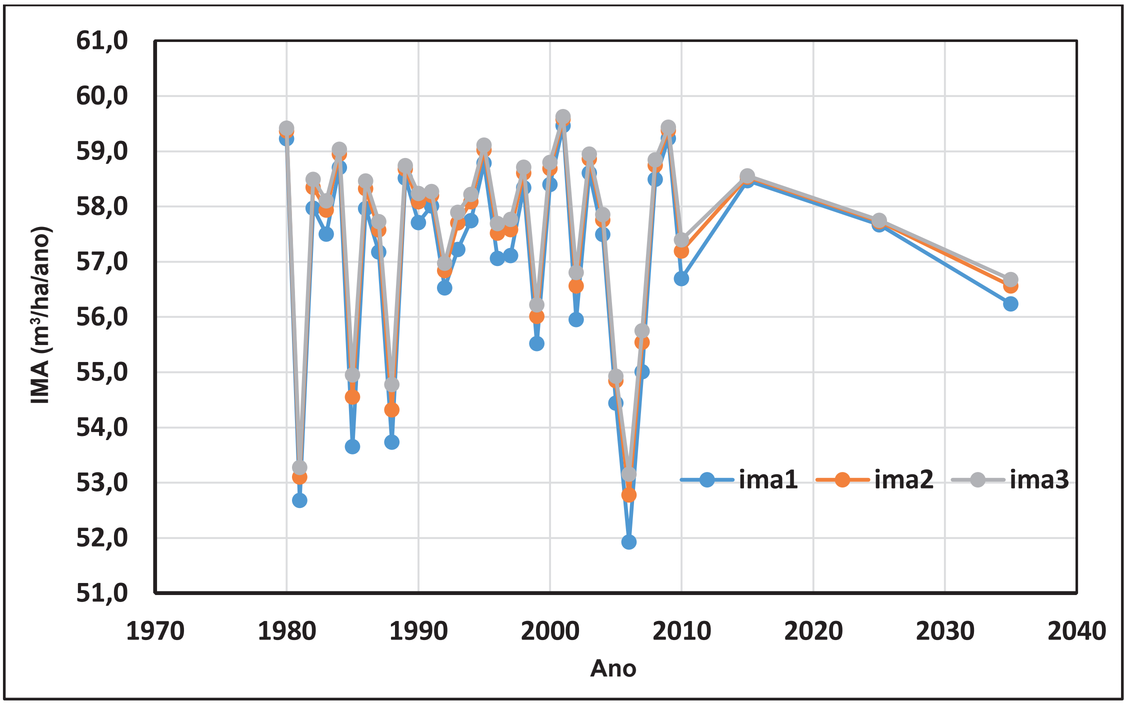

Figure 27. Temporal variation in mean annual increment (MAI) for Telêmaco Borba, PR, 1980-2040, considering soil types 1 (MAI1), 2 (MAI2), and 3 (MAI3).

The annual variations in WRSI (Table 30) are more evident in the years 1981, 1985, 1988, and 2006, when MAI is lower.

In 1981, 1985, 1988, and 2006, the total annual rainfall was approximately 350 mm lower than the annual average, which was 1,602 mm. This reduction can be explained by the reduction in rainfall observed in the region, as seen in the data in Table 31. It should be noted that the HADEGEM2-ES2 model indicates a reduction in productivity, albeit with very slight impact in Telêmaco Borba (on the order of 1-2 m^3/ha/year).

Table 30. Annual variation in water requirement satisfaction index (WRSI) and mean annual increase (MAI) for soil types 1. 2. and 3 in Telêmaco Borba (PR) during 1980-2035. with years with lower rainfall highlighted in yellow.

Year	WRSI 1	WRSI 2	WRSI 3	MAI1	MAI 2	MAI 3
				m^3/ha/year		
1980	0.84	0.85	0.85	59.2	59.4	59.4
1981	0.68	0.69	0.69	52.7	53.1	53.3
1982	0.81	0.82	0.82	58.0	58.4	58.5
1983	0.79	0.81	0.81	57.5	57.9	58.1
1984	0.83	0.83	0.84	58.7	58.9	59.0
1985	0.70	0.72	0.73	53.7	54.6	55.0
1986	0.81	0.82	0.82	58.0	58.3	58.5
1987	0.79	0.80	0.80	57.2	57.6	57.7
1988	0.70	0.71	0.73	53.7	54.3	54.8
1989	0.82	0.83	0.83	58.5	58.7	58.7
1990	0.80	0.81	0.81	57.7	58.1	58.2
1991	0.81	0.81	0.82	58.0	58.2	58.3
1992	0.77	0.78	0.78	56.5	56.8	57.0
1993	0.79	0.80	0.81	57.2	57.7	57.9
1994	0.80	0.81	0.81	57.7	58.1	58.2
1995	0.83	0.84	0.84	58.8	59.0	59.1
1996	0.78	0.80	0.80	57.1	57.5	57.7
1997	0.78	0.80	0.80	57.1	57.6	57.8
1998	0.82	0.82	0.83	58.3	58.6	58.7
1999	0.74	0.76	0.76	55.5	56.0	56.2
2000	0.82	0.83	0.83	58.4	58.7	58.8
2001	0.85	0.85	0.85	59.5	59.6	59.6
2002	0.75	0.77	0.78	56.0	56.6	56.8
2003	0.83	0.83	0.83	58.6	58.9	59.0
2004	0.79	0.80	0.80	57.5	57.8	57.9
2005	0.72	0.73	0.73	54.4	54.8	54.9
2006	0.66	0.68	0.69	51.9	52.8	53.2
2007	0.73	0.74	0.75	55.0	55.5	55.8
2008	0.82	0.83	0.83	58.5	58.7	58.8
2009	0.84	0.85	0.85	59.2	59.4	59.4
2010	0.77	0.79	0.79	56.7	57.2	57.4
2015*	0.82	0.82	0.82	58.5	58.5	58.6
2025*	0.80	0.80	0.80	57.7	57.7	57.8
2035*	0.76	0.77	0.77	56.2	56.6	56.7

*Values estimated by the HadGEM2-ES model.

Table 31. Total annual rainfall values for the Telêmaco Borba region (PR) during the years in which the model estimated lower values. in millimeters.

Year	Annual rainfall (mm)	Year characterized as
1981	1,310	Normal
1985	1,207	Normal
1988	1,256	Normal
2006*	1,242	Normal

*In this year there were two 25-day and one 35-day dry warm spells (*veranicos*), which may have caused the reduction in the WRSI.

Otacílio Costa (SC)

In order to analyze the critical conditions, the water balance was initially established for the years 1980-2015 using daily weather data.[3] As a climatic water balance, an AWC of 100 mm was established. Table 32 shows the input parameters for the water balance, and Table 33 shows the monthly mean parameters for establishing the water balance.

Table 32. Input parameters for the Thornthwaite water balance for eucalyptus cultivation in Otacílio Costa, SC, 1980-2015.

Location	
Latitude (degrees)	-27.63 S
Altitude (meters)	884
Solo e clima	
Available water capacity (mm)	100
Estimated temperature (°C)	Mean temperature
I index*	81.52
A index*	1.76

*A and I indexes are adjustment indexes for the Thornthwaite water balance.

Table 33. Monthly average climate data for establishing the water balance in Otacílio Costa, SC.

Month	Rainfall (mm)	Temperature (ºC)		
		Maximum	Minimum	Mean
January	178	26.71	16.72	21.72
February	166	26.60	16.89	21.74
March	119	25.61	15.88	20.74
April	102	23.01	13.58	18.30
May	114	19.78	10.44	15.11
June	112	18.16	8.81	13.48
July	139	17.88	8.25	13.06
August	113	19.76	9.32	14.54
September	160	20.11	10.41	15.26
October	172	22.10	12.54	17.32
November	131	24.10	13.94	19.02
December	151	25.85	15.59	20.72

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[3] The period was extended until 2015 as a function of the productivity curves.

Table 34 presents the probability of ETR occurrence in the city of Otacílio Costa from the months of January to December, considering soil types 2 and 3 (since type 1 soils are very uncommon in this region). In general, no unfavorable conditions for forestry were seen.

Table 34. Probability of occurrence of real evapotranspiration (ETR) in Otacílio Costa (SC) from 1980 to 2015, in percentage.

Month	ETR (mm)							
	0-3	3-5	5-7	> 7	0-3	3-5	5-7	> 7
	Soil type 2				Soil type 3			
	Probability of ETR occurrence (%)							
January	0	92	8	0	0	92	8	0
February	3	97	0	0	3	97	0	0
March	36	64	0	0	36	64	0	0
April	100	0	0	0	100	0	0	0
May	100	0	0	0	100	0	0	0
June	100	0	0	0	100	0	0	0
July	100	0	0	0	100	0	0	0
August	100	0	0	0	100	0	0	0
September	97	3	0	0	97	3	0	0
October	8	92	0	0	8	92	0	0
November	0	100	0	0	0	100	0	0
December	6	94	0	0	3	97	0	0

Table 35 presents future ETR values in millimeters from January-December in the years 2015, 2025 and 2035, considering soil types 2 and 3 (because type 1 soils are uncommon in this region).

Table 35. Future real evapotranspiration (ETR) from January-December 2015, 2025, and 2035, considering soil types 2 and 3 in Otacílio Costa, SC, in millimeters.

Month	Type 2			Type 3		
	2015	2025	2035	2015	2025	2035
	Future ETR (mm)					
January	4.72	4.85	4.96	4.72	4.85	4.96
February	4.13	4.16	4.20	4.13	4.16	4.20
March	3.39	3.46	3.52	3.39	3.46	3.52
April	2.44	2.49	2.54	2.44	2.49	2.54
May	1.61	1.67	1.72	1.61	1.67	1.72
June	1.46	1.50	1.54	1.46	1.50	1.54
July	1.51	1.58	1.65	1.51	1.58	1.65
August	2.41	2.53	2.66	2.41	2.53	2.66
September	2.74	2.80	2.86	2.74	2.80	2.86
October	3.63	3.74	3.85	3.63	3.74	3.85
November	4.35	4.51	4.66	4.35	4.51	4.66
December	4.74	4.96	5.18	4.74	4.96	5.18

Table 36 presents the normal annual water balance for the period 1980-2015. Notably, the water deficit is zero or very low throughout the year, and there is a water surplus.

Tabela 36. Balanço hídrico anual-normal para o período de 1980 a 2015, no município de Otacílio Costa, SC.

Months	Rainfall	Deficit	Storage	Surplus
	mm			
January	178	0	100	38
February	166	0	100	54
March	119	0	100	21
April	102	0	100	37
May	114	0	100	69
June	112	0	100	74
July	139	0	100	93
August	113	0	100	45
September	160	0	100	81
October	178	0	100	38
November	166	0	100	54
December	119	0	100	21

These results indicate a situation favorable for eucalyptus cultivation in Otacílio Costa, with climatic restrictions during the dry period when the ETR is 2.0-3.0 mm, indicating low water demand. No water deficit was observed.

Because the calculation was made for an AWC of 100 mm, which is the normal water balance, the results will be even better for the 105 mm, 135 mm, and 150 mm AWC values that correspond to soil types 1, 2, and 3, respectively. Finally, Figure 28 presents a complete summary of the water balance for Otacílio Costa from 1980 to 2015.

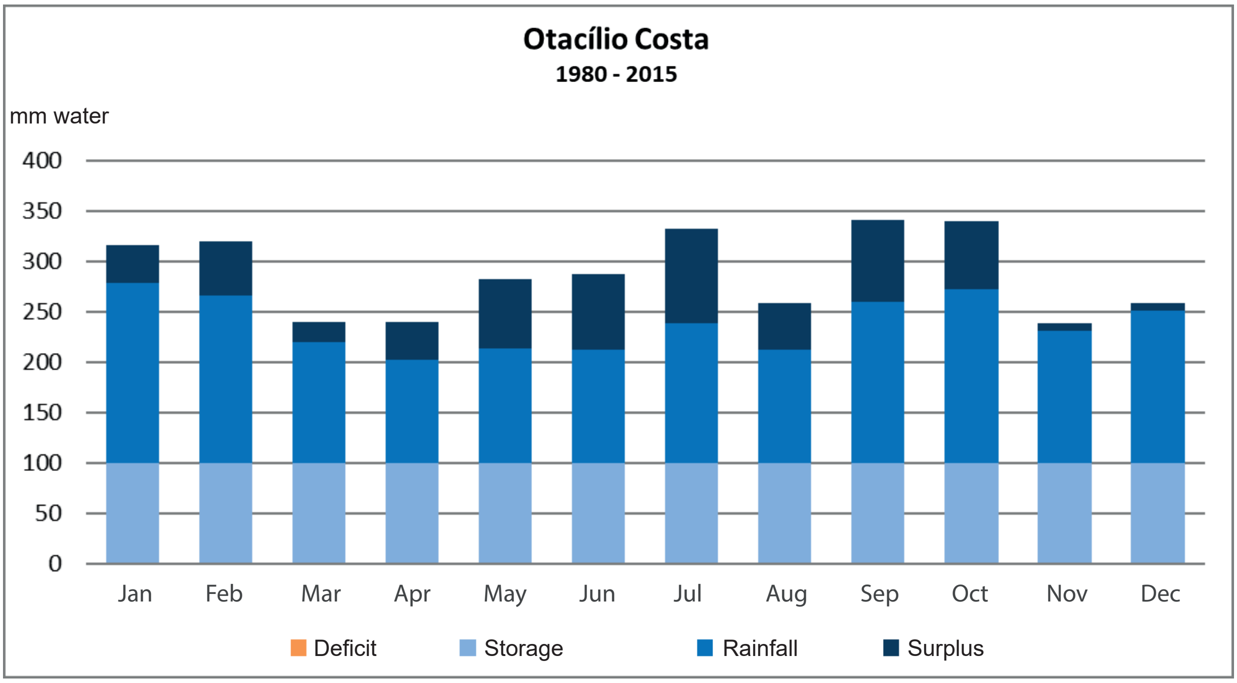

Figure 28. Normal water balance for Otacílio Costa, SC, 1980-2015.

To verify the impact of global warming in future years over the 2010-2020, 2020-2030, and 2030-2040 periods, the water balances were calculated for these years, considering the central year of each series. Foram estabelecidos os balanços hídricos para estes anos, considerando o ano central de cada série, e que encontram nas Figuras 29, 30 e 31, respectivamente (????)

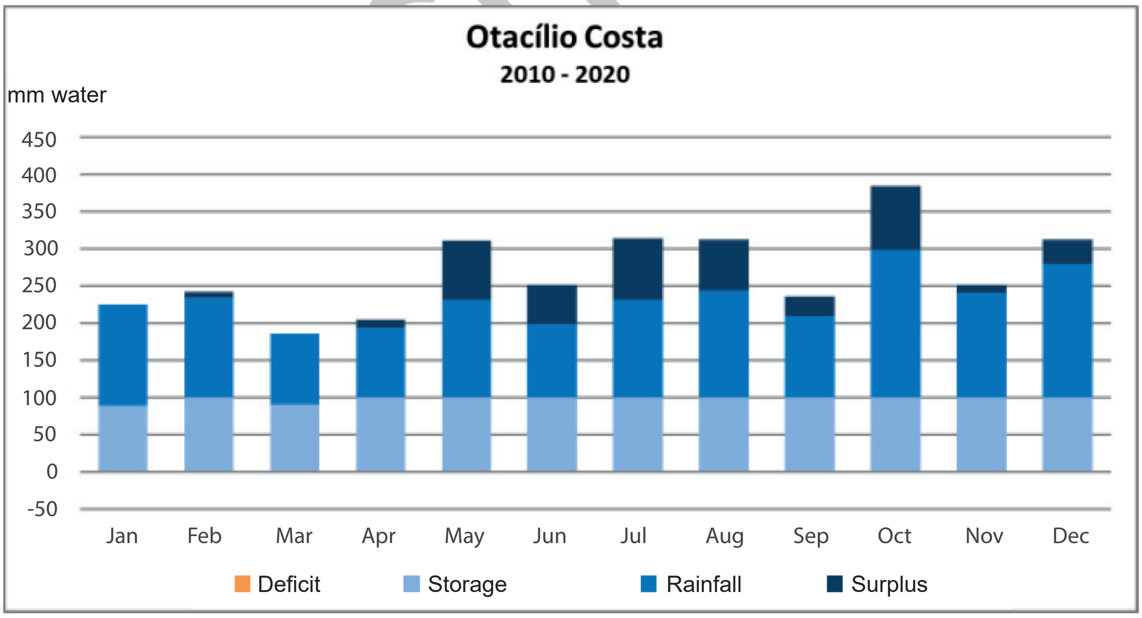

Figure 29. Water balance in Otacílio Costa, SC, 2010-2020.

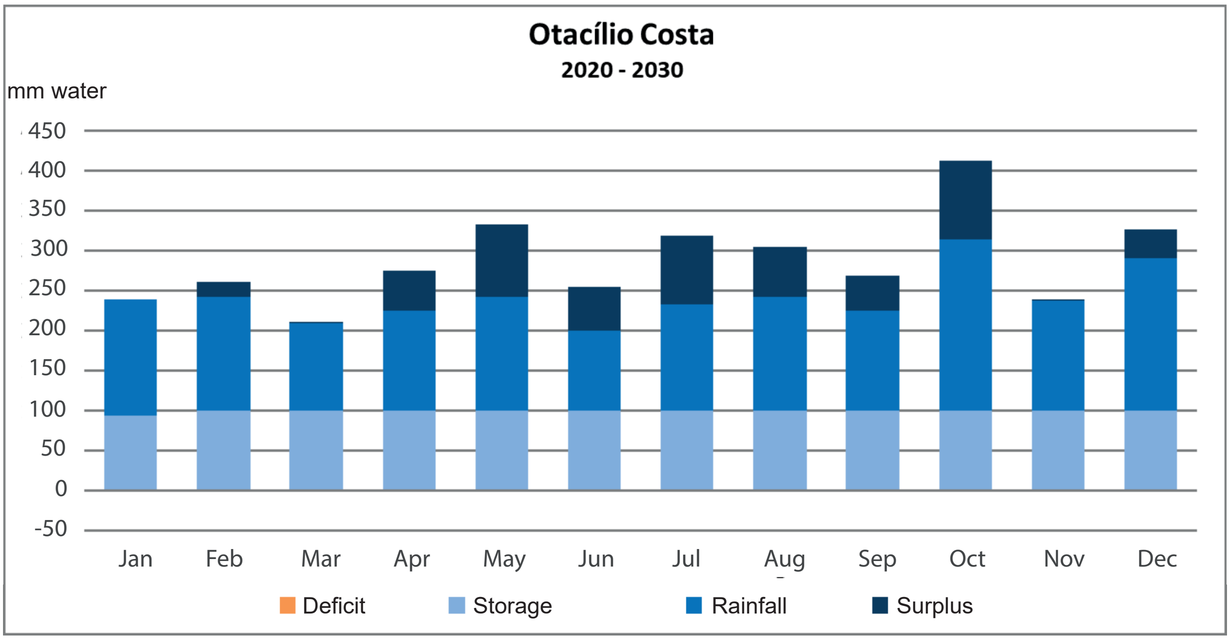

Figure 30. Water balance in Otacílio Costa, SC, 2020-2030.

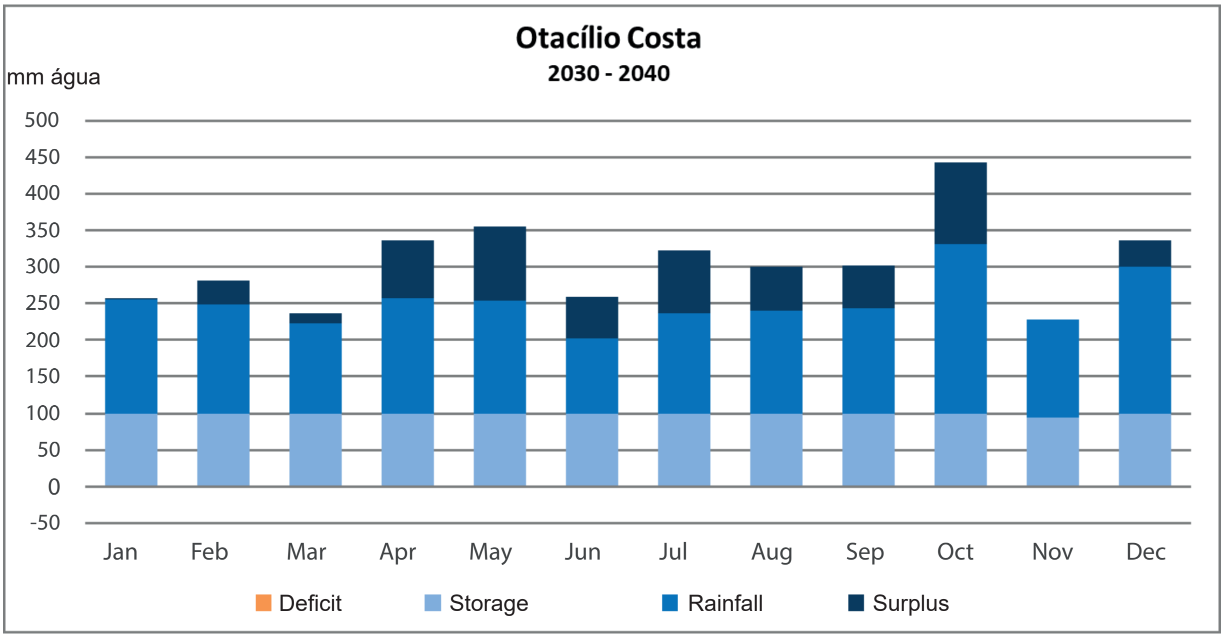

Figure 31. Water balance in Otacílio Costa, SC, 2030-2040.

With the increase in temperature as a function of the estimate obtained from the HadGEM2-ES model, the water deficit does not exceed the critical value of 200 mm/year at any point in the 2010-2040 period.

In the analysis of extreme phenomena, five occurrences of temperatures above 34 °C were observed in October, November, December and January. There is no marked tendency toward increased extreme heat wave phenomena in the region. The same cannot be said, however, for frost risk. Among the 13,092 minimum temperature values analyzed, 244 registered screen temperatures below 2 °C, which means -1.34 °C on the surface of the plant (frost); this region is strongly prone to frost. As for maximum rainfall, only one rainfall event was observed in 35 years with precipitation exceeding 100 mm/day, but there was no flooding of soil that could damage the eucalyptus crop. Water deficit was not observed, but additional care should be taken with the shallow soils, which can cause oxygenation deficit in the roots.

Table 36 shows the frequencies of consecutive days without rainfall during the 1980-2015 period. Note that there are no critical periods with marked warm dry spells of summer-like weather (*veranicos*), which are very unlikely to occur in the municipality of Otacílio Costa (Table 36).

From the MAI, CAI, and commercial production data, growth curves and relations with the WRSI could be constructed for the municipality of Otacílio Costa Figure 32 shows that in Otacílio Costa, the greatest increase in CAI occurs in the fourth year after planting, while for MAI it is during the fifth year after planting.

Using meteorological parameters and field data, MAI and WRSI could be calculated for the first seven years of eucalyptus cultivation in São Paulo (Table 37).

With the WRSI for this period, the growth curve was then adjusted correspondingly (i.e. with a given WRSI, the MAI value estimated by the model). The calculation to determine the maximum MAI extended to year seven, considered the main harvest year.

Table 36. Frequencies of days without rain observed during 1980-2015 in Otacílio Costa, SC, expressed as a percentage.

Month	Duration of period without rain (days)						
	Up to 5	6-10	11-15	16-20	21-25	26-30	31-35
January	62	74	9	3	0	0	0
February	29	62	12	0	0	0	0
March	53	100	15	6	0	0	0
April	41	100	44	9	3	0	0
May	44	88	29	12	9	0	6
June	59	100	38	12	0	0	0
July	26	100	26	6	3	0	0
August	26	100	38	9	6	9	0
September	47	94	21	0	3	6	0
October	50	91	15	0	0	0	3
November	41	100	12	0	0	6	0
December	47	100	18	3	0	0	3

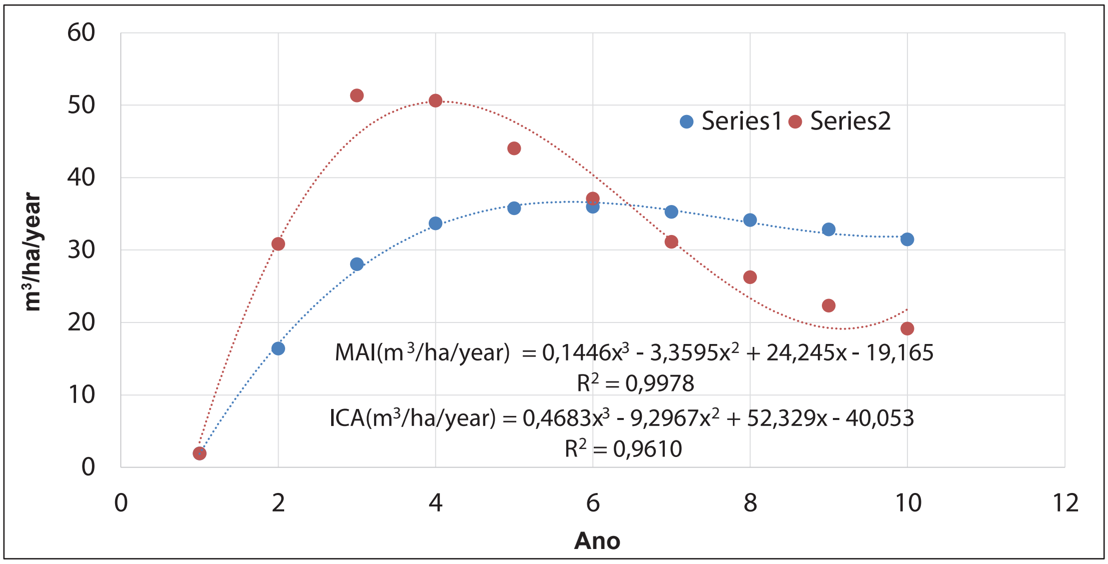

Figure 32. Adjusted growth curves for mean annual increment (MAI) and current annual increment (CAI) for *Eucalyptus benthamii* and *Eucalyptus dunnii* in Otacílio Costa, SC, 2005-2015.

Table 37. Variation in mean annual increment (MAI) and water requirement satisfaction index (WRSI) after adjusting the curves for the first seven years of eucalyptus cultivation in Otacílio Costa, SC.

Year	MAI (m³/ha/year)	WRSI	Year	MAI (m³/ha/year)	WRSI
	Eucalyptus dunnii			*Eucalyptus benthamii*	
1st	1	0.14	1st	2	0.14
2nd	14	0.34	2nd	16	0.34
3rd	27	0.50	3rd	28	0.50
4th	34	0.60	4th	34	0.60
5th	37	0.75	5th	36	0.75
6th	39	0.87	6th	36	0.87
7th	39	0.86	7th	35	0.86

The relationship between WRSI and MAI is shown in Figure 33. The WRSI accounts for 97% of the MAI variation, which is a good relationship between observed MAI and estimated WRSI. The temporal variation in MAI for the period 1980-2040 is shown in Figure 34.

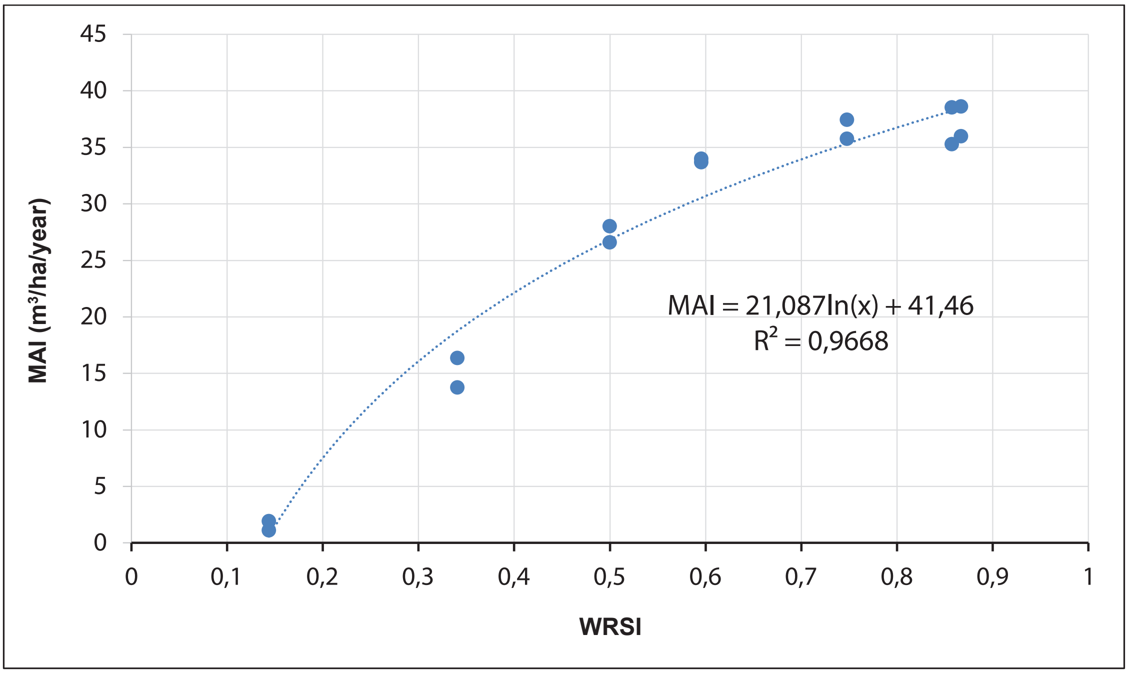

Figure 33. Mean annual increment (MAI) adjusted according to the water requirement satisfaction index (WRSI) for the Otacílio Costa, SC, region for the period 2005-2015.

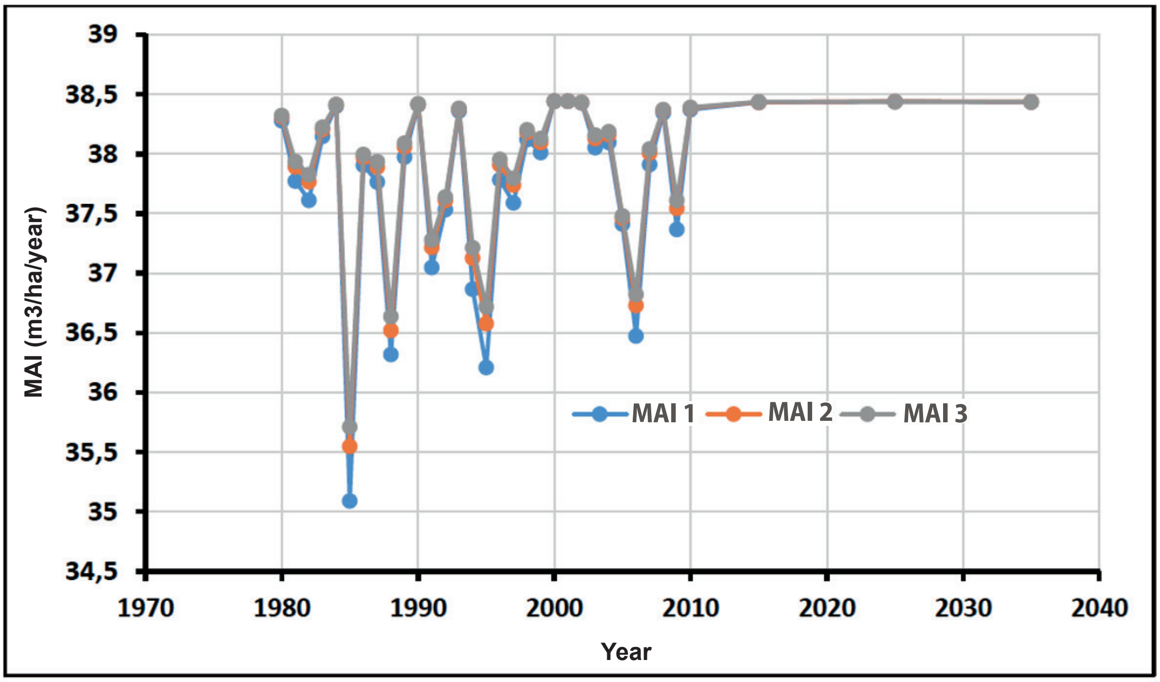

Figure 34. Temporal variation in the mean annual increment (MAI) for Otacílio Costa, SC from 1980 to 2040, considering soil types 1 (MAI 3), 2 (MAI2), and 3 (MAI3).

In 1985, 1988, 1995, and 2006, the total annual precipitation was approximately 400 mm lower than the annual average, which was 1,658 mm (Table 38). Therefore, the annual variations in WRSI (Table 39) are more evident in these years when MAI is lower. It should be noted that the HadGEM2-ES model does not indicate a tendency toward reduced eucalyptus productivity in this region.

Table 38. Total annual rainfall values for the Otacílio Costa, SC, region during the years in which the model estimated lower MAI values in millimeters.

Year	Annual rainfall (mm)	Year characterized as
1985	1,210	Dry
1988	1,123	Dry
1995	1,256	Dry
2006	1,037	Dry

Table 39. Annual variation in water requirement satisfaction index (WRSI) and mean annual increment (MAI) (m^3/ha/year) for soil types 1, 2, and 3 in Otacílio Costa, SC, for the 1980-2035 period, with years with less rainfall highlighted in yellow.

Year	WRSI 1	WRSI 2	WRSI 3	MAI 1	MAI 2	MAI 3
1980	0.86	0.86	0.86	38.27	38.31	38.32
1981	0.84	0.84	0.85	37.77	37.89	37.94
1982	0.83	0.84	0.84	37.61	37.77	37.83
1983	0.85	0.86	0.86	38.15	38.21	38.23
1984	0.87	0.87	0.87	38.40	38.41	38.41
1985	0.74	0.76	0.76	35.09	35.55	35.71
1986	0.84	0.85	0.85	37.91	37.97	38.00
1987	0.84	0.84	0.85	37.77	37.89	37.94
1988	0.78	0.79	0.80	36.32	36.52	36.64
1989	0.85	0.85	0.85	37.98	38.06	38.09
1990	0.87	0.87	0.87	38.41	38.42	38.42
1991	0.81	0.82	0.82	37.05	37.22	37.28
1992	0.83	0.83	0.83	37.53	37.61	37.64
1993	0.86	0.86	0.86	38.36	38.38	38.38
1994	0.80	0.81	0.82	36.87	37.13	37.21
1995	0.78	0.79	0.80	36.21	36.58	36.72
1996	0.84	0.85	0.85	37.78	37.91	37.96
1997	0.83	0.84	0.84	37.59	37.74	37.80
1998	0.85	0.86	0.86	38.12	38.18	38.20
1999	0.85	0.85	0.85	38.01	38.10	38.13
2000	0.87	0.87	0.87	38.44	38.44	38.44
2001	0.87	0.87	0.87	38.44	38.44	38.44
2002	0.87	0.87	0.87	38.43	38.43	38.43
2003	0.85	0.85	0.86	38.05	38.13	38.16
2004	0.85	0.86	0.86	38.10	38.16	38.19
2005	0.83	0.83	0.83	37.41	37.46	37.48
2006	0.79	0.80	0.80	36.47	36.73	36.82
2007	0.85	0.85	0.85	37.91	38.01	38.04
2008	0.86	0.86	0.86	38.35	38.37	38.37
2009	0.82	0.83	0.83	37.37	37.54	37.61
2010	0.86	0.86	0.86	38.37	38.39	38.39
2015*	0.87	0.87	0.87	38.43	38.44	38.44
2025*	0.87	0.87	0.87	38.44	38.44	38.44
2035*	0.87	0.87	0.87	38.44	38.44	38.44

*Values estimated by the HadGEM2-ES model.

Carbon accumulation in planted eucalyptus forests

In developing countries, agriculture, livestock, fisheries, and forestry account for 25% of the damage and losses related to extreme events caused by changes in climate patterns which are related to climate change (FAO, 2015a). Considering that the occurrence of these events may increase as populations grow (and that along with human numbers the demand for food, fiber, and energy will rise), the challenge is to understand how environments and crops will be affected in order to direct efforts towards minimizing impact through adaptation and mitigation strategies, avoiding or at least reducing losses in productive potential.

Around the world, between 1991 and 2015 planted forests were responsible for containing an average of approximately 1.1 Gt CO year^{-1} (Federici et al., 2015). Since the UN Convention on Climate Change was established in 1992, the role of forests in policy related to global climate change has changed rapidly and in a complex manner, through the commitments in the Kyoto Protocol, the mitigation actions assumed by various nations, REDD+, and even the Paris Agreement (Brazil, 2016), in which Brazil committed to reducing 37% of its national GHG emissions from 2005 to 2025. Among the actions listed to achieve this goal is the recommendation to restore and reforest 12 million hectares. According to data from Ibá (2014; 2020), the area planted with forests between 2006 and 2019 grew 2.8 million ha, below the national target established by the ABC Plan, which had set a goal of 3.0 million ha by 2020 (Brazil, 2012). However, expansion of eucalyptus plantations during the same period reached 3.5 million hectares (IBÁ, 2014, 2020).

The planted forest sector is included in national commitments as a strategy to mitigate GHG emissions. The main carbon reservoirs in forests are plant biomass and soil carbon; according to FAO (2015b), these two compartments account for more than 75% of the carbon contained in forests. In order to account for the carbon contained in vegetative biomass, relationships with crop productivity are adopted, such as those represented in the IPCC methodological guide (Eggleston et al., 2006). In order to estimate carbon storage in the soil, this guide utilizes the relationships between use conversions involving planted forests.

Carbon in biomass (vegetation)

Brazilian eucalyptus plantations are recognized worldwide for their high productive potential, frequently reaching a mean annual increment of over 40 m^3/ha/year in commercial plantations, with a national average of 35.3 m^3/ha/year (IBÁ, 2020). All this increased productivity is the result of genetic improvement and highly specialized silvicultural management practices, which have been improved over decades of production. Management practices for planted forests with respect to forest protection have changed their focus; in the past, the main concerns about risks to planted forests concentrated on fire, pests, and diseases. More recently, wind damage and drought have also become key problems (Foelkel, 2014), and the impacts of these phenomena are being intensified by climate change.

As an example of the scale of these challenges, in Mato Grosso do Sul (one of the states where the area planted with eucalyptus has expanded the most over the past decade), 8% of the area of planted forests was damaged by wind between 2014 and 2019. This impact reflected the total loss of 40% of these reforested areas, resulting in direct economic losses from reduced productivity as well as operational problems such as difficulty carrying out forestry operations, greater risk of accidents, and higher harvesting costs (Dias; Silva, 2019). According to studies conducted in Minas Gerais, operational costs to harvest forests where such damage has occurred may be 38% to 55% higher, depending on the level of damage (Cardoso et al., 2011).

From 2002 and 2016, the MAI for eucalyptus cultivation decreased (IBÁ, 2014, 2020). Two climatic factors during this period have been considered to explain this decline:

- In Minas Gerais, the state with the largest area planted with eucalyptus, climate variations and scarcity of rainfall have been frequent, especially in Cerrado (dryland) regions. At the end of the last decade, data from Emater/MG indicated losses in more than 150,000 hectares of crops (Paula, 2018).

- The 2014-2017 drought in southeastern Brazil brought irregular and insignificant rain between 2013 and 2015; it began in São Paulo and extended to the other states in the southeast, as well as several areas in the states of Minas Gerais and Espírito Santo in 2016 and 2017 (Gonçalves et al., 2017).

As demonstrated in the previous sections and in the brief examples mentioned earlier, changes in climate patterns (rain, temperature, evapotranspiration, and water deficit) can affect the productivity of forest crops and, in turn, production of timber products and carbon stocks contained in the forest, and also impacts the carbon removal potential of planted forests.

Based on the MAI values projected up to 2035 for the region and the individual municipalities (Tables 10, 21, 30, and 39), the potential for annual carbon removal by eucalyptus forests and the accumulated carbon stocks contained in these eucalyptus forests were estimated, making it possible to measure the potential impact on carbon storage from projected changes in climate variables.

The estimates were based on the methodologies used in the *Third Reference Report on Emissions and Removals from the Land Use, Land-Use Change, and Forestry Sector* (Brasil, 2015), according to IPCC (Eggleston et al., 2006). The method recommended by the IPCC (Eggleston et al., 2006) for estimating carbon in forest plantations suggests using the average productivity of forests in volume (MAI). From the MAI in volume, the annual increases in C from eucalyptus were estimated, which considered the contributions from the plant biomass in the aerial as well as root portions (IncRef). The parameters adopted in the estimated IncRef are presented in Table 40. In this way, the mean annual increment for carbon in eucalyptus biomass (in t C ha^{-1} $year^{-1}$) was obtained using the MAI, the basic wood density, biomass expansion factor, root-shoot biomass ratio, and %C in the plant biomass.

Table 40. Parameters used to estimate the mean annual increment in carbon in cultivated eucalyptus, in t C/ha/year.

Parameters	Amount	Source
Wood density (kg/m^3)	0.425	Brasil (2015)
Biomass expansion factor	1.2	Brasil (2015)
Root-shoot ratio	0.35	Brasil (2015)
C content in biomass (%)	0.47	Eggleston et al. (2006)

The mean annual increment in eucalyptus was estimated by the average MAIs for the study region and municipalities. For regional estimates of carbon storage, the area of eucalyptus plantations was considered to correspond to the total for the states of SC, PR, and SP (the study region). The change in area planted with eucalyptus in this region is illustrated in Figure 35. In recent years, the rate of forest planting in the region has exceeded 100,000 hectares per year, which is four times higher than the planting rate in the previous period (2004-2014) and indicates consistent investments in the forestry sector.

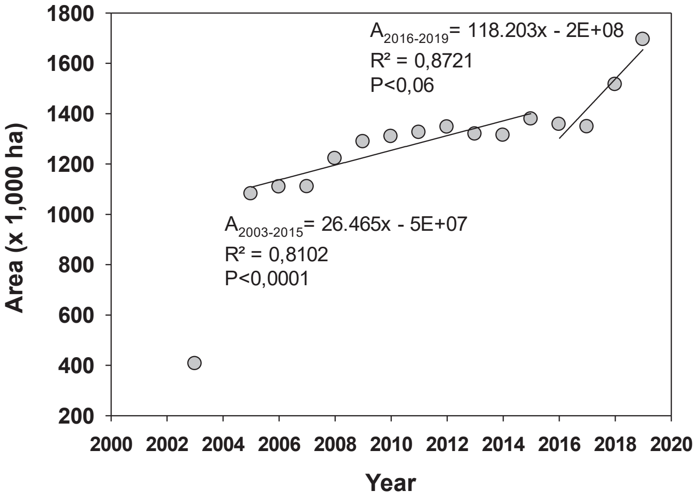

Figure 35. Change in the area planted with eucalyptus forests in the states of SP, PR, and SC.

Source: Adapted from IBÁ (2020).

The C removed from the atmosphere by eucalyptus during 2019 in the study region corresponded to approximately 30 million tons, with the equivalent of 137 Mt of C stored in eucalyptus forests (Figure 36). The IncRef for eucalyptus between 2003 and 2035 varied from 15.8 t to 18 t C/ha/year, and has a potential value of 18.4 t C/ha/year (Figure 36). The projected value for 2035 was 17.9 t C/ha/year, which reflects a loss of less than 1% in the projected annual carbon increment and 3% in relation to the maximum value, considered here as potential (Figure 36). This drop in the IncRef projected for 2035 resulted from a loss of just 0.3 m^3/ha/year in the potential MAI (Table 10). In this scenario, in 2035 Brazil would no longer remove approximately 580 tons of C/year from the atmosphere. If this loss does not occur (i.e., if it is avoided by adaptation and mitigation practices) and the production area continues to grow at the rate observed during 2016-2019 (approximately 118,000 hectares/year), the potential for annual carbon removal by eucalyptus in this region will reach 320 million tons of carbon in 2035 (Figure 36). However, if the projected loss in MAI does occur, the carbon that will not be removed could reach eight million tons (Figure 36). This potential reduction in carbon removal in 2035 would be the equivalent of neglecting the C accumulated by 450,000 hectares of eucalyptus forests in Brazil.

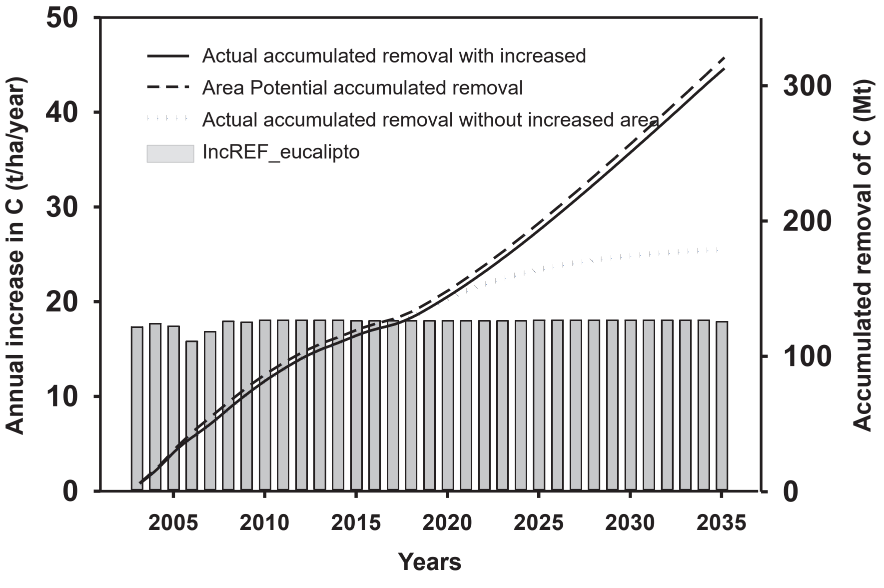

Figure 36. Mean annual increment (IncRef) and accumulated carbon removal by eucalyptus cultivation during 2003-2019 and projected up to 2035.

The IncRef was calculated for the municipalities of Itapetininga, Telêmaco Borba, and Otacílio Costa (Table 41). In the comparison, Itapetininga and Telêmaco Borba presented very similar IncRef values for eucalyptus, ranging from 17 tC/ha/year to 20 tC/ha/year. In Otacílio Costa the IncRef for eucalyptus was lower, varying from 11.8 tC/ha/year to 12.4 tC/ha/year. The projected IncRef values for 2025 and 2035, for Itapetininga as well as Telêmaco Borba, indicate losses of up to 2 tC/ha/year in the MAI, while for Otacílio Costa no losses are expected. In this way, in Otacílio Costa there will be virtually no reduction in eucalyptus's ability to remove C, but in Itapetininga and Telêmaco Borba there may be losses of up to 5% and 12%, respectively.

Table 41. Mean annual increment (IncRef) in tC/ha/year for eucalyptus in the municipalities of Itapetininga, SP, Telêmaco Borba, PR, and Otacílio Costa, SC.

Years	Itapetininga			Telêmaco Borba			Otacílio Costa		
	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
2003	18.9	19.1	19.1	19.0	19.1	19.1	12.3	12.3	12.3
2004	18.3	18.5	18.6	18.6	18.7	18.7	12.3	12.3	12.4
2005	18.4	18.5	18.5	17.6	17.7	17.8	12.1	12.1	12.1
2006	17.8	18.0	18.1	16.8	17.1	17.2	11.8	11.9	11.9
2007	17.2	17.4	17.5	17.8	18.0	18.1	12.3	12.3	12.3
2008	17.5	17.8	17.9	18.9	19.0	19.0	12.4	12.4	12.4
2009	19.5	19.6	19.6	19.2	19.2	19.2	12.1	12.1	12.2
2010	17.7	17.9	18.0	18.3	18.5	18.6	12.4	12.4	12.4
2015	18.8	18.9	17.9	18.9	18.9	19.0	12.4	12.4	12.4
2025	18.4	18.5	17.8	18.7	18.7	18.7	12.4	12.4	12.4
2035	17.5	17.8	17.3	18.2	18.3	18.3	12.4	12.4	12.4
Potential	19.5	19.6	19.6	19.3	19.3	19.3	12.4	12.4	12.4

*Potential value is the highest value already registered or projected.

Soil type had practically no effect on losses in IncRef for eucalyptus, with variations of less than 3% in Itapetininga and 1% in Telêmaco Borba. Much has been discussed about the capacity of soils with higher clay content to retain greater amounts of water in the soil and consequently alleviate water stress in plantations. But in this comparison, the differences in the amount of water available from soil types 1, 2, and 3 were not reflected in C accumulation in the eucalyptus biomass.

Climate change is clearly affecting the carbon accumulation potential of forest plantations. However, some regions will be more impacted than others, and some environments or production sites may be more susceptible, depending on their characteristics. It is also important to emphasize that losses should not be restricted to the C stored in plant biomass, since planted forests are transformed into forest products that can also be C drains for long periods, depending on what manufacturing process the wood is directed toward.

Considering these projections, the best strategies to protect forests from loss of productive potential (and, in turn, their capacity to mitigate greenhouse gases) must include improvement of genetic materials that consider characteristics related to resisting the main risks that affect eucalyptus: water stress, high temperatures, lower evapotranspiration, and wind. Thinking optimistically, part of this reduction in mitigation capacity may be offset by productivity gains via genetic selection and improvement. Still, silvicultural practices can also be definitive in determining greater resilience to the effects of climate change in cultivated forests as they simultaneously serve as a C drain and adaptive measure.

Carbon in forest soils

Changes in soil use impact carbon storage in the soil, reflecting GHG mitigation capacity, with effects on climate change control strategies (Fialho; Zinn, 2014; Higa et al., 2017; Veloso-Gomes et al., 2018). The accumulation of carbon in the soil is defined as the transfer of atmospheric CO_2 to the soil through plants mainly via vegetable residues, which are stored and retained in the soil as part of its organic matter (Lal et al., 2015). In addition to helping mitigate GHG emissions, carbon accumulation in the soil is also related to a larger set of benefits that improve soil quality, such as better nutrient cycling, biological activity, physical properties, and water storage (Rangel et al., 2008; Campanha et al., 2009).

Several factors impact C accumulation in soil, such as previous land use, climate, forest species, plantation age, silvicultural practices, and also soil texture (Paul et al., 2002; Caldeira et al., 2003; Jandl et al., 2007; Shi; Cui, 2010; Denardin et al., 2014; Fialho et al., 2019). This section analyzes how previous land use and climate determine the magnitude of change in soil carbon in eucalyptus plantations in Brazil, and how this factor changes the contribution of this reservoir to GHG removal/ emissions. This analysis will be based on the compiled set of findings by Zanatta et al. (2020).

Brazil, according to the study by Alvarez et al. (2013) has nine predominant climate types based on the Köppen climate classification that are related to temperature and rainfall, as described briefly below:

- Af: Tropical climate, with average temperature in the coldest month >18 °C and without a dry season (at least 60 mm of rain per month).
- Am: Tropical climate, with average temperature in the coldest month >18 °C and monsoons (short dry season).
- As: Tropical climate, with average temperature in the coldest month >18 °C and dry summers.
- Aw: Tropical climate, with average temperature in the coldest month >18 °C and dry winters.
- BSh: Dry climate, semi-arid, with low latitudes and longitudes, and average annual temperature >18 °C.
- Cwa: Humid subtropical climate, with average temperature in the coldest month <18 °C and >-3 °C; temperature in the hottest month is >22 °C and there are at least 4 months with temperature >10 °C; dry winters.
- Cwb: Humid subtropical climate, with average temperature in the coldest month <18 °C and >-3 °C; no month with average temperature >22 °C and at least 4 months with temperature >10 °C; dry winters.
- Cfa: Humid subtropical climate, with average temperature in the coldest month <18 °C and >-3 °C; mean temperature in the hottest month >22 °C and at least 4 months with temperature >10 °C; no dry season.
- Cfb: Humid subtropical climate, with average temperature in the coldest month <18 °C and >-3 °C; mean temperature in the hottest month <22 °C and at least 4 months with temperature >10 °C; no dry season.

Brazil has eucalyptus plantations in regions with all these climate types (Table 42), but most frequently they are located in Aw, Cfa, and Cwa regions, where over 65% of the productive area of eucalyptus plantations is concentrated. Because of the concentration of productive area in these climates, the survey of changes in carbon storage in the soil recorded the largest number of studies in these climates. Among the available publications, 22 comparisons were found involving converting native forests to eucalyptus, and 28 comparisons considering pasture converted into eucalyptus plantations.

Table 42. Distribution of planted forests among the climate types observed in Brazil in 2017.

Climate type	Area of eucalyptus (ha)	Climate type	Area of eucalyptus (ha)
Af	421,930	Cfa	1,598,688
Am	708,889	Cfb	762,958
As	183,482	Cwa	934,176
Aw	2,280,740	Cwb	505,334
BSh	12,332		

Source: IBGE (2019).

Considering the climate types, the factor for change in carbon stored in the soil (fC) was estimated by the mean of the ratios between carbon storage in the soil in eucalyptus forests and in the original/previous use (Tables 43 and 44).

Table 43. Factor for change in carbon stored in the soil after converting native forests into eucalyptus plantations. by climate type in Brazil.

Climate	Depths (cm) and probability (p)				Source
	0-20	p<	0-100	p<	
Aw	0.93 (7)	0.05	0.96 (3)	0.06	Zinn et al. (2002, 2011); Rezende et al. (2007); Schulthais (2009)
Am	0.80 (3)	0.33	0.76 (1)	-	Beldini et al. (2009); Lopes et al. (2015)
Cfa	0.98 (7)	0.19	1.02 (2)	-	Antunes (2007); Sandi (2009); Sotomayor (2009); Teixeira et al (2009); James et al. (2019)
Cwa	0.98 (8)	0.19	0.98 (3)	0.45	Demolinari et al. (2007); ; Schulthais et al. (2007); Lima (2008); Pulrolnik et al. (2009); Fialho et al. (2019)
Cwb	0.94 (1)	-	-	-	Inácio (2009)
National average	0.94	0.07	0.95	0.09	

( ) = Values between parentheses represent the number of data points used to generate the mean.

Table 44. Factor for change in soil carbon storage after converting pastures into eucalyptus plantations. by climate type in Brazil.

Climate	Depths (cm) and probability				Source
	0-20	p<	0-100	p<	
Aw	1.15 (8)	0.13	0.88 (3)	-	Lima (2004); Pegoraro et al. (2014); Vicente (2016)
Af	1.13 (2)	-	1.19 (2)	-	Silva (2008)
Cfa	1.14 (15)	0.12	1.17 (9)	0.14	Maquere et al. (2008); Rufino (2009); Santos et al. (2009, 2013); Soares (2009); Sotomayor (2009); Wink (2009); Godoi (2012); Wink et al. (2015)
Cfb	0.76 (1)	-	-	-	Klug (2014)
Cwa	1.07 (5)	0.27	-	-	Lima (2004); Teixeira et al. (2020)
National average	1.11	0.06	1.12	0.11	

( ) = Values between parentheses represent the number of data points used to generate the mean.

Table 43 presents the results for fC when native forests were converted for eucalyptus plantations. For all conditions in establishing eucalyptus plantations after removing the native forest, carbon storage in the soil decreased, predominantly by values from 1% to 20%. In the average for the studies/locations this reduction was 5-6%. Powers et al. (2011), who also investigated changes in carbon storage in tropical regions, observed losses of 15-18% in carbon stocks in conversions of primary forests and savannas for planted forests. Some key factors may explain the decrease in carbon storage by planted forests when they replace native forests, such as less input from vegetation detritus for the forest crop, especially during the initial phase of cultivation (Barros et al., 2017). Turning the soil to plant in lines, rupturing aggregates and releasing carbon that was physically protected (Qu et al., 2019), as well as increased microbial decomposition activity due to greater oxygenation in the soil, higher soil temperature, and less turnover of the leaf litter due to more recalcitrant vegetative waste (Silva, 2008) may also be contributors.

Also with regard to converting native forest for eucalyptus plantations, the fC value observed in Aw climates (0.93) was slightly higher than in Am climates (0.80). In subtropical conditions, the fC value was similar in Cfa and Cwa climates (0.98). Comparing between Aw and Am climates, the presence of a dry winter may encourage greater fC in Aw climates, since rainfall and higher humidity in the environment accelerate decomposition of vegetative waste and organic matter in the soil.

In tropical climates (Aw and Am), fC varied from 0.80 to 0.93 in the superficial layer and from 0.76 to 0.96 in the 0-100 cm layer, while in humid subtropical climates (Cfa, Cwa, and Cwb) the value for fC varied from 0.94 to 0.98 and from 0.98 to 1.02 in the 0-20 cm and 0-100 cm layers, respectively. These results suggest that in tropical climates, fC tends to be lower than in humid subtropical ones. Because of warmer temperatures in tropical climates, there may simultaneously be greater production of biomass and higher rates of decomposition, leading to less carbon reposition in the soil compared to humid subtropical climates. This behavior leads to greater losses related to carbon in establishing areas in tropical regions, especially in Am climates, with greater challenges involved in maintaining carbon stocks in the soil and mitigating GHG emissions and, in turn, climate risk in these regions.

As for converting pastures to eucalyptus plantations, unlike when native forests are converted to eucalyptus plantations, most of the fC values indicate increased carbon in the soil when forests are planted. In this case, the gains in carbon stocks in the soil varied from 7% to 19% (Table 44). These gains can most likely be explained by the historical land use, particularly the productive capacity of the pastures which were replaced, measured by their biomass. According to Dias Filho (2014), forest plantations in Brazil are advancing into pasture areas that for the most part produced low yields. For this reason, they are being replaced with well-managed production systems that provide vegetative matter waste that in turn boosts carbon storage. This justifies the increase in carbon in the soil observed when eucalyptus is planted, which has also been reported in other studies (Scott et al., 2006; Shi; Cui, 2010).

Also for converting pastures to eucalyptus plantations, the fC value in tropical and Cfa climates were very similar (mean 1.14), and slightly higher than the values seen in Cwa (1.07). In soil layers, only in Aw climates was a clear tendency to less carbon storage in the soil seen in the 0-100 cm layer, while this value improved 15% in the superficial layer. In the other climate types, analysis of the 0-20 cm or 0-100 cm layers yielded very similar results, with C increases varying from 13% to 19%. In the national average, the carbon alteration factor is 1.11 in the 0-20 cm layer and 1.12 in the 0-100 cm layer, indicating that when (low productivity) pastures are converted to eucalyptus plantations increases in soil carbon storage can be observed.

Today, regardless of previous crops, Brazil has adopted the factor from the *Third National Communication on Climate Change*, 0.67 (Brasil, 2015). But studies investigating soil use conversions involving forest plantations in Brazil show that eucalyptus plantations do not lead to such significant losses of carbon, and can even add C to the soil when they are established over former pasturelands. These estimates are a first approach to fC for eucalyptus plantations in Brazil, and require refinement to include studies that consider environments which have not been investigated in detail but are equally important for forest production, with major contributions to studies on climate risk amid scenarios of climate change.

Conclusions

This study investigated climatic behavior in southern Brazil and the capacity for carbon emissions/removal in soils where eucalyptus is cultivated. In the study region, the projections indicate increases in temperature as well as water deficit, but with deficit values below or near 200 mm/year, as well as surplus in the Itapetininga region. In this region the water deficit will increase over time, and could negatively impact eucalyptus productivity; this area could be classified as low risk for eucalyptus production over the next thirty years.

Studies in recent years involving projections made by the HadGEM2-ES model have intervals of over 20 years; this is the first to utilize ten-year periods. By increasing the temporal resolution of this model, uncertainties appear; in this case, they center around the 2021-2030 period. A more reliable analysis of the results of this model, considering that the increases in temperature, rainfall variation, and estimated water deficit are linear between 2021 and 2040, makes it possible to project the results for the final period (2031-2040).

Objectively, the final results in terms of climate risk point to lower production risk in the study region. With the possibility of minimum temperature increase and a small water deficit, the study region is the most suitable for eucalyptus production in the next 30 years. The water requirement satisfaction index (WRSI) showed little variation in the study region and in the municipalities of interest (Itapetininga, Telêmaco Borba and Otacílio Costa), as a consequence of both the increase in ETo and the reduction in rainfall. The periods of water deficit will become more intense, with water deficit beginning to become critical at the end of the 2020-2030 period in Itapetininga and Telêmaco Borba.

It is important to emphasize that the impact on eucalyptus productivity (analyzing the MAI variation) indicates a low level in the study region, mainly in Itapetininga, and little or no impact in Telêmaco Borba and Otacílio Costa, where the quantitative impact in 30 years is less than 3 m^3/ha/year.

In terms of carbon in eucalyptus forest biomass, the region will continue to have high carbon accumulation potential, with climate reducing C removal by less than 10%, depending on the region. The most affected region will be Itapetininga, where the reduction in the annual carbon increment rate in eucalyptus could reach 2.3 tC/ha/year. In Telêmaco Borba the projected losses in the annual carbon increment will be 1tC/ha/year, and the conditions observed in this study will continue and there will be no losses in Otacílio Costa. However, it is necessary to point out that the productive potential of eucalyptus in Otacílio Costa is almost 30% lower than in Telêmaco Borba and Itapetininga, making the losses in the region quite significant, mainly because they will occur in regions with high productive potential. On the other hand, soil type within the same municipality had little effect on rates of carbon accumulation in the eucalyptus biomass.

Despite the apparent resilience that the relative data place on the annual rate of carbon increment in the forest, the accumulated losses in absolute terms are significant and could reach more than eight million tons of carbon in the study region in 2035, representing a loss of 2.5% of the carbon stored in forests in the states of SP, PR, and SC. If the growth rate is maintained, the region will account for approximately 320 million tons of carbon sequestered by eucalyptus forests in 2035, demonstrating the high potential of this region to contribute to environmental quality and climate change control policies. It also creates an excellent opportunity for the commercialization of carbon in the form of credits, since the studied region accounts for almost 20% of the area cultivated with eucalyptus in the country.

This opportunity to sell forest carbon credits is expected to benefit from storage of carbon in the soil. The impact of planted forests on soil carbon stocks depends more on the previous use than on variations between climatological types in the country, which in turn reflect differences in rainfall and temperature. In most studies, eucalyptus plantations that were established in converted pastures demonstrated gains in soil carbon storage. Since the region's forests have expanded widely on already consolidated uses such as pasture and agricultural uses, an increase in carbon storage in the soil can be expected, increasing the environmental benefits of planted forests.

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