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Article

Assessing and Modeling the Vegetation Cover in the W and Pendjari National Parks and Their Peripheries Using Landsat Imagery and Climatic Data in Benin, West Africa

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Abstract: Today, satellite imagery has made a major contribution to the reconstruction and spatial prediction of sensitive or complex areas such as Pendjari and W Transboundary Reserves which constitute biodiversity reservoirs and habitats for wildlife conservation. Despite the protection to which they are subject, they remain dependent on climatic hazards that can influence their stability. This study has applied remote sensing techniques, combined with climate records from the last thirty years, to analyze the past dynamics of land use and climate changes, to predict the future states of the vegetation cover of the two national parks in Benin, as well as their periphery. The methodology used remote sensing and GIS techniques that allowed the supervised classification of Landsat images of 1985, 2000 and 2015. Climatic data were combined in R software to identify the break periods for climatic parameters. Finally, the predictive vegetation cover for the year 2030 was made by combining vegetation and climate in the "Land Change Modeler" extension. Ten land use and land cover classes were obtained. These are the agglomerations, mosaics of fields and fallows, water bodies, dense forests, gallery forests, clear forests and wooded savannahs, swamp forests and shrubby wooded savannahs, saxicolous savannahs and bare ground. The natural vegetation decreased from 90.85% in 1985 to 83.54% in 2000 then to 79.56% in 2015, a decline of 11.39% over a 30-year period. The analysis of the climatic curves revealed the presence of break, meaning drought frequency. The predictive modeling revealed that land use units projected to 2030 are consistent with past trends, but with the continued expansion of fields and fallows (2%) at the expense of vegetation cover. This study will motivate many others in the field.

Keywords: remote sensing; spatial modeling; climate change; pendjari; W Biosphere Reserve; vegetation

1. Introduction

Remote sensing has become an important decision tool in recent times for various fields of interest including vegetation science and biodiversity assessment [1]. It serves to assess the dynamics of the vegetation cover and land use of various ecosystems worldwide. Studies undertaken on vegetation using remote sensing would not be possible using only manual surveys. The management and ecological monitoring of protected areas require great financial investment [2]. There is a need

to assess the vegetation cover of natural areas like national parks. Moreover, in order to help people adapt to the effects of a warming planet and to protect biodiversity, vegetation cover needs to be monitored (www.panda.org). Many habitats are, and will be, altered by the global warming. It was recently concluded at the COP15 held in 2022 that regarding the alarming loss of nature, the World needs a strong agreement to restore species, the places and spaces representing their homes (www.panda.org). National parks play a key role in biodiversity conservation and monitoring their vegetation cover is a valuable tool to assess the conservation efforts. Furthermore, assessing the land use surrounding large national parks and nature reserves will provide information on what kind of occupations are undertaken by human populations in areas adjacent to these parks. Given the extent, status and importance of these protected areas for communities, emphasis should be placed on spatial tools and technologies capable of reconstructing the past state of their ecosystems for better conservation planning.

This craze has given rise to a great deal of research into spatial dynamics based on remote sensing. In fact, [3] applied remote sensing to demonstrate that dense forest and light forest decreased while cultivated areas increased in the Niger river delta of Nigeria. By comparing remote methods such as Dynamic World, World Cover and Esri Land Cover, [4] found water to be the most accurately identified class followed by the built environment and tree cover. Elsewhere, [1] recorded 16% loss of vegetation cover in the Ouémé river delta in Benin over a period of 30 years through analysis of Landsat imagery. These authors also predicted the vegetation cover of this humid ecosystem in 2035. In Saudi Arabia, [5] reported a loss of rangeland, forest and shrubland based on Landsat imagery analysis. Such studies show the importance of remote sensing in the assessment of vegetation cover and land use.

Concerning the Pendjari National Park and the W Park, the most two important protected areas in Benin and among the most important in West Africa, research undertaken ten years ago [6] in the Sudanian zone of North Benin revealed a significant decrease in forest, from 25.3% in 1972 to 8.8% in 2006 with loss of savannah areas. However, agricultural land showed an increase to 28.4% over the same period and human population growth was mentioned as the main cause of these changes. From 1972 to 2008, forest areas decreased from 22.7% to 17.0% in the W National Park while the mosaic of fields and fallows exhibited an increase from 1.38% to 13.97% in the vicinity of the park due to population growth [7]. Although these investigations in the present study area were undertaken several years ago, they provide relevant information confirming pressure on the two National Parks in recent decades [8,9]. Recently, significant changes in land use and land cover around ecotourism hotspots in the Pendjari National Park have been reported, and other drivers of such changes should be better researched [10]. The vegetation found on termitaria in the Pendjari National Park differs from that recorded on hotspots in farm and fallow areas surrounding the park [11]. More scientific activities to determine the change in vegetation cover and land use for a relatively long period of years are crucial. Moreover Dossou-Yovo et al. [12] reported important medicinal uses of plant species collected in fields and fallows surrounding the Pendjari National Park. Both herbaceous and woody plants are collected from the wild for medicinal purposes in Benin [13,14]. Most of this literature focuses on the dynamics of vegetation cover. But very few studies have combined remote sensing and climate data to assess the impact of climate on the health of forest ecosystems in these protected areas. However, the availability of satellite images and climate data already suggests that research on the mutual influences of these two parameters is of great interest. The present study on the vegetation cover of Pendjari and W National Parks and change in land use surrounding them for a period of 30 years (1985 to 2015) will provide a relevant scientific insight into the conservation efforts towards these protected areas and will help predict vegetation states in and around the two parks, and point out the impact of human activities on these vegetation dynamics. Moreover, the predictive analysis performed in this paper is also expected to serve as a sustainable decision tool that political leaders and other stakeholders can use for a better management of parks in Benin. The methods used in this paper were recently applied [1] to assess the vegetation cover and land use change and predict the trends for 2035. Many other studies had already used this method with satisfactory results on the reconstitution of the vegetation from satellite imagery [15,16]. In addition,

climatic data in this paper serve to correlate the changes in vegetation over the period covered with the variations in such drivers; a novelty leading to predictive analysis taking into account climate change [17–19]. In fact, [20] assessed the sensitivity of vegetation cover to climate change in a river basin by using remote sensing methods. Similarly, [21] reported vegetation modeling as a tool in studying response to climate changes. Most of the studies conducted on the two Biosphere Reserves focused on only one of these protected areas [8,11,22], even though they are very close and linked by hunting areas that serve as corridors for various flows and exchanges of biological. It is therefore necessary to undertake a comprehensive study on the spatial configuration of the vegetation cover of these two ecosystems together to understand the connectivity between them and their peripheries. In addition, these two protected areas are part of the largest network of protected areas in West Africa, with a double status of protection as Biosphere Reserves, and UNESCO World Heritage sites. Elsewhere, the integrated management of such a complex requires an understanding of the response of the vegetation cover to climate change. This is a major challenge for environmental conservation [23,24]. It is important to highlight that no study has yet addressed such research aspects on the protected areas of northern Benin, particularly using remote sensing tools.

2. Materials and Methods

The study area is the entire complex of protected areas (Pendjari and W-Benin Biosphere Reserves), their hunting areas as well as their periphery. The peripheries, approximately 25 km wide, made up of village territories, were considered because they benefit from special protection measures within the framework of a vast program of integrated management of transboundary protected areas in northern Benin. Table 1 shows the different zones and their respective surface areas.

Table 1. Categories of territories in the study area.

Categories	Status	Surface area (km²)
Protected areas	National Park of Pendjari	2761.23
	National Park of W Benin	5772.35
Hunting areas	Hunting zone of Pendjari	1823.50
	Hunting zone of Konkombri	259.65
	Hunting zone of Mékrou	1072.63
	Hunting zone of Djona	1189.47
Buffer zone	Village lands on the outskirts, 25 km wide	9676.41
Total	-	22555.24

Source: Field work, 2022.

This space extends between latitudes 10° 40' N and 12° 30' N and between longitudes 0° 50' E and 3° 22' E (Figure 1). With an area of approximately 22555 km², the study area crosses the districts of Tanguiéta, Toucoutouna, Kouandé and Kérou in the department of Atacora and the districts of Banikoara, Kandi and Malanville in the department of Alibori [25]. The climate of the region is Sudanian, characterized by an average annual rainfall between 694 and 1145 mm, with a rainy season and a dry season [11,12]. The same authors mentioned that the rainy season covers the period from April to October and the dry season covers the period from November to March. As for the temperature, the annual average is 26 ± 4°C (Figure 2). The relief of this region is uneven in places with altitudes varying between 106 and 591 m. The main soils are mineral soils, hydromorphic, vertisols and ferruginous soils [26]. The main plant formations are savannahs and open forests [27]. However, there are also gallery forests, swamp forests and agro ecosystems, especially outside of the parks. Agriculture is the main income generation activity for the surrounding populations of the W-Pendjari complex in northern Benin. The main crops grown around the complex are food crops such as sorghum, millet, maize, cowpea, yams, cassava yams, cassava, and cash crops (cotton), which occupy a great deal of agricultural land [11]. In recent years, cashew nut agroforestry has increasingly

been developed in the southern part of the W Biosphere Reserve. Animal husbandry remains the second most important activity practiced by the local populations. In addition to the traditional agricultural activities, the local people collect numerous non-timber forest products (NTFPs) such as shea, baobab, tamarind and many other products that generate significant income for local populations in the periphery of the reserve [25,28].

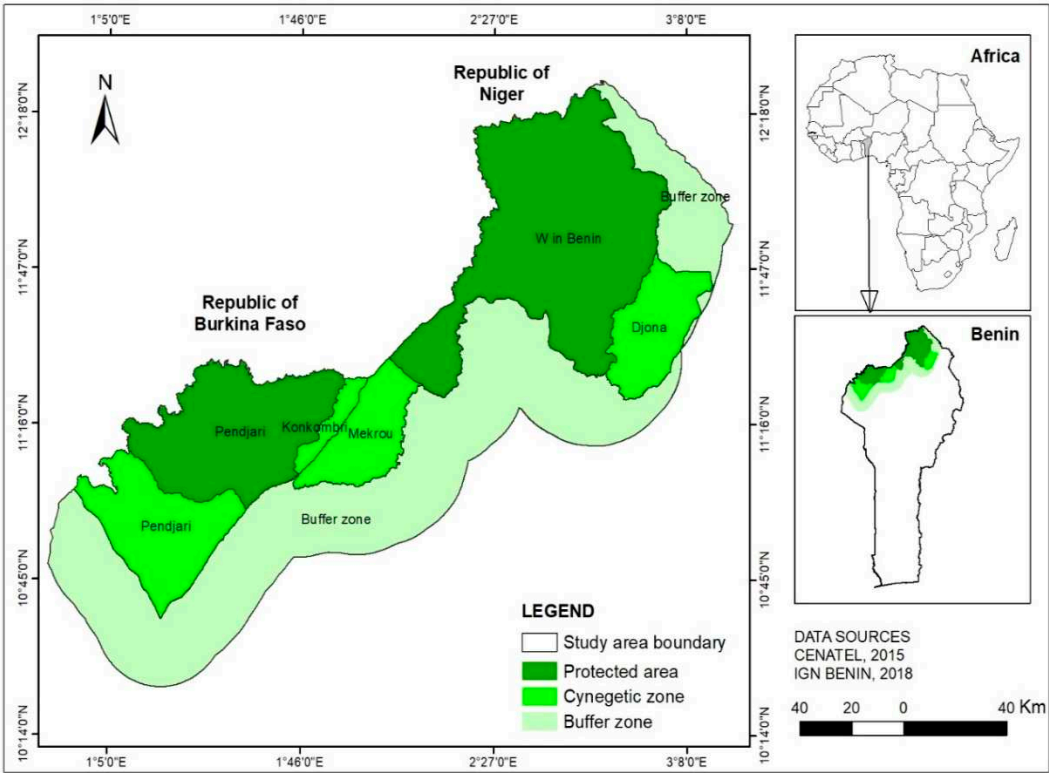


Figure 1. Geographical location of the study area.

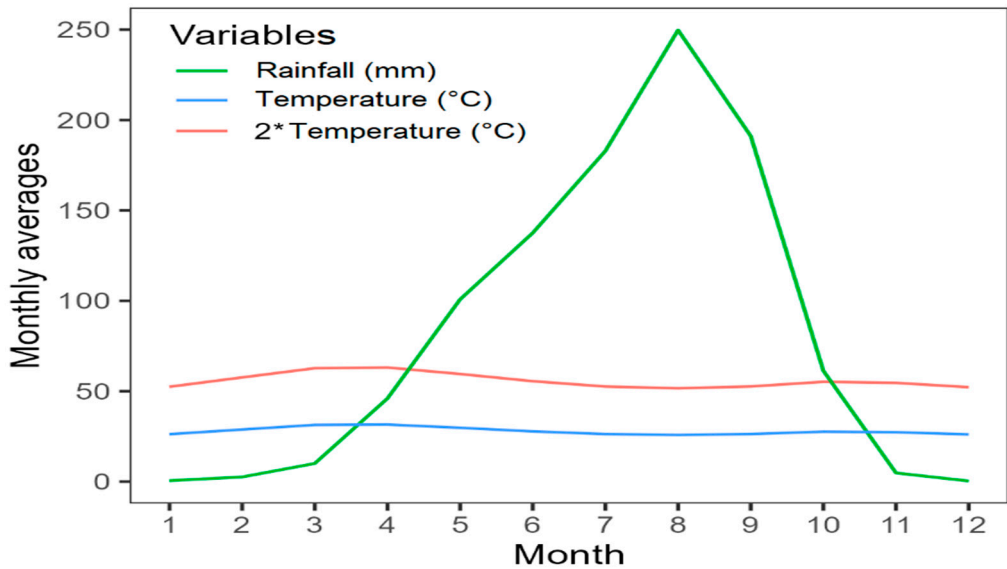


Figure 2. Ombrothermic diagram from 1985 to 2015 for W-Pendjari Biosphere Reserve.

Methods

- Dynamics of land use in the Pendjari and W protected areas in northern Benin.

Prior to the image processing, the topographic sheets of northern Benin at 1:200000 were used to geo-locate the reference frame and analyze environmental components of the study area. Then, Landsat satellite images available on the USGS (United States Geological Studies) website (<https://earthexplorer.usgs.gov/>) were downloaded. A preview of such images allowed the selection of the scenes 192-52; 193-52 and 193-53 for three years: 1985 (Landsat TM), 2000 (Landsat ETM+) and 2015 (Landsat OLI). The choice of these years is motivated by the aim to investigate the vegetation cover until 2015, a period before the designation of the complex of transboundary protected areas between three countries (Benin, Burkina Faso and Niger) in the UNESCO World Heritage [25]. Since the study focuses on forest ecosystems benefiting from in situ conservation measures, dry season images were chosen in order to reduce phenological contrasts as much as possible [29,30]. In addition, field surveys were conducted in December 2022, through georeferencing of 20 points per land use unit, to guide the definition of training plots on images. For the analysis of satellite images, the scenes covering the study area were grouped in the form of a mosaic using the ENVI 5.3 software. Then an enhancement was performed to increase the contrast between colors and to establish uniform illumination conditions on the assembled scenes [31]. For the interpretation of the images, false color compositions were performed in order to distinguish land cover units, including vegetation, from a grid of identification and interpretation of colors through spatial remote sensing. During the processing, ten (10) land use units were identified, with reference to the nomenclature of the Cartographic Atlas of Land Use Dynamics in Benin [32]. There were agglomeration (AG), dense forests (DF), gallery forests (GF), swamp forest (SF), field and fallow mosaics (FF), water bodies (W), open forests and wooded savannahs (OF), wooded and shrubby savannahs (SS), bare soil (BS) and saxicolous savanna (SxS). The images were then submitted to a supervised classification using the Maximum Likelihood algorithm, which calculates the probability of a pixel belonging to a given unit or not. The Pontius matrix was used for the validation of the classification. This method quantifies the inconvenience and allocation errors associated with image processing [33]. The choice of the Pontius matrix is related to its level of efficiency in post-classification decision making compared to the Kappa index [34]. Indeed, although the Kappa index is widely used, it is increasingly questioned for its effectiveness, whereas in recent years the Pontius matrix is suggested to be in line with current research. Thus, the Pontius Matrix 4.2.Xlsx version was used to evaluate the accuracy of classifications based on quantification and allocation of annoyances. Finally, the data from the digital processing was vectorised and exported to ArcMap for integration into the GIS, from which the vegetation cover and other land use units were extracted with their areas.

- Analysis of land use dynamics between 1985 and 2015

The changes in land use status between 1985 and 2015 were described by comparing the areas of each unit over the periods 1985, 2000 and 2015. The changes observed over these periods were highlighted by the transition matrix, which reflects the forms of conversion that the land use units underwent between two dates. It consists of x rows and y columns. The number x of rows in the matrix indicates the number of classes present at date t_1 , while the number y of columns in the matrix indicates the number of converted classes at date t_2 . The diagonal indicates the areas of classes that have remained unchanged over time. In this matrix, the transformations are made from rows to columns. The different matrices were obtained by crossing the 1985-2000, 2000-2015 and 1985-2015 maps.

- Analysis of correlations between climate and vegetation

The effect of climate change on forest ecosystems has been the subject of much reflection in recent years, given the changes observed in forest areas around the world. It is therefore necessary to highlight the contribution of climate to future changes in vegetation cover, particularly in the Pendjari and W transboundary Biosphere Reserves in northern Benin.

Thus, based on climatological data provided by the Benin meteorological observation network, records from the rainfall stations of Karimama, Alfakoara, Banikoara, Tanguiéta and Matéri were used. Similarly, the agro-climatic stations of Guéné, Kérou, Dassari and Porga were used to extract climate parameters such as rainfall, relative humidity, temperature and wind speed.

Meteorological data on the study sites were obtained from the Benin Agency of Meteorology (Météo Bénin). There were monthly records of temperature, rainfall, humidity and wind speed from 1980 to 2022. Such data were processed and analyzed within the Integrated Development Environment of Rstudio [35] by using the software R v4.1.2 [36]. The missing observations in the chronological series of each climatic variable were filled by predicted values through linear interpolation under forecast R package [37,38]. In order to get a unique rainfall series per site (Biosphere Reserves), the monthly mean rainfall per site was computed considering the observations of all townships covered by the Biosphere Reserve. The total rainfall was calculated per year for both Biosphere Reserves considering the mean rainfall of each month. Monthly mean temperatures, humidity and wind speed were computed per year for both Pendjari and W Biosphere Reserves.

In order to assess the temporal distribution of rainfall over the period of the study, each sery was converted in times series (ts) object under the R package stats [36] and 5 years centered moving averages were calculated using forecast R package. The real trends with moving averages were plotted using ggplot2 R package [39,40] for each variable per Biosphere Reserve. Breakpoints analysis was then performed to check for structure change in values of each climatic variable from 1985 to 2015. Thus, several segmentations were performed on each sery using strucchange R package [41,42] and the corresponding Residual Sum of Squares and Bayesian Information Criterion (BIC, hereafter) were computed to find out the optimal numbers of breakpoints to be considered. Vertical red lines were plotted at each breakdate of the optimal segmentation on each series. The optimal segmentation is the one which recorded the lowest BIC. Further, the annual standardized precipitation index (SPI) was computed and the ombrothermic diagram was plotted for each of the two Biosphere Reserves for finding out dry and rainy times throughout the study period. In fact, the SPI was applied, three decades ago, by McKee et al. (1993) [43] to assess the relationship between drought frequency and time scale. Its formula [44] is known as:

Where P is the annual precipitation of a given year, P_m represents the mean annual precipitation over the period 1985-2015, and meaning the standard deviation of annual precipitations over the same period.

A spatial interpolation was made on two of these parameters, which were associated with the land cover in Land Change Modeler (LCM), available on IDRISI LCM in order to predict the vegetation cover at the horizon 2030. This model is widely employed in studies on land cover or land use changes [45,46]; 1], based on cellular automata. The two parameters considered are rainfall and humidity, given their strong influence on vegetation. In fact, scientists reported vegetation as a response to water availability, including rainfall and humidity [47–49]. Moreover, evaluated the impact of rainfall and moisture dynamics in a foggy desert, concluding that these two parameters are the most important determining vegetation dynamics.

Although the peripheries of the two parks were included in the present study, the climatic variations were correlated to the land use and land cover in these areas because of the diverse environmental impacts of climate [50] In other words, the choice of land use by indigenous people living around the national parks is highly driven by the variation in climate especially rainfall and moisture. Furthermore, the variation in land use by indigenous people in tropical countries was reported as a climate change adaptation [51], meaning that land use changes are in relation with the climatic variations. As a result, local communities can use the information provided by this study to develop adaptive capacities to avoid reducing ecosystem services. In addition, decision-makers will use findings to define resilience strategies against future changes in climate and vegetation cover in this region.

3. Results

In total, ten land use units were clearly identified and used for the analysis of land cover dynamics. The reliability of the processing, shown in Figure 3, indicates the low inconvenience and allocation errors associated with image processing. This allows validation of the satellite image classification.

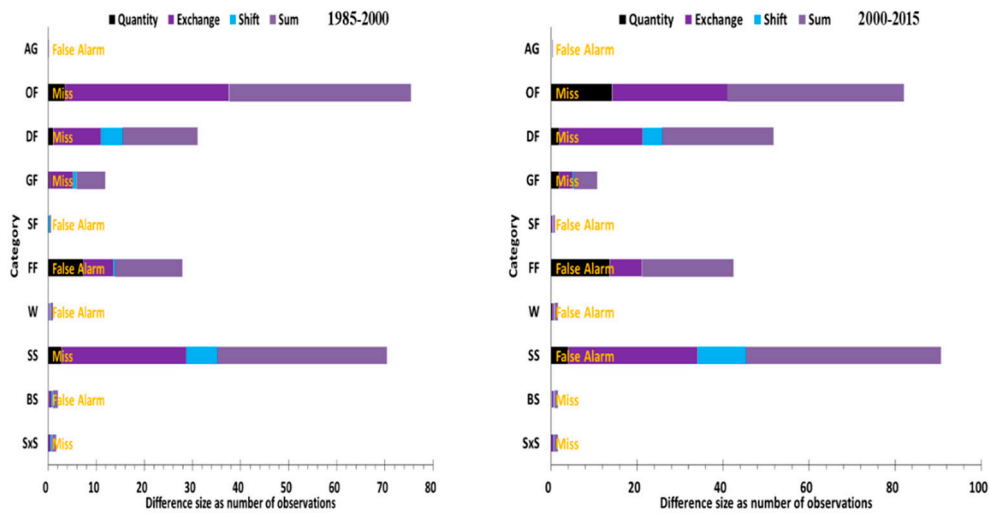


Figure 3. Size of the difference in the number of observations of land use units in W and Pendjari parks and their peripheries between 1985 and 2015.

The different land use units, which are presented in Figure 4, can be grouped into two categories:

- Natural vegetation formations consisting of dense forests, open forests and tree savannas, gallery forests, swamp forests, tree and shrub savannas and saxicolous savannas.
- Other land use units such as bare soil and water bodies scattered throughout the study area, followed by settlements and fields and fallow land mostly located outside the two protected areas and their hunting zones.

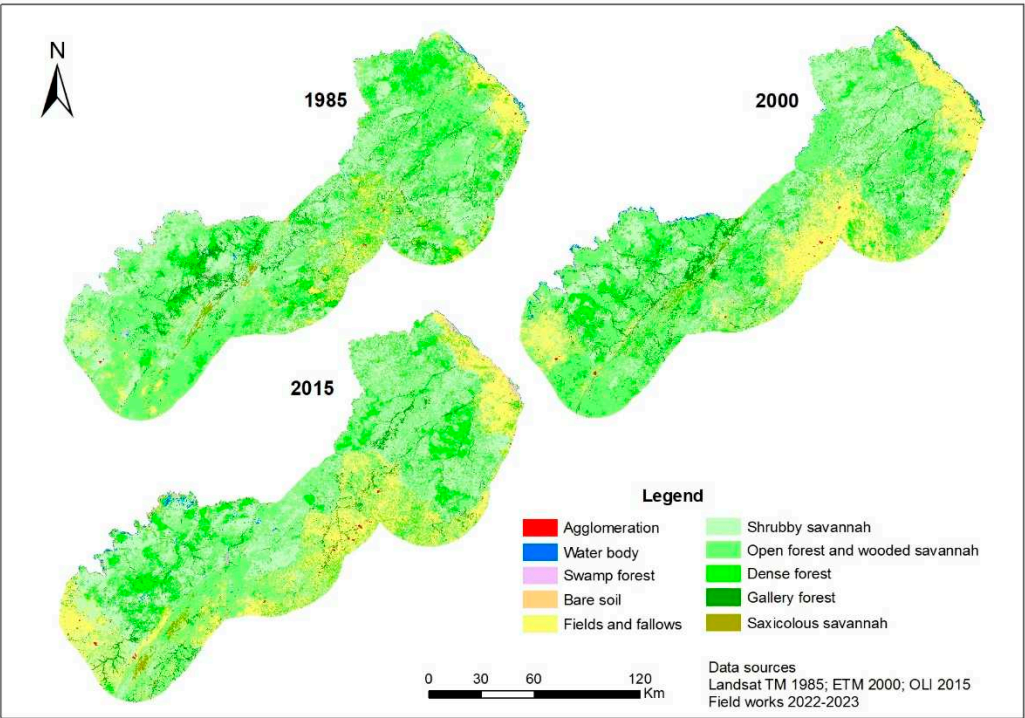


Figure 4. Reconstitution of land use units in W and Pendjari parks and their peripheries between 1985 and 2015.

- Land use dynamics of the W and Pendjari parks and their peripheries between 1985 and 2015

Overall, natural formations decreased from 90.85% in 1985 to 83.54% in 2000 and 79.56% in 2015 (Figure 5). This indicates a decline in vegetation cover of 11.39% over the study period (1985-2015). However, it is during the first observation period (1985-2000) that the loss of vegetation cover was greatest, 7.41% compared with 3.98% in the second period (2000-2015). On closer inspection, the clear forests and wooded savannahs have lost the most area. The latter decreased from 33.89% in 1985 to 30.92% in 2000 and 25.29% in 2015. A similar trend was observed for gallery forests, which fell from 4.38% to 3.97% and then to 3.10%. Saxicolous savannah showed insignificant losses. As for dense forests, they fell from 16.52% to 15.40%, before experiencing a slight increase of 0.09% in 2015. The same trend was observed in tree and shrub savannahs (35.39%, 32.56% and 35.01%). Meanwhile, swamp forests remained constant between 2000 and 2015, after increasing by 0.03% in the previous period.

In contrast, the other land use units of settlements, fields and fallow land and bare soil have expanded over the entire observation period. Indeed, settlements, which occupied 0.11% of the total area of the study area, increased to 0.14% in 2000 and then to 0.17% in 2015. Fields and fallow land have seen the greatest increase in area, rising from 8.10% in 1985 to 15.24% in 2000 and 18.93% in 2015, an increase of 10.83% in 30 years. The increase in area of bare soil was very small (0.07%) between 1985 and 2000, but remarkable between 2000 and 2015 with a value of 0.28% of the total area of the study area. Over the whole study period, the area of water bodies, which was estimated at 0.43% in 1985, remained almost unchanged (0.5% for 2000 and 2015).

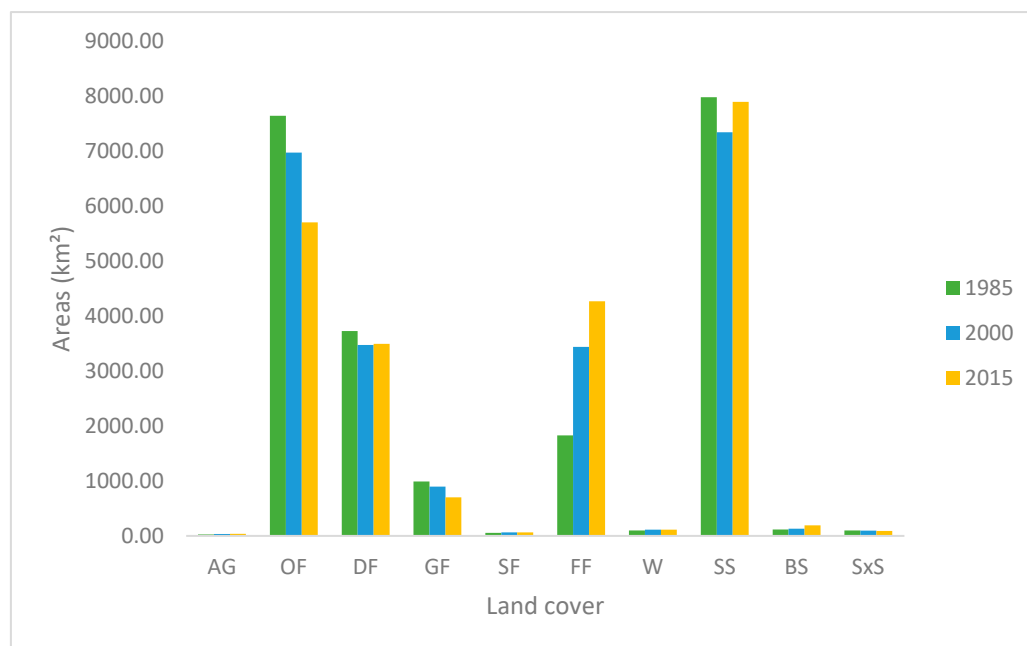


Figure 5. Evolution of the areas of the land use units of the W and Pendjari parks and their peripheries between 1985 and 2015. Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannahs (OF), Wooded and Shrubby Savannahs (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

Analysis of land use conversions from 1985 to 2015

Between 1985 and 2000, 10.19% and 5.09% of the total area of the study area was transformed into open forest and wooded savannah and field fallow mosaics respectively (Table 2). It was also noted that fields and fallows recorded the highest gain, estimated at 7.34% in absolute value, equivalent to 90.51% in relative value. Meanwhile, open forest and wooded savannahs as well as tree

and shrub savannahs suffered the greatest losses (respectively -3.5% and -2.78% of the total area in absolute value; equivalent to -10.21% and -7.88% in relative value).

In the period from 2000 to 2015, the changes in land use were more rapid, with no conversion exceeding 9.3% of the study area (Table 3). This maximum value (9.3%) represents a gain of tree and shrub savannahs over the other land-use units, the majority of which (8.53%) comes from open forest and wooded savannahs. In sum, in relative terms, tree and shrub savannahs have lost 17.91% of their area. Gallery forests lost 24.38% and saxicolous savannahs 4.55%. Settlements and fields and fallow land continued to expand, with increases of 21.43% and 27.27% respectively. The increase in the area of bare land was remarkable over this observation period, with a gain of 61.02% in absolute terms. The analysis of mutations over the whole study period shows that no conversion exceeds 8.64% in the form of loss in open forest and wooded savannah (Table 4). In contrast, the maximum gain was recorded in tree and shrub savannahs (13.29%). The highest conversion rates, expressing area gains, were recorded in fields and fallows (131.98%) followed by bare soils (82.69%). Meanwhile, open forests and wooded savannahs, followed by gallery forests, saw their area decrease by 26.29% and 29.60%, respectively.

Table 2. Transition matrix of land use units (as % of total area) between 1985 and 2000.

	AG	OF	DF	GF	SF	FF	W	SS	BS	SxS	T2 (2000)
AG	0.1	0	0	0	0	0.01	0	0.03	0	0	0.14
OF	0	13.68	4.37	0.74	0.01	1.46	0.05	10.19	0.16	0.11	30.77
DF	0	4.52	8.09	0.47	0	0.17	0.01	1.96	0.01	0.1	15.33
GF	0	0.93	0.41	1.23	0.02	0.18	0.08	1.13	0.03	0.06	4.06
SF	0	0.02	0.1	0	0.07	0.01	0.02	0	0	0	0.22
FF	0.01	1.9	3.28	0.33	0	4.8	0	5.09	0.03	0	15.45
W	0	0.07	0.02	0.03	0.01	0.01	0.17	0.16	0.01	0	0.49
SS	0	12.89	0.01	1.51	0.1	1.28	0.04	16.3	0.21	0.16	32.5
BS	0	0.12	0.07	0	0	0.19	0	0.17	0.05	0	0.59
SxS	0	0.15	0.02	0	0	0	0	0.26	0	0.01	0.44
T1 (1985)	0.12	34.27	16.38	4.3	0.21	8.11	0.37	35.28	0.52	0.43	100
T2-T1	0.02	-3.5	-1.05	-0.24	0.01	7.34	0.12	-2.78	0.07	0.01	-
TC	16.67	-10.21	-6.41	-5.58	4.76	90.51	32.43	-7.88	13.46	2.33	-

Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannahs (OF), Wooded and Shrubby Savannahs (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

Table 3. Transition matrix of land use units (as % of total area) between 2000 and 2015.

	AG	OF	DF	GF	SF	FF	W	SS	BS	SxS	T2 (2015)
AG	0.06	0.03	0.01	0	0	0.06	0	0.01	0	0	0.17
OF	0.01	9.57	4.15	0.91	0.04	1.67	0	8.53	0.04	0.33	25.26
DF	0	7.22	4.85	1.27	0.05	1.79	0.15	0	0.03	0	15.35
GF	0	0.62	0.36	0.87	0	0.35	0.08	0.79	0	0	3.07
SF	0	0.01	0	0.15	0.03	0.01	0.08	0	0	0	0.28
FF	0.06	3.41	1.91	0.22	0.02	9.83	0.02	3.06	0.21	0.05	18.79
W	0	0.17	0.05	0.04	0	0	0.11	0.06	0.02	0	0.44
SS	0	9.3	3.89	0.52	0.08	1.36	0.03	19.83	0.2	0.06	35.27
BS	0	0.18	0.05	0.08	0	0.36	0.03	0.15	0.09	0	0.95

SxS	0	0.26	0.06	0.01	0	0.01	0	0.08	0	0	0.42
T1 (2000)	0.14	30.77	15.33	4.06	0.22	15.45	0.49	32.5	0.59	0.44	100
T2-T1	0.03	-5.51	0.02	-0.99	0.06	3.34	-0.05	2.77	0.36	-0.02	
TC	21.43	-17.91	0.13	-24.38	27.27	21.62	-10.20	8.52	61.02	-4.55	

Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannas (OF), Wooded and Shrubby Savannas (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

Table 4. Transition matrix of land use units (as % of total area) between 1985 and 2015.

	AG	OF	DF	GF	SF	FF	W	SS	BS	SxS	T2 (2015)
AG	0.05	0.02	0.02	0	0	0.04	0	0.04	0	0	0.17
OF	0	10.51	3.68	0.76	0.04	1.23	0.02	8.64	0.09	0.28	25.26
DF	0	4.92	4.66	0.98	0.04	0.59	0.04	4.04	0.07	0.01	15.35
GF	0	1.03	0.37	0.75	0.01	0.21	0.04	0.63	0.01	0.01	3.07
SF	0	0.01	0.03	0.03	0.01	0.05	0.1	0.05	0.01	0	0.28
FF	0.06	4.03	3.65	0.26	0.01	4.53	0.01	6.2	0.02	0.02	18.79
W	0	0.09	0.04	0.02	0.01	0	0.07	0.19	0.01	0	0.44
SS	0	13.29	3.76	1.5	0.11	1.14	0.06	15.12	0.21	0.08	35.27
BS	0	0.1	0.16	0	0	0.26	0.02	0.3	0.09	0	0.95
SxS	0	0.27	0.01	0	0	0.05	0	0.06	0	0.04	0.42
T1 (1985)	0.12	34.27	16.38	4.3	0.21	8.1	0.37	35.29	0.52	0.43	100
T2-T1	0.05	-9.01	-1.03	-1.23	0.07	10.69	0.07	-0.02	0.43	-0.01	
TC	41.67	-26.29	-6.29	-28.60	33.33	131.98	18.92	-0.06	82.69	-2.33	

Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannas (OF), Wooded and Shrubby Savannas (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

These observations showed that similar land use dynamics was noticed between 1985 and 2000 then 2000 and 2015 (Table 5). In other words, from 1985 to 2000, all conversions concerned 55.5% of the total area, of which 27% was lost. Land use remained almost unchanged during the following fifteen years, when conversions were estimated at 54.76%, of which 24.13% was lost. The stable areas were almost equal (44.5% and 45.24% respectively) over the two observation periods. However, this trend in stable areas changed slightly when considering the whole period from 1985 to 2015, where the stable areas were 35.83% and almost equal to the areas gained (35.59%). The losses were therefore around 28.58% and are thus very slightly higher than in the sub-period observations.

Table 5. Summary of area dynamics over the periods 1985-2000, 2000-2015 and 1985-2015.

Period	Stability (%)	Increase (%)	Loss (%)
1985-2000	44.5	28.44	27.06
2000-2015	45.24	30.63	24.13
1985-2015	35.83	35.59	28.58

- **Analysis of climatic parameters of the W and Pendjari parks and their peripheries between 1985 and 2015**
- Rainfall

The annual mean precipitation had a high variability (coefficient of variation CV= 11.63%) during this study. The five-year centered moving averages show an increasing trend during 1985-1996, 2000-2010 but a decreasing trend during 1996-1999 and 2010-2015 (Figure 6a). The lowest annual average precipitation (802.9 mm) was received in 2000 and the highest (1218.9 mm) occurred in 2003. However, the BIC criterion suggests that there was not enough evidence to accept a break in the annual mean precipitation series over the period 1985-2015. The standardized precipitation index (SPI) fluctuates between -1.60 and 2.01 over the study period. This means that there was a succession of droughts (rainfall deficit) and heavy rains (rainfall excess) during this period. The drought periods were 1985-1990, 1992-1993, 1995, 1997, 2000-2001, 2006, 2011 and 2013-2015 respectively with low ($-1 < \text{IPS} < 0$) and moderate ($-1 \geq \text{SPI} > -1.5$) intensity. Severe drought ($-1.5 \geq \text{SPI} > -2$) was particularly noticed in 2000. Heavy precipitation of moderate intensity ($1 < \text{IPS} \leq 1.5$) was recorded during the years 2009 and 2011 but heavy precipitation of extreme intensity was recorded during the years 1991, 1994, 1998, and 2003 (Figure 7). Considering the entire period of this study (1985-2015), the ombrothermic diagram (Figure 3) of the W-Pendjari Biosphere Reserve exhibited a unimodal rainfall regime with a rainy season and a dry season (Rainfall $> 2 \times \text{temperature}$). The rainy season usually begins in mid-April and ends in early October, while the dry season begins in early October and ends in mid-April (rainfall $< 2 \times \text{temperature}$).

- **Monthly average temperature**

Monthly mean temperature showed very little variability (coefficient of variation CV= 1.20%) during this study. The five years centered moving averages showed an increasing trend for the period 1985-2010 (with a high rate from 2001 to 2005), but a decreasing trend from 2010 to 2015 (Figure 6b). The lowest monthly average temperature (27.16 °C) was recorded in 1989 and the highest (28.48 °C) in 2010. The BIC criterion for the breakpoint test identifies a breakpoint date and then suggests two segments as the optimal number of segments to model this series. The corresponding break date was the year 2002 (Figure 6). The average difference in monthly mean temperature between the two periods was 0.44°C, representing an increase.

- **Monthly mean humidity**

For the present study, there was only slight variability in the monthly average humidity (coefficient of variation CV= 4.99%). The five years centered moving averages revealed an increasing trend during 1985-1994 and 2001-2015, with a steep rate from 2001 to 2015, but a very gradual decreasing trend during 1995-2000 (Figure 6c). The lowest monthly average humidity of 53.21% occurred in 1987, while the highest (63.33%) occurred in 2014. Based on the BIC criterion for the breakpoint test, a breakpoint date was identified, and two segments were recommended as the optimal number of segments to model this series. The corresponding break date was noticed in 2003. The average difference in monthly mean moisture between the two periods was 4.54%, indicating an increase.

- **Monthly average wind speed**

The monthly mean wind speed showed a large variability during this study (coefficient of variation CV= 31.76%). The five years centered moving averages show an increasing trend during 1985-1989, 1991-1993 and 2009-2015 with the highest rate during 1991-1993, but a very slow decreasing trend during 1989-1991 and 1993-2009 (Figure 6d). The lowest monthly average wind speed (0.925 ms⁻¹) was recorded in 1987 whereas the highest (3.29 ms⁻¹) occurred in 2014. The BIC criterion for the breakpoint test identifies a breakpoint date and then suggests two segments as the optimal number of segments to model this series. It was noticed that rainfall in the study areas had no structure break. However, the mean temperature and mean humidity in the study areas exhibited respectively the break at years 2002 and 2003 (vertical red line) while the mean wind of the areas showed two break years (1992 and 1998). The average difference between periods in the monthly mean wind was -0.89 ms⁻¹ for period 1 and period 2, which represents an increase; - 1.01 ms⁻¹ for period 2 and period 3, which represents a decrease; -0.12 m s⁻¹ for period 1 and period 3, being a decrease.

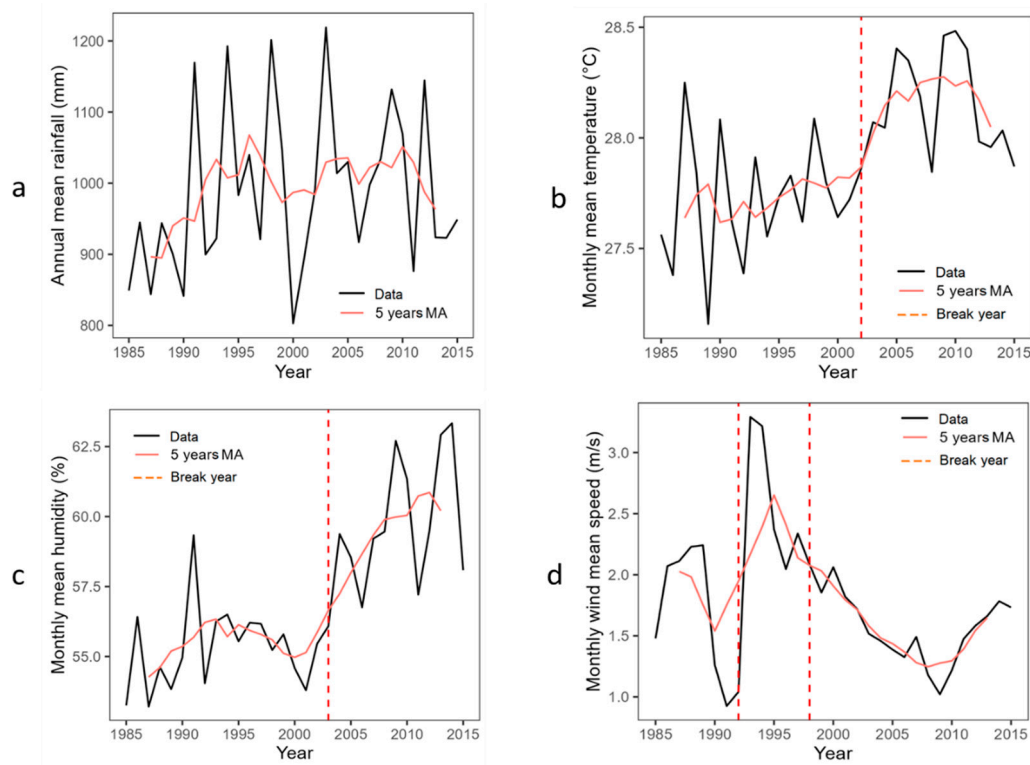


Figure 6. Global trend of climate parameters from 1985 to 2015 for W-Pendjari Biosphere Reserve with change points in the moving averages (MA). (a) Trend of annual mean rainfall; (b) Trend of monthly mean temperature; (c) Trend of monthly mean humidity; (d) Trend of monthly mean wind speed.

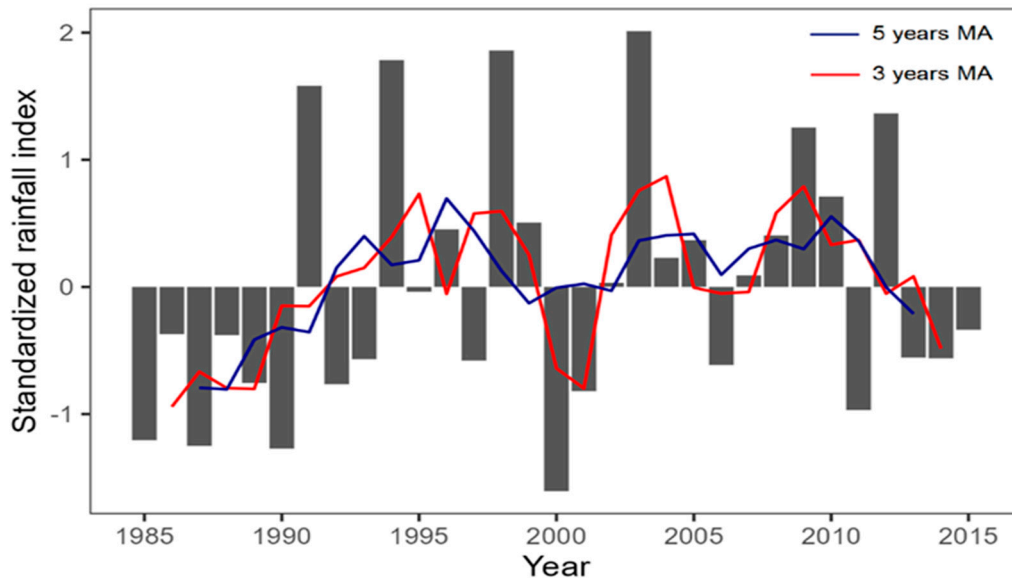


Figure 7. Trend in Standardized Precipitation Index (SPI) from 1985 to 2015 for W-Pendjari Biosphere Reserves with 3 and 5 years moving centered averages (MA).

- **Predictive modelling of the vegetation cover of the W and Pendjari parks and their peripheries by 2030**
- **Distribution of climatic factors around the W and Pendjari parks**

Precipitation and humidity were the two parameters used for model calibration. Their distribution in the study area indicated that precipitation ranges from 15 to 110 mm of rainfall, and humidity ranged from 51.13 to 55.25% (Figure 8). While humidity was almost constant over the entire

observation period, rainfall varied considerably, with a spatio-temporal shift in maximum rainfall intensities.

Indeed, the greatest rainfall amplitude was observed in 2000, while the lowest was noticed in 1985. Furthermore, in 1985, the maximum rainfall intensity was around 92 mm, whereas in 2000, it increased to 94 mm before rising to 110 mm in 2015. This is an increasing trend in rainfall, with a shift in heavy rainfall from the central region of both parks in 1985 to the southwest in 2000, confirmed in 2015. In other words, the Pendjari park, the Komkombri and Mekrou hunting zones, and their peripheries, were the areas that received the most rains in 1985. In 2000, this front of maximum rainfall intensity shifted completely to the Pendjari and its southern hunting zone only, confirmed in 2015. With these shifts in the rainfall front, it is highly likely that low intensities will be recorded over the two protected areas towards the end of the current decade. This would represent a future threat to the vegetation cover of the study area.

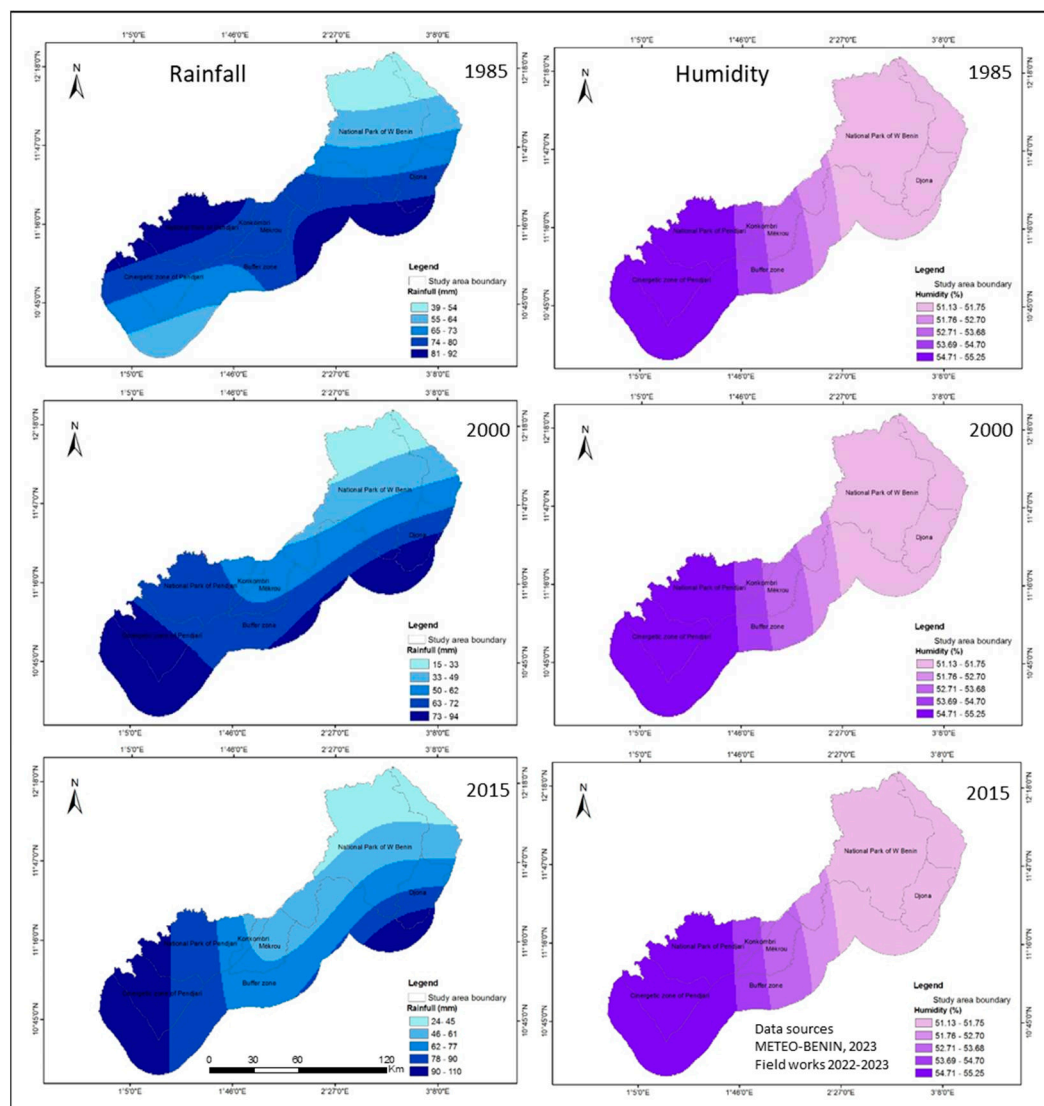


Figure 8. Spatial distribution of rainfall and humidity over the periods 1985, 2000 and 2015 in the Pendjari and W protected areas and their peripheries in Benin.

Model test on 2015

Prior to predicting the vegetation cover in the Pendjari and W parks and their periphery in Benin by 2030, a test was carried out on the model using data from 1985 and 2000 to predict vegetation cover in 2015, which is already known through satellite image processing. As an assumption, the modelling considers that the previously observed evolutions will continue under the control of the

protection measures already applied. Thus, the comparison of the 2015 reference map with the simulated map for the same year (Figure 9), indicated a good representation of the land use units in the study area. However, in the Komkombri and Mekrou hunting zones, the model overestimated the dense forests, and the mosaics of fields and fallows in the periphery of the W park. These differences in surface condition were to be expected based on the high presence of these land use units in these compartments between 1985 and 2000, whereas they were less represented in 2015. However, the simulated areas are quite close to those determined from the satellite image (Table 6). The largest absolute differences are for open forests and wooded savannahs, which increased by 4%, while dense forests and tree and shrub savannahs decreased by just over 2% in the simulation. These small differences do not prevent the method from being used for the 2030 prediction.

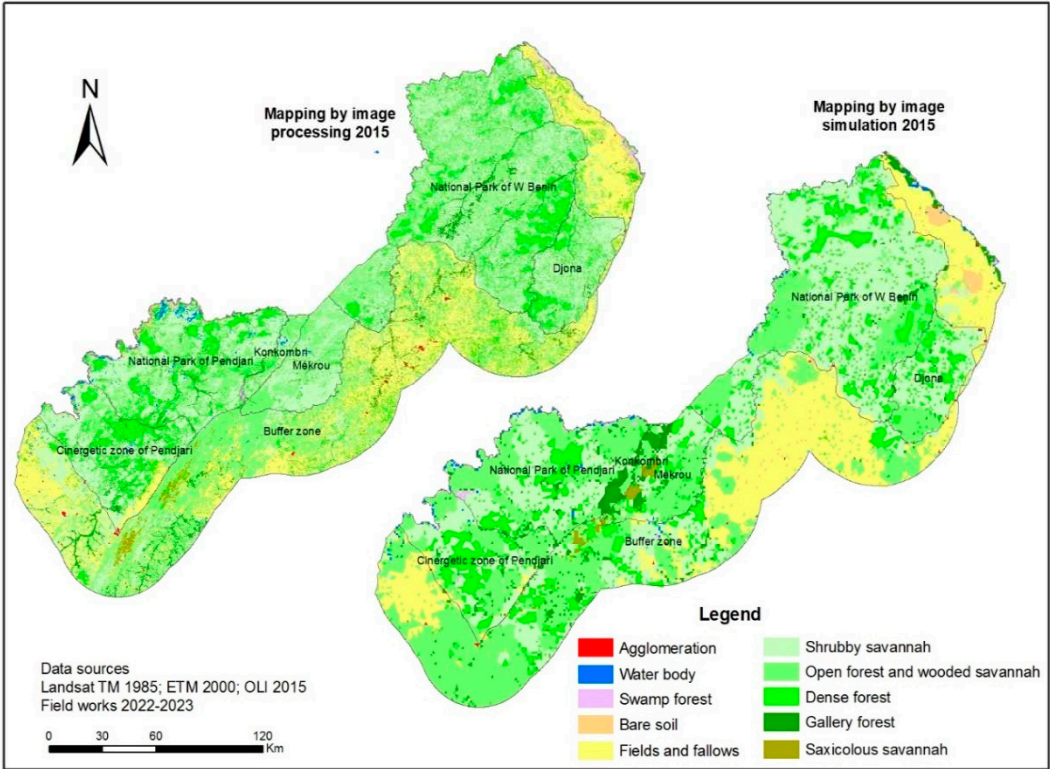


Figure 9. Comparative mapping of classification and simulation for 2015.

Table 6. Comparison of classified and modeled areas for 2015.

Uni	Classified areas 2015		Predicted areas 2015		Absolute deviation
	km ²	%	km ²	%	
AG	37.30	0.17	14.5547	0.07	0.10
OF	5703.39	25.29	6789.83	30.10	-4.82
DF	3493.06	15.49	2977.83	13.20	2.28
GF	699.28	3.10	762.072	3.38	-0.28
SF	62.38	0.28	50.4147	0.22	0.05
FF	4269.19	18.93	4295.41	19.04	-0.12
W	113.11	0.50	107.605	0.48	0.02
SS	7896.86	35.01	7278.66	32.27	2.74
BS	190.56	0.84	176.129	0.78	0.06
SxS	90.13	0.40	103.301	0.46	-0.06
Total	22555.25	100	22555.80	100	

Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannas (OF), Wooded and Shrubby Savannas (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

• Prediction of the vegetation cover by 2030

The results obtained on the basis of the application of the method to the period 2015-2030 indicated the maintenance of the same land use units (Figure 10). The most dominant entities remain tree and shrub savannas (35%), open forest and wooded savannas (25%), fields and fallows (19%) and dense forest (16%) (Figure 11). It is also noted that the projected land use units are related to past developments, based on the climatic parameters (rainfall and humidity) used. Thus, the prediction informs of a further reduction of natural formations, but in lesser proportions than over the periods 1985-2000 and 2000-2015 (Table 7). However, the extension of tree and shrub savannas is expected to continue in a lower proportion (0.40%). Similarly, fields and fallow land will continue to increase at the expense of vegetation cover (2%).

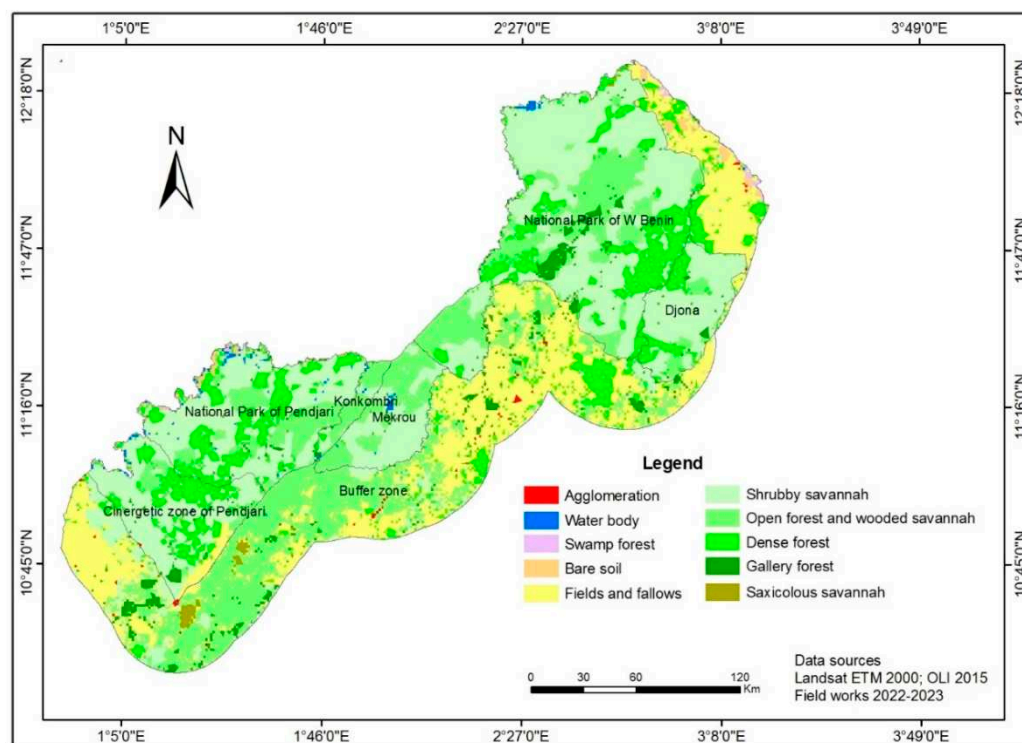


Figure 10. Predictive mapping of the vegetation cover of the Pendjari and W parks and their peripheries in Benin by 2030.

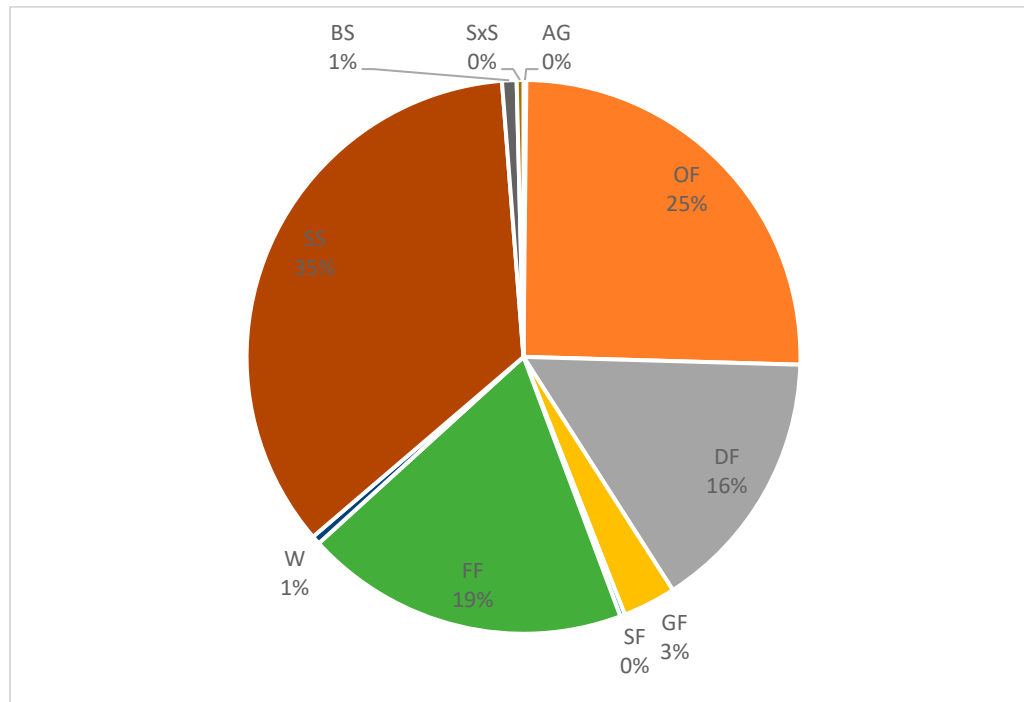


Figure 11. Proportion of land use units predicted in 2030 for Pendjari and W protected areas and their peripheries in Benin. Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannahs (OF), Wooded and Shrubby Savannahs (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

Table 7. Probable evolution of the areas of land use units between 2015 and 2030.

Unit	Classified surface 2015		Predicted surface 2030		Evolution (absolute %)
	km ²	%	km ²	%	
AG	37.30	0.17	36.61	0.16	- 0.01
OF	5703.39	25.29	5549.64	24.60	- 0.68
DF	3493.06	15.49	3195.73	14.17	- 1.32
GF	699.28	3.10	639.15	2.83	- 0.27
SF	62.38	0.28	61.47	0.27	- 0.01
FF	4269.19	18.93	4738.94	21.01	2.08
W	113.11	0.50	83.44	0.37	- 0.13
SS	7896.86	35.01	7986.34	35.41	0.40
BS	190.56	0.84	184.78	0.82	- 0.02
SxS	90.13	0.40	78.99	0.35	- 0.05
Total	22555.25	100.00	22555.1161	100	-

Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannahs (OF), Wooded and Shrubby Savannahs (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

Regarding the speed of future changes, the probabilities calculated by the model indicate that within the vegetation cover, tree and shrub savannas should be more stable ($p = 0.60$). They will be followed by dense forests ($p = 0.32$), open forests and wooded savannahs ($p = 0.31$), and forest galleries ($p = 0.24$). The greatest stability will be observed in fields and fallows ($p = 0.63$), which will be maintained and even expand further (Table 8).

Table 8. Probability of changes within land use units between 2015 and 2030.

	AG	OF	DF	GF	SF	FF	W	SS	BS	SxS
AG	0.42	0.03	0.06	0.00	0.00	0.35	0.00	0.09	0.03	0.00
OF	0.00	0.31	0.23	0.01	0.00	0.11	0.01	0.30	0.01	0.01
DF	0.00	0.27	0.32	0.02	0.00	0.12	0.00	0.25	0.00	0.00
GF	0.00	0.24	0.28	0.24	0.03	0.06	0.00	0.12	0.01	0.01
SF	0.00	0.16	0.21	0.06	0.14	0.05	0.04	0.30	0.013	0.00
FF	0.00	0.10	0.12	0.02	0.00	0.63	0.00	0.09	0.02	0.00
W	0.00	0.01	0.19	0.21	0.14	0.10	0.27	0.05	0.04	0.00
SS	0.00	0.26	0.00	0.02	0.00	0.10	0.00	0.60	0.00	0.00
BS	0.01	0.03	0.04	0.01	0.01	0.44	0.01	0.34	0.13	0.00
SxS	0.00	0.70	0.01	0.00	0.00	0.10	0.00	0.19	0.00	0.00

Agglomeration (AG), Dense Forests (DF), Gallery Forests (GF), Swamp Forest (SF), Field and Fallow mosaics (FF), Water Bodies (W), Open Forests and Wooded Savannas (OF), Wooded and Shrubby Savannas (SS), Bare Soil (BS), Saxicolous Savanna (SxS).

Discussion

The importance of remote sensing in analyzing change of land use in Pendjari and W parks and their peripheries in Benin

The vegetation formations within the parks have changed over the observation period (1985 to 2015). These changes mainly affect dense forests, gallery forests, open forests and wooded savannas, as well as tree and shrub savannas. The same observation was made by Avakoudjo et al., (2014) [52] who analyzed the changes in the vegetation formations of Park W between 1978 and 2008. This confirms the strength of the use of remote sensing for occupancy mapping and its applications in the analysis of forest landscape dynamics [53,54]. Although these images are of medium resolution, they have enabled us to develop our first knowledge of the study area's past, on the understanding that archives provide no reliable data on the evolution of ecosystems. In the present study, the most remarkable gains were in fields and fallows, which both expanded in area to meet the agricultural land needs of the surrounding populations at the expense of open forests and wooded savannas, and shrub and tree savannas. The accessibility of these vegetation formations, especially during the dry season, is said to be the reason for this situation [8]. However, it should be recognized that most of the fields and fallows are outside the parks and their hunting zones. Thus, the strong degradation of the vegetation cover observed is localized in the village lands surrounding the parks [55]. However, some incursions of fields and fallows have been observed on the southern periphery of the Pendjari and in the northern W. This is certainly due to farmers' lack of awareness of park boundaries [56]. According to Akpona et al. (2016), [57] this is a recurrent anthropogenic disturbance that results from the reluctance of surrounding populations who think they are taking advantage of the weakness of the management systems that have succeeded each other over the past decades [58]. However, with the management of the two parks entrusted to private operators since 2017, this trend of anthropisation of the peripheries seems to be under control [8].

A strong propensity of the surface area of settlements and fields and fallows to increase was observed over this period from 1985 to 2015. Given that these land-use units are mostly located outside protected areas, this indicates the extent of anthropisation in the peripheries of the parks [6]. This constitutes a threat to the vegetation cover, to wildlife *in situ* and to the reserve-dwelling communities [59]. Indeed, on the one hand, the degradation of the peripheries of protected areas gives rise to conflict situations [60], with the possibility of animals escaping to village lands, where they are slaughtered by communities, especially hunters [59]. On the other hand, escaping wildlife confuses people in their concessions, sometimes resulting in loss of human life [61]. The result is a mutual psychosis between animals and humans, which can lead to some species becoming

completely isolated from their habitats, sometimes creating the flight or total disappearance of some heritage species from these protected areas [62]. This is the case of the cheetah (*Acinonyx jubatus*), which is the flagship animal and the emblem of the Pendjari, and which has remained without any sign of presence for several years in the whole region [63]. Its fearful, extremely sensitive and vulnerable nature has certainly not facilitated its adaptation to psychosis and environmental changes. In view of these considerations, for good conservation of vegetation cover within protected areas, particular attention should be paid to their peripheries, in order to ensure good cohabitation of humans and wildlife [64].

Influence of climate on vegetation cover in the two parks and their surroundings

The climatic parameters studied, i.e. rainfall, temperature, relative humidity and wind speed, made it possible to highlight the evolution of the climate around the two biosphere reserves between 1985 and 2015. The analysis of the curves obtained shows the presence of break periods indicating drought years in the study area over the 30-year period. This makes it possible to draw valid conclusions on climate variability at the scale of the Pendjari and W biosphere reserves [23], and to deduce its implications on the behavior of the vegetation cover in the Sudanian zone [24]. Numerous studies linking climate and vegetation have highlighted that low rainfall and humidity are constraints to the sustainability of forest ecosystems [65]. The climate of the region being of Sudanian type, it presents a uni-modal rainfall regime, leaving the plant cover under water stress for about six (06) months in a year (November to March). This fact, which is already unfavorable to the stability of plant formations, is aggravated by the periods of disruption observed between 1985 and 2015 in terms of climatic parameters, which were analyzed in this study. Indeed, although the rainfall analysis does not show a break between 1985 and 2015, there was a considerable drop in rainfall in 2000, confirmed on the average displayed in Figure 4(a). As a result, during this period, there was a strong drought marked by the partitioning of the vegetation cover of the Sudanian zones of West Africa, resulting in the migration of fauna in search of water and forage [66]. The analysis of the vegetation cover dynamics of the W and Pendjari Biosphere Reserves between 1985 and 2015 confirms this observation through a continuous decrease in gallery forests and open forests and wooded savannahs from the year 2000 to 2015. Similarly, dense forests, swamp forests and saxicolous savannahs experienced this decrease in surface area from 2000, before stabilizing between 2000 and 2015. Only tree and shrub savannahs saw their surface areas increase in 2015 after having fallen between 1985 and 2000. These changes show that, even if it is not asserted as the main factor, the behavior of the Sudanian climate contributes to changes in vegetation cover [24], particularly in the W and Pendjari biosphere reserves between 1985 and 2015. Similar findings were reported by [67], who established a link between forest evolution and climate in the south-eastern regions of Benin, more precisely in the classified forest of Dogo-Kétou. The same hypotheses have been verified by Seguin (2012) in other regions of the world.

Apart from rainfall, temperature and relative humidity showed a clear break around 2002 and 2003 respectively, while wind shows two breaks, the first in 1992 and the second in 1998. However, it has been shown that low humidity induces poor vegetation performance in Sudanian environments [24,69]. Thus, the loss in area reported for certain plant formations, including gallery forests, dense forests, swamp forests, saxicolous savannahs and open forests and wooded savannahs from 2000 to 2015 is indicative of a probable correlation with the drop in relative humidity observed during the same period in these two reserves. This confirms the response of the vegetation cover to the influence of climate in the study area [70].

The future of the vegetation cover of the W and Pendjari Biosphere Reserves in the context of climate change

The distribution and evolution of climatic parameters over the first study period (1985-2000) show that in those 15 years, climatic change had already begun, with a change in the state of the vegetation cover of the protected areas in northern Benin. This change was confirmed by the test carried out on the LCM model in which rainfall and humidity were integrated as explanatory variables to simulate land cover in 2015. The results obtained indicate that the simulated vegetation landscape configuration is close to that obtained by reconstruction based on satellite images. Such

simulations were carried out by Wang et al. (2022) and Leta et al. (2021) on protected forest entities with conclusive results. In the case of the present study, even if some differences are noted statistically, the differences in area do not exceed 4%, and this in open forest and wooded savannah. This implies a good response of the model in establishing the link between climate and vegetation cover [71,72]. On this basis, the projected simulation of vegetation cover in the W and Pendjari biosphere reserves for 2030, based on current climate conditions, indicates that the loss of vegetation cover will continue, particularly of open forests and wooded savannahs, tree and shrub savannahs and dense forests, but at a slightly slower rate than in the past. This indicates a probable stability of natural formations, which could be controlled if future climate projections are favorable [73].

Alternatively, the study could have first predicted rainfall and relative humidity in 2030 and used these results for the simulation of projected vegetation cover. This option would give quite different results from those currently obtained. However, as the area is protected, changes will not lead to the disappearance of one or more land cover units, as the climatic gradient remains the same [23].

The model helped highlight the climate-vegetation interrelationship in the two large protected areas of Benin, as described in the Sudanian zone [74]. However, taking into account other anthropogenic factors influencing the dynamics of the vegetation cover for future studies is essential to better predict the spatialization of the land cover and to better translate the acceleration of changes by 2030, leading to results that are perhaps more realistic than those currently obtained [75]. To ensure sustainable services including medicinal utilizations [14] that people get from vegetation with regards to the global warming, there is a huge need to frequently monitor dynamics in vegetation types in these two reserves.

Conclusion

This study served to reconstruct the vegetation cover of the W and Pendjari Biosphere Reserves and to predict future changes in context of climate change in the Sudanian zone of northern Benin. It was possible to use remote sensing and GIS techniques to combine satellite and climate images from 1985 to 2015 to produce quantitative and qualitative information on the vegetation landscape of the study area. It was found that the vegetation cover of the study area is made up of dense forests, gallery forests, open forests and tree savannahs, swamp forests, tree and shrub savannahs, and saxicolous savannahs. Within the protected areas, these ecosystems have undergone changes by mutations, especially between open forests and wooded savannas and tree and shrub savannas. Outside the protected areas, it is the fields and fallow land that have been cutting into the other land-use units, to the point of threatening the periphery of the protected areas. The region's climate is Sudanian and has a uni-modal regime, putting vegetation under water stress for half the year. Spatial modelling based on these data shows a future trend similar to that observed between 1985 and 2015 in terms of vegetation cover evolution. This future trend remains a simulation and will only be realistic if natural resource conservation efforts are made by stakeholders. This study, which is the first to link vegetation and climate in the study area, provides a baseline and a framework for stimulating further researches. Based on these considerations, the following recommendations are made:

- The boundaries of these two protected areas need to be re-defined and clearly demarcated to prevent the development of the agricultural encroachment within them;
- Participatory management measures need to be strengthened outside these protected areas to support existing socio-economic development, without encouraging the destruction of the remaining pockets of vegetation in these areas;
- Future research could combine man-made factors with climatic parameters, in order to investigate scenarios to be compared with the reality on the ground in 2030.

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