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Modelling the Ecological Niche of the Five Predominant Mega-Trees Species and Their Implications for the Management of the Azagny National Park in the Southern Côte d'Ivoire

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Abstract

Although mega-trees represent only a small proportion of the flora in the various forest ecosystems, they provide the bulk of ecosystem services. However, their degradation, accentuated by strong and changing climatic and ecological constraints, is intensifying under the impact of human activities. With this in mind, this study was carried out to analyse the potential effect of climate change on their geographical distribution. To this end, surface surveys of 2500 m^2 and itinerant surveys were carried out in the Azagny National Park. Based on occurrence data collected from literature reviews and online databases (GBIF, RAINBIO), and environmental variables (bioclimatic and edaphic), ecological niche models were established under two climate scenarios (SSP245 and SSP585) for 2070. The study revealed that 49 mega-tree species were identified, including five predominant mega-tree species using the importance value index (IVI). The results also show that these five species are highly preponderant in current habitats in southern Côte d'Ivoire. In addition, there was a general reduction in highly favourable habitats in the State Forest Domains under the SSP585 scenario. The Random Forest method proved to be the most effective in the modelling. The study provides essential information for the conservation and adaptive planning of forest resources in the face of climate change.

Keywords

Spatial Distribution, Mega-Trees, Modelling, Species Importance Value

1. Introduction

In Africa, tropical forests represent vast reservoirs of biodiversity (Abrou et al., 2019) and play an essential role in meeting the basic needs of local communities (Akinnifesi et al., 2006). They are home to a wide variety of plant species, including mega trees. These mega-tree species provide numerous ecosystem services, including the production of wood and non-wood forest products, carbon storage, reducing the impact of climate change, and protecting water and soil resources (MEA, 2005). However, forests are undergoing significant changes in their floristic composition and structure, which directly affects their biodiversity (FAO, 2011). Demographic pressure, deforestation, vegetation fires, agriculture, and livestock farming are the major anthropogenic causes of the disappearance of forest mega-tree species in their natural habitats (Asseh et al., 2019). In addition to anthropogenic threats, climate change is also a cause of biodiversity loss (Vignal & Andrieu, 2016). Fluctuations in climatic variables such as precipitation and temperature are likely to have an impact on biological diversity and on the geographical distribution of habitats favourable to species in general (IPCC, 2007) and mega-trees in particular. Faced with the challenges of conserving biodiversity, a better understanding of the response of these species to climate change may improve the ability to anticipate or recognise their decline or expansion and to highlight future habitats favourable to their conservation. There is, therefore, an urgent need to assess the potential consequences of future climate change on mega trees and to undertake adaptive management planning that enables current and future conservation decisions to be formulated (Tchatchou et al., 2015). However, despite scientific research efforts, very few studies to date have focused on the potential impact of climate change on the geographical distribution of potentially favourable mega-tree habitats (Djotan et al., 2018). Scientific information on the potential impact of climate change on the geographical distribution of habitats favourable to these mega-trees is therefore important in order to better justifying the choice of areas where they will be conserved now and in the future. Such studies are also necessary for the conservation of forest species and for a better understanding of species/habitat interactions. There is therefore an urgent need for in-depth ecological research to help define conservation strategies for these mega-trees. To this end, what is the potential effect of climate change on the geographical distribution of mega-tree species by 2070? This is the question that prompted the present study, the aim of which is to determine the predominant species and predict how their populations will change over time.

2. Methodology

2.1. Study Site

Azagny National Park (ANP) is located in the south of Côte d'Ivoire, in the coastal sector, 120 kilometres west of the city of Abidjan (**Figure 1**). It lies between 5˚14 and 5˚31 north latitude and 4˚76 and 5˚01 west longitude (Lauginie, 2017). Due to its position on the coast and the activities that took place there in the past, several plant formations (rainforests on dry land or marshland: old-growth forests; secondary forests; crop-fallow mosaics resulting from former peasant occupations) are found in the PNA (Gnagbo et al., 2016).

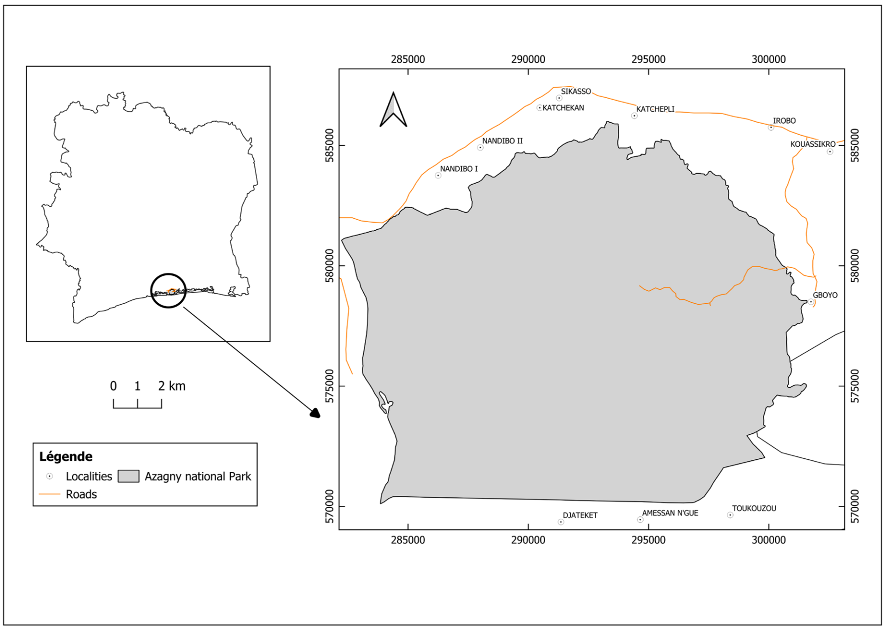

Figure 1. Location of Azagny National Park in southern Côte d'Ivoire.

2.2. Data Collection

2.2.1. Occurrence Data

The data were collected in the various biotopes of the Azagny National Park. Plots measuring 50 m × 50 m were set up in each stratum. Within each plot, the points of occurrence of each mega-tree species (dbh ≥ 70 cm) were recorded using a GPS. During the botanical inventories, environmental conditions beyond the habitat were taken into account, because if a species was currently absent from the study area, it may find suitable conditions there in the future. To cover the full distribution of each species in the study area, additional data sources, such as online platforms Global Biodiversity Information Facility (GBIF, https://www.gbif.org) and the RAINBIO database (Dauby et al., 2016), and scientific articles were explored in addition to field data. Other data collected were extracted from previously published scientific papers detailing the occurrences of certain mega-tree species studied in the defined study area or elsewhere. These surveyed points were re-projected using QGIS version 2.18 to minimise bias. The raw GBIF and RAINBIO data underwent a complete cleaning process, removing duplicates and records without geographical coordinates. The data were then partitioned according to the study area, which is the Azagny National Park. The final dataset, including field occurrence data, occurrence data from literature reviews, GBIF, and RAINBIO, was obtained by combining all these occurrences from the data sources and checking for autocorrelation using Occurrence Rarefaction from SDM tools (Brown, 2014). In total, 431 hits were selected.

2.2.2. Selection of Species and Environmental Variables

1) Species Selection (IVI)

To determine the predominant species in all habitats, the Species Importance Value Index (SIV), developed by Cottam and Curtis (1956), was calculated. This index characterises the importance of a species in relation to other species within the vegetation (Adou Yao & N'Guessan, 2005). The mathematical expressions of these indices are

$$IVI = FR\ esp + Do\ R\ esp + De\ R\ esp \quad (1)$$

The relative frequency of a species (FR esp) is the ratio of its specific frequency to the total of the specific frequencies of all the species, multiplied by one hundred. The specific frequency of a species is the number of plots in which this species is present. The relative dominance of a species (Do R esp) is the quotient of its basal area (i.e., the surface of the section of the trunk corresponding to the dbh) with the total basal area of all the species. The relative density of a species (De R esp) is the ratio of its absolute density (i.e., the number of individuals per unit area) to the total absolute densities of all species.

In this study, the top five species were chosen and their spatial distributions were illustrated.

2) Environmental Data

Ecological niche modelling is a crucial tool that was used in this study to assess the impact of climate change on the distribution of mega-tree species by relying mainly on two types of data: the presence/absence of mega-tree species and environmental factors. In this study, three main types of environmental factors: bioclimatic, edaphic, and topographical were used to examine the effects of climate change on the habitat suitability of mega-tree species. These bioclimatic factors are based on high-resolution WorldClim data. These data include 19 bioclimatic variables based on monthly temperature and precipitation values. Soil data are taken from the African soil profile database. Parameters measured in the soil data include bulk density, cation exchange capacity, clay content, organic carbon content, pH, and sand and silt contents, assessed at several depths.

Biophysical data with varying resolutions were resampled to align with the bioclimatic resolution of 30 arc seconds. Projections of future mega-tree habitat were made for the year 2070 using the Shared Socio-Economic Pathways (SSP) scenarios SSP245 and SSP585. The SSP245 scenario represents a moderate approach with mitigation and adaptation efforts. In contrast, the SSP585 scenario is characterised by high emissions and low mitigation, which will result in significant climate impacts.

3) Variable Selection

Variable selection is necessary when modelling the ecological niches of species, as it enables accurate results to be obtained and all the variables that influence the distribution of the species in its natural habitat to be identified. To select a set of environmental variables that determine the appropriate habitat for each of the five predominant mega-tree species, a jackknife test was carried out using the R SDM package. This method was used to identify the most influential predictors and measure their impact on model performance (Vignali et al., 2020). Multicollinearity was assessed by the Variance Inflation Factor (VIF), and Pearson correlation tests were verified using the usdm package (Naimi et al., 2014). All variables with a VIF greater than 8 or a Pearson correlation coefficient greater than or equal to $|0.7|$ ($r \geq |0.7|$) were removed from the model (Dormann et al., 2013). For each mega-tree species, the five most contributing variables were retained for modelling.

4) Modelling the Ecological Niches of Mega-Tree Species

The current and future habitats of mega trees were evaluated using four machine learning algorithms through the R package sdm version 1.1 - 8 (Naimi & Araújo, 2016). These are generalised additive models (GAM), generalised linear models (GLM), maximum entropy (Maxent), and random forest (RF). Maxent is particularly good at handling presence data and complex environmental relationships (Phillips et al., 2006). GAM algorithms are known to be an efficient study for non-linear relationships (Wood, 2017). GLMs use linear predictors to study species-environment interactions in an independent and easily interpretable linear fashion (Dobson & Barnett, 2018). RF performs best at handling binary (presence/absence) data with a minimal database. The models were built by averaging the results of the four algorithms, hence the name ensemble model. Ensemble models are a robust modelling framework that deals with various aspects of the complexity of ecological data and tends to improve the quality of predictions compared with the use of a single method or algorithm (Elith & Leathwick, 2009). For each species, the model was calibrated ten times using 70% of the data for training and the remaining 30% for testing. The effectiveness of the model was assessed using two common measures: the area under the curve (AUC), which is independent of threshold, and the true proficiency statistic (TSS), which depends on threshold. The AUC assesses the model's ability to differentiate between sites of presence and background (Phillips et al., 2006), with AUC values between 0.5 and 0.6 indicating low accuracy, values between 0.6 and 0.9 representing good accuracy, and values above 0.9 indicating high accuracy (Araújo et al., 2005). The TSS measures the accuracy of the model in predicting actual attendances and absences by combining sensitivity and specificity with values ranging from −1 to +1. Higher TSS values reflect better model accuracy (Allouche et al., 2006).

5) Mapping the Habitat of Dominant Mega-Trees

The distribution of mega trees was mapped using QGIS version 2.18, and the average results of the four machine learning algorithms mentioned above were imported into QGIS and clipped to the Côte d'Ivoire border. A gap analysis was carried out at the Côte d'Ivoire level as well as within the state forest domain (SFD). In this study, the SFD is made up of protected areas and classified forests whose management is under the control of the State of Côte d'Ivoire. The current and future geographical distributions of suitable habitats for each mega-tree species were mapped on the basis of the logistic probability of occurrence (p). Habitats were considered weakly suitable when $p \leq 0.4$, moderately suitable between $0.4 < p \leq 0.6$, and highly suitable with $p > 0.6$ (Shen et al., 2021). All non-binary raster outputs from the five mega-trees were averaged by scenario (current, SSP245, and SSP585) to identify the region of high species concentration. The State Forest Estate network was then overlaid to obtain the best conservation method.

3. Results

3.1. Preponderance of Mega-Tree Species

Table 1 shows the 49 species, ranked in descending order of IVI. The first five (5) predominant species are: *Alstonia boonei* (34.4%), *Ceiba pentandra* (21.5%), *Lophira alata* (18.5%), *Entandrophragma angolense* (16.7%), and *Piptadeniastrum africanum* (15.3%).

Table 1. Importance index values for mega-tree species.

N°	Species	Rel Do	Rel Frq	Rel De	IVI
1	*Alstonia boonei* De Wild.	16.8	6.7	11.0	34.4
2	*Ceiba pentandra* (L.) Gaertn.	9.8	5.0	6.7	21.5
4	*Entandrophragma angolense* (Welw.) C. DC.	7.4	5.0	4.3	16.7
3	*Lophira alata* Banks ex Gaertn.f.	6.8	5.0	6.7	18.5
5	*Piptadeniastrum africanum* (Hook. f.) Brenan	5.0	4.2	6.1	15.3
6	*Antiaris africana* Engl.	4.1	5.0	3.7	12.8
7	*Petersianthus macrocarpus* (P.Beauv.) Liben	4.1	4.2	3.0	11.3
8	*Scottellia klaineana* Pierre	2.4	4.2	3.7	10.3
9	*Parinari glabra* Oliv.	2.4	3.3	3.0	8.7
10	*Parinari excelsa* Sabine	2.7	3.3	2.4	8.4
11	*Canarium schweinfurthii* Engl.	2.4	3.3	2.4	8.2
12	*Afzelia bella* Harms	2.4	2.5	2.4	7.4
13	*Sterculia oblonga* Mast.	1.5	3.3	2.4	7.3
14	*Pycnanthus angolensis* (Welw.) Warb.	1.4	3.3	2.4	7.2
15	*Antiaris toxicaria* (Pers.) Lesch.	1.4	2.5	2.4	6.3
16	*Sacoglottis gabonensis* (Baill.) Urban	2.5	1.7	1.8	6.0
17	*Nauclea diderrichii* (De Wild. & T. Durand) Merr.	1.5	2.5	1.8	5.8

Continued

18	*Chrysobalanus icaco* Linn. subsp. Icaco	1.3	2.5	1.8	5.6
19	*Anopyxis klaineana* (Pierre) Engl.	1.8	1.7	1.8	5.3
20	*Mangifera indica* L.	1.6	0.8	2.4	4.9
21	*Amphimas pterocarpoides* Harms	1.7	1.7	1.2	4.5
22	*Bombax brevicuspe* Sprague	1.0	1.7	1.2	3.9
23	*Afrosersalisia afzelii* (Engl.) A.Chev.	0.8	1.7	1.2	3.7
24	*Berlinia confusa* Hoyle	0.7	1.7	1.2	3.6
25	*Albizia ferruginea* (Guill. & Perr.) Benth.	2.1	0.8	0.6	3.5
26	*Milicia excelsa* (Welw.) C.C. Berg	1.3	0.8	1.2	3.4
27	*Ficus vogeliana* (Miq.) Miq.	0.8	0.8	1.2	2.9
28	*Entandrophragma utile* (Dawe & Sprague) Sprague	1.0	0.8	0.6	2.4
29	*Guibourtia ehie* (A.Chev.) J. Léonard	0.7	0.8	0.6	2.1
30	*Dacryodes klaineana* (Pierre) Lam	0.6	0.8	0.6	2.0
31	*Terminalia ivorensis* A.Chev.	0.5	0.8	0.6	2.0
32	*Anthocleista nobilis* G. Don	0.5	0.8	0.6	2.0
33	*Klainedoxa gabonensis* Pierre	0.5	0.8	0.6	2.0
34	*Discoglypremna caloneura* (Pax) Prain	0.5	0.8	0.6	1.9
35	*Ficus sagittifolia* Mildbr. & Burrett	0.5	0.8	0.6	1.9
36	*Celtis mildbraedii* Engl.	0.4	0.8	0.6	1.9
37	*Irvingia gabonensis* (O' Rorke) Baill.	0.4	0.8	0.6	1.9
38	*Holarrhena floribunda* (G. Don) Dur. & Schinz	0.4	0.8	0.6	1.9
39	*Holoptelea grandis* (Hutch.) Mildbr.	0.4	0.8	0.6	1.8
40	*Flacourtia jangomas* (Lour.) Raeusch.	0.3	0.8	0.6	1.8
41	*Synsepalum afzelii* (Engl.) T.D.Penn.	0.3	0.8	0.6	1.8
42	*Uapaca heudelotii* Ball.	0.3	0.8	0.6	1.8
43	*Morinda lucida* Benth.	0.3	0.8	0.6	1.7
44	*Albizia zygia* (DC.) J.F.Macbr.	0.3	0.8	0.6	1.7
45	*Ficus polita* Vahl	0.3	0.8	0.6	1.7
46	*Milicia regia* (A.Chev.) Berg	0.3	0.8	0.6	1.7
47	*Dialium aubrevillei* Pellegr.	0.2	0.8	0.6	1.7
48	*Phyllocosmus africanus* Klozsch	0.2	0.8	0.6	1.7
49	*Cola nitida* (Vent.) Schott & Endl.	0.2	0.8	0.6	1.7

Note: Rel Do = Relative Dominance; Rel Frq = Relative Frequency; Rel De = Relative Density.

The figure below shows the distribution of the five main mega-tree species in Côte d'Ivoire (**Figure 2**).

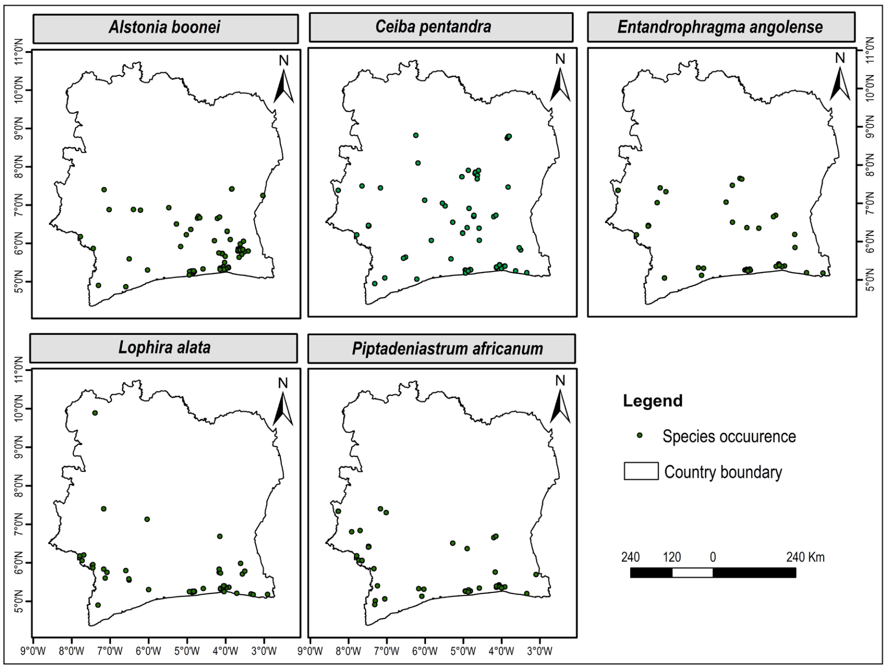

Figure 2. Distribution map of the five main species in Côte d'Ivoire.

Figure 3 shows the relationship between the number of species and the number of occurrences according to the different sources of data collection: field data, bibliographical reviews, and the GBIF and RAINBIO databases.

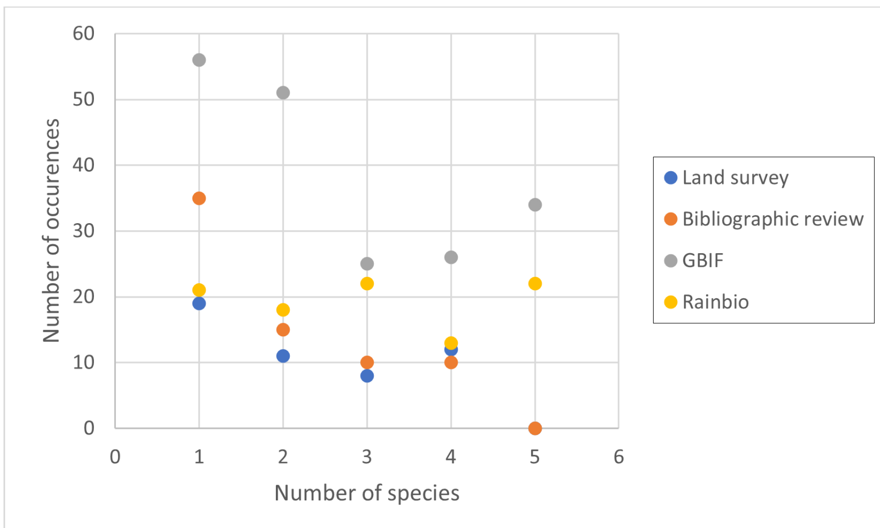

Figure 3. Distribution of occurrence points according to data collection sources.

3.2. Model Accuracy

The figures below show the distributions of the AUC values and TSS values obtained for four modelling methods (GLM, GAM, RF, and Maxent) for all the mega-tree species studied. It can be seen that the RF (Random Forest) method shows the highest performance for both the AUC (0.92) and the TSS (0.78), with a very low dispersion, showing its robustness. Logistic regression (GLM) showed the lowest scores for AUC and TSS (median AUC −0.82; median TSS −0.60) and the greatest dispersion, indicating less stable performance. Thus, RF is the best performing and most consistent method, while GLM appears as shown in Figure 4.

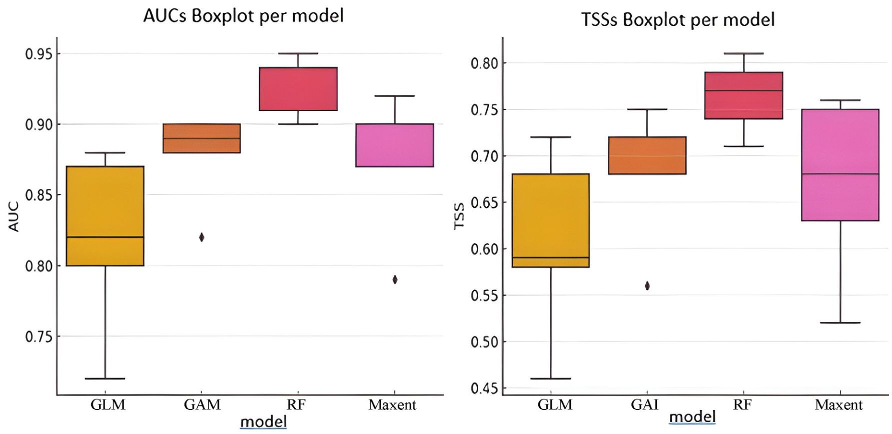

Figure 4. Assessment of model performance based on AUC and TSS.

3.3. Key Environmental Variables

The analyses of the environmental variables show the performance of the four algorithms Generalized Additive Models (GAM), Generalized Linear Models (GLM), Maximum Entropy (MaxEnt) and Random Forest (RF) in predicting the distribution of the different mega-tree species on the basis of their Area Under the Curve (AUC) and True Skill Statistic (TSS) values, as shown in Figure 5. Thus, for each mega tree, the environmental variables are:

Alstonia boonei: Growth and reproduction of *A. boonei* are linked by temperature seasonality (bio4), indicating temperature variation over the year. Prediction of this species is also influenced by low rainfall during the year (bio14) with fertile, slightly acidic to neutral soils with adequate magnesium availability (EMGX_d2), essential for chlorophyll formation and physiological functions.

Ceiba pentandra: *C. pentandra* growth and distribution are influenced by a maximum temperature in the hottest month (bio5) and minimum rainfall during the dry period (bio14). According to the histogram, *C. pentandra* thrives in deep, well-drained, fertile soils with good moisture retention capacity (EMGX_d2).

Entandrophragma angolense: The development and growth of *E. angolense* are characterised by maximum temperature in the hottest month (bio5) with rainfall in the wettest quarter (bio16). It prefers deep, well-aired soils with low bulk density (EACKL_d1).

Lophira alata: The dominant variables here are mean annual temperature (bio1) and annual rainfall (bio12). *Lophira alata* is commonly found in tropical rainforests with clay-rich soils. A high clay content provides stability, nutrient retention, and moisture regulation, which are essential for its slow but dense growth (CLYPPT_d1).

Piptadeniastrum africanum: Its growth depends on its maximum temperature in warm periods (bio5) and annual rainfall (bio12) in acidic tropical soils (SLTPPT_d1).

Analysis of forest species trends reveals a variety of dynamics depending on environmental conditions.

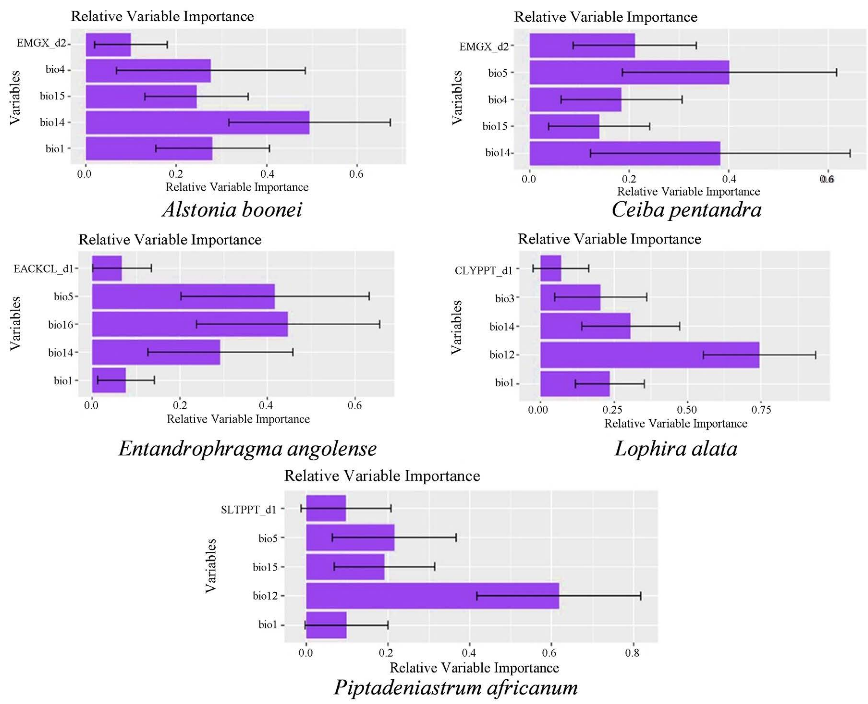

Figure 5. Evolutionary trend of the five mega-tree species.

3.4. Analysis of the Modelling Map

Figure 6 shows the distribution of habitats for the five mega-tree species under the two future emission scenarios (SSP245 and SSP585) compared with the current state. The different zones on the map indicate the quality of the habitats, classified into three categories: poorly favourable habitat, moderately favourable habitat, and highly favourable habitat. In addition, the State Forest Domain (SFD) zones are highlighted, providing an overview of the relative conservation of these mega-tree species in various climatic contexts.

3.5. Current Status

The different species have distinct habitat distributions: *Alstonia boonei* spreads mainly in highly favourable habitats covering 39% of the national territory, although areas of low adaptation (36.2%) are also present, particularly in the east. *C. pentandra*, on the other hand, is relatively evenly distributed, with 44.2% coverage in favourable habitats, while *E. angolense* is more scattered, with only 10% coverage in these habitats. L. alata is mainly concentrated in favourable habitats but is also present in areas of poor adaptation, indicating a dependence on particular conditions. Finally, *P. africanum* stands out for its high occupancy of poorly adapted habitats, indicating a greater capacity to adapt.

3.6. Future Scenarios (SSP245 and SSP585)

1) SSP245 (Intermediate Scenario)

Overall, *A. boonei* and *C. pentandra* continue to benefit from the majority of highly suitable habitats, despite some localised decreases. On the other hand, *E. angolense* and *L. alata* are seeing their optimal habitat space contract to the benefit of less suitable areas, while *P. africanum* retains a certain resilience but may increasingly depend on more extensive but poorly adapted habitats.

2) SSP585 (Pessimistic Scenario)

Overall, the highly favourable habitats for *A. boonei*, *C. pentandra*, and *E. angolense* continue to shrink, revealing increasing vulnerability to climate change; *L. alata* is experiencing a sharp contraction in its highly suitable habitat, increasing the risk of its populations disappearing. *P. africanum*, on the other hand, seems to be less affected, showing a degree of resistance or adaptability to these new conditions.

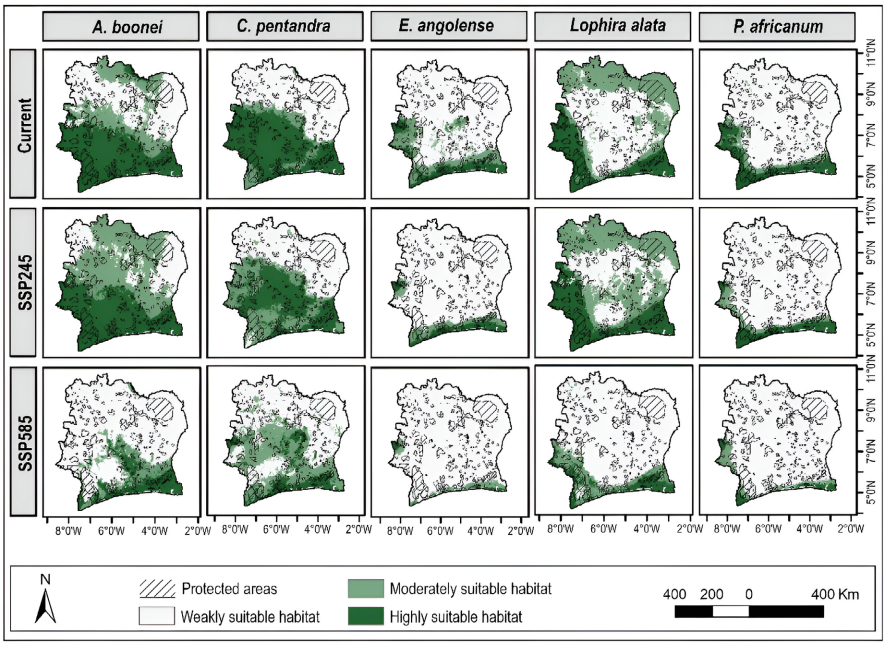

Figure 6. Potential current and future habitats of the five mega-tree species.

With regard to the variation of the five mega-tree species on the State Forest Estate, several trends were observed.

3.7. Species with an Overall Variation in Potential Habitat in Côte d'Ivoire

Almost all mega-tree species show a clear downward trend in highly favourable areas, often accompanied by an increase in weakly favourable areas, indicating a change in habitat suitability.

Analysis of the map shows that, nationally, *Alstonia boonei* will lose space in low-favourable habitats (−15.1%) and high-favourable habitats (−2.9%) under the moderate scenario (SSP245). In the SSP585 scenario, however, there will be an increase in low-favourable habitats (37%) in favour of highly favourable habitats.

Mega-tree species such as *Ceiba pentandra* and *Lophira alata* show the same trend as *Alstonia boonei*, with decreases in low-favourable and high-favourable habitats under SSP245 compared with the SSP585 scenario. There was an increase in the area of low-favourable habitats in favour of highly favourable habitats. *Entandrophragma angolense* showed marked declines in highly favourable areas under SSP245 (−4%) and SSP585 (−8.6%). Whereas this species will show positive trends in low-favourable habitats under SSP245 (13.3%) and SSP585 (20.5%).

3.8. Species with an Overall Variation in Potential Habitat within the State's Domain

Figure 7 shows the evolution of the five species in different areas. The state forest domain will be very effective in conserving *Alstonia boonei* in the less severe scenario (SSP245). However, in the severe scenario (SSP585), the opposite trend is observed, as the habitat that is not very favourable for this species will increase by 44.8% to the benefit of the favourable habitat, which will decrease drastically. The same trend was observed for the Lophira alata species. On the other hand, for the species *Ceiba pentandra, Entandrophragma angolense*, and *Piptadeniastrum africanum*, there were minor changes in low-favourable habitats under SSP245 and a drastic reduction in favourable habitats under SSP585.

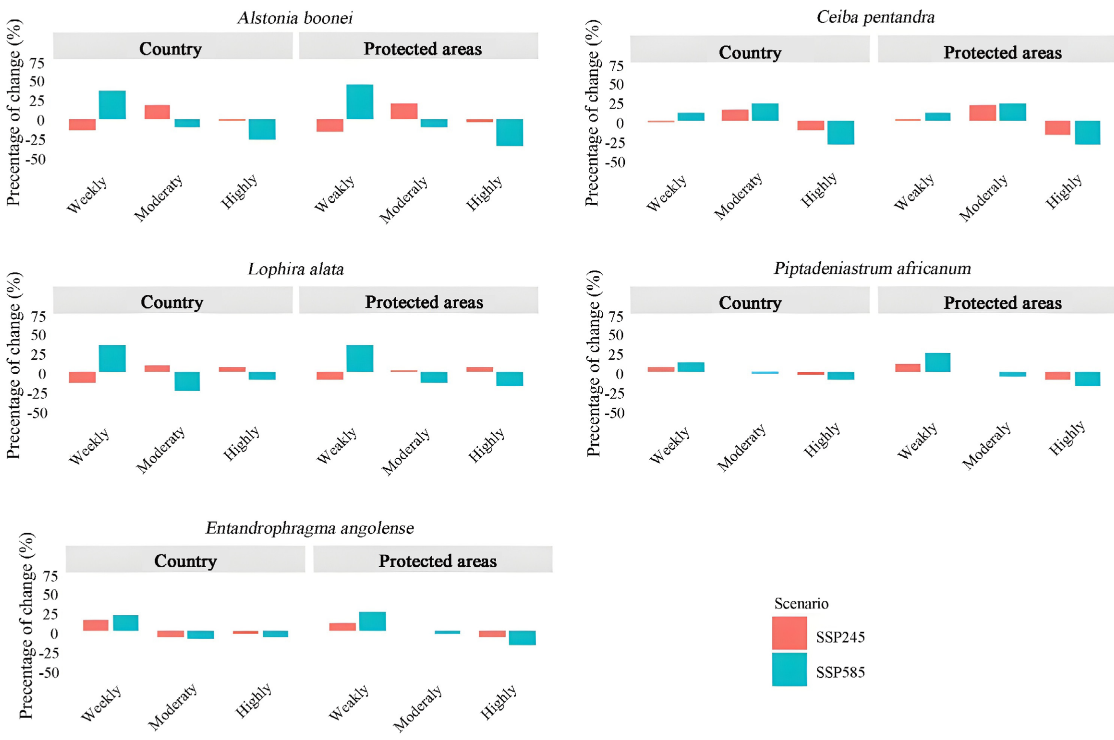

Figure 7. Percentage variation in suitability levels for the five mega-tree species.

4. Discussion

4.1. The Preponderance of Certain Mega-Tree Species in the Biotopes of the ANP

The Azagny National Park (ANP), located in a marshy depression between the Ebrié Lagoon and the Bandama River, is dominated by a variety of biotopes (old-growth forests, secondary forests, crop/fallow mosaic, etc.) characterised by their own optimal conditions. This configuration creates ideal ecological conditions for certain typical tree species. The preponderance of mega-tree species, notably *Alstonia boonei*, *Ceiba pentandra*, *Entandrophragma angolense*, *Lophira alata*, and *Piptadeniastrum africanum* in the PNA can be explained by their specific adaptations to the flooded and light conditions of forest formations, as well as by their strategy of rapid regeneration in formerly disturbed environments. In fact, *A. boonei* and *L. alata* are pioneer, heliophilous species that prefer biotopes that tolerate periodic flooding and hydromorphic soils. These observations are similar to those made by Kouamé et al (2010) in their respective studies carried out in the town of Man in western Côte d'Ivoire and in rainforests. For these authors, the two species in question frequently appear in gallery forests and flooded wetlands, due to their tolerance of hydromorphic soils and their ability to pioneer after clearing or disturbance. In addition, the rapid colonisation capacity of *A. boonei* enables it to colonise gaps created by windfall (FAO, 2011). However, *L. alata* is highly prized for its resistant wood, which explains the special monitoring of its status, but in protected areas such as the Azagny National Park, its exploitation is prohibited, favouring its natural presence.

4.2. Key Environmental Indicators

In the present study, certain discriminant variables were used to best predict the distribution of the five predominant mega-trees. For example, in the case of *Asltonia boonei*, the variables bio4, bio14, and soil quality EMGX_d2 ensure that this species is well distributed. This can be explained by the fact that the seasonal regime (bio4) could affect the life cycles of this *Asltonia boonei* species by influencing its flowering and fruiting. As for rainfall in the driest month (bio14), this is a crucial measure for understanding the minimum humidity conditions required for the species to survive. These observations are similar to those made by Zébazé Dongmo (2024) during his work in the forests of south-east Cameroon. The author shows the impact of climate in different ecosystems on the spread of *Alstonia boonei*. This species grows most of the time in tropical environments, and can be sensitive to low levels of rainfall. Soil composition also affects the speed of drainage and moisture retention, two essential factors for the health of this plant. For *Ceiba pentandra*, high temperatures can inhibit growth, especially if they exceed the optimum threshold for photosynthesis. Low rainfall corresponds to a measure of minimum rainfall during the driest month, a key factor in the survival of the species. If rainfall is too low, *Ceiba pentandra* can suffer water stress, affecting its growth and reproduction. In addition, in terms of soil quality, a high silt content is beneficial for *C. pentandra* as it improves soil aeration and water retention, which supports its rapid growth and root system. The distribution of *Enatndrophragma angolense* could be explained by the fact that bio5 temperature is crucial to understanding resistance to heat stress. Excessively high temperatures can cause water stress by increasing evapotranspiration and reducing photosynthesis. On the other hand, the high level of rainfall during this period favours the germination and growth of young plants of this species. The low apparent density could indicate good soil porosity and aeration, essential for *E. angolense* root expansion and water infiltration. As for *Lophira alata*, the good prediction would be due to the annual rainfall (bio12), which represents the total rainfall over the year, a key factor for water availability for *Lophira alata*. Insufficient annual rainfall can lead to water stress, affecting the growth and reproduction of the mega tree. A good temperature (bio1) is also essential for assessing the conditions favourable to the expansion of *L. alata*. Finally, this species would be sensitive to clay-rich soils, as the high clay content provides stability, nutrient retention, and moisture regulation, which are essential for its slow but dense growth. For *Piptadeniastrum africanum*, the good distribution of this species could be explained by the fact that water is available throughout the year, a factor that allows the species to develop. In fact, insufficient water supply could cause water stress, particularly during periods of active growth, thus compromising the development of *P. africanum*. As far as the soil is concerned, *P. africanum* is adapted for growth in acidic tropical soils, since exchangeable acidity is a critical factor influencing nutrient availability and microbial activity. This activity could also affect its growth.

4.3. Model Accuracy

The current and future projection of the five mega-tree species was carried out using an ensemble model combining four algorithms: GLM, RF, GAM, and Maxent. Of these, Random Forest (RF) consistently performed best in both metrics (AUC and TSS), whatever the species. In fact, the RF is particularly efficient and robust for modelling the distribution of species. This observation is similar to that of Bai (2014) and Elith et al. (2006). These authors state in their work that RF is generally one of the best-performing models for species prediction. RF performs well in ecological applications using AUC in particular. Recent studies by Dogbo et al (2024) confirmed the superiority of RF for assessing the vulnerability of 12 species to climate change in Benin. However, the integration of several algorithms in ensemble modelling remains a subject of debate within the scientific community. According to Araújo and New (2007), this approach consists of combining algorithms in order to take advantage of the benefits of each method, thus making it possible to obtain more robust forecasts while reducing bias and uncertainty. Numerous studies (Marmion et al., 2009; Hao et al., 2020; Dogbo et al., 2024) support the view that ensemble models generally outperform individual models in predicting species distribution and assessing the impact of climate change, although sometimes they do not systematically outperform simple unadjusted models.

4.4. Impact of Variables in the Mega-Tree Distribution

This study used species distribution models to assess the future habitat suitability of five mega-tree species under different climatic conditions. The results indicate an overall downward trend in highly favourable habitats for almost all species of *Alstonia boonei*, *Ceiba pentandra*, *Entandrophragma angolense*, *Lophira alata*, and *Piptadeniastrum africanum* under future climate scenarios (SSP245 and SSP585). This change suggests that these species could face considerable challenges in maintaining their current distributions and optimal growth conditions.

In general, the current situation shows that these species, *Alstonia boonei*, *Ceiba pentandra*, *Entandrophragma angolense*, *Lophira alata*, and *Piptadeniastrum africanum*, have an uneven distribution, with several highly valued areas in the south, but also a disparate presence in the rest of the country, probably due to human activity or other evolutionary factors. Indeed, the uneven distribution of these mega-tree species, *Alstonia boonei*, *Ceiba pentandra*, *Entandrophragma angolense*, *Lophira alata*, and *Piptadeniastrum africanum*, bears witness to the complex interactions that exist between their natural habitat, human activities, and evolving ecological factors. Economic growth, urbanisation, and the exploitation of natural resources play a major role in the fragmentation of their habitats, preventing them from spreading uniformly throughout the territory. These results are identical to those obtained by Tchouto et al. (2019). These authors highlight the impact of urbanisation and the exploitation of natural resources on forest biodiversity in Central Africa. Furthermore, Kouame et al. (2015) show how deforestation, agriculture, and urbanisation modify the distribution of forest species, in particular *Alstonia boonei* and *Ceiba pentandra*. Dawoud et al. (2020), in their work on *The Impact of Urbanisation on Forest Biodiversity in Africa*, illustrate how habitat fragmentation prevents the spread of species across the territory.

Under the SSP245 scenario, habitats remain generally favourable, particularly in the south, despite some localised reductions. On the other hand, scenario SSP585 leads to a clear deterioration in habitat quality, with a sharp reduction in favourable habitats, especially in the north and around urban centres. With regard to mega-tree species, under scenario SSP245, the five species studied mostly retain favourable habitats, particularly in the south of the country, with relative stability for *Piptadeniastrum africanum* and good habitat conservation for *Alstonia boonei* and *Lophira alata*, particularly in protected areas. *Ceiba pentandra* and *Entandrophragma angolense* also maintain a distribution close to the current state, although some weak areas appear. On the other hand, under the SSP585 scenario, there is a general deterioration in the quality of habitats for all species, marked by a significant loss of highly favourable areas, especially in the north and centre of the territory. Habitats become predominantly weak or unfavourable, particularly affecting *L. alata*, *E. angolense*, and *P. africanum*, while *C. pentandra* and *A. boonei* also show a significant decline in their favourable distribution. Our results are similar to those of Dogbo et al (2024). The authors suggest that in their work in Benin, some habitats are likely to decline while others may expand. Kakpo et al. (2019) found significant reductions in suitable habitats for *M. excelsa* in Benin under future climate scenarios (RCP 4.5 and RCP 8.5).

5. Conclusion

This study shows that the five mega-tree species studied, *Alstonia boonei*, *Ceiba pentandra*, *Entandrophragma angolense*, *Lophira alata*, and *Piptadeniastrum africanum*, currently occupy ecologically favourable habitats in Azagny National Park, particularly in the south, thanks to their adaptation to local climatic, edaphic, and hydromorphic conditions. However, future projections under the SSP245 (moderate) and SSP585 (severe) climate scenarios reveal a significant contraction in highly favourable habitats, particularly under SSP585, with an increased risk for *Lophira alata*, *Entandrophragma angolense*, and *Piptadeniastrum africanum*. These results highlight the fact that the majority of favourable areas disappear in the scenario with high emissions (SSP585), posing a problem for the survival and conservation of these mega-trees. Furthermore, this study highlights the urgent need to strengthen conservation strategies, particularly in protected areas, and to integrate these mega-tree species into sustainable agricultural systems such as agroforestry. Modelling as a whole, and the Random Forest algorithm in particular, has proved to be a reliable tool for anticipating climate impacts on forest species in general and on mega-trees in particular, and should be put to greater use in the sustainable management of tropical ecosystems.

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Declaration on Data Availability

To protect the confidentiality of respondents, data is available on request from the corresponding author.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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