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Articles

Agroclimatic zoning for eucalyptus in the southern mesoregion of Bahia State, Brazil

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Abstract - Forestry promotion is one of the approaches to forestry production with an increasing tendency in Brazil. The objective of this work was to present an agroclimatic zoning (AGZ), based on environmental conditions necessary for the planting of four species of eucalyptus in the southern mesoregion of Bahia State, Brazil, on a surface of 54,642.35 km². AGZ was proposed for *Eucalyptus grandis* Hill, *E. urophylla*, *E. camaldulensis* and *Eucalyptus urograndis* (*E. grandis* X *E. urophylla*), using geographic information systems for crossing spatial variables of temperature, precipitation, water deficit, evapotranspiration, soils, altitude, slope, conservation units and land use. The region showed planting aptitude of 27.93, 11.87, 3.74 and 1.70%, for *E. grandis*, *E. urophylla*, *E. camaldulensis* and *Eucalyptus urograndis,* respectively. The AGZ is an important alternative to minimize, in the long term, the negative effects of a monoculture with a high rate of transpiration that could compromise environmental sustainability and reduce water availability in a region.

Zoneamento agroclimático para o eucalipto na mesorregião Sul da Bahia, Brasil

Resumo -O fomento florestal é uma das ações que influenciam a produção florestal com tendência de aumento no Brasil. O objetivo deste trabalho foi elaborar uma proposta de zoneamento agroclimatológico, baseando-se em condições ambientais necessárias para o plantio de quatro espécies de eucalipto na mesorregião Sul da Bahia, Brasil, em uma superfície de 54.642,35 km². O zoneamento agroclimático (ZAG) foi proposto para *Eucalyptus grandis* Hill, *E. camaldulensis, E. urophylla* e *Eucalyptus urograndis* (*E. grandis* X *E. urophylla*), utilizando sistemas de informações geográficas para o cruzamento de variáveis espaciais de temperatura, precipitação, déficit hídrico, evapotranspiração, solos, altitude, declividade, unidades de conservação e uso da terra. Os resultados do ZAG para as quatro espécies estudadas na região mostrou aptidão de plantio de 27,93, 11,87, 3,74 e 1,70%, para *E. grandis*, *E. camaldulensis, E. urophylla*, e *E. urograndis,* respectivamente. A AGZ é uma alternativa importante para minimizar, em longo prazo, os efeitos negativos de uma monocultura com uma alta taxa de transpiração que poderia comprometer a sustentabilidade ambiental e reduzir a disponibilidade de água em uma região.

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Introduction

On a global scale, the natural forest area is decreasing while the expansion of planted forest is growing due to the demand for forest products and services. According to FAO (2016) there has been an increase of 105 million ha since 1990, representing 7% of the planted forest area worldwide.

The states of Minas Gerais (2,060,260 ha), São Paulo (1,354,734 ha) and Mato Grosso do Sul (1,124,637 ha) contribute with the main Brazil's eucalyptus production, and Bahia accounts for 7.8%, with 585.600 ha (IBÁ, 2021).

The conflicts over the growth of the eucalyptus monoculture are the result of actions that have affected the population. In order to minimize environmental risks, assist territorial planning and guarantee rationality in land use and compatibility between conservation and development, zoning has become an extremely important Brazilian environmental instrument, being a requirement in environmental planning at different scales (Lopes et al., 2019). This instrument is supported by the National Environmental Policy, Environmental Impact Assessment and environmental planning and management studies (Brasil, 1981). Its applicability in planning processes occurs in the territorial compartmentalization in management zones, demarcating areas with permission, restriction or adequacy of activities, aiming to ensure the environmental development of cities, regions and territories (Paixão & Aiala, 2013).

In Brazil, several proposals and types of zoning were elaborated usually with ecological-economic, environmental, socioeconomic, risk and agroclimatic zoning (Lopes et al., 2019). Agroclimatic zoning has been developed for almost three decades in Brazil by Empresa Brasileira de Pesquisa Agropecuaria (Embrapa), but also by Instituto Agronômico de Campinas (IAC), Instituto Agronômico do Paraná (IAPAR) and the Empresa de Pesquisa Agropecuária e Extensão Rural De Santa Catarina (EPAGRI), among other institutions being considered effective in delimiting potential areas for agriculture, with agronomic and climatic characteristics necessary for correct planting, compatible with the conservation of natural resources (Wollmann & Galvani, 2013).

The rapid expansion of eucalyptus and the dynamics of silviculture has directed studies in this field, especially to assess the conditions for production with low impact and greater productivity beyond higher quality of life for the population; it has become an important strategy for a more sustainable cultivation. The study by Higa & Wrege (2010) presented a zoning for *Eucalyptus grandis*, aiming to guide the choice of places for planting, showing that frost is the climatic factor of greatest restriction and the soil water availability at shallow areas of southern Brazil affects the initial planting period. In Bahia, Lima et al. (2011) developed agroclimatic zoning for *Eucalyptus camaldulensis* Dehn. and *Corymbia citriodora* (Hook) K.D.Hill & L.A.S.Johnson, indicating potential areas suitable for planting depending on the climate.

Considering that several species are characterized by specificities in the climatic condition, including the predisposition of precipitation, temperature, water deficit and evapotranspiration, the establishment of an agroclimatic zoning focused on territories with strong expansion for the production of eucalyptus is justified by the need to guide the production that has been characterized as one of the main sources of income in the region.

In addition, having a territory planning is necessary, as it is a tool compatible with the sustainable use of natural resources, guaranteeing the well-being of the present and future population (Sanchez & Roberts, 2019). This work aimed to develop a proposal for agroclimatic zoning, taking into account climatic, pedological and topographical factors and use and occupation of soils for planting four species of eucalyptus (*Eucalyptus grandis* Hill (ex Maiden), *Eucalyptus urophylla* S.T. BLAKE, *Eucalyptus camaldulensis* Dehnh and *Eucalyptus urograndis* (*E. grandis* X *E. urophylla*) in the southern Bahia mesoregion.

Material and methods

Study area

The study area is located in the Costa do Descobrimento and Extreme South, totaling 21 municipalities located further south in the State of Bahia (Figure 1).

Climate Data

Precipitation and temperature data were obtained in the WorldClim global database over a period of 50 years (1950-2000) for the study area (Fick & Hijmas, 2017)

with resolution of 30 arc-sec (~90 m). The data were acquired and segmented for the study area, allowing the presentation of spatialized climate information. Water deficit and evapotranspiration were calculated using the method of Thornthwaite & Mather (1955).

Pedological and topographic data

The pedological information of the territory was acquired in the database of the Institute of Environment and Water Resources (INEMA), in scale 1: 1,250,000 (Bahia, 2004), while the topographic data were estimated from obtaining the digital elevation models (DEM) of the Shuttle Radar Topography Mission (SRTM) project, downloaded from TOPODATA/INPE (INPE, 2020). The DEM was processed using the QGIS software (QGIS Development Team, 2020) and the percentage of slope in the area was calculated, according to Embrapa classification (Santos et al., 2018).

Analysis of land use and protected areas

Land use was obtained on the MapBiomas 3.1 project platform for the year 2018 (Mapbiomas, 2019). The study area presented twelve land use: natural forest formation, savanna formation, mangrove, planted forest, other non-forest natural formation, pasture, mosaic of agriculture and pasture, beach and dune, urban infrastructure, other non-vegetated area, apicum ecosystem, river, lake and ocean. The conservation units were obtained from the Brazilian Ministry of the Environment's database, considering their category of integral protection or sustainable use (Brasil, 2020).

A marginal strip of 10 km from the coast towards the continent was generated, determined in a regional agreement of the Bahia Forestry Forum as restricted to planting or to forest production. The range was defined according to the geographical and administrative delimitation of the municipalities by the Brazilian Institute of Geography and Statistics (IBGE, 2019).

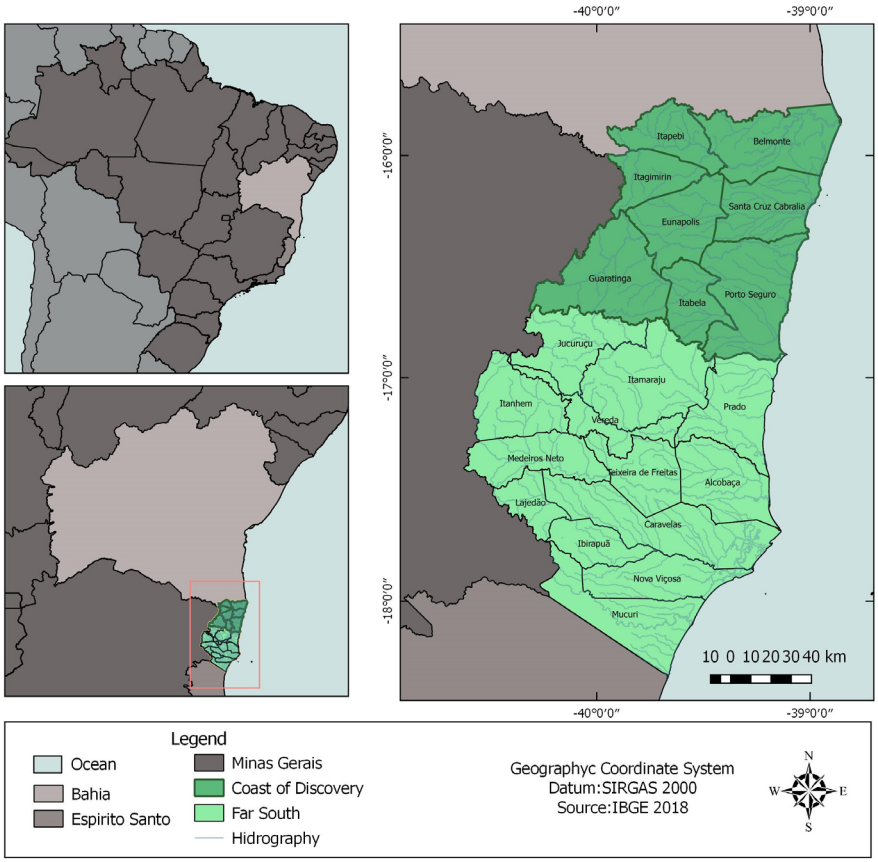

Figure 1. Location of the Territories of the Costa do Descobrimento and Extreme South of Bahia in the mesoregion of Southern Bahia, Brazil.

Zoning proposal

For the definition of the proposal, the variables were classified in areas suitable or not suitable, as described in the literature on the environmental conditions for the development of each species, as shown in Table 1.

For land use, all areas considered natural, equivalent to restingas, forest fragments of the Atlantic Forest, mangroves, humid areas and built environments were considered unsuitable while areas of pasture, planted forests and agriculture were considered suitable. The conservation units and the marginal strip in the coastal zone were considered as restricted areas.

After classification, the variables were submitted to a multicriteria analysis (AMC), using the analytic hierarchy process (AHP) developed by Thomas Saaty in the 1970 (Saaty, 2008). AHP defines itself as a mathematical-based theory that organizes and assesses the relative importance between criteria and provides the consistency of judgments, through the index known as the consistency ratio).

The determination of the weights of importance and the comparison of the variables were built with a paired matrix, based on extensive discussions between specialists, assigning weights of importance.

The weights of importance attributed to each species were observed, as shown in Table 3. To aggregate this information, the weighted tool available in the QGIS software was used (QGIS Development Team, 2020). According to the limitations of the species, the parameter that presented the greatest restriction for each species was considered as the most important.

The spatial obtaining of the management zones for the zoning of each species occurred with the intersection of the variables, using as basis the importance weight of each variable in the process, according to the equation developed in this study (Equation 1).

Table 1. Climatic requirements, soils and altitude for eucalyptus species.

Parameters	*E. grandis* Hill (ex Maiden)	*E. urophylla* S.T. Blake	*E. camaldulensis* Dehnh.	*E. urograndis* (*E. grandis* X *E. urophylla*)
Temperature (^{0}C)	17 - 23[1]	19 - 26[1]	17 - 25[2]	18 - 25[1]
Annual precipitation (mm)	1,000 - 1,750[3]	900 - 1,800[5]	225 - 1,200[5]	720 - 1,800[1]
Annual water deficit (mm)	0 - 120[1]	30 - 210[1]	0 - 90[3]	15 - 170[1]
Annual Evapotranspiration (mm)	700 - 1,200[5]	900 - 1,250[5]	700 - 1,400[5]	460 - 1,731[7]
Altitude (m)	500 - 1,200[3]	400 - 3,000[6]	0 - 1,000[3]	500 - 600[4]
Slope	< 45°	< 45°	< 45°	< 45°
Soils[8]	Argisols and Latosols	Argisols and Latosols	Argisols and Latosols	Argisols and Latosols

Source: [1]Sperandio et al. (2010); [2]Lima et al. (2011); [3]Pryor (1981); [4]Santos (2014); [5]Ferreira (1997); [6]IPEF (2017); [7]Torres (2012); [8]Bahia (2004).

Table 2. Importance weight scale of the analytic hierarchy process.

Less important				Equal	More important			
Extremely	Very strong	Strong	Moderately	Equally	Moderately	Strong	Very strong	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

Source: adapted from Saaty (2008).

Table 3. Final weights of importance for eucalyptus species.

Parameters / Species	*Eucalyptus urograndis*	*Eucalyptus camaldulensis*	*Eucalyptus urophylla*	*Eucalyptus grandis*
Land use	0.1607	0.1057	0.1662	0.0992
Precipitation	0.3501	0.1675	0.3574	0.3611
Temperature	0.0165	0.0175	0.0170	0.0171
Evapotranspiration	0.0989	0.0627	0.2354	0.2366
Water deficit	0.0241	0.3570	0.0972	0.0261
Altitude	0.2495	0.2265	0.0583	0.1551
Slope	0.0609	0.0382	0.0427	0.0617
Soils	0.0392	0.0249	0.0258	0.0432
Consistency index	0.10	0.08	0.08	0.07

$$ZAG: (((P*x)+(E*x)+(DH*x)+(T*x)+(A*x)+(D*x)+(S*x)+(U*x))/8)*(restricted\ zones) \quad (1)$$

where: ZAG = agroclimatic zoning; P = precipitation; DH = water deficit; T = temperature; A = altitude; D = declivity; S = soils; UCs = conservation units; E = evapotranspiration; U = land use; and x = weight of importance.

The management zones were characterized considering their division in high, medium, low and no aptitude, being described to guide the sustainable development and the conservation of the natural resources, as well as the coordination for a better use and occupation of the soil.

The zone of high aptitude corresponds to an area that presents characteristics of climate, soils and topography that are optimal for the development and planting of the species; the medium aptitude zone is the area that presents intermediate conditions for the establishment of the cultivation; and the area with low fitness refers to an area with unfavorable conditions for cultivation. The unsuitable zone constitutes the areas restricted by the conservation units, natural areas of relevant interest for conservation and the coastal strip with no planting.

Results

The south of Bahia can be considered complex due to the climatic diversity of the region. The average annual temperature varies between 22 °C to the west and 26 °C to the southeast of the south coast. The accumulated precipitation for the same respective regions were from 878 to 1,619 mm.

The slope of the area showed relief varying between flat and steep, denoting the peculiar characteristic of coastal areas and their variation along the continent; the altitudes reach 1,121 m. The predominant pedology is the Dystrophic Yellow Latosol, Dystrophic Yellow Argisol and the Dystrophic Red-Yellow Latosol. In the area there are 56 conservation units located mostly in the eastern region of the studied territory.

The agroclimatic zoning for the four species of eucalyptus are presented in Figure 2 and the number of areas in the management zones and their area distribution in the territories are indicate in Table 4.

The area of high aptitude for *Eucalyptus grandis* represents 27.9% of the territory, with optimal conditions for cultivation. Of the species studied, *E. grandis* covers a larger area of high fitness for its establishment.

The area of medium aptitude for *E. grandis* represents 8.6% within the territory. The species has a different spreading pattern than the other species, located in the northeast and southwest regions. The area of low fitness for the species occupies 19.9% located in the western region of the territory.

For *E. camaldulensis*, the high fitness zone occurs in 11.9% of the territory.

The medium aptitude zone is less representative in *E. camaldulensis* occupying an area of 1.2%, located in the west and center of the territory, however the 43.4% located within the low aptitude zone was observed in small areas of the west and center. The species with the least coverage in the high fitness zone is *E. urograndis*, equivalent to 1.7% of the territory.

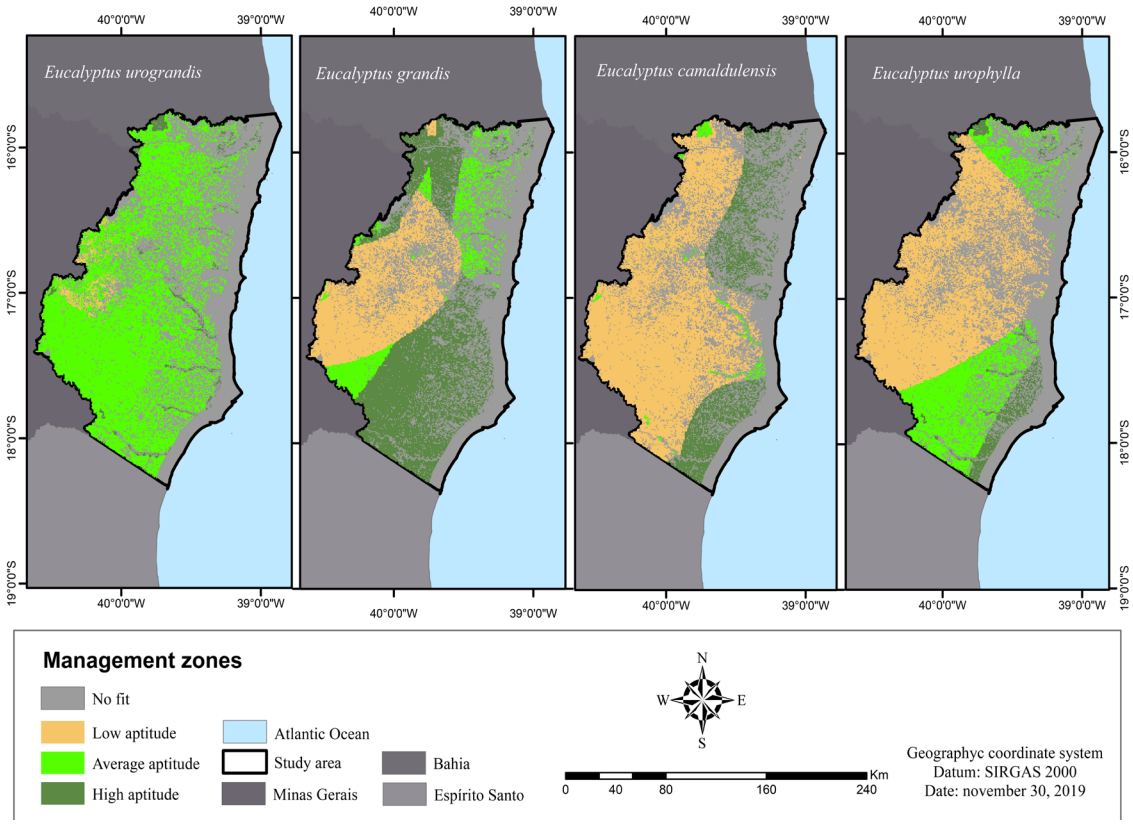

Figure 2. Agroclimatic zoning for four species of Eucalyptus in Costa do Descobrimento and Extreme South of Bahia, Brazil.

Table 4. Quantitative of agroclimatic zoning management zones.

Management Areas	*E. camaldulensis* Dehnh.		*E. urophylla* S.T. Blake		*E. grandis* Hill (ex Maiden)		*E. urograndis* (*E. grandis* X *E. urophylla*)	
	Area Km²	%	Area Km²	%	Area Km²	%	Area Km²	%
Low	13,259.70	43.4	10,656.47	34.9	6,093.02	19.9	552.31	1.9
Average	371.65	1.2	5,458.99	17.9	2,626.57	8.6	16,188.19	52.9
High	3,628.32	11.9	1,144.23	3.7	8,540.12	27.9	519.18	1.70
Not fit	13,319.74	43.5	13,319.74	43.5	13,319.71	43.6	13,319.74	43.5

The area of medium fitness showed greater territorial coverage for the species *E. urograndis*, with more than half of the area (52.9%) between the north, south, east and west of the territory.

The area of low fitness for this species is small, totaling a 1.8% of the territory, located in the west was characterized by a greater slope, greater than 45° and altitude reaching 1,121 m.

The unfit zone represents 43.6% (Table 4) of the territory and it is characterized by not being suitable for eucalyptus planting, restricted according to the use of the land and protected area.

It was noted that the species under study showed adaptation to the temperature parameter, since this parameter was never decisive in the classification for the inability of any area to the studied cultures.

Precipitation, in three of the four species, was the most limiting variable in terms of disability. The water deficit was also limiting for *E. camaldulensis*.

Discussion

Regardless of the cultivated species, not just eucalyptus, industrial plantations can intensify impacts on water sources, since such high-performance plantations consume quantities of water in direct proportion to the rapid growth of plants. So production planning must consider the different environmental conditions of the planting region and their impacts in the short, medium and long term (WRM, 2016).

The rains are the result of the interactions of several meso and microscale mechanisms in the area, also influenced by the continentality and land use and occupation throughout the study region. According to Mencía et al. (2021), this precipitation variability in region influence on annual evapotranspiration and average temperature, resulting in greater annual water deficit to the west the southern mesorregion of Bahia.

Considering the evapotranspiration parameter of eucalyptus species, whose range is greater than 1,000 mm per year, there may be a decrease in the flow of rainwater, losing part of the water that would sustain rivers and streams (WRM, 2016). It should be considered that certain species lose their leaves to reduce losses due to evapotranspiration when rainfall is low, but this does not happen with fast-growing species. With this, eucalyptus plantations can be considered a risk for subsurface and groundwater.

It is also noteworthy that in the areas zoned as medium and low aptitude, the species will be able to develop reasonably, however they may not reach all their genetic growth potential and productivity that indicate the high aptitude areas. Thus, agroclimatic zoning becomes useful to foster the perception of environmental conditions, as well as a tool for planning agroforestry, as it defines the most suitable zones and zones in which planting should not be carried out in the long term, considering their particularities, vocations and restrictions (Dorneles, 2010). The *Eucalyptus grandis* does not support rainfall less than 1,000 mm annually, but it does support water deficits of up to 120 mm and an evapotranspiration rate of 700 to 1,200 mm annually (Pryor, 1981; Ferreira, 1997; Sperandio et al., 2010).

These restrict characteristics for *E. grandis*, representing a large part of the cultivation area due to the climatic restrictions to the west, can cause reduction in productivity and generate a high demand for water in these regions, since the restricted areas indicated more than 43%.

The greatest aptitude for *E. camaldulensis* was located in the northeast and southeast of the study area, in disagreement with Lima et al. (2011) who estimated that, in the state of Bahia, there is aptitude for planting this species only in the west of the study area. This difference can be explained, although these authors use precipitation data in the 250-600 mm range, while in this study the values used were 225-1,200 mm, 825 mm more than the range. The species does not have much limitation in terms of water availability, since it can survive under minimum rainfall of 225 mm per year (Ferreira, 1997), supports water deficit up to 90 mm (Pryor, 1981) and evapotranspiration rates from 700 to 1,400 mm per year (Ferreira, 1997). On the other hand, the region in its largest central and western portion, has a water deficit of 90 mm (Pryor, 1981), which restricts the increase in the planting area for this species.

The low aptitude for the species coincides with the results of Lima et al. (2011), since dependence on the evapotranspiration was observed, suggesting the west as a less favorable region for *E. camaldulensis*, as this area presents a great deficit water and low rainfall. The requirement for *E. urophylla* is precipitation, from 900 to 1,800 mm but the greatest rainfall is 1,619 mm annually (Mencía et al., 2021).

E. urophylla can reach values of 1,250 mm annual evapotranspiration and supports higher values of water deficit in comparison with the other studied species, reaching up to 210 mm. It is noteworthy that in the state of Espírito Santo, a state bordering the study area, this species demonstrated greater potential than *E. grandis, E. citriodora* and *E. urograndis,* because it supports greater water deficit and greater thermal range for its establishment, besides of this, the rainfall in Espírito Santo is greater than in Bahia, reaching 1,863.4 mm per year (Sperandio et al., 2010). The biggest limitation for this species is the altitude, since its best development is from 500 to 600 m (Santos, 2014). It can accept a minimum precipitation of 720 mm per year (Sperandio et al., 2010) and evapotranspiration rate up to 1,700 mm per year (Torres, 2012). Predominant to the west, intermediate declivity and lower rainfall (Mencía et al.,

2021), making it vulnerable to the production of this species, since the rivers that supply the coastal areas are born west of the region, compromising the reduction of surface and underground water resources. Management guidelines should be intensified in the areas of medium and low fitness.

The spatial delimitation of the eucalyptus plantation restriction helps in the process of conservation of the territory's natural resources, provides basis for environmental inspection and the adequacy of rural properties regarding the area's vocation and its legal limitations. As Vieira et al. (2015) pointed out, the increase in information about the network of conservation units in the area is essential for raising people's awareness of the role and value of these areas for ecosystem service, in addition to planning and territorial development.

It is noteworthy that although the permanent preservation areas (APPs) and legal reserves (RLs) were not included in this study, due to spatial and scale issues, it is suggested that the applications of eucalyptus cultivation in the apt areas will demand attention to the need to adapt rural properties and urban conventions as to the environmental regularization of the process. Recalling that, the suppression of APPs and RLs would prevent protected areas from being segmented between agricultural landscapes, they as are essential for the offer of ecosystem services and sustainability in Brazil (Metzger et al., 2019). Therefore, the use of this zoning proposal must be used in association with other environmental mechanisms and their respective legislation.

Conclusions

The south of Bahia has high aptitude with greater potential for the species *Eucalyptus grandis*. *E. urograndis* presented a larger area in the medium aptitude management zone, although despite that it is important to follow intense controls for sustainable forest management since there is a high pressure on water resources.

It is worth mentioning that, although aptitude has been observed for the four species of Eucalyptus, the uses of monocultures must be controlled, especially regarding to water resources and hydrographic basin protections, therefore, agroclimatic zoning is a functional tool and potential for the management of Eucalyptus plantation in the region.

It is necessary to consider also the other mechanisms of environmental suitability, in order to adapt this zoning for small productions, avoiding the process of territorial degradation, city and hydrographic basins, as well as proposing greater water security and quality of life for the population.

Conflict of interest

The authors have no conflict of interest to declare.

Authors' Contributions

Francis Paola Hernandez Mencia: Conceptualization, formal analysis, investigation, methodology, writing-original draft, writing-review & editing.

Elfany Reis do Nascimento Lopes: Formal analysis, investigation, methodology, supervision, writing-original draft, writing-review & editing.

Fabricio Berton Zanchi: Formal analysis, investigation, methodology, supervision, writing-original draft, writing-review & editing.

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