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Characterization of forest ecosystems in the Agropole of the Kara River basin in northern Togo (West Africa)

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ABSTRACT: In the context of climate emergency and biodiversity loss due mainly to agriculture, this study aims to characterize the forest ecosystems of the Kara basin agropolis and a 10 km buffer zone. The methodology is based on two approaches: land cover mapping using Landsat satellite images and a detailed description of forest ecosystems, focusing on the floristic composition of woody species to assess their conservation, structure and ecological functioning. This characterization was carried out through 56 20 mx 20 m inventory surveys, where all species presents were counted and woody individuals with a DBH ≥ 10 cm measured. The results show that 67% of the area consists of cultivated and fallow land, with a higher proportion in the agropole (72%) than in the buffer zone (63%). Forests account for 13% in the agropole and 21% in the buffer zone. The floristic survey identified 105 woody species in 79 genera and 31 families, with a higher average diversity in the agropole (H' = 2.69) than in the buffer zone (H' = 2.13). Four species are on the IUCN Red List. Although tree density is lower in the agropole (97.2 trees/ha) than in the buffer zone (119.08 trees/ha), basal area is greater in the buffer zone (32.30 m^2/ha) than in the agropole (29.86 m^2/ha), indicating an annual pressure on tree species.

KEYWORDS: agropole, tree density, floristic survey, IUCN red list.

1 INTRODUCTION

Agriculture is a fundamental element of economic and social development, particularly in developing countries, where it often represents a significant share of the Gross Domestic Product (GDP) and employs a considerable proportion of the active population [1]. However, it is also a major source of ecosystem degradation in tropical Africa, exacerbated by unsustainable agricultural practices [2], [3], [4], [5], [6]. This ecosystem degradation affects not only the environment but also the social well-being of populations, as these ecosystems provide vital services such as climate regulation, water purification, erosion control, and the supply of food and medicinal resources. Therefore, it is essential to adopt integrated approaches that consider the complex interactions between agriculture and biodiversity to ensure a sustainable future [5]. The central issue lies in the need to balance agricultural expansion and biodiversity conservation, as sustainable agriculture is intrinsically linked to the health of surrounding ecosystems [7]. In Togo, agropoliss like the Kara agropolis have been established to bring together various actors in the agricultural value chain, promoting a collaborative approach in the agri-food sector. However, their development can exert significant pressure on local ecosystems, leading to concerning environmental consequences (Jeune Afrique, 2020). Previous research has also emphasized the importance of agri-food transformation that considers environmental and social impacts to avoid adverse effects on biodiversity [8]. This innovative development model could serve as a framework for harmonizing economic growth objectives with natural resource conservation, addressing the challenges of environmental degradation and growing food security needs [9], [3], [4]. The Kara agropolis requires an integrated approach encompassing the three dimensions of sustainability: economic, social, and environmental [7], [10]. To meet the challenge of environmental sustainability within this agropolis, it is crucial to gain an in-depth understanding of its ecosystems. Mapping and characterization of forest ecosystems within the agropolis are therefore essential to ensure sustainable management of this area [11], [12]. This approach will not only preserve local biodiversity but also ensure that agricultural activities are harmoniously integrated into the surrounding ecological landscape. This study aims to characterize the ecosystems of the Kara agropolis to contribute to the effective and sustainable development of this area. Ultimately, it will help understand the distribution of forests, identify areas requiring special protection, and make informed decisions to balance agricultural interests with biodiversity conservation.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study focuses on the Kara agropolis and a 10 km buffer zone around it. These areas are part of the Kara River basin (5,287 km^2), a sub-basin of the Oti basin (75,859 km^2), which is itself part of the Volta basin (398,390 km^2) in West Africa. The Kara River basin is a transboundary basin located in parts of Togo and Benin. It lies between longitudes 0°30′ and 1°38′E and latitudes 9°15′ and 10°01′N. The Kara agropolis covers several prefectures in the Kara region (Doufelgou, Kéran, Bassar, and Dankpen prefectures) and is located between 9°37′ and 9°52′ North latitude and 0°54′ and 1°10′ East longitude (Fig 1). With a total arable area of 164,970 hectares, including 11,100 hectares of Planned Agricultural Development Zones (ZAAP), the area has rugged topography with mountain ranges such as the Defale, Djamdè, and Lama ranges, and a dense hydrographic nandwork with the Kara River and its tributaries. The climate is predominantly tropical humid, with a rainy season from March to October. The soils are leached tropical ferruginous soils and hydromorphic soils along the watercourses. The landscape is dotted with wooded savannas and open forests with species such as shea trees and néré. Population density is high in some localities such as Broukou, Léon, and Misséouta, with a local economy mainly based on subsistence farming (maize, rice, yam) and cash crops (cotton).

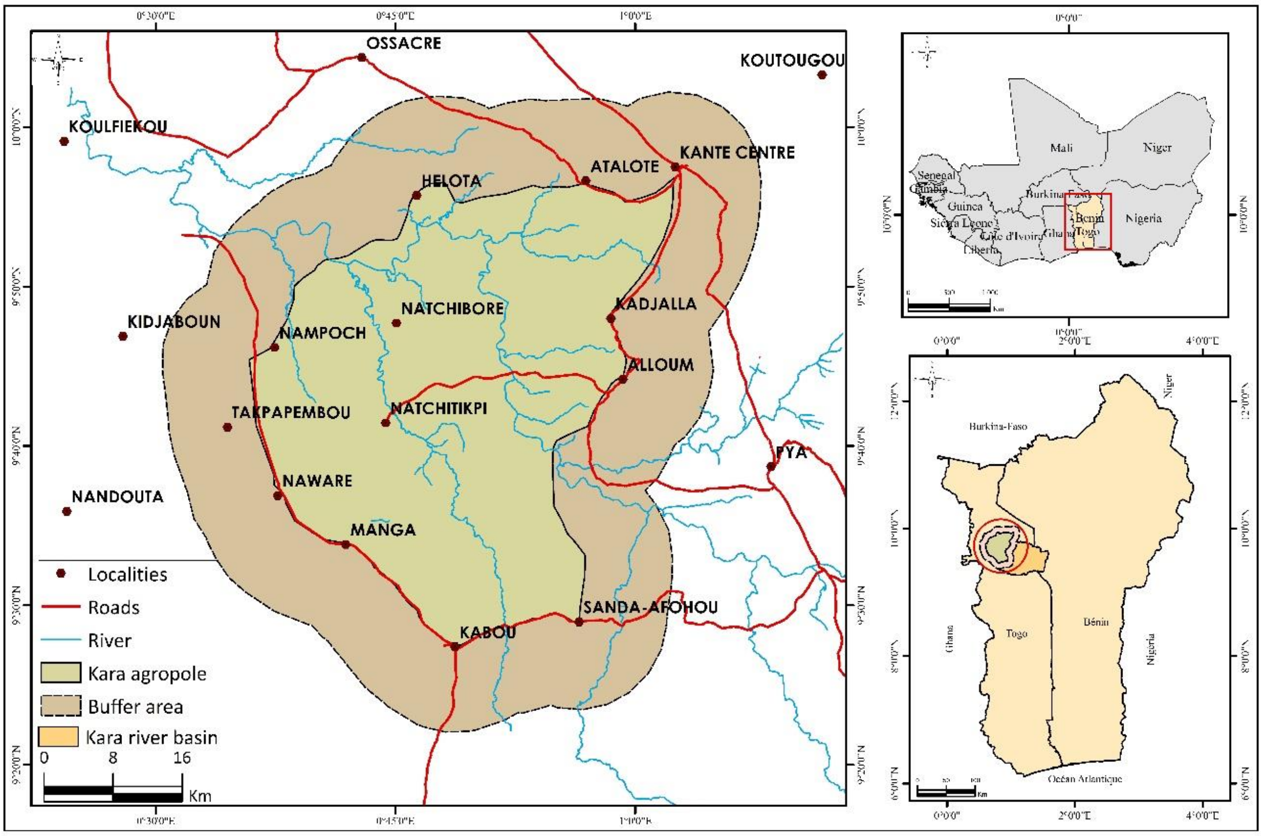

Fig. 1. Geographical situation of the study area

2.2 METHODOLOGY

A multi-source approach was adopted to characterize the baseline state of forest ecosystems in the agropolis. This approach combines two key steps:

- Land Use Mapping, which is crucial for understanding and managing forest ecosystems. It is based on the interpretation of aerial images and the classification of vegetation formations according to predefined criteria.
- Detailed characterization of each identified ecosystem, considering its specific composition, complex structure, and ecological functioning. This step is based on forest inventories and ecological field surveys.

This multi-source approach provides a complete and accurate picture of forest biodiversity, with is essential for sustainable forest management.

2.2.1 DATA COLLECTION

Two types of data were collected for this study. These are cartographic data including satellite images and topographic maps, and data relating to the characterization of forest ecosystems obtained from field forest inventories.

- **Cartographic Data**

The Landsat data with full spatial and spectral resolution (30 x 30 m resolution) for the end of the dry season (January 2023) and with less than 10% cloud cover were downloaded from the portal of the "Center for Earth Resources Observation and Science (EROS) of U.S. Geological Survey (USGS) " (https://earthexplorer.usgs.gov/). Level 2 products (Surface reflectance) from the Landsat 8 satellite in January 2023 were selected to obtain geometrically and radiometrically corrected data. Using Landsat data for land cover analysis is a wise choice, particularly for vegetation and land use studies. The 30-mander spatial resolution is suitable to distinguish between forested areas from non-forested areas, which is essential for natural resource management and environmental planning. Furthermore, the availability and free access to Landsat 8 satellite images make it an ideal tool. The data to be analyzed, such as training and validation plots, were collected in the field. A total of 310 polygons were digitized in the field to serve as training and validation plots. This data was used to improve classification accuracy and enhanced understanding of terrain characteristics, which is fundamental for land use characterization. Data for Characterization of Forest Ecosystems.

To characterize the structure of forest ecosystems and the woody flora in the agropolis of the Kara River basin, three types of data were collected: phytosociological data, ecological data, and forest inventory data. Togo's national forest inventory system (IFN1) was used for data collection. This system consists of a circle with a radius of 20 m, within which a circular plot with a radius of 4 m has been delimited. Within this 4 m plot, four small circles with a radius of 1 m were placed at the four cardinal points. This choice of circular plots helps reduce edge effects compared to other plot shapes [13]. The sampling plan was guided by the results of preliminary mapping. A buffer zone was defined around the Kara River basin agropolis, and 56 plots were randomly selected within the agropolis and the buffer zone. The forest inventory included all trees with a diameter at breast height (DBH) of 10 cm or more, considered as mature individuals located within a circle of a 20 m radius.

2.2.2 DATA PROCESSING

- **Cartographic Data Processing**

Classification was performed based on the Random Forest (RF) algorithm, developed by Breiman [14]. This algorithm was selected for its strong predictive capabilities for land use [15]. The RF algorithm was used for mapping based on over 300 training pixels, with classes determined in the field. Classification validation was carried out based on control points collected in the field. Several authors have shown that land cover classifications with RF outperform classifications using other types of algorithms, such as maximum likelihood classification [15]. Its ability to handle many input variables and to estimate missing values makes it particularly useful in situations where data is complex or incomplete. Additionally, the RF's aggregation method, which combines the results of multiple decision trees, enhances accuracy and controls overfitting, making it a robust choice for analyses [16].

To maximize information from the bands and eliminate noise to improve class discrimination, indices were used, notably the Normalized Built-Up Index (NDBI), the Soil-Adjusted Vegetation Index (SAVI), and the Normalized Difference Water Index (MNDWI) [17].

- **Normalized Difference Vegetation Index: NDVI**

The Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between near-infrared (which vegetation reflects strongly) and red light (which vegetation absorbs). The NDVI uses the near-infrared (NIR) and red channels in its formula:

$$NDVI = NIR - Red \div NIR + Red$$

- **Enhanced Vegetation Index: EVI**

In dense cover areas where the Leaf Area Index (LAI) is high, NDVI values can be improved by utilizing information in the blue wavelength. Information in this part of the spectrum can help correct soil background signals and atmospheric influences. The Enhanced Vegetation Index (EVI) is an “optimized” vegetation index designed to improve the vegetation signal with enhanced sensitivity in high-biomass regions and better monitoring of vegetation through decoupling the canopy background signal and reducing atmospheric influences.

EVI is calculated using the following equation:

$$EVI = 2{,}5 \times (NIR - Red) \div (NIR + 6 \times Red - 7{,}5 \times Blue + 1)$$

- **Normalized Differential Water Index: NDWI**

The NDWI is a remote sensing indicator sensitive to changes in leaf water content [18]. It is used to differentiate between continental forests and mangroves. Its formula is as follows:

$$NDWI = (NIR - SWIR) \div (NIR + SWIR) NDMI = (NIR - SWIR) \div (NIR + SWIR)$$

The different land use classes retained are:

- **Forest**

This includes gallery forests, open forests, and forest plantations.

- **Savannas**

This class mainly consists of shrub and tree savannas, typically characterized by vegetation rich in shea, néré, tamarind, and acacia.

- **Crops and Fallow Lands**

This class groups together food crops such as maize and soybeans. The fallow lands consist of previously cultivated areas left to rest for a few years.

- **Bare and Built-Up Lands**

This includes land without vegetation or with low vegetation cover, encompassing bare soils, rocky outcrops, roads, and settlements.

- **Water Bodies**

This includes rivers, dams, and ponds, which may be temporary.

- **Processing of Floristic and Structural Data**

The collected data was entered into an Excel spreadhead for easier manipulation. Prior to processing, scientific names were corrected by referring to the International Plant Name Index (IPNI) database, and synonyms were used to refine the species list based on the "World Flora Online" synonym database. The adopted nomenclature followed the recommendations of the Angiosperm Phylogeny Group [19]. Once the floristic lists had been purified, several analyses were conducted. First, a floristic analysis was performed to establish the woody species composition of the environment in terms of species richness, as well as to calculate diversity indices such as the Shannon-Weaver Diversity Index (H’) [20] and Piélou’s evenness index (E). Next, a chorological and phytogeographic analysis was undertaken for each species to determine their geographical distribution and origin. Biological forms or types (TB) refer to the adaptive behavior of plant species. In this work, after identifying each species, biological forms were named according to the Raunkiaer system [21] applied by [22], [23], [24], [25]. Phytogeography studies the distribution of plant species across the globe [26], [27]. The aim is to determine the chorological affinities of the different recorded species. This analysis was based on the chorological subdivisions for Africa established by White adopted by [28], [29], [30]. The phytogeographical types retained are AT = Afrotropical; SZ-GC = Soudano-Zambézienne/Guinéo-Congolaise; SZ = Soudano-Zambézienne; GC = Guinéo-Congolaise; S = Soudanienne; SG = Soudano-Guinéenne; Pal = Paléotropical; Pan = Pantropical. The conservation status of species at the international level was evaluated with reference to the IUCN Red List [31]: Extinct (EX), Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD), Not Evaluated (NE). The structural characterization of ecosystems in the study area was based on the distribution of individuals with DBH ≥ 10 cm by diameter and height class using Minitab software coupled with Microsoft Excel. Minitab software was used to calculate the various parameter values for the Weibull distribution probability, as well as means and standard deviations. The diameter class range is 10 cm, and the minimum diameter is 10 cm. For height classes, the range is 3 m. The structures of the stands were fitted to the theoretical distribution function based on the three (3) parameters of Weibull. Density, mean diameter, and basal area were used to describe the structure of adult stands. Stand density is defined as the total number of stems per unit area (hectare) for trees with dbh ≥ 10 cm; it is calculated using the formula:

$$N = \frac{Total\ number\ of\ trees\ in\ the\ plot}{Area\ of\ the\ plot\ (expressed\ in\ hectares)}$$

The mean diameter and the average total height are calculated directly through arithmetic calculation. The basal area is the sum of the cross-sectional areas at 1.30 m above ground level for all trees, converted to a per-hectare basis. It is obtained using the following formula:

G=π4∑di2

Where:

- ✓ G = basal area
- ✓ did_idi = diameter of tree iii at 1.3 m

3 Results

3.1 Land Use

The Kara agropolis and its buffer zone are occupied by forests (dense vegetation formations, including gallery forests, remnants of open forests, and plantations), savannas, crops and fallow land, bare and built-up soils, and water bodies (Fig 2). The accuracy assessment at the pixel level yielded an overall accuracy of 95%. This indicates that many pixels were correctly classified in relation to reference data. This level of accuracy provides a solid foundation for further analysis and informed decision-making in the land management of land use planning.

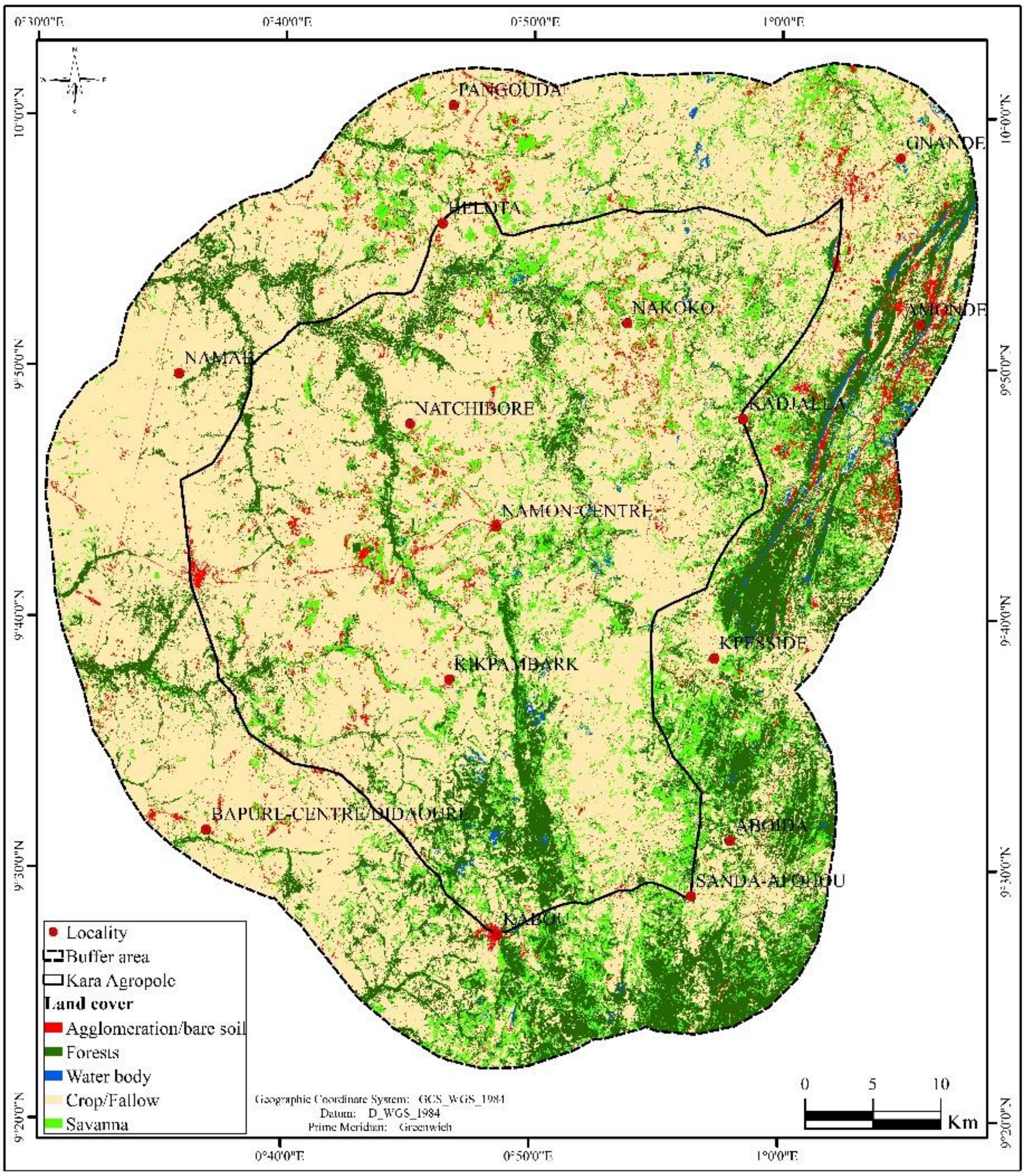

Fig. 2. Land use in the Kara agropole and its surroundings in 2023

Generally, the results show that cropland and fallow land occupy a large proportion of the total area of the study zone, amounting to 250,518 hectares, which represents 67% of the total surface. Compared to the buffer zone, the agropolis has a slightly higher proportion of crop and fallow land, with 72% compared to 63% for the buffer zone. Forests, accounting for about 13% in the agropolis and 21% in the buffer zone, are the second most prevalent land use, followed by savannas and residential areas (Table 1). Water bodies represent the smallest land use class in the area, totaling 41,934 hectares, or less than 1%.

Tableau 1. Areas of land use in 2023 in the Kara agropole and the buffer zone

	Study area Area (ha)	Agropolis Area (ha)	Proportion (%)	Buffer Area (ha)	Proportion (%)
Bare soil agglomeration	11858	4806	2,91	7052	3,40
Forest	65508	22004	13,34	43504	21,00
Water	2346	750	0,45	1596	0,77
Crop/fallow	250518	118764	71,99	131754	63,59
Savanna	41934	18647	11,30	23287	11,24

3.2 CHARACTERIZATION OF THE INITIAL STATE OF ECOSYSTEMS

3.2.1 FLORAL DIVERSITY

The study of woody vegetation, carried out through 56 surveys, identified 105 species belonging to 79 genera and 31 botanical families (Fig 3). The most represented families are Fabaceae (22%, with 27 species), Combretaceae, and Rubiaceae (10% each, with 11 species each), as well as Moraceae and Phyllanthaceae (7%, with 7 species each). These five families dominate the population, representing over 55% of all identified species, while the remaining families are less well represented, totaling 45% of the counts. At the generic level, species distribution highlights certain genera that are particularly diversified within this woody flora. These include Terminalia (7 species), Ficus (5 species), and Combretum (3 species).

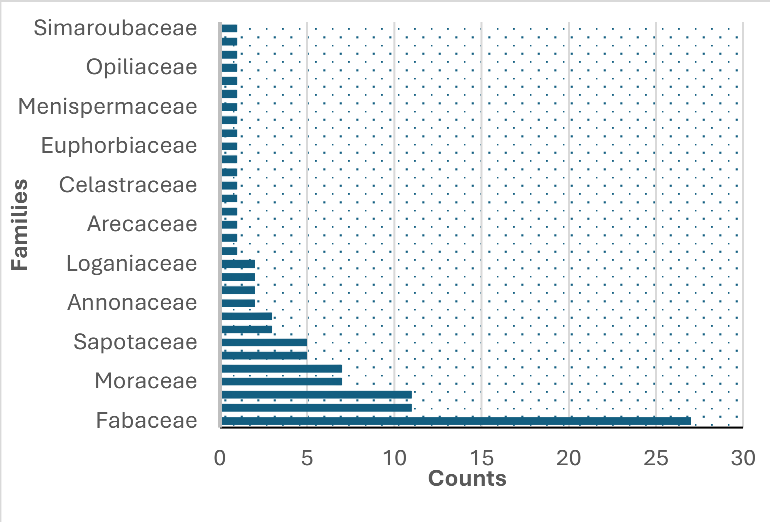

Fig. 3. Dominant families of woody flora in the Kara Basin agropole

- **Variation of Diversity Indices**

The following table (Table 2) presents the analysis of the variation of diversity and equitability indices in the study area. A moderate diversity is noted in the agropolis area (H' = 2.69 bits) and the buffer zone (H' = 2.13 bits). Regarding the Pielou equitability index, it is higher in the agropolis area (E = 0.59 bits) than in the buffer zone (E = 0.43 bits). However, at the global scale of the study area, high diversity is observed (H' = 4.19 bits) associated with a strong Pielou equitability index (E = 0.90 bits). This indicates that all species at the scale of the study area as a whole exhibit significant diversity with a very equitable distribution of individuals among the different species, without marked dominance of any single species. On the other hand, there are somewhat pronounced differences between the agropolis area, which has moderate diversity and equitability, and the buffer zone, which presents lower values for both indices.

Tableau 2. Variation of diversity indices or ecological paramanders

	Agropolis	Buffer zone	Study area
Specific richness (S)	95	84	105
Shannon index (H')	2,69	2,13	4,19
Maximum diversity Hmax (bits)	4,55	4,43	4,65
Pielou's evenness E	0,59	0,48	0,90

- **Biological and Phytogeographical Spectra of the Woody Flora**

The analysis of the distribution of biological types (Fig 4) reveals the predominance of microphanerophytes (48.57%), followed by mesophanerophytes (30.47%), while nanophanerophytes (11.42%) are also poorly represented. Other biological forms (larger phanerophytes, chamaephytes, etc.) are present in small numbers.

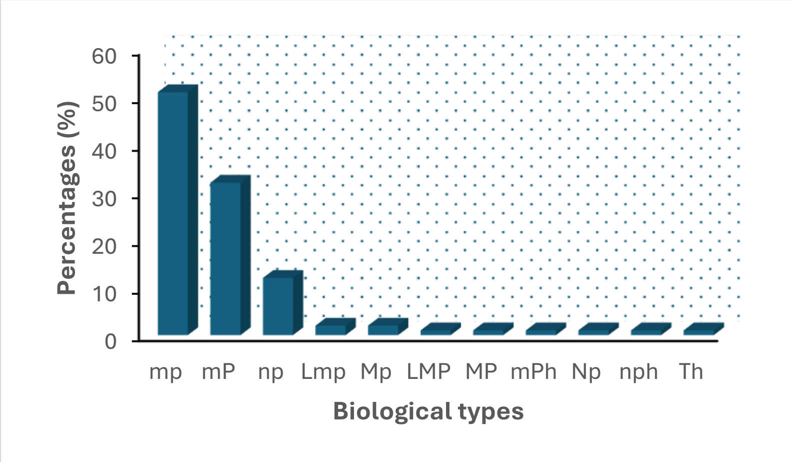

Fig. 4. Dominant families of woody flora in the Kara Basin agropole

mp: microphanerophyte; np: nanophanerophyte; mP: mesophanerophyte; MP: megaphanerophyte; G: geophyte; H: hemicryptophyte; Th: therophyte.

From a phytogeographical perspective (Fig 5), the most represented species are those from the Sudano-Zambesian region, accounting for 45.71% of the identified woody taxa. There are followed by species with Guineo-Congolese and Sudanese affinities, representing 20% and 11% of the counts, respectively. This distribution reflects the association of this flora with the Sudanese and Sudano-Zambesian phytogeographical domains, which are the main centers of plant diversity in this part of Africa.

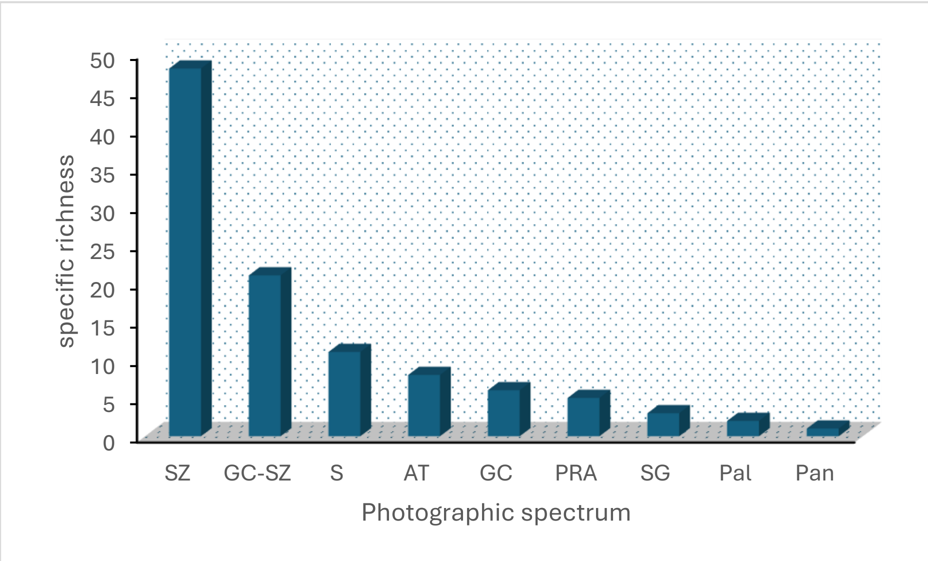

Fig. 5. Phytogeographic spectra, as a percentage of the number of species, of the woody flora in the Kara Basin agropole

AT = Afrotropical; SZ-GC = Sudano-Zambesian/Guineo-Congolese; SZ = Sudano-Zambesian; GC = Guineo-Congolese; S = Sudanese; SG = Sudano-Guinean; Pal = Paleotropical; Pan = Pantropical

The analysis of the woody flora reveals that four species are listed on the International Union for Conservation of Nature (IUCN) Red List, exhibiting different degrees of threat. Two species, *Afzelia africana* and *Vitellaria paradoxa,* are classified as Vulnerable (VU). One species, *Pterocarpus erinaceus,* is classified as Endangered (EN) (Fig 6). Finally, one species, *Raphia sudanica,* is classified as Near Threatened (NT). This analysis highlights the importance of closely monitoring the conservation status of these threatened woody species to varying degrees in the studied area.

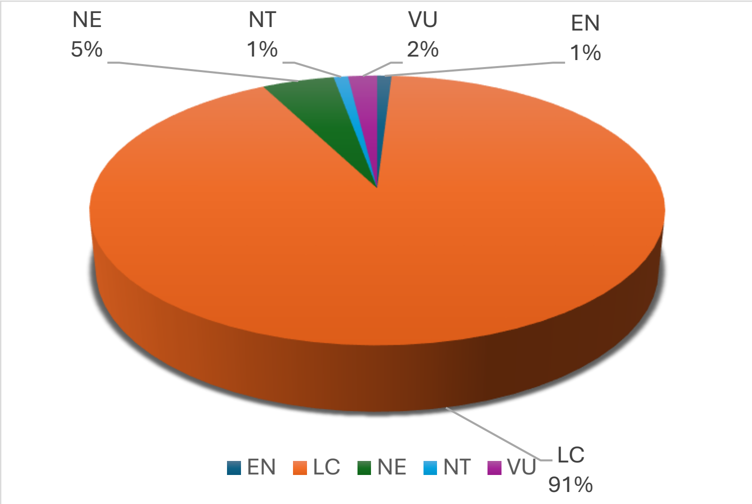

Fig. 6. Species status according to the International Union for Conservation of Nature

3.2.2 FOREST CHARACTERISTICS

The Agropole area has a relatively low tree density of 97.2 trees/ha, compared with 119.08 trees/ha in the buffer zone. However, the average tree diameter (18.91 cm) and their average height (7.6 m) are slightly lower in the buffer zone compared to the Agropole area (Table 3). On the other hand, the basal area of 32.30 m^2/ha is greater in the buffer zone than in the Agropole area, which is only 29.86 m^2/ha. These structural characteristics indicate that the forest stand in the Agropole area is relatively young and is under greater anthropogenic pressure than that in the buffer zone.

Tableau 3. Main forest characteristics by agropole and buffer zone

Zone	Density (tree/ha)	Mean diameter (Cm)	Mean height (m)	Total area (m^2/ha)
Agropolis	97,20	19,87 ± 12,72	7,89±3,54	29,86± 0,07
Buffer zone	119,08	18,91± 11,52	7,6± 3,12	32,30±0,06

3.2.3 DEMOGRAPHIC STRUCTURE OF WOODY POPULATION BASED ON DIFFERENT LAND USES

- **Distribution by Diameter Class**

The analysis of the shape parameters (c) according to diameter distribution reveals distinct trends based on land use types. In open forest and wooded savanna, the diameter structure of the woody population presents an inverted J-shape, with a parameter c of less than 1. This regressive structure indicates a strong representation of young individuals in the diameter class [10-20 [, as well as a presence of individuals of medium size in the class [20-30 [, with a low number of older individuals. In contrast, the woody stands in shrub and wooded savannas, as well as those in crop/fallow and gallery forests, display a positively skewed distribution, with shape parameters c ranging from 1 to 3.6 (Table 4). These values suggest a predominance of young individuals, indicating dynamism in these ecosystems. This difference in diameter structures highlights the importance of recognizing that these land uses are subject to anthropogenic pressure resulting from different management practices and environmental conditions.

The analysis of tree distribution by diameter class shows that both areas exhibit an inverted "J" shape (Fig 7). The shape coefficient (c) for diameter class distribution in the Agropole (0.93) and in the buffer zone (0.95) is less than 1. This reflects a strong representation of young individuals in the diameter class [10-20 [, medium individuals in the diameter class [20-30 [, and a low number of old individuals. This distribution shows that the forest population in this area is characterized by its youth and greater anthropogenic pressure compared to that of the buffer zone. This distribution demonstrates strong potential for regeneration and excessive pressure on woody resources in the project area.

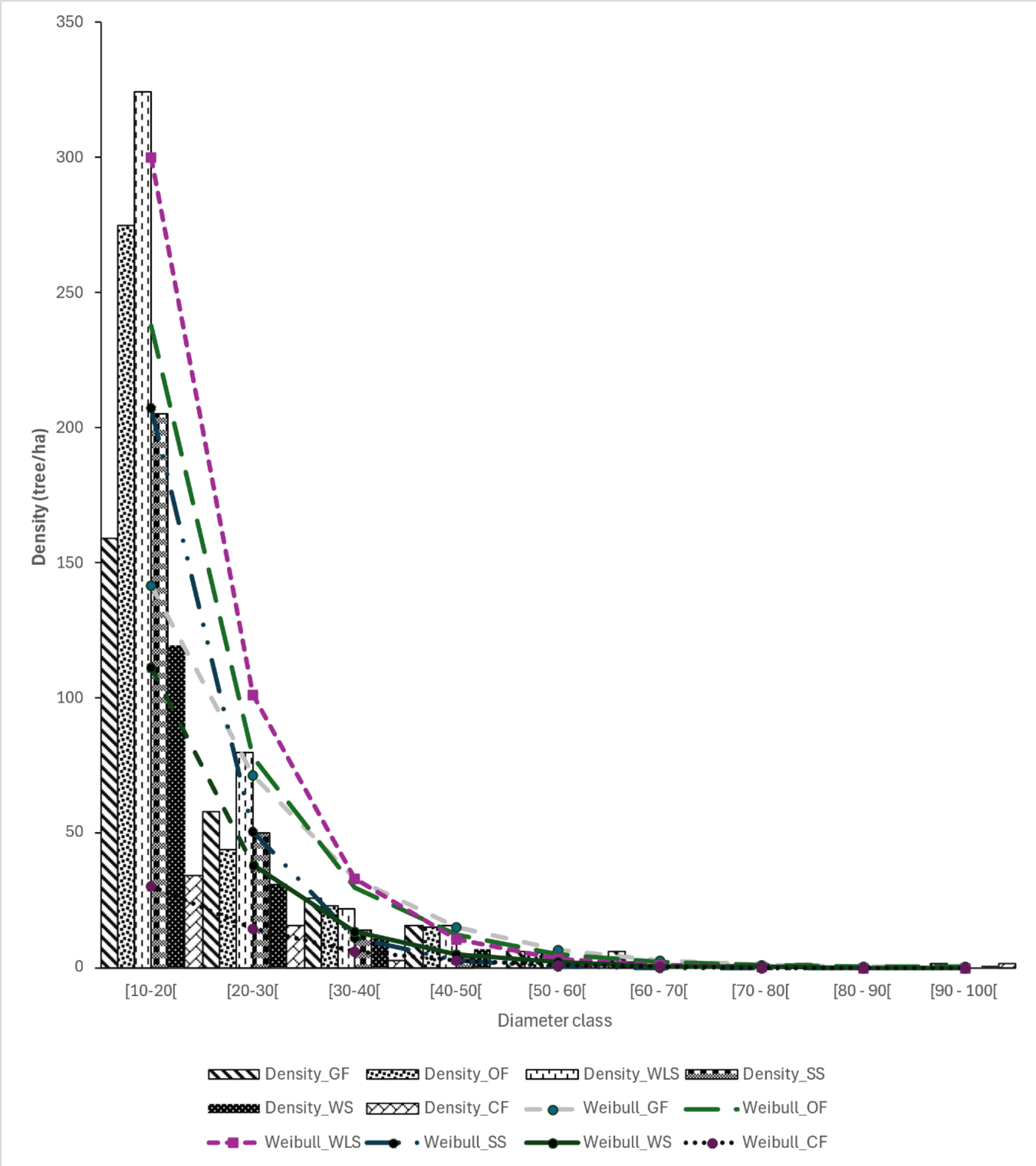

Fig. 7. Diameter structure of trees in the buffer zone and agropole

Cultivation/Fallow (CF), Open Forest (OF), Gallery Forest (GF), Tree Savanna (TS), Shrub Savanna (SS), Wooded Savanna (WS)

- **Distribution by Height Class**

The fit of the vertical distribution of trees to the Weibull distribution in the different formations of the study area presents shape indices (c) ranging from 1 to 3.6 (Table 4). These bell-shaped distributions indicate a positively skewed or right-skewed distribution, characteristic of stands with a relative predominance of young and short individuals. The height classes most represented based on the different land uses in the buffer zone and the Agropole are [3-6 [, [6-9 [, and [9-12 [(Fig 8).

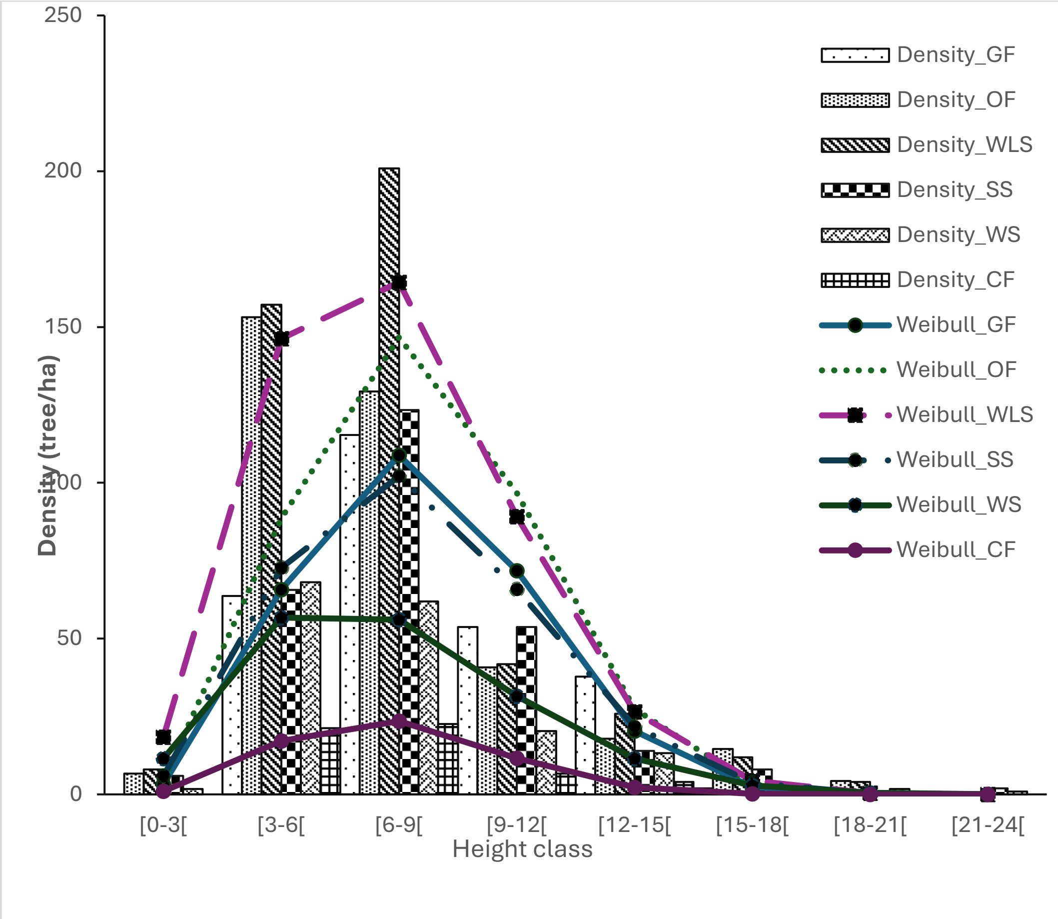

Fig. 8. Height structure of trees in the buffer zone and agropole

Cultivation/Fallow (CF), Open Forest (OF), Gallery Forest (GF), Tree Savanna (TS), Shrub Savanna (SS), Wooded Savanna (WS)

Tableau 4. Values of shape parameter (c) of the distribution by diameter and height class

Zone	**Les values of the shape parameter (c)**	
	Diameter	**Height**
Agropolis	0,93	2,06
buffer	0,95	2,24

4 DISCUSSIONS

Anthropized Zones Mainly Disturbed, with Richly Diverse Forest Ecosystems

Understanding the ecological and cartographic baseline of the Kara Agropole site provides a better grasp of the area's environmental challenges and offers the potential for more resilient measures adapted to sustainability principles. Indeed, land use mapping reveals that anthropized areas account for a significant portion of the total area under study. This anthropization manifests through the expansion of arable land, increased grazing areas, and urban sprawl. There are also variations in land use units based on the level of anthropogenic pressure exerted. These observations are corroborated by several studies [32], [33]. This finding underscores the importance of thoughtful management of natural resources to reconcile human development with environmental preservation.

The results of the floristic composition and structure of the woody vegetation conducted in the project area present both similarities and divergences with previous studies in the Sudanian zone. The floristic investigations carried out in the study area identified 105 species belonging to 79 genera and 31 botanical families. This specific richness is slightly higher than that of forest formations in the northern Atakora mountains in Togo, which have 102 species [34] and community forests in the Dankpen prefecture, which have 84 species (Atakpama and al., 2022). In contrast, it is lower than that of the Djamdè reserve, which has 126 species [35] and the Mô River basin, with 142 species [36] located in ecological zone II. The higher biological diversity observed in the Djamdè reserve can be explained by the fact that these areas benefit from a protected status that limits anthropogenic pressures. Indeed, protected areas generally exhibit greater species diversity compared to unprotected areas. The Mô basin, on the other hand, benefits from its isolation, which seems to have contributed to preserving its ecosystems from massive destruction.

The most diverse families are Fabaceae, Combretaceae, Malvaceae, Moraceae, Phyllanthaceae, and Rubiaceae. These families indicate the more humid climatic conditions favorable to the development of woody plants. The Fabaceae and Rubiaceae have been the most reported in previous studies in ecological zone II of Togo [37]. The results from Awitazi [35] also show a predominance of these families, just like in the present study. These convergences highlight the importance of these taxonomic groups in the composition of plant formations in the Sudanian-Guinean savannas of West Africa. The biological types of woody flora indicate conservation status and ecology of the ecosystems. Microphanerophytes dominate the vegetation formations in the agropole project area, followed by mesophanerophytes. The high percentage of microphanerophytes and mesophanerophytes in the vegetation formations is due to the young individuals of woody species (such as Combretum) and to adult individuals of certain species with significant socio-economic value, such as *Vitellaria paradoxa* and *Parkia biglobosa*. Phytogeographically, the species of Guineo-Congolese/Sudano-Zambesian transition and Sudano-Zambesian species are the most predominant. This confirms the transitional nature of the plant formations in zone II. The dominance of Sudano-Zambesian species in the study corroborates the work carried out in the Aledjo reserve and Fazao-Malfakassa Park [38]. The floristic richness was relatively higher in the agropole zone (95 species) and somewhat lower in the buffer zone (84). This may explain the higher diversity and Pielou index in the agropole compared to the buffer zone. However, at the overall scale of the study area, a high diversity (H' = 4.19 bits) is observed, associated with a high Pielou equity index (E = 0.90 bits). This indicates that the entire species assemblage across the study area presents significant diversity with a very equitable distribution of individuals among different species, without a marked dominance of any one of them. Thus, the high value of the Shannon index in the agropole results from the conservation of certain valued species in the cultivated areas. The Pielou regularity index obtained is low in the buffer zone, reflecting the high anthropogenic pressure from activities such as grazing, bushfires, and logging for firewood and charcoal.

In the study area, the presence of threatened species, such as *Afzelia africana, Pterocarpus erinaceus,* and *Vitellaria paradoxa* in the Agropole, and species such as *Afzelia africana, Pterocarpus erinaceus, Raphia sudanica,* and *Vitellaria paradoxa* in the buffer zone, should draw the attention of policymakers to the importance of closely monitoring the conservation status of these threatened woody species in the study area during the implementation of the Agropole project.

The height structure of woody species is positively skewed, while the diameter structure exhibits an inverted "J" shape across all studied zones. This demographic state is like that in ecological zone II of Togo [34], [39], [40] and in the sacred forest of Nassou in the Sudanian zone of Benin [41]. These two types of distributions indicate that all formations in the study area are highly disturbed, which may be explained by adverse climatic conditions and anthropogenic pressure. However, this strong predominance of small-diameter trees in the buffer and agropole zones could be an asset for any vegetation restoration efforts according to a sustainable management plan [39], [42]. The advantage is that small-diameter trees generally have a higher growth rate, allowing for rapid regeneration of vegetative cover, thereby facilitating ecosystem restoration.

5 CONCLUSION

In the Sudanian zone of Togo, particularly in the Kara region, anthropogenic pressure and climatic conditions influence the dynamics of forest ecosystems. The characteristics of the plant formations in the study area indicate that the horizontal and vertical structure of the woody populations remains dominated by trees of small diameter classes. The current floristic diversity and structural characterization of the vegetation stands in the agropole area are consequences of land-use practices. The mapping of land use in the study area has provided a comprehensive view of the distribution of plant formations. Today, new approaches to food security through the establishment of agropoles must integrate various biodiversity conservation actions through management plans that include the three dimensions of sustainable development. This would enhance the resilience capacity of ecosystems while contributing to mitigating the effects of climate change.

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