CERNE

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CLIMATE ZONING FOR THE CULTIVATION OF AFRICAN MAHOGANY SPECIES IN BRAZIL

HIGHLIGHTS

Brazil has high climatic aptitude for African mahogany species.

K. anthotheca and *K. grandifoliola* show high aptitude in more than 70% of Brazil.

K. ivorensis presented the lowest proportion of area with high fitness to the planting.

K. senegalensis is the most sensitive species to low temperatures.

ABSTRACT

African mahogany is the common name given to different species of the genus *Khaya*. They are tree species native to the African continent, which have a wood quality that allows their noble use in making fine furniture, and in the civil and naval industries. Currently, African mahogany cultivation has received notoriety in Brazil and given its climatic conditions. The country has great potential for planting these species. The purpose of this work was to identify climatic aptitude zones for African mahogany in Brazil. Based on the Kppen classification and in the means of relative air temperature and annual rainfall, a base map interpolation was performed to select regions suitable and restricted to planting and adequate growth of African mahogany species. In general, the regions that presented temperatures between 22 °C and 30 °C were considered of high fitness, while temperature values below 14 °C restricts plantations growth. Regarding to precipitation, areas considered to be of high aptitude have between 700 to 3,000 mm·year^{-1}, extreme values may indicate regions of low suitability and restricted to the cultivation of African mahogany. From the climatic characteristics, it was determined that about 60% of the Brazilian area was of high fitness, between 16% and 32% of medium fitness, and less than 20% as low fitness. The Northeastern semi-arid region proved to be restricted to the cultivation of these species due to the low annual rainfall and a few places in the South region was also restricted due to low temperatures and risks of frost.

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INTRODUCTION

Wood product has great and worldwide demand, which stimulates the production and cutting of trees that have economic importance. The predatory exploitation has caused the degradation of several Brazilian biomes, increasing the risk of extinction of timber forest species, such as *Araucaria angustifolia* (Bertol.) Kuntze, *Cedrela fissilis* Vell., *Dinizia excelsa* Ducke, *Dipteryx odorata* (Aubl.) Willd., *Hymenaea courbaril* L., Swietenia macrophylla King, *Handroanthus serratifolius* (Vahl) S.Grose, among others (IUCN, 2018; Brandes et al., 2020). The Amazon region has increasing deforestation rates, reaching maximum levels in 2004 and 2019 (INPE, 2020). An alternative to reduce illegal deforestation in native areas is the use of wood from commercial plantations of forest species in addition to the sustainable forest management.

The implantation of commercial forests has been a new market trend, as they are important for reducing the forest deficit, protecting remaining native areas, fixing atmospheric carbon, and regulating the hydrological cycle (Grattapaglia and Kirst, 2008; Payn et al., 2015). In 2018, Brazil had about 7.83 million hectares of commercial forests that serve to several economic purposes (IBÁ, 2019). The *Eucalyptus* spp. and *Pinus* spp. occupy 72.4% and 20.1%, respectively, of this planted area, while species destined exclusively for sawnwood use, such as those of the genus *Khaya* A. H. L. De Juss, represent less than 5% (IBÁ, 2019).

The *K. anthotheca* (Welw.) C. DC., *K. ivorensis* A. Chev., *K. grandifoliola* C. DC. and *K. senegalensis* (Desr.) A. Juss. are known as African mahogany (Lamprecht, 1990; Opuni-Frimpong et al., 2008; Reis et al., 2019b). They are large trees belonging to Meliaceae's family, with extensive stem, dense crown, and wood quality for noble uses Opuni-Frimpong et al., 2016; Dipelet et al., 2019; Pakull et al., 2019). African mahogany has been increasingly used by reforesters in Brazil, due to the advances in producing seedlings, the fast growth, and the high economic value of wood in the international market (Falesi and Baena, 1999; Ribeiro et al., 2017; ITTO, 2020). It is estimated that the Brazilian territory has more than 37 thousand hectares, making Brazil the world's largest reforestation of African mahogany (Reis et al., 2019b).

Another factor that boosted the cultivation of African mahogany was the prohibition on the exploitation of wood Brazilian mahogany, *S. macrophylla* (Gasparotto et al., 2001; Couto et al., 2004; Brasil, 2008). Was believed African mahogany to have total resistance to *Hypsipyla grandella* Zeller, the shoot borer, that causes wood damage, common in Brazilian mahogany (Poltronieri et al., 2002; Krisnawati et

al., 2011). However, a few attacks by *H. grandella* have already been reported, punctually, in *K. ivorensis* plantations (Zanetti et al., 2017; Lemes et al., 2019), not restricting the technical and economic advantages for planting these species in Brazil.

Commercial forests may be responsible for meeting not only the demand for timber products, but also products such as resins and medicines. African mahogany has antifungal, anti-inflammatory, insecticidal, and preventive compounds against malaria and other diseases (Nikiema and Pasternak, 2008; Zhang et al., 2009; Abdel-Wareth et al., 2014).The adaptation and production of commercial forests is directly influenced by climatic conditions. To obtain greater forest productivity, adjustments in silvicultural treatments, promotion of genetic improvement of the species used and the search for better climatic adaptation are necessary.

Climatic variables, such as air temperature and rainfall, are influenced by other factors e.g. geographical relief, altitude, and vegetation (Alvares et al., 2013b). Thus, the climate is a limiting and conditioning factor for the commercial planting of forest species. The climate is the condition with the least chance of intervention, allowing only some control in small and protected areas, such as greenhouses (Casaroli et al., 2018).

Except for the species *K. ivorensis*, information is lacking that portrays the ideal climatic conditions to guide African mahogany plantations in Brazil. *K. ivorensis* already had a climatic zoning elaborated by Derblai et al. (2018). However, recently in Brazil, *K. ivorensis* has come by a correction in its botanical classification, being called *K. grandifoliola* (ABPMA, 2020). Thus, the zoning proposed by Derblai et al. (2018), must also be reviewed.

Climatic zoning is an important tool for choosing species and silvicultural treatments in a region, promoting the best use of the natural resources available. Therefore, climatic zoning is fundamental in decision-making, as it assesses the compatibility between species and the cultivation environment, in order to delimit regions that provide greater or lesser fitness, defining areas with foremost potential for implantation (Golfari et al., 1978). Under these circumstances, the objective of this work was to carry out climatic zoning for the different species of African mahogany cultivated in Brazil, aiming to give subsidies regarding to the indication of potentially species suitable for plantation in different Brazilian regions.

MATERIAL AND METHODS

The determination of zones with greater or lesser climatic fitness of the different species of African mahogany planted in Brazil (*K. anthotheca*, *K. grandifoliola*, *K. ivorensis* and *K. senegalensis*) was based on climatic characteristics

of the naturally occurring areas of these species (Figure 1). Climatic data were collected from all countries where African mahogany species occur (CJBG and SANBI, 2012; Bouka et al., 2019). In those areas there are several climatic typologies described by Köppen and Geiger (1928), standing out the types Af, Am, Aw and Bsh (Table 1).

The climatic aptitude criteria for each of the species evaluated were established based on the climatic characteristics of the places of natural occurrence of the populations of *Khaya* spp. (Table 2). The African mahogany species evaluated have a wide distribution in the African continent (Figure 1). The intervals of the averages of the optimal values of air mean temperature, annual rainfall, and altitude in the naturally occurring environments of each species were considered as. Values outside the optimal development limits were considered to have low tree growth capacity.

To classify climatic suitable zones for African mahogany species in the national territory, climatic data from 5571 Brazilian municipalities were used. The values of altitude, temperature, and rainfall represent the average of the pixels (100 m) within the perimeter of each municipality. Only the most representative Köppen climate type (% in area) was considered in each municipality. These climatic data were made available by IPEF (2020).

The temperature values were obtained by Alvares et al. (2013a) through a model produced by ordinary kriging from the average of the temperature data of 2,400 weather stations. These temperature predictor model had an excellent performance ($R^2 = 0.93$, RMSE = 0.80 °C, DW statistical test = 2.01). The altitudes were generated by Alvares et al. (2013a) by the digital elevation model (DEM) from SRTM images (Shuttle

TABLE 1 Interval of average annual rainfall (mm) and average annual temperature (°C) and Kppen-Geiger climate classification predominant for the countries that form the regions of origin of the African mahogany species (*Khaya* ssp.).

Countries	Rainfall (mm)	Temp. (°C)	Climate Classification of Kppen-Geiger	*Khaya anthotheca*	*Khaya grandifoliola*	*Khaya ivorensis*	*Khaya senegalensis*
Angola	1500 - 2000	21 - 23	Aw	x			
Benin	1500 - 2000	27 - 28	Aw	x	x		x
Burkina Faso	1000 - 2000	27 - 28	Aw, BSh	x			x
Burumbi	1000 - 1500	21 - 23	Aw	x			
Cameroon	2000 - >3000	23 - 26	Am, Aw, BSh	x	x	x	x
Central African Republic	1500 - 3000	24 - 26	Aw	x	x		x
Chad	600 - 2000	26 - 27	Aw, BSh				x
Congo	2000 - 3000	23 - 26	Am, Aw	x		x	
Côte d'ivoíre	1500 - 3000	24 - 25	Am, Aw	x	x	x	x
Democratic Republic of the Congo	1000 - >3000	22 - 26	Af, Am, Aw, Cwa, Cwb	x	x	x	x
Equatorial Guinea	>3000	23 - 24	Am			x	
Gabon	2000 - >3000	24 - 26	Am, Aw			x	x
Gambia	1500 - 2000	26 - 28	Aw				x
Ghana	1500 - 3000	26 - 27	Am, Aw	x	x	x	x
Guinea	2000 - 3000	25 - 26	Am, Aw	x	x	x	x
Guinea Bissau	1500 - 2000	25 - 26	Aw				x
Kenya	1000 - 1500	25 - 26	Aw	x			
Liberia	>3000	24 - 25	Af, Am	x	x	x	
Malawi	600 - 1500	21 - 24	BSh, Cwa, Cwb	x			
Mali	1000 - 3000	26 - 28	Aw, BSh				x
Mozambique	600 - 1500	23 - 25	Aw, BSh	x			
Niger	1000 - 1500	27 - 29	BSh				x
Nigeria	1000 - >3000	25 - 27	Am, Aw, BSh	x	x	x	x
Senegal	1000 - 3000	26 - 29	Aw, BSh				x
Sierra Leone	>3000	25 - 26	Am	x	x		x
South Sudan	1000 - 2000	23 - 28	Aw		x		x
Sudan	400 - 1000	23 - 29	Bsh, BWh				x
Tanzania	600 - 2000	20 - 26	Aw, BSh, Cwa	x	x		
Togo	1000 - 3000	25 - 28	Aw	x	x	x	x
Uganda	1000 - 3000	22 - 24	Am, Aw	x	x		x
Zambia	600 - 2000	20 - 25	Aw, BSh, Cwb	x			
Zimbabwe	600 - 1500	22 - 23	BSh, Cwb	x			

Source: Kppen and Geiger (1928); Kottek et al. (2006); FreeMeteo (2020). Af: Tropical rainforest climate; Am: Tropical monsoon climate; Aw: Tropical savanna climate dry-winter characteristics; BSh: Hot Semi-arid climate;; BWh: Arid climate; Cfa: Humid subtropical climates; Cfb: Oceanic climate; Cwa: Dry-winter humid subtropical climate; Cwb: Dry-winter subtropical highland climate.

TABLE 2 Classes of climatic aptitude for the cultivation of the different species of African mahogany (*Khaya* spp), based on their areas of natural distribution.

| African Mahogany Species	Rainfall (mm)			Temperature (°C)			Altitude (m)			Köppen Climate
	High Aptitude	Low Aptitude	Unapt	High Aptitude	Low Aptitude	Unapt	High Aptitude	Low Aptitude	Unapt	Types
K. anthotheca	1,000-3,250	600-999 or >3,250	<600	21-28	<21 or >28	<12.5	0-1,800	1,800-2,200	>2,200	Af, Am, Aw, BSh, Cwa, Cwb
K. grandifoliola	1,000-3,100	760-999 or >3,100	<760	22-28	<22 or >28	<12.7	200-1,800	<200 or 1,800-2,200	>2,200	Af, Am, Aw
K. ivorensis	1,500-3,250	815-1499 or >3,250	<815	22-28	<22 or >28	<13.0	0-800	800-1,200	>1,200	Af, Am, Aw
K. senegalensis	1,000-3,000	560-999 or >3,000	<560	23-29	<23 or >29	<13.5	0-1,800	1,800-2,200	>2,200	Am, Aw, BSh, BWh

Source: Lamprecht, 1990; Preciak et al., 2013; Opuni-Frimpong et al., 2016; Reis et al., 2019a. Af: Tropical rainforest climate; Am: Tropical monsoon climate; Aw: Tropical savanna climate dry-winter characteristics; BSh: Hot Semi-arid climate; BWh: Arid climate; Cwa: Dry-winter humid subtropical climate; Cwb: Dry-winter subtropical highland climate.

Radar Topography Mission) in GEOTIFF format with spatial resolution of 90 meters and SIRGAS2000 datum (Jarvis et al., 2008; Farr and Kobrick, 2000).

Precipitation values were obtained by Alvares et. al. (2013b) through a punctual ordinary kriging estimator was used for geostatistical interpolation from data to 2,950 weather stations distributed throughout the Brazilian territory. These rainfall estimators had an excellent performance, with the estimated residues were low and a high coefficient of determination (R^2), above 0.97, and a strong SDI, spatial dependence index (Alvares et al., 2013b).

Alvares et al. (2013b) found 12 types Köppen climates throughout Brazil, being: Af, Am, Aw, As, BSh,
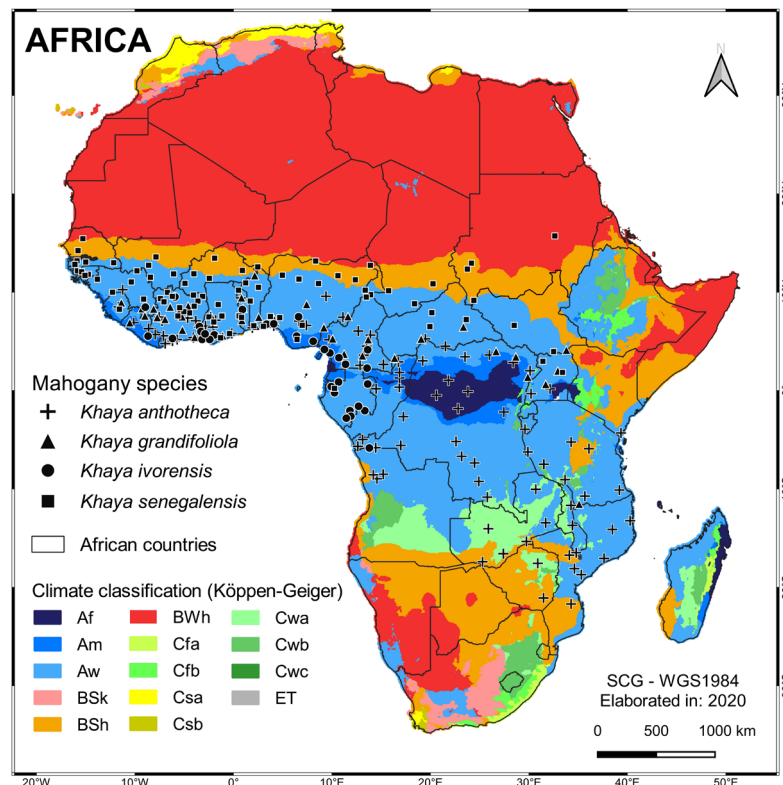
FIGURE 1 Area of natural occurrence of African mahogany species and Kppen-Geiger climate classification for the African continent. Source: Kppen and Geiger (1928); Kottek et al. (2006); CJBG and SANBI (2012); Dipelet et al. (2019). Af: Tropical rainforest climate; Am: Tropical monsoon climate; Aw: Tropical savanna climate dry-winter characteristics; BSh: Hot Semi-arid climate; BSk: Cold Semi-arid climate; BWh: Arid climate; Cfa: Humid subtropical climates; Cfb: Oceanic climate; Csa: Mediterranean hot summer climates; Csb: Mediterranean cool summer climates; Cwa: Dry-winter humid subtropical climate; Cwb: Dry-winter subtropical highland climate; Cwc: Dry-winter subpolar oceanic climate; ET: Tundra climate.
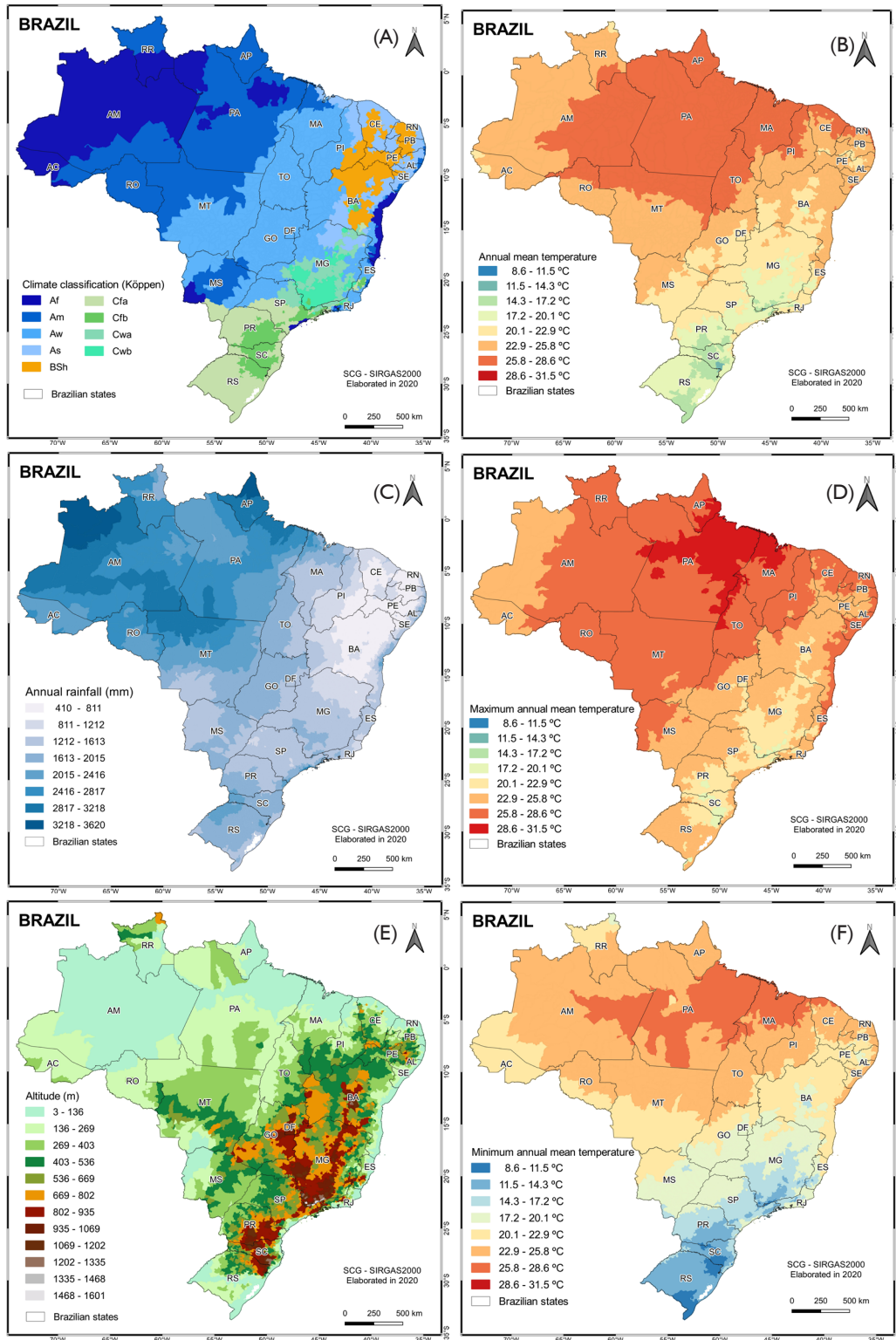
FIGURE 2 Base map of climate classification in Brazil at the municipal boundary: A) Köppen-Geiger climate classification; B) map of average annual temperatures (°C); C) annual rainfall map (mm year⁻¹); D) map of maximum annual mean temperatures (°C); E) map of altitudes (m); F) map of minimum annual mean temperatures (°C). Source: Köppen and Geiger (1928); Alvares et al. (2013b); IBGE (2018); INMET (2020); IPEF (2020). Af: Tropical rainforest climate; Am: Tropical monsoon climate; Aw: Tropical savanna climate dry-winter characteristics; As: Tropical savanna climate dry-summer characteristics; BSh: Hot Semi-arid climate; Cfa: Humid subtropical climates; Cfb: Oceanic climate; Cwa: Dry-winter humid subtropical climate; Cwb: Dry-winter subtropical highland climate.

Cfa, Cfb, Cwa, Cwb, Cwc, Csa and Csb (Figure 2). These Köppen climate types are symbolized by two or three characters, where the first indicates the climate zone and is defined by temperature and rainfall, the second considers the rainfall distribution and the third is the seasonal temperature variation. The layers of latitude and longitude were obtained in decimal degrees using the central coordinates of each pixel.

The base maps of the Köppen altitude, temperature, rainfall, and climate type values were built respecting the perimeter of each municipality (Figure 2), according to the climatic data obtained by Alvares et al. (2013b) and available by IPEF (2020). From the union of information on the climatic requirements of the species of *Khaya* spp. assessed and the conditions of the Brazilian climates (Figure 2), classes of aptitude were created to recommend the best environments for the development of each species.

Through the base maps it was possible to create maps of climatic fitness for each species through boolean overlay, through the union of information on their climatic requirements using the pre-established criteria (Table 2). The boolean overlay method is one of the simplest for making thematic maps (Riad et al., 2011; Palmer et al., 2019). This technique is great for dealing with environmental data, because boolean overlays allow to combine several thematic maps to generate another one reflecting these combined information (Watson & Hudson, 2015; Palmer et al., 2019; Cao et al., 2019).

Thus, five aptitude classes were created, three for suitable environments and two for restricted or unfit use. In environments favorable to planting, the classes are subdivided into high, mean and low aptitude. The high climatic aptitude for the African mahogany species comprises the high aptitude classes for each variable considered. The medium aptitude comprises classes of high aptitude and medium aptitude, whereas the low aptitude comprises the classes of low aptitude for all the considered characteristics. Low annual rainfall favors ineptitude due to water deficit, while low temperatures can restrict the vegetative development of plants, especially when frost occurs.

The climate fitness maps for African mahogany were generated using Geographic Information Systems (GIS) in the free software QGIS 3.14.1 Pi (QGIS, 2020).

RESULTS

The species *K. anthotheca* showed high climatic aptitude in 77.6% of the national territory, based on annual rainfall, temperature averages, altitude and Köppen climate types considered in this study. These high climatic aptitude areas are concentrated in the Midwest region (DF, GO, MS and MT states), North (AC, AM, AP, PA, RO, RR and TO states), Southeast (ES, MG, RJ and SP) and the Northeast coast (Figure 3A).

Areas with mean aptitude represent 10.3% of the Brazilian territory, while 7.7% are areas with low fitness. The mean aptitude is identified in part of the states in the North (AM and AP states) and South (PR and SC states) regions, and in all states in the Northeast and Southeast regions. Areas of low aptitude for *K. anthotheca* are concentrated in the interior of the Northeast region (AL, BA, CE, MA, PB, PE, PI, RN and SE states) and in the South region (PR, RS and SC states), surrounding the restricted areas to the development of *K. anthotheca*.

Favorable growth restrictions are due to low annual rainfall in the Northeast and low average air temperatures in the South. These restricted areas correspond to 2.3% and 2.1% of the national territory, respectively.

The species *K. grandifoliola* showed high climatic fitness for all the Midwest region, almost all the North region, as well as the Northeast coast and part of the Southeast region, which corresponds to about 72% of the Brazilian territory (Figure 3B). Areas with mean aptitude for *K. grandifoliola* are found in parts of the AM, MA, PR, SP, MG, RJ, ES and PI states, which consist of 10.5% of the country.

The low aptitude of the species reaches only 9.3% of Brazilian territory, in areas in the South and Northeast, north of AP state and far west of AM state. The restrictions on the good development of *K. grandifoliola* are due to the low annual rainfall in the Northeast and the low average air temperatures in the South, which together make its growth impossible in 8% of the national territory.

The species *K. ivorensis* also showed high climatic aptitude in 62,8% of Brazilian territory, including the Midwest and North regions, except for part of the MT, MS, AM, AP and TO states (Figure 3C). The areas with mean aptitude for *K. ivorensis* account for 13.2% of the national territory and represent a transition zone between the high and low aptitude areas. The low aptitude areas represent 14% of the Brazilian area, concentrated in most part of the South, Southeast regions and Northeast and northwest of AM state. Among the species evaluated, *K. ivorensis* has the largest area of planting restriction, being 2.9% due to the occurrence low temperatures and 7.1% due to water deficiency, concentrated in the northeast region (Figure 3C).

The species *K. senegalensis* shows high climatic aptitude in 68.1% of the Brazilian territory, including
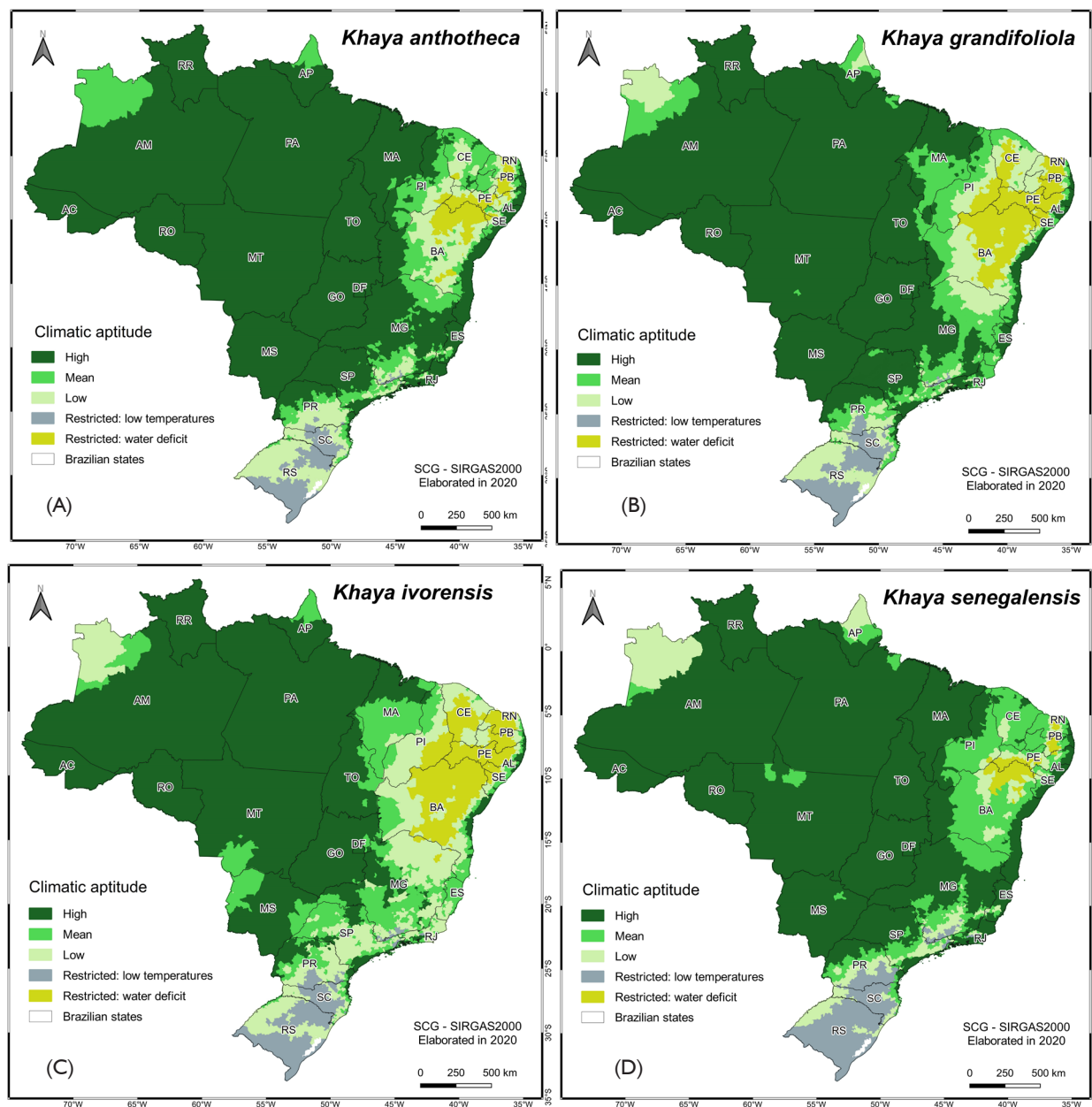
FIGURE 3 Climatic aptitude map for *Khaya* spp species in Brazil. A: *Khaya anthotheca*; B: *Khaya grandifoliola*; C: *Khaya ivorensis*; D: *Khaya senegalensis*. Source: Alvares et al. (2013b); IBGE (2018); INMET (2020); IPEF (2020). AC: Acre; AL: Alagoas; AM: Amazonas; AP: Amapá; BA: Bahia; CE: Ceará; DF: Distrito Federal; ES: Espírito Santo; GO: Goiás; MA: Maranhão; MG: Minas Gerais; MT: Mato Grosso; MS: Mato Grosso do Sul; PA: Pará; PB: Paraíba; PE: Pernambuco; PI: Piauí; PR: Paraná; RJ: Rio de Janeiro; RN: Rio Grande do Norte; RO: Rondônia; RR: Roraima; RS: Rio Grande do Sul; SC: Santa Catarina; SE: Sergipe; SP: São Paulo; TO: Tocantins.

almost the totality North, Southeast and Midwest regions, in addition to MA state and the Northeast coast (Figure 3D). The areas with mean climatic aptitude for *K. senegalensis* are concentrated in the Northeast region, north of MG state and in narrow lanes in PR and SP states, and south MG state, totaling 22.6% of the national area.

The areas with low fitness, however, account for only 4.7% of the Brazilian territory, being distributed in the north of Amapá and Amazonas and in small

parts in the South, Southeast and Northeast regions. *K. senegalensis* has the lowest restriction in relation to water deficit, about 1.6% of the total area, and 3% of Brazil. This species presents restriction of 4.43% of Brazilian territory area is due to low temperatures.

DISCUSSION

When considering the climatic variables and the geographical relief, it is noted that Brazil is predominantly

suitable for all the observed African mahogany species. The *K. anthotheca* species originally occurs in several vegetation formations, from wet to dry semideciduous forests, and in transition areas between these and the savanna, in addition to perennial wet forests (Maroyi, 2008; Opuni-Frimpong et al., 2016; Reis et al., 2019a).

K. anthotheca grows well in fertile, deep moist or well-drained soils, as is the majority of Brazilian soils (Santos et al., 2018) and does not occur at high altitudes (Maroyi, 2008; Praciak et al., 2013).Therefore, *K. anthotheca* has the capacity to adapt in different environments and throughout Brazil (Figure 3), as it is the species with the greatest territorial coverage in the African continent (Figure 1).

Until recently, the species *K. grandifoliola* was classified in Brazil as *K. ivorensis*, due to its botanical similarities and anatomical properties of wood (ABPMA, 2020; Dipelet et al., 2019). Therefore, some studies have reported silvicultural aspects such as productivity and adaptation of *K. grandifoliola* as being of *K. ivorensis* (Ribeiro, et al. 2017, Casaroli et al., 2018).

Until the present moment, this is one of the first studies that reports the aspects of climatic adaptation, with the true naturally occurring environments of *K. grandifoliola* (Figure 1 and Table 1). Among the African mahogany species evaluated, *K. grandifoliola* is the most planted in Brazil, owing to its rapid growth, showing high potential for cultivation in the country, since 72.2% of the national territory has high aptitude for planting (Figure B).

The species *K. grandifoliola* has a smaller territorial distribution in the African continent than *K. anthotheca* but is found in several environments such as savanna formations and semideciduous forests (Opuni-Frimpong, 2008; Praciak et al., 2013). This fact probably explains the high fitness found in Brazil, mainly in the regions under the influence of the Cerrado, Amazon Forest and Atlantic Forest biomes and their transition zones.

The species *K. grandifoliola* presents good development in well-drained soils, the majority of Brazilian soils (Santos et al., 2018), and just like *K. anthotheca*, can support long periods of drought (Opuni-Frimpong et al., 2016), which reiterates its high suitability in the Cerrado biome.

Among the species evaluated, *K. ivorensis* is the one with the smallest extension of natural area, occurring at low-lying humid tropical regions (Lampecht, 1990; Lemmens, 2008; Opuni-Frimpong et al., 2016). This species is, currently, the most endangered and over the years, and even today, it has been the most commercially exploited (IUCN, 2018; ITTO, 2020). In Brazil, *K.*

ivorensis was the one with the lowest proportion of high aptitude, corresponding to 62.8% of the country's area (Figure 3C).

K. ivorensis has a good development in perennial and semideciduous forests (Lemmens, 2008; Reis et al., 2019a). Thus, this species has a good capacity for adaptation in regions such as the Cerrado and its transition areas with other biomes, as long as it is not in places with long periods of severe drought (Lamprecht, 1990), which explains the high aptitude in a great extension of Brazil (Figure 3C).

The area of natural occurrence of *K. senegalensis* covers a wide area in the transition zone between Sub-Saharan Africa and tropical forests as can be seen in the figure 1 (Lamprecht, 1990; Nikiema and Pastenak, 2008; Praciak et al., 2013). *K. senegalensis* showed high fitness in 68.1% of the Brazilian territory (Figure 3D). Although it is not the species with the greatest aptitude, it is the least restrictive to water deficit due to its natural occurrence in sites with warmer and arid climates than the other species (Figure 1 and Table 1).

According to Matos et al. (2016) the species *K. senegalensis* adapts to moderate water deficits, that as it occurs in a good part of the Northeastern semiarid. Thus, among the species evaluated, *K. senegalensis* is the one with the best performance in areas under the influence of the Caatinga biome, and, also in the areas of sandy soils and subject to water deficit, characteristics of the Cerrado biome.

The areas with mean fitness reflect that the rainfall or average air temperature are outside the optimal levels, while the areas with low fitness reflect both criteria below the desired levels (Table 2). The restricted areas, on the other hand, make the growth and development of these African mahogany species infeasible at certain times of the year, with low temperatures or low rainfall.

One of the basic factors that guarantees the success of reforestation is the use of adapted species to climatic conditions. Thus, the relation of the classification of the Brazilian territory to its aptitude to cultivate the different species of African mahogany is fundamental to guide future plantations regarding the choice of species to be used.

The cultivation of African mahogany (*Khaya* spp.) in Brazil continues to expand, going from just over 10,000 hectares in 2017 to around 37 thousand hectares in 2018 (Ribeiro et al., 2017; Reis et al., 2019b). Most of these plantations are of the species *K. grandifoliola* and *K. ivorensis* (ABPMA, 2020). With the recent reclassification, in Brazil, from the species *K. ivorensis* to *K. grandifoliola*

(ABPMA, 2020), it is still imprecise to distinguish which is the real planted area of each species.

This botanical divergence has implications for the correct indication of the best planting sites for certain species. This is due to the fact that wood of *K. ivorensis*, *K. anthotheca* and *K. grandifoliola* are similar and exported in mixed consignments such as African mahogany with similar commercial value in the international market (Maroyi, 2008; Ribeiro et al., 2019; ITTO, 2020).

African mahogany has great variability between species and individuals in native areas and in commercial plantations of seminal origin (Sexton et al., 2015; Soares et al., 2020). The genotypes commercialized in Brazil may not reflect all the existing genetic variability and in consequence, there may be reports of poor silvicultural performance of the species assessed in areas of high climatic aptitude.

The genus *Khaya* is still in the wild, with excellent potential for genetic improvement (Nikles et al., 2008). Taking advantage of the variability existing in natural or cultivated populations, strategies for conservation, domestication and silvicultural improvement of these species can be established (Lemes et al., 2011). Thus, it is possible to explore this variability to maximize the species aptitude in different climatic and edaphic conditions (Chaikaew et al., 2020). To date, there are no genetic breeding programs for the genus *Khaya* in Brazil (Soares et al., 2020).

In the face of climate and social changes, commercial forest plantations for solid wood are the future guarantee of wood supply, being able to provide all the world demand for wood (Chisika & Yeom, 2020). The area planted with African mahogany is increasing in Brazil and in the world (Reis et al., 2019b).

To keep increasing the plantations of *Khaya* spp. it is necessary to know suitable regions suitable for cultivation of these species, to maximize your productivity. Through this study it is possible to select suitable regions to planting the different species evaluated to maximize productivity of the African mahogany throughout the national territory.

CONCLUSION

It was observed that in Brazil there is a high aptitude for all species of African mahogany, mainly to *K. anthotheca* and *K. grandifoliola*.

Therefore, African mahogany cultivation must be encouraged and continued in Brazil, as well as the development of breeding programs, paying attention to the better use of the existing climatic zoning.

It is recommended that other studies with climatic zoning and soil analyzes for African mahogany should be carried out in conjunction with surveys of species productivity *in loco*.

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