Climate Change in Southeast Benin and Its Influences on the Spatio-Temporal Dynamic of Forests, Benin, West Africa

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Abstract: The impact of anthropogenic activities on the spatiotemporal dynamics of the forest of Dogo-Kétou has been studied in relation to climate change observed in southeastern Benin. Especially, this study has detected the changes in climate parameters in southeast Benin from 1954 to 2016 and in forestland use from 1986 to 2018. A climatic break was detected, and the annual and monthly rainfall and temperature averages, the rainfall indexes, the concentration of precipitation, the number of rainy days according to the World Meteorological Organization and the bioclimatic aridity indexes were assessed. A GIS analysis was also performed based on Landsat images from 1986, 2000 and 2018 to detect the dynamic of land use and land cover of the classified forest of Dogo-Kétou. Excel 2016, Rs64 4.1.2, RclimdeX301, Khronostat1.01 and ArcGIS were used. The rainfall series showed a break in 1969. The segment from 1954 to 1968 was a period of excess rainfall with an average of 1420.46 mm/year. The segment from 1969 to 2016 was a rainfall deficit period with a reduction of 12 to 37% of rainy days and an increase of dry days for 21.4 days/year. In this last segment, southeast Benin experienced trends of its climate towards a sub-arid and arid climate. The agglomerations and bare soil of the forest of Dogo-Kétou increased to an area almost double the size between 1986 and 2018. The tree and shrub savannas gained in space from 12.1% in 2000 to 38.9% in 2018 and the dense forest and wooded savannas regressed by 52.6% in 1986 to 36.1% in 2000 then to 4.3% of the forest area in 2018. The subequatorial climate of southeastern Benin is gradually evolving towards a dry climate. The dense forest in this area is also gradually disappearing, giving way to savannas. This transformation towards the savannas was due to anthropogenic actions whose effects were strongly accentuated by climate change in this part of Benin and West Africa.

Keywords: climate change; land use; GIS; climate beak; forest; sustainable; Benin; West Africa

1. Introduction

Tropical forests are vulnerable to climate change and adaptation is necessary to reduce their vulnerability [1]. Indeed, climate change has significant negative impacts on the natural environment, specifically the loss of forest and biodiversity [2]. Over the past decades, the levels of carbon dioxide (CO₂) and other greenhouse gases in the Earth’s atmosphere have increased dramatically from the burning of fossils and other human activities [3]. Changes in the climate and the concentration of carbon dioxide therefore undoubtedly affect the structure and function of ecosystems and the ecological interactions of species and their ranges, with definite consequences for biodiversity [4]. Thus, current trends in climate change affect species and their ecosystems and lead to the reduction of ecosystem services in forests [5]. This loss of ecosystem services will also reduce human well-being at all scales [1]. It is in this context that forests in general are essential to mitigate the impacts of global climate change because of their important role in carbon sequestration [6]. In
general, forests provide an important basis for creating and safeguarding living communities that are the most resilient to variations in climatic parameters [7]. This resilience reflects the capacity of an ecosystem such as the forest or the living communities to absorb the disturbance and to reorganize itself while undergoing change in order to always and essentially maintain its same function, structure, identity and feedback [8]. Faced with climate change, the two fundamental answer options provided for this purpose are respectively mitigation and adaptation. Mitigation refers to controlling global climate change by reducing greenhouse gas emissions and improving carbon sinks, while adaptation mainly focuses on moderating the impacts of climate change through a broad range of actions targeted on the vulnerability system [7]. Adaptation thus aims to reduce vulnerability, the degree to which the ecosystem is unable to cope with the adverse effects of climate change, including climate variability in its extremes [9,10].

Thus, to better understand the vulnerability and resilience of the natural dense forests of Benin, it is urgent to provide answers to the worrying questions about the natural forests of the world in general and of Africa and Benin in particular, such as, what is the state of vulnerability of the natural forests of Benin in West Africa in the context of climate change and anthropogenic pressures?

It is already known that variations in precipitation and temperature have an impact on the biological diversity and the geographical distribution of favorable habitats of species [11–14]. Faced with these habitat modifications accentuated by human activities, the sustainable management of forest resources in general and those of Africa and Benin in particular is a major concern. Indeed, these forest resources are not immune to threats linked to the cumulative adverse effects of climate change and anthropogenic pressures [15,16].

A geographical information system (GIS) is the best way to study the spatio-temporal dynamics of land use [17–20]. However, specific and updated work on the dynamics of the landscape units of the classified forest of Dogo-Kétou is insufficient and not updated with regard to the work of [21], which was limited to GIS processing unrelated to the dynamic of land use and land cover of the forest with climate change. This is why this study aimed to understand the vulnerability and resilience of natural dense forests in Benin in the context of climate change. Specifically, this study made it possible to detect climate change in the southeast of Benin from 1954 to 2016 and to evaluate the effect of anthropogenic pressures on the spatiotemporal dynamics in the forest of Dogo-Kétou from 1986 to 2018.

2. Materials and Methods

2.1. Study Area

The study was carried out in the forest of Dogo-Kétou in the Southeast Benin (Figure 1). The classified forest of Dogo-Kétou covers an area of 29.703 ha, with that of Kétou over 12.255 ha. This zone is located in the Guinean climatic zone of Benin, characterized by two rainy seasons and two dry seasons. There is a subequatorial climate with a bimodal rainfall regime with 1300 mm of rainfall per year. The rainy season begins from March to November with a deficit of rains between July and September, and the dry season lasts from November to March. The average annual temperature is 26.5 °C and the relative humidity averages 75% per year. The geological bedrock essentially comprises two discordant sedimentary formations: clay-sandy tertiary formations attached to the Continental Terminal and secondary clayey, sandy or sandstone formations of the Cretaceous age [22].
2.2. Data Collection

Landsat TM/ETM + and OLI satellite images, over the time intervals of 1986, 2000 and 2018 were used. They were imported into the ArcGIS geographic information system for processing. Five images from three sensors, Thematic Mapper, Enhanced Thematic Mapper Plus and Operational Land Imager from the Landsat satellite, were used. Those orthorectified and georeferenced images captured in the dry season have a cloud cover going from 0% to 10% and projected in the UTM system (Universal Transverse Mercator), Zone 31 North WGS-84 (World Geodetic System).

In addition to these satellite images, there are maps of the forest and climatic data (rainfall, temperature, humidity) for the southeastern area of Benin. Climatic data relating to the minimum (Tmin) and maximum temperature (Tmax) and daily precipitation (Rain) over the period from 1954 to 2016 were collected at the Agency for the Safety of Air Navigation (ASECNA) of Cotonou for southeastern Benin.

2.3. Data Analyses

2.3.1. Climatic Data Analyses

The climatic data of rainfall and temperature were processed using Excel, R
\(^{\text{\textmd{\textcopyright}}}\) 4.1.2 and “RClImDex\textsubscript{301}” to calculate climatic indexes (rainfall and temperature) in order to detect and monitor climate change over the period from 1954 to 2016. Thus, the following indexes were calculated:
annual averages of minimum and maximum temperatures, rainfall amounts, number
of rainy days;
the rainfall index (IP) or reduced centered anomalies made it possible to better study
the rainfall variability. Also called the reduced centered index, this index is the ratio
of the deviation of the variables $X_i$ from the mean to the standard deviation of the
annual rainfall levels. It results in the following formula [23]:

$$IP = \frac{X_i - \bar{X}}{\delta}$$  \hspace{1cm} (1)

$\bar{X}$: is the mean amount of precipitation, $X_i$ is the amount of rainfall in the year $i$;
$\delta$ represents the standard deviation. Positive values indicate rainfall excess while negative
values indicate rainfall deficits.

2.3.2. Detection of Climatic Break within Annual Rainfall Series

The annual rainfall series were analyzed using KhronoStat1.01 [24] in order to detect
any breaks linked to non-stationarity. To check the homogeneity of the annual rains, a
Scheffé test was carried out, and a correlation test on the RANG was carried out also on the
rainfall series from 1954 to 2016 to check the randomness. For the homogeneity tests, in
order to show an absence of a break in the series, the nonparametric method of PETTITT,
the BUISHAND test and WOOD ellipse, the Bayesian method of LEE and HEGHINIAN
and the HUBERT segmentation method were carried out. For all of these tests, the null
hypothesis $H_0$ corresponds to the absence of a break at 1% threshold. These tests are
particularly sensitive to a change in mean, and if the null hypothesis of homogeneity of the
series is rejected, they propose an estimate of the date of the break [25]. Among the break
tests grouped together in KhronoStat, three are renowned for their robustness and power
and have been the subject of several applications in different regions of Africa [26–33].
These are the tests of PETTITT and LEE and HEGHINIAN and the segmentation method
of HUBERT. The HUBERT method is the only one that makes it possible to detect several
existing breaks in a time series of data [30,34].

2.3.3. Rainfall Concentration Index PCI

Calculation of the precipitation concentration index (PCI) is a useful indicator for
estimating the monthly heterogeneity of precipitation. It has been calculated on a supra-
seasonal and annual basis according to the following formula according to [35]:

- On an annual basis: $PCI_{annual} = \sum_{i=1}^{12} \frac{p_i^2}{(\sum_{i=1}^{12} p_i)^2}$ with $p_i$ the monthly precipitation.
- On a supra-seasonal basis: $PCI_{supra-seasonal} = \sum_{i=1}^{6} \frac{p_i^2}{(\sum_{i=1}^{6} p_i)^2}$

It is a question here of making the calculation via the wet sequence. The wet sequence
runs from April to September.

The interpretation of the values of the precipitation concentration index (PCI) is given
in Table 1 below:

| PCI Values | Interpretation                        |
|------------|--------------------------------------|
| PCI < 10   | Uniform distribution of precipitation|
| 10 ≤ PCI < 16 | Moderate distribution of precipitation|
| 16 ≤ PCI < 20 | Irregular distribution of precipitation|
| PCI > 20   | Highly irregular distribution of precipitation|

Source: [35].

2.3.4. Number of Rainy Days and Daily Precipitation Classes Characterization

The number of rainy days per year was calculated from the daily rainfall data. Any
day of the year that receives an amount of precipitation more than or equal to 1 mm was
considered to be rainy. Then, the average number of rainy days was calculated on both sides of the break dates. This allowed the deficits of the post-break period versus the pre-break period to be assessed in terms of the number of rainy days. The characterization method consisted of calculating, for southeast Benin, the frequency of the daily precipitation classes on either side of the break date in the annual series. The different classes were defined according to the number of rainy days with a height of between 1 and 10 mm (P1), 10 and 30 mm (P2), 30 and 50 mm (P3) and more than 50 mm (P4). This typology of daily precipitation was linked to the international threshold standards defined by the World Meteorological Organization [36] and then taken up by [37] in their studies.

2.3.5. Analysis of Bioclimatic Indexes of the Southeast Benin Region

Analysis of the variation diagrams of the ombrothermal indexes according to Gaussen and Bagnouls (1952).

This index takes into account the monthly average precipitation (P in mm) and temperature (T in °C) and gives a relative expression of summer drought in duration and intensity. This was assessed through a drought index S (= ombrothermal index), calculated by making the difference between the curves P and T for the driest month(s).

A given month was considered to be dry when P < 2T, that is to say when the evapotranspiration potential (TPE) was more than precipitation. Conversely, when P > 2T, the month was considered wet. To identify the “dry” and “wet” months and highlight the periods of drought in a locality, we generally drew ombrothermal diagrams. These diagrams used the two curves of temperature and precipitation for the 12 months of the year, which has made it possible to define an ombrothermal area. The larger the area, the drier the season [38].

\[ P < 2T = \text{dry month}; \ P > 2T = \text{wet month} \]

Aridity Index

This index made it possible to characterize the evaporating power of air from temperature, evaporation being considered as a linear function of temperature. Ten (10) was added to the thermometric averages to avoid negative index values. The aridity increases as the index value decreases. Low aridity corresponds to abundant rains and/or low temperatures. De Martonne proposed six major types of climates according to the values of the annual index [39].

- \( IM = \frac{P(\text{mm})}{(T(\degree\text{C}) + 10)} \)
- \( MI < 5 \) absolute aridity desert without cultivation
- \( 5 \leq IM < 10 \) (arid) desert and steppe; no cultivation without irrigation
- \( 10 \leq IM < 20 \) semi-arid herbaceous vegetation, steppes or savannas. Irrigation required for crops requiring moisture
- \( 20 \leq IM < 30 \) semi-humid natural grasslands; irrigation generally not required
- \( 30 \leq IM < 40 \) humid, trees play an increasingly large role in the landscape
- \( IM > 40 \) humid, the forest is everywhere. Cereal crops tend to be replaced by grasslands.

2.4. Analysis of Satellite Images

The calculation of the vegetation indexes took place in several steps with the use of the software ENVI5.1.

2.4.1. Image Pre-Processing and Calculation of the Normalized Vegetation Index

Radiometric and Atmospheric Corrections

Radiometric and atmospheric corrections were applied to the images to correct for sensor irregularities, sensor noise or atmospheric noise, and the data were converted so that they could accurately represent reflected or emitted radiation measured via the sensor. The FLAASH (Fast Line-of-sight Atmospheric Analysis of Hypercubes) algorithm based on the MODTRAN (MODerate resolution atmospheric TRANsmission) algorithm was used to
correct wavelengths in the visible through the NIR (near-infrared) and SWIR (shortwave
infrared) up to 3 μm. Then, the images were segmented from the cartographic coordinates
of the boundaries of each forest.

Normalized Difference Vegetation Index

This index was calculated from the reflectance (ρ) in the near-infrared (NIR) and red
(R) bands according to the formula [40,41]: \( NDVI = \frac{\rho_{\text{NIR}} - \rho_{\text{R}}}{\rho_{\text{NIR}} + \rho_{\text{R}}} \) where 0 < NDVI < 1.

The result of the index takes the form of a new image whose value for each pixel is
between 0 (bare soil) and 1 (maximum vegetation cover). Plant formations, for their part,
have positive NDVI values, generally between 0.1 and 0.7. The highest values correspond
to the densest covers. Analysis of the range of shades extending between these extreme
values provides information on the density of the vegetation cover and the amount of green
biomass [42].

2.4.2. Realization of Colorful Compositions

Different colored compositions have been made in the graphic planes of red-green-blue
colors. The best combinations between the different spectral bands and the NDVI images
generated via transformation making it easier to choose the sampling areas are presented
in Table 2.

Table 2. Colored compositions made from spectral bands and NDVI.

| Sensors     | Date of Image Acquisition | Bands/Neo-Channels |
|-------------|---------------------------|---------------------|
| Landsat 5 TM| 13 January 1986           | SWIR 1, NIR, Red    |
| Landsat 7 TM+| 6 February 2000          | SWIR 1, NIR, Red    |
| Landsat 8 OLI | 23 December 2018       | Red, NDVI, Green    |

The different combinations of channels (Table 2) made it possible to display the healthy
vegetation in green (high NDVI value), the saturation of which increases with the gradient
of the vegetation cover, while the very degraded vegetation, the areas of crops, the built-up
areas and bare soils are displayed in yellow, red and blue (Figure 2).

![Figure 2. Color composition of Landsat TM, ETM + and OLI images from 1986, 2000 and 2018 Path 192 Row 55.](image)

2.4.3. Image Processing: Classification and Analysis of Images

The objective of classification in remote sensing is to make the correspondence between
the classes of interest and the spectral classes, which are groups of pixels having the same
characteristics. The supervised (non-automatic) classification technique was used with
the maximum likelihood algorithm, to classify the images of the three dates chosen for
this study. Each pixel has therefore been assigned to a class for which the probability of
membership is more than or equal to 0.70. A separability analysis of the spectral signature
of the classes was performed by calculating the Jeffries-Matusita, transformed divergence
indexes. These indexes measure the statistical independence of defined class pairs. The
values taken vary from 0 to 2. The values close to 2 indicated a high degree of separability,
while those close to 0 indicated a low degree of separability [43,44]. Classes with a low
degree of separability have similar spectral signatures [43] and were therefore combined in the same class.

2.4.4. Image Post-Processing and Classification Validation

The defined occupancy classes were validated on the basis of a field mission carried out which consisted of walking the entire forest on foot using a field guide in order to confirm the realities on the ground on the occupations of the ground compared to the results presented via the analysis of processed satellite images. After validation of the classification using field data, the overall and individual precision of the classes was assessed by calculating a confusion matrix and the parameters as the commission error, the error of omission, the user, the overall accuracy of the classification and the Kappa index for each classified image.

3. Results
3.1. Analysis of Climate Change in Southeast Benin from 1954 to 2016
3.1.1. Analysis of Average Annual Rainfall Parameters

Figures 3 and 4 show the great climatic variability in southeast Benin from 1954 to 2016. The annual rainfall regime was characterized by high inter-annual variability with an average of 1210.85 mm/year. The period of excess covered the years 1954 to 1969, which resulted in a high frequency of wet years and having an inter-annual average of 1420.46 mm/year, i.e., an annual surplus of 12% compared to the inter-annual average (1211.85), with peaks in 1963 (2149 mm), 1968 (2020.3 mm) and 1965 (1769 mm). The rainfall deficit period was from 1970 to 2016 and corresponded to a relatively high frequency of dry years. The average annual rainfall for this period was around 1124.58 mm, which was an annual deficit of 28% compared to the inter-annual average. Strong deficits were observed for the years 1967, 1971, 1977, in 1998 and in 2015. These episodes of rainfall deficit reflect many drought years observed between 1970 and 2018.

![Figure 3. Rainfall amount from 1954 to 2018.](image)

*Figure 3. Rainfall amount from 1954 to 2018.*
3.1.2. Comparative Analysis between Rainfall and Temperature

Figure 5 (1–3) below showed the inter-annual variations of the minimum, maximum and average temperatures and the confirmation of their rate at the threshold of 5% using Rclimdex (Figure 5 (1,2)). The average maximum temperature is 30.36 °C. The curve of the inter-annual variation of the maximum temperature (Figure 5 (1,3)) showed a large variation which was observed in an increasing way from 29 °C around 1954 to 31 °C around 1970 corresponding to a period of good rainfall in this region of Benin. However, after 1970, an increase in the average value of the maximum temperature was observed until 2016 when it increased to 33 °C. This period corresponds to low rainfall deficit being recorded. Thus, the variation of the average maximum and minimum temperature curve was statistically significant ($p = 0 < 0.05$).
The different variations presented by the climatic parameters confirmed that the climate in the southeast of Benin presented great variability distributed in two very distinct periods, the first period being before 1970, which seems to indicate the best rainfall with excess and had a maximum temperature between 29 °C and 31.5 °C. The second period, from 1970 until 2016, presented the worst climatic conditions, able to generate significant water stress for plants and trees which will have more difficulty in taking advantage of nature for their good growth and presenting the characteristic greenery of their good health. It was then more obvious for the forests to present more difficulties during this second period.

Figure 6 presents on the same graph the variations in the curves of the rainfall and temperature indexes from 1954 to 2016. The high variability of the annual rainfall regime in southeast Benin between 1954 and 2016, characterized by high inter-annual variability, is also observed at the level of the temperature index curve. It can be seen that when the rainfall index curve is clearly above that of temperature, it is in a period of abundant rainfall with an annual excess of 12% over the inter-annual average (1211.85). This period corresponds to that of 1954 to 1970 and shows temperature deficits of up to −1.79 °C compared to the average of 27.43 °C ± 0.51 °C. The period of rainfall deficit went from 1971 to 2016 with many dry years. Strong deficits were observed for the years 1977 (593.7 mm and 27.43 °C), 1998 (687.7 mm and 28.11 °C), 2015 (709.6 mm and 28.51 °C) and 1971 (808.7 mm and 27.24 °C).

![Variation of rainfall and temperature indices from 1954 to 2016](image)

**Figure 6.** Variation in rainfall and temperature indexes from 1954 to 2016.

Climatic parameters, mainly temperature and rainfall, had a strong interaction and the variations recorded in temperatures had an impact on the variation in rainfall. We note that these two climatic parameters varied greatly over the period from 1954 to 2016 over the 62 years of data that were analyzed. This allowed confirmation that climate variability is then present in Benin in general and specifically with regard to this study in the southeast of the country.

3.1.3. Climatic Break Detection Tests in the Rainfall Series from 1954 to 2016

**Randomness Verification Test**

The RANG correlation test was performed on the rainfall series from 1954 to 2016. The result shows that the rainfall series is random at the level of 99% confidence and the value of the computational variable is −1.6904.

**BUISHAND Test and BOIS ELLIPSE**

The result of this test shows in Figure 7 that there is only one break localized around the year 1969 at the level of 99% confidence as highlighted in red.
Nonparametric Method

The result of the failure identification test using the nonparametric method of PETTITT on the rainfall series from 1954 to 2016 (Figure 8) shows that the rainfall series presents a probability of exceeding the critical value of the test of $1.54 \times 10^{-2}$ in 1970 at the level of 99% confidence.

Bayesian Method

The result of the break identification test using the Bayesian method of LEE and HEGHINIAN on the time series from 1954 to 2016 (Figure 9-1,2) shows that the rainfall series presents a mode of the posterior probability density function of the position from the break point 0.2749 in 1968. The figure below shows the exceedance on the diagram for the year indicated.
The Segmentation

At the significance level of 1% for the Scheffé test, Hubert’s segmentation revealed a breaking point in 1968 and two segments in the climatic chronology.

In view of the results of the break identification tests carried out, including that of the Bayesian method of LEE and HEGHINIAN, the first segment was from 1954 to 1968 with an annual average of 1464.9 mm and a mean temperature of 26.88 °C. The second segment was from 1969 to 2016 with a rainfall of 1131.45 mm with a standard deviation of 244.05, as shown in Table 3. The reduction of the mean of rainfall from the first segment to the second was from 1969 to 2016 with a rainfall of 1131.45 mm with a standard deviation of 244.05, as shown in Table 3. The reduction of the mean of rainfall from the first segment to the second matched with the increase of the mean temperature from the first segment to the second at 27.60 mm/year.

Table 3. Result of identification of the break following the segmentation of HUBERT.

| Start | End   | Means of Rainfall mm/Year | Standard Deviation | Means of Temperature °C/Year |
|-------|-------|---------------------------|--------------------|-------------------------------|
| 1954  | 1968  | 1464.947                  | 337.092            | 26.88                         |
| 1969  | 2016  | 1131.45                   | 244.058            | 27.60                         |

3.1.4. Rainfall Concentration Index

Figure 10 summarizes the variation of the precipitation concentration indexes (PCI) calculated for each year from 1954 to 2016 and by rainy season over 6 months from April to September over the same period in order to see the variation in the distribution of rainfall from one year to another. Between 1954 and 1983, the rainfall concentrations fluctuated a lot and showed between two consecutive years an irregular distribution for a moderate distribution. However, this period has shown that the distribution of annual rains kept a strong moderate trend until 2016. The rainy period also shows a trend of variation from a moderate distribution towards a regular one of the rains following the same periods.

Figure 10. Change in the rainfall concentration index from 1954 to 2016.
3.1.5. Variation in the Length of the Rainy Season on Either Side of the Break

Figure 11 shows the variation in the number of rainy days from 1954 to 2016 with the year of break expected in 1968, which has made it possible to analyze these two periods. The days without rain (p0 = [0; 1 mm]) show a stable trend with a variation around the average number of dry days evaluated at 275 days/year. On the other hand, in the second segment, an increase is observed in the number of dry days per year to 296 on average, which indicates an increase of more than 21 dry days per year when we move from the first segment to the second segment. For the other classes of rainfall, there was a downward trend in the number of rainy days when we move from the period 1954–1968 to the period 1969–2016. Indeed, the calculated averages indicate an average of 44 days to 32.5 days for when moving from the first segment to the second segment (1969–2016).

Table 4 shows the average number of dry days calculated for the classes of rainfall (ranging from 0 to 50 mm) and for the two chronological segments. For the class of heavy rainfall (30 ≤ rain < 50 mm), the same decrease was noted, and for 9 days on average for P3 this average number was reduced to 7.8 days; for 5 strongly stormy days in the first segment, it was reduced at 3.8 very stormy days per year in the second segment.

Figure 12 shows the ombrothermal diagrams over the two identified segments (A and B) before and after the climatic break. The rainfall regime in southeast Benin was

| Classes of Rainy Days | Numbers of Rainy Days Segment S1 1954–1968 | Numbers of Rainy Days Segment S2 1969–2016 | Gap (Deviation S1–S2) | Observations |
|-----------------------|-------------------------------------------|-------------------------------------------|------------------------|--------------|
| P0                    | 275                                       | 296.4                                     | –21.4                  | Increase in day |
| P1                    | 44                                        | 32.5                                      | +11.5                  | Decrease in day |
| P2                    | 33                                        | 25.0                                      | +12.0                  | Decrease in day |
| P3                    | 09                                        | 7.9                                       | +1.1                   | Decrease in day |
| P4                    | 05                                        | 3.8                                       | +1.2                   | Decrease in day |

Overall, an increase was noted in the number of dry days from the first segment (1954–1968) to the second segment and a decrease in the number of rainy days for all classes when moving from the first segment to the second segment (1969–2016).

3.1.6. Analysis of Bioclimatic Indexes

Analysis of the Variation Diagrams of the Ombrothermal Indexes

Figure 12 shows the ombrothermal diagrams over the two identified segments (A and B) before and after the climatic break. The rainfall regime in southeast Benin was
bimodal regardless of the period in which it was located from 1954 to 2016. It was consisted of a large rainy season between March and July with the peak rainfall recorded in June and a relatively weak rainy season compared to the first and which covers the months of September and October. This regime includes a large dry season recorded between November and February and a relatively wet dry season because the rainfall curve always remains above the double temperature curve in August. However, from one segment to another the first mode of rain was very heavy and seemed to decrease from a peak of more than 300 mm on average in June (Figure 12A) to around 175 mm (Figure 12B) concerning the comparison between two equal segments. In the second half of the series, the peak passed in the small rainy season in the month of October, which became the rainiest (around 150 mm on average). In fact, in the first segment (Figure 12A) the rainfall peak corresponded to a humid and very humid period of the chronological series. However, in the second segment this peak decreased in June (Figure 12B), which explains why the rains lost intensity in the second segment. August was getting drier in the region.

![Umbrothermal diagrams of different periods from 1954 to 2016 (A) = from 1954 to 1968; (B) = from 1969 to 2016).](image)

**Figure 12.** Umbrothermal diagrams of different periods from 1954 to 2016 (A) = from 1954 to 1968; (B) = from 1969 to 2016).

**Aridity Index (1926)**

Figure 13 shows the variation of the De Martonne aridity index from 1954 to 2016. With De Martonne the aridity increases when the value of the index decreases. Low aridity corresponds to abundant rains and/or low temperatures. This implies that the climate
was more in the humid zone with trends towards the very humid zone from 1954 to 1968, but from 1969 to 2016, this climate was more humid in 44.7% of the years presenting this climate with trends towards the semi-humid climate with 36% of years and 6% of years presenting the climate of the semi-arid zone.

From the analysis of all these bioclimatic indexes, overall, southeast Benin was experiencing the aridity of its rainfall more and more, which was tending toward the rainy climate of Benin center. All its disturbances marked by high variability in rainfall from 1970 to 2016 justified that southeast Benin was experiencing high climatic variability with irreversibility observed over the six decades of data studied. The direct consequence will be felt on the type of plant formations formerly characteristic of this region, which will have a tendency to present species from dry areas such as Shea trees (Vittelaria paradoxa), of which the forest of Dogo-Kétou has shown a strong presence of individuals of this species. Thus, southeastern Benin was experiencing a progression although slow towards annual rainfall close to semi-arid and arid zones.

3.2. Impacts of Climate Change and Anthropogenic Pressures on Land Cover and Land Use Classes’ Classifications

3.2.1. Classification Validation

Land cover was very heterogeneous in the classified forest of Dogo-Kétou and the transitions were made according to the size of the units of occupancy. Seven (7) land use units were sufficient to set up a cartographic analysis of the landscape of these ecosystems. Several images of the different land use units of the classified forest of Dogo-Kétou were taken during the research carried out in the field for the establishment of the nomenclature and the implementation of the classification.

Open Mountain Forests

The open mountain forests shown in Figure 14 are small in area in these ecosystems and are located on mountains where fraudulent logging and charring is difficult. The open forests are deciduous with a low vegetation index in the dry season.
Figure 14. Open mountain forests.

Wooded Savannas

Wooded savannas are degraded vegetation with a few large trees in place as shown in Figure 15. The foliage is deciduous with a lower vegetation index in the dry season.

Figure 15. Wooded savannas.

Tree and Shrub Savannas

The tree and shrub savannas shown in Figure 16 are very degraded vegetation with a few trees and many shrubs. The vegetation index in these formations is very low (close to zero) in the dry season.

Figure 16. Tree and shrub savannas.

Agglomerations and Bare Soils

The dwelling and bare soils shown in Figure 17 include areas inhabited by farmers, settlements of transhumant Fulani, tracks, areas of carbonization where vegetation has been removed and bare soils due to various logging activities. This unit of occupation is colonized by herbaceous plants in the rainy season and can be confused during the dry season with plots of bare crops.
Crops and Fallows

Crops and fallows (Figure 18) are cultivated areas, varying in extent, located throughout the forest. These plots are often bare during the dry season. They also include old plots cultivated and abandoned with progressive enrichment. These units of occupation could be confused with savannas and plantations.

Water Bodies and Streams in the Forest

Water Bodies and streams (Figure 19) are areas made up of open water surfaces (river, pond) and flood zones (swamps, shallows). The rivers of the classified forest of Dogo-Kétoù are mainly composed of the rivers “Agbossassa” and “Sahoun”, which are tributaries of the river Ouémé, which constitutes the limit of the classified forest Dogo-Kétoù.
Forest Galleries

The forest galleries in the classified forest of Dogo-Kétou, as shown in Figure 20, bring together the wooded stands that run along the river “Ouémé” and its tributaries. Forest galleries could be confused with savannas and open forests in the dry season when the vegetation index is low.

3.2.2. Variation of the Normalized Vegetation Index (NDVI) in the Forest Dogo-Kétou

Figure 21 shows the variation of the NDVI from 1986 to 2018 in the forest of Dogo-Kétou. The minimum of NDVI was obtained in areas with low vegetation density while the maximum was obtained in areas where high vegetation density was observed. Over the period from 1990 to 2018, the maximum NDVI was recorded in the forest up to 0.85 in 1990. This implies that during this period of nearly 30 years the forest of Dogo-Kétou suffered a reduction in its density in the wet season. The minimum of NDVI recorded in January shows no great variation; in January it is close to zero of bare soil indicating a very low density of the forest.

![Figure 21. Variation of NDVI from 1986 to 2018 in the forest Dogo-Kétou.](image)

3.2.3. Impact of Climatic Variations and Anthropogenic Pressures on Land Use Units in the Forest of Dogo-Kétou

Figure 22 shows the mapping of the different land use units in the forest of Dogo-Kétou over the periods of 1986, 2000 and 2018. Land use was very heterogeneous in the classified forest Dogo-Kétou and the transitions were made according to the size of the occupancy units.
Table 5. Transition matrix of land use in the classified forest of Dogo-Kétou from 1986 to 2000 (areas are in ha).

| Occupation Units in 1986 | Occupation Units in 2000 Dogo-Kétou |
|-------------------------|------------------------------------|
|                        | ASN      | CJ        | FC        | GF        | PE        | SAA       | SB        | Total %  | Total ha     |
| ASN                     | 74.33    | 391.39   | 41.48    | 104.26   | 33.54    | 25.53     | 315.01   | 2.30%    | 985.55       |
| CJ                      | 287.93   | 1036.20  | 65.24    | 162.39   | 104.86   | 402.57    | 1968.71  | 9.40%    | 4027.9        |
| FC                      | 171.54   | 1168.48  | 1048.69  | 1077.32  | 397.43   | 361.45    | 1645.54  | 13.70%   | 5870.45       |
| GF                      | 74.31    | 157.90   | 2024.95  | 547.69   | 32.62    | 47.67     | 157.20   | 7.10%    | 3042.35       |
| PE                      | 45.83    | 239.18   | 761.52   | 540.28   | 130.23   | 168.58    | 513.98   | 5.60%    | 2399.6        |
| SAA                     | 186.41   | 688.82   | 84.37    | 513.78   | 110.73   | 815.27    | 1585.67  | 9.30%    | 3985.05       |
| SB                      | 1074.65  | 5745.31  | 371.77   | 1943.27  | 750.22   | 3359.22   | 9294.66  | 52.60%   | 22539.1       |
| Total %                 | 4.50%    | 22.00%   | 10.30%   | 11.40%   | 3.60%    | 12.10%    | 36.10%   | 100.00%  | 42,850        |
| Total                   | 1914.99  | 9427.28  | 4398.02  | 4888.99  | 1539.64  | 5180.29   | 15480.78 | 42,850   |               |

NB: ASN = agglomerations and bare soil; CJ = crops and fallow; FC = clear forest; GF = forest gallery; PE = water places; SAA = arboreal and shrub savannas; SB = wooded savannas.

Table 6 presents the land use transition matrix in the classified forest of Dogo-Kétou between 2000 and 2018. Between 2000 and 2018, agglomerations and bare soil have increased in area to almost double their covered area to 7.8% of the total, i.e., 3352.86 ha and at the same time crops and fallow land decreased in space to 14.7% instead of 22.1% in 2000. This shows an effort to reduce human activity. The wooded and shrub savannas gained in
space by 12.1% in 2000 and therefore increased to 38.9%. This increase could be explained by the impact of the growth of the population, which accentuated the deforestation of the wooded savanna because it regressed from 52.6% in 1986 to 36.1% in 2000 then to 4.3% of the area of the forest in 2016. The wooded forest has almost disappeared and has contributed to the increase of tree and shrub savanna, which has very few large trees. At the level of gallery forest and clear forest (12.7%), we still note an increase compared to the year 2000 even if it is low in terms of percentage. The same observation is made for the gallery forest, which has experienced a sustained increase of up to 19.4%, whereas in 1986 it covered nearly 7.1% of the forest, despite the decrease in water bodies to 3.6% in 2000 against 5.6% in 1986 and 2.1% in 2016. This could be explained by the adaptability of the species which particularly like this type of forest. We note in particular that the wooded savanna is the one that has been greatly impacted; it covered over 52% of the forest and today was reduced to insignificant occupation in this forest. The great progression of savanna formations was also noted through the wooded and shrub savannas, which dominated the forest landscape with trees of very small diameter, very little of which exceeds the regulatory level of 10 cm from the recruitment threshold.

Table 6. Land use transition matrix in the classified forest of Dogo-Kétou from 2000 to 2016 (areas are in ha).

| Occupation Units in 2000 | Occupation Units in 2018 |
|-------------------------|--------------------------|
|                         | ASN    | CJ      | FC      | GF      | PE      | SAA     | SB      | Total % | Total 2000 |
| ASN                     | 151.65 | 379.04  | 47.59   | 339.46  | 38.57   | 839.73  | 132.21  | 4.50%   | 1928.25    |
| CJ                      | 379.63 | 1862.85 | 261.90  | 2245.46 | 313.35  | 4088.55 | 275.27  | 22.00%  | 9427       |
| FC                      | 1.58   | 93.13   | 3267.05 | 857.28  | 16.45   | 122.57  | 55.48   | 10.30%  | 4413.55    |
| GF                      | 11.58  | 668.78  | 1449.16 | 1689.97 | 89.98   | 831.79  | 143.64  | 11.40%  | 4884.9     |
| PE                      | 126.02 | 163.99  | 79.11   | 272.96  | 51.91   | 726.15  | 122.46  | 3.60%   | 1542.6     |
| SAA                     | 1223.63| 594.37  | 84.74   | 407.55  | 73.72   | 2568.43 | 232.41  | 12.10%  | 5184.85    |
| SB                      | 1458.77| 2537.04 | 258.16  | 2516.32 | 330.02  | 7492.45 | 876.10  | 36.10%  | 15468.85   |
| Total %                 | 7.80%  | 14.70%  | 12.70%  | 19.40%  | 2.10%   | 38.90%  | 4.30%   | 100.00% | 42.85%     |
| Total 2018              | 3352.86| 6299.21 | 5447.70 | 8328.99 | 914.00  | 16669.67| 1837.57 | 42.85%  |

NB: ASN = agglomerations and bare soil; CJ = crops and fallow; FC = clear forest; GF = forest gallery; PE = water places; SAA = arboreal and shrub savannas; SB = wooded savannas.

4. Discussion

4.1. Analysis of Climate Change in Southeast Benin from 1954 to 2016

This research has allowed analysis of the climatic variability of precipitation and the minimum and maximum temperatures at the daily, monthly and annual scales from 1954 to 2016 in southeast Benin. Firstly, the annual and monthly data averages were analyzed to understand the variations at these two levels over the period, and secondly, the average data on a daily scale made it possible to complete the initial analyses. Then, in a third step, the bioclimatic indexes made it possible to see the global evolution of the climate in southeast Benin. These analyses were carried out in order to confirm or reject the visible land cover transformations strongly influenced by climate change already recorded through the study of the social perception of the impacts of climate change carried out in the same region [45]. In fact, in southeast Benin, a gradual decrease in average annual rainfall was identified, marked by a greater presence of dry years or periods of rainfall deficit between 1969 and 2016. These average annual variations have also made it possible to confirm that the annual rains experienced many disturbances over nearly 40 years. The chronological series of daily rainfall from 1954 to 2016 presenting random data at 99% threshold following the RANG test revealed a climatic break located in the years 1968 and 1969 thanks to the tests of BUISHAND and WOOD ellipse, to the nonparametric test of PETTITT and to the
test of the Bayesian method of LEE and HEGHINIAN. However, HUBERT's segmentation also confirmed the breaking point between 1968 and 1969 with the two climatic segments identified from 1954 to 1968 and from 1969 to 2016. A “break” can be defined as a change in the probability law of a rainfall series at a given time [46]. Thus, this climatic break has allowed detection of climatic changes in the characteristics of the rainfall series marked by a significant drop in daily rainfall and annual averages in the second segment with an increase in the average temperature over the same period. The break observed between 1968 and 1969 indicates that southeast Benin is under the influence of the fluctuation of the rainfall regime observed at the end of the 1960s and at the beginning of the 1970s in West Africa. It was in this period that several scientific studies located most of the chronological breaks in this part of Africa [25,47,48]. In the segment before the climatic break, the aridity index of De Martonne indicated that the climate of southeastern Benin was humid with many very wet years. However, in the second segment, the variation of this index confirmed the very wet years of the first segment practically disappeared in the second segment with the appearance of rainfall tending towards the semi-arid and arid climate of the dry zones. This explains the strong presence in the southeast region of species from dry areas such as Shea trees and other herbaceous plants indicating the region’s savannization [21,49]. This change in rainfall of southeast Benin towards that of the sub-dry and dry zones was justified by the variation in the number of rainy days at the level of all classes ranging from days with low rainfall to stormy days. In fact, the number of dry days from the first segment (1954–1968) to the second segment experienced an increase of 7.78%, while a decrease was recorded in the number of rainy days at the level of all classes defined according to [36]. Thus, from the first segment to the second segment a decrease in the number of rainy days of 26.14% was recorded for the class between 1 and 10 mm, a decrease of 36.37% of the number of rainy days in the class between 10 and 30 mm, a decrease of 12.22% in the stormy class from 30 to 50 mm and a decrease of 24% in the number of very stormy days in the class with more than 50 mm. This downward trend in the number of rainy days was confirmed by the study of [25] in Mali in the West African sub-region. The decrease in daily rainfall observed in the period 1969–2016 with the presence of dry days and dry years could be explained by deregulation in the seasonal migration of the intertropical front (ITF) to the north. This ITF shift was dependent on the thermal contrast between the continent and the oceans [48]. This decrease in rainfall and climate variability are also accentuated by anthropogenic actions such as deforestation, which is linked to population growth, and the increase in human needs to be met [45].

4.2. Analysis of the Dynamics of Land Cover and Use in the Forest of Dogo-Kétéou in the Context of Climate Variability and Anthropogenic Pressures in Southeast Benin

The interrelationships between climate and land use have been assessed in this study. It allowed evaluation of the state of degradation of the natural forest of Dogo-Kétéou and the real impacts of global changes as obtained through surveys among local populations in southeast Benin [45]. The Normalized Vegetation Index (NDVI) reflects the health of the vegetation based on its cover density as well as its reflectance of sunlight. Indeed, the region of southeast Benin is experiencing visible transformations due to anthropogenic pressure accentuated by climate change. Analysis of satellite images has confirmed that for nearly 30 years the forest of Dogo-Kétéou has suffered a sharp reduction in its density and forest cover. The results of this study reveal from 1986 to 2018 a regression of dense forests. In fact, over the period from 1990 to 2018 the normalized maximum vegetation index decreased from 0.9 in 1990, reflecting a high density of trees, to 0.6 in 2018. This period of decrease corresponds to a period where the local populations have reported the perceived impacts of climate change and human actions exerting simultaneously on the forest during the last decades [45]. Indeed, the pluviometric deficits noted through the decrease in rainfall have serious consequences on the vegetation. These rainfall deficits have increased the mortality of forest trees, making regeneration more difficult, destroying the grass cover, which was very sensitive to the lack of water, and increasing the pressure
on surviving trees [50]. This explains the various changes observed in the occupation and land use classes. A change in one element of the ecosystem has an effect on the other component [51]. Understanding land use changes will impact policy for decision-making for an effective sustainable management of ecosystems, and this was how several authors have described the processes of land use dynamics in Benin [52–54]. However, the results of the present study have revealed from 1986 to 2018, a regression of dense forests and wooded savannas in favor of shrub savannas, agglomerations and bare soils. These results agree with those of [21,55]. The latter specified that under conditions characterized by a relatively high frequency of dry years, there is the destruction of mostly woody vegetation and an increase in the infiltration of rainwater and the appearance of species from dry areas. For [56], seasonal attacks on forest vegetation by breeders in search of fodder and water resources were one of the main causes of the decline of dense natural vegetation. In addition, the population growth rate in the study, estimated at 4.02% from 2000 to 2013 [57], also reflects that strong pressure on natural resources and could also lead to considerable degradation if sustainable management measures of these ecosystems are not implemented.

Refs. [21,58] showed in their studies of the dynamic of land use within the forest of Dogo-Kétou in the period from 1986 to 2000 that open forest and tree savannas had decreased while gallery forest, wooded savannas, shrub savannas and fields and fallows had increased. This analysis confirms the results made within the framework of this study during this same period with regard to the trends recorded. However, in 2014, [21] demonstrated that formations of the forest of Dogo-Kétou were unevenly distributed and under pressure from crops and fallow land and natural risks related to flooding with relatively significant deforestation and variable vulnerability of plant formations to fragmentation. The land cover consisted of forest gallery (37.16%), open forest (9.99%), wooded savannas (25.74%), tree savannas (0.47%), shrub savannas (2.93%), ferralitic soils (2.63%), ferruginous soils (16.33%), crops and fallow land (3.50%) and water (1.24%). The dominant formations of the vegetation being the gallery forest and the wooded savannas in 2014. But in 2018, this study confirmed that the areas of agglomerations have greatly increased reaching 7.8% of the forest area; tree and shrub savannas have also increased in area from 12.1% in 2000 to 38.9%. This increase could be explained by the impact of population growth, which has accentuated the deforestation of dense formations such as gallery forests and wooded savannas, since the latter fell from 52.6% in 1986 to 36.1% in 2000 then to 4.3% of the forest area in 2018. The wooded savannas have therefore almost disappeared with the increase of shrubby savannas. Indeed, the regression of dense natural forests has changed the landscape cover of the classified forest of Dogo-Kétou. Within the framework of participatory forest management, some vegetations as savannas were cultivated in the forest studied. The forests were invaded by populations who have their homes in permanent materials and schools in this forest. It was therefore evident that the regressive dynamics of the vegetation cover were strongly linked to anthropogenic factors accentuated by the effects of climate change [59]. The authors of [60] have shown that the more the environment is degraded, the less it is diversified in species. The regression of natural forest vegetation has changed the landscape cover of the classified forest of Dogo-Kétou. At the same time, soil erosion, degradation of forest resources and desertification, slow and potentially irreversible processes, threaten food security and continue to amplify in response to the increase in extreme climate events and human pressures [60–62]. These results agree well with those of [63] and [45] obtained in southeast Benin. The study of [64] based on an inventory of the forest of Dogo-Kétou has shown a low Shannon floristic index between 2.80 and 3.58 bits and confirmed that this forest was exposed to strong anthropogenic pressures, which prevent the establishment of a mature dense forest in the southeast of Benin. [64] have confirmed that the analysis of the diameter structures revealed a lack of big trees with a diameter superior than 45 cm, which are both mature and seed trees capable to ensure a good regeneration of the forest in the future. This study has confirmed the disappearance of dense forest formations.
Among the species encountered in the forest of Dogo-Kéto, Shea trees appeared at many places. It was a species traditionally known in the drier central and northern parts of countries such as Benin, Cameroon, Côte d’Ivoire, Ghana, Nigeria, Togo and Uganda. It was a species of African savannas and more precisely of West Africa where it is known as endemic [65–67]. The species was found more in Sudanese and Sudano-Sahelian climates with a rainfall of less than 1000 mm [56]. The forest of Dogo-Kéto was the most northerly part of the southeast and it is this forest which presents more visible impacts of global changes. Also, a gradual transition of the sub-equatorial climate of the southeast towards the Sudanese climate or Sudano-Sahelian climate is in progress in this part of Benin and West Africa. Tree species adapted to the drier climate could be considered in reforestation or enrichment plans for the forest of Dogo-Kéto, which has a very advanced state of degradation, confirmed by our study. Indeed, an emergency plan has to be developed for assisting this forest in its regeneration and accompanying this plan with rigorous monitoring through a development plan drafted for this purpose.

5. Conclusions

This study brought out the climatic variations and their effects on the classified forest of Dogo-Kéto. It emerges from this that most of these climatic variations have been observed from year to year via variation in rainfall and temperature. The consequences are the changes observed at the level of plant formations (open forests, forest savannas, dense semi-deciduous forests) and of crops and fallows. Even though climatic factors really influence the good health of the forests studied, their degree of degradation is more marked by human actions. In this forest, the forest savannas have undergone a total transition, mainly in fallow crops, while the dense forests have undergone transition, mainly in open forests. The transition from dense semi-deciduous forests to open forests is mainly due to the human actions that accentuate the effect of climate change in this area. While taking measures to integrate the factor of the climate change in the choice of species to be reforested in this area of Benin from the view of their ecological needs, it is also necessary to carry out actions to raise awareness of the local populations on the climate changes in progress and their irreversibility and the need for humans to adapt and change some behaviors that do not favor the conservation of forest resources.

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