

Analysis of the Spatiotemporal Trends in the Ecological Impacts of Wetlands on the Vitality and Diversity of the Flora in the Ziama Biosphere Reserve from 2000 to 2024 in the Republic of Guinea

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Abstract

The Ziama Biosphere Reserve (ZBR) is recognized as one of the largest areas dense rainforests in the Republic of Guinea due to its biodiversity. Owing to its low-altitude topography, it serves as one of the main habitats for African forest elephants in Guinea. However, this forest ecosystem faces significant anthropogenic pressure, leading to the degradation and fragmentation of its natural habitats. The objective of this study was to analyze the impact of anthropogenic pressure associated with the exploitation of low-lying areas on the condition and diversity of vegetation in the Ziama Biosphere Reserve (ZBR). To achieve this objective, we collected LANDSAT satellite imagery was obtained data from the website <http://earthexplorer.usgs.gov/>. We selected six spectral bands (B2, B3, B4, B5, B6, and B7) based on their relevance to this study. The calculated of Normalized Difference Vegetation Index (NDVI) allowed us to characterize the condition and dynamics of the vegetation based on the difference in reflectance between the near-infrared and red bands. Correlation coefficient was calculated to identify the main factors associated with vegetation condition in the reserve. The results showed that NDVI values were relatively similar in 2000 (0.3595 - 0.8544) and in 2010 (0.3192 - 0.8539), whereas a marked decrease was observed in 2024, with values ranging from 0.1202 to 0.2517, indicating substantial degradation of vegetation cover. Re-

garding changes in the vegetation index, the linear trend revealed a continuous decline in the NDVI over the 2000-2024 period. Strong negative correlations were also observed between the NDVI and fallow land, as well as between the NDVI and low-lying areas, with correlation coefficients (r) ranging from -0.910 to -0.692 . These results highlight a gradual decline in the vitality of the vegetation cover associated with changes in land-use categories, particularly in low-lying areas. The sustainable conservation of the ZBR therefore requires improved management of low-lying areas, a reduction in human pressures, and the implementation of strategies for restoring degraded habitats.

Keywords

Vitality, Floristic Diversity, Anthropogenic Pressure, Correlation, Normalized Difference Vegetation Index

1. Introduction

Protected areas constitute major reservoir of biological diversity and play an essential role in maintaining ecological balance and providing ecosystem services that are indispensable to human well-being. They also contribute to climate regulation, habitat and species conservation, and sustainable development [1]. Some protected areas have been designated as Biosphere Reserves with the aim of promoting socioeconomic studies on the value of forest resources and land, thereby supporting a sustainable management planning that takes into account the needs and practices of communities living near these protected areas [2].

Despite these benefits, increasing anthropogenic pressure poses significant threats to biodiversity, jeopardizing the vitality and diversity of vegetation within these ecosystems. These anthropogenic pressures contribute to climate change and forest loss. The global forest area, estimated at 4.077 billion ha in 1990, decreased to 3.952 billion ha in 2005, representing a significant decline in forest cover worldwide [3].

Furthermore, the Republic of Guinea, like many other African countries, is not immune to such anthropogenic pressures. According to Guinea's Forest Code, local communities have certain customary use rights that allow them, in particular, to harvest resources from low-lying areas and non-timber forest products (NTFPs), provided that they comply with regulations governing the sustainable management of forest resources [4].

Unfortunately, the country's forest ecosystems are facing fragmentation due to human pressures on natural resources. Local residents take advantage of their usage rights to engage in various activities that may affect biodiversity, particularly through the harvesting of Non-Timber Forest Products and the establishment of cash crops. [5]. Consequently, the country's forest area, which was estimated at 7,264,000 ha in 1990, decreased to 6,364,000 ha in 2015, a reduction of 900,000 ha over the period in question [6] [7].

Indeed, the Ziamia Biosphere Reserve (ZBR), located in southeastern Guinea and covering an area of 119,019 hectares, is of major concern for the preservation of the region's biodiversity and ecological integrity. Designated a forest reserve in 1942 and established as a Biosphere Reserve in 1981 by UNESCO, it is one of Guinea's main areas of dense rainforest and is home to significant biological diversity, notably including populations of African forest elephants [8]. To ensure sustainable management, local communities have the right to harvest NTFPs and use lowland areas for rice cultivation with authorization from the reserve management authorities, as stipulated in the Forest Code.

However, farmers no longer adhere strictly to the rules of conduct established to ensure the sustainability management of the reserve [9] [10]. They may go beyond the practices permitted under these rules, particularly through the expansion of cash crops and the overexploitation of NTFPs to meet their household needs [10] [11]. Consequently, the floristic and faunal diversity of the ZBR may be affected, leading to the emergence of invasive species and the loss of important species [12] [13].

Despite existing research on floristic diversity and anthropogenic pressures within the ZBR, the spatiotemporal evolution of the effects associated with the exploitation of lowlands on vegetation condition remains insufficiently documented. An analysis based on remote sensing data thus makes it possible to characterize changes in the condition of the vegetation cover and to identify the relationships between land-use changes and vegetation dynamics.

The objective of this study was therefore to analyze anthropogenic pressures and characterize the condition of vegetation in the ZBR.

2. Materials and Methods

2.1. Overview of the Study Area

This study was conducted in the Ziamia Biosphere Reserve (ZBR), located in southeastern Guinea, and covering an area of 119,019 ha (**Figure 1**). It lies between 8°03' and 8°32' north latitude and 9°08' and 9°32' west longitude [14]. The reserve's vegetation comprises two main zones: a lower zone located at the foothills of the mountains at an elevation of less than 1000 m, and a montane zone extending up to approximately 1400 m above sea level. This variation in vegetation is primarily associated with in ecological and altitudinal conditions [15]. The climate is sub-equatorial, characterized by alternating dry and rainy seasons. The main watercourses that cross and drain the reserve are the Diani, Lélé, Veleoro, Véré, Loffa, Avilli, Laoua, and Libiguié [8]. This hydromorphic environment has enabled the ZBR to develop a significant number of low-lying areas suitable for rice cultivation, thereby meeting the food needs of local communities [16] [17].

2.2. Methods

The data collected for this study consisted primarily of satellite imagery acquired from LANDSAT satellites, and freely downloaded from the USS Earth Explorer

portal (<http://earthexplorer.usgs.gov/>). Among the various available spectral bands, bands B2, B3, B4, B5, B6, and B7 were selected based on their relevance to the analysis of vegetation cover and condition (Table 1).

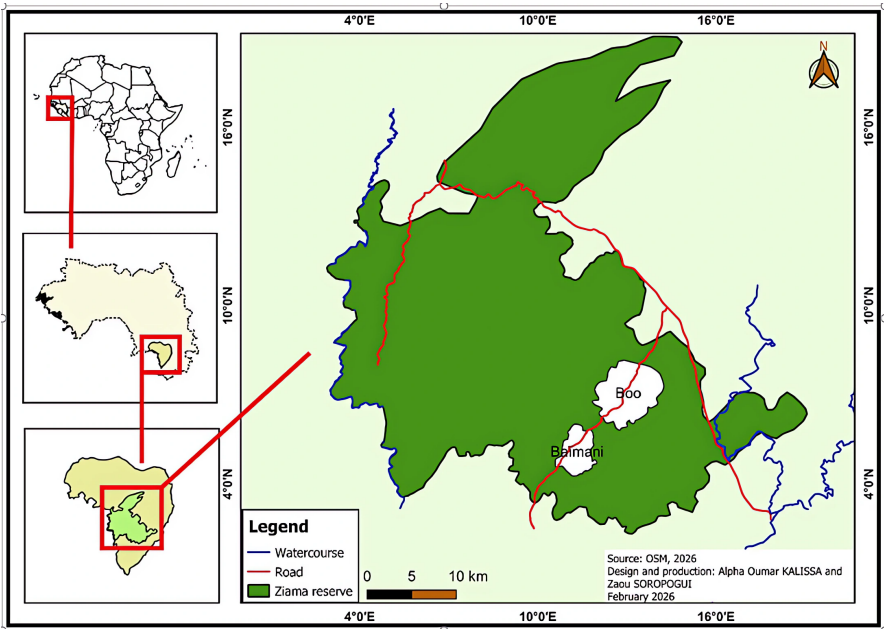


Figure 1. Map of the Ziama biosphere reserve.

Table 1. Bands of Landsat 8/9 satellite images.

N°	Name (band)	Description	Wavelength
1	B2	Blue	496.6 nm (S2A)/492.1 nm (S2B)
2	B3	Red	560 nm (S2A)/559 nm (S2B)
3	B4	PIR	560 nm (S2A)/559 nm (S2B)
4	B5	PIR	664.5 nm (S2A)/665 nm (S2B)
5	B6	Red Edge 2	703.9 nm (S2A)/703.8 nm (S2B)
6	B7	Red Edge 3	740.2 nm (S2A)/739.1 nm (S2B)

The table below (taken from the image collection log) will be added as a supplementary table covering the 2012-2013 period, which is the focus of the reviewer’s attention. The values marked with an * correspond to a second reading (line WRS 55) acquired on the same date (Table 2).

- Compositing rule: For each year, all scenes with cloud cover $\leq 30\%$ and valid pixel coverage $\geq 60\%$ within the reserve’s boundaries were selected and mosaicked using a maximum (or median) NDVI composite; scenes below this threshold were excluded rather than averaged.
- Cloud/shadow masking: Applied using the QA_PIXEL band (cloud, cloud shadow, and snow bits) prior to compositing, for ETM+ products such as OLI.

- Season: Images acquired during the dry season (approximately November–March) were prioritized when available, in order to reduce the cloud contamination typical of the rainy season in this region; this will be explicitly stated, along with any exceptions (e.g., the May 2013 scene).
- Atmospheric correction: Level 2 Surface Reflectance Collection 2 product (already atmospherically corrected); this will be explicitly stated rather than implied.

Table 2. Landsat 8/9 satellite image bands per year.

Date of Acquisition	Sensor	Cloud cover (%)	Valid pixels (%)
2012-01-14	Landsat 7 ETM+ (SLC-off)	0.0	71.0
2012-03-18	Landsat 7 ETM+ (SLC-off)	5.0	70.5
2012-04-03	Landsat 7 ETM+ (SLC-off)	18.0	69.5
2012-11-29	Landsat 7 ETM+ (SLC-off)	0.0	66.1
2012-12-15	Landsat 7 ETM+ (SLC-off)	22.0	68.9
2013-01-16	Landsat 7 ETM+ (SLC-off)	0.0	70.0
2013-02-01	Landsat 7 ETM+ (SLC-off)	0.0	70.5
2013-03-21	Landsat 7 ETM+ (SLC-off)	0.0	63.5
2013-05-24	Landsat 7 ETM+ (SLC-off)	6.0	60.1
2013-12-02	Landsat 7 ETM+ (SLC-off)	22.0	23.5
2013-12-18	Landsat 7 ETM+ (SLC-off)	33.0	38.2
2013-10-07	Landsat 8 OLI	39.9	33.4
2013-11-08	Landsat 8 OLI	13.5	28.5
2013-11-24	Landsat 8 OLI	7.3/44.9*	54.0/21.6*
2013-12-10	Landsat 8 OLI	0.0/17.4*	100.0/38.9*
2013-12-26	Landsat 8 OLI	0.0/0.0*	100.0/39.4*

This data was then used to calculate the Normalized Difference Vegetation Index (NDVI) in order to analyze the condition of the vegetation in relation to land-use and management practices. Several studies have shown that the NDVI is a relevant indicator for characterizing the condition and dynamics of vegetation [18] [19]. The NDVI was derived from preprocessed Landsat imagery following radiometric correction and extraction of the study area.

Land cover/land use classes (bare ground, fallow land, low-lying areas/wetlands, forest, etc.) were defined using explicit spectral and/or auxiliary criteria applied to the classification for each year.

The sample sizes for the training and validation sets by class, the source of the reference data (dates of field surveys or high-resolution imagery used for photoin-

terpretation), and the accuracy metrics (overall accuracy, Kappa coefficient, and confusion matrix) have been added.

The NDVI allowed us to characterize the condition of the vegetation by exploiting the difference in reflectance between the near-infrared (NIR) band, which is strongly reflected by healthy vegetation, and the red (RED) band, which is strongly absorbed by chlorophyll. The index is calculated using the following formula:

$$\text{NDVI} = \frac{R(\text{NIR}) - R(\text{VIS})}{R(\text{NIR}) + R(\text{VIS})}$$

For Landsat images, the NIR corresponds to band 5 (Landsat 8) or band 4 (Landsat 5/7), and the RED band corresponds to band 4 (Landsat 8) or band 3 (Landsat 5/7). The processing was performed in QGIS using the raster calculator, which generated a continuous map of the NDVI index covering the entire Ziama Biosphere Reserve.

All annual NDVI values presented are averages for the entire reserve, calculated solely from valid pixels (free of clouds, shadows, or gaps) within the same reserve boundary mask for each year.

2.3. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a multivariate statistical method used to reduce the dimensionality of a dataset while retaining a significant portion of the original information. In this study, PCA was used to transform the initial spectral variables into a set of uncorrelated principal components, to summarize the spectral information contained in the selected bands and to facilitate the discrimination of different land-use classes. The first component (PC1) accounts for the largest proportion of the total variance, followed by the second component (PC2), and then by the subsequent components.

The first components, which explain the largest share of the variance, were thus selected for interpreting spectral patterns and distinguishing land-use classes. All principal component analyses were performed using image processing and raster analysis tools available in QGIS. The results provided a multispectral image for identifying different land-use classes [10] [20]. The classes identified from satellite data were validated through field surveys. The geographic coordinates of the various observation sites were recorded using a GPS to verify and validate the interpretation of the satellite imagery.

2.4. Correlation Coefficient for Data Related to Vegetation Vitality

The Pearson correlation coefficient (Pearson, 1895), also used by [21], revealed linear relationships between climatic variables (precipitation and temperature), biophysical variables (NDVI), and land-use variables (bare soil, fallow land, and low-lying areas). Data on precipitation, temperature, NDVI, bare soil, fallow land, and low-lying areas collected or extracted from 2000 to 2024 were processed using Python software to calculate Pearson's linear correlation coefficients between the various variables. The source of the climate data (*climexp.knmi.nt*), its native res-

olution, and the spatial aggregation method (average over the reserve) were explicitly specified, along with the units (mm/year, °C) and the number of annual observations ($n = 25$, 2000-2024). 95% confidence intervals (or p-values) are reported for each Pearson correlation coefficient.

This analysis aimed to identify the variables associated with variations in NDVI and, consequently, to better characterize the factors associated with variations in the vitality of the ZBR's vegetation cover [21].

The Pearson linear correlation coefficient (r) was calculated using the following formula:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 * \sum (y_i - \bar{y})^2}}$$

where:

r : Represents Pearson's linear correlation coefficient

x_i, y_i : Represent the observed values of the two variables under consideration

$\bar{x}, \bar{y}$: Represent the means of the various variables, and

Σ : Is the symbol for the sum of the values under consideration

The strength of the linear correlation coefficient (r), measured between two variables, is shown in the table below (Table 3).

Table 3. Accuracy of the linear correlation coefficient.

Value of r	Interpretation
0 to ± 0.3	low
± 0.3 to ± 0.6	moderate
± 0.6 to ± 0.8	strong
± 0.8 to ± 1	very strong

Similarly, r denotes the linear correlation coefficient, which measures the strength and direction of the linear relationship between two variables (Rahimi *et al.*, 2025). It ranges from -1 to 1 . To calculate it:

- If $r = +1$: the correlation is considered positive and perfect;
- If $r = -1$: the correlation is considered negative and perfect;
- If $r = 0$: there is no correlation between these variables.

Thus, the correlation analysis identified the variables with the strongest linear relationships with the NDVI, thereby allowing for a better characterization of the factors associated with the vegetation cover vitality variables in the Ziama Biosphere Reserve.

3. Results

3.1. Analysis of Changes in the Vegetation Index from 2000 to 2024

The three vegetation maps of the ZBR shown in Figure 2 illustrate changes in the

Normalized Difference Vegetation Index (NDVI). They allow us to assess the spatiotemporal dynamics of vegetation cover over a 24-year period based on Landsat satellite imagery and to characterize the spatial variations in vegetation condition (Figure 2). The results are presented as maps corresponding to the years 2000, 2010, and 2024. These maps primarily serve to visually illustrate changes in the forest landscape within the reserve.

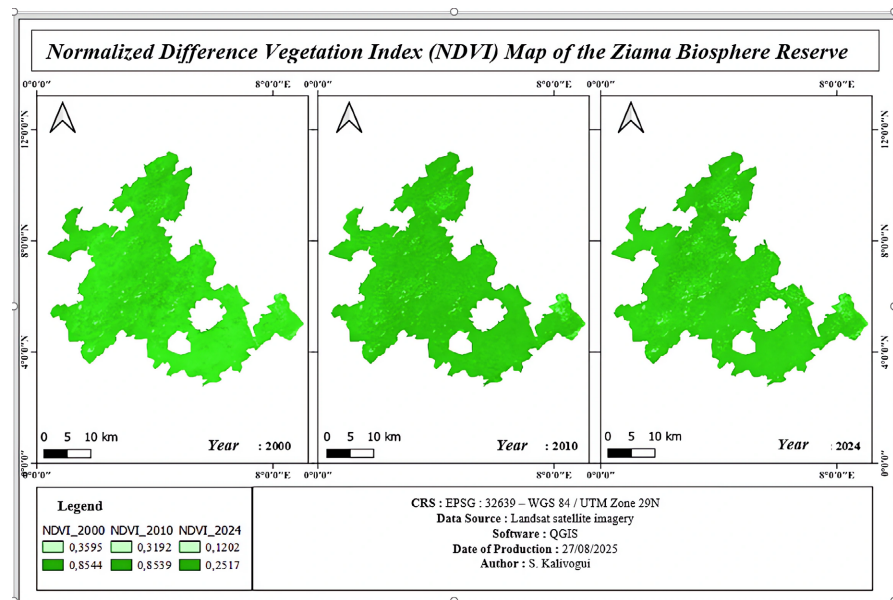


Figure 2. Trends in vegetation indices based on normalized difference.

The maps show the spatial distribution of NDVI values for the three periods studied. The NDVI values for 2000, 2010, and 2024, as indicated in the legend, show substantial spatial variations in vegetation condition. In 2000, NDVI values ranged from 0.3595 to 0.8544, while in 2010 they ranged from 0.3192 to 0.8539. These two periods thus exhibit relatively similar ranges of values. In contrast, in 2024, NDVI values ranged from 0.1202 to 0.2517, reflecting a marked decrease in index values and suggesting a substantial deterioration in vegetation condition.

For the year 2000, the map shows a generally favorable condition of vegetation cover. The green colors indicate a relatively uniform distribution of areas characterized by high NDVI values, corresponding to dense and relatively well-developed vegetation cover. However, these areas may correspond to different types of vegetation cover, including herbaceous formations, or areas affected by human-induced disturbances.

For the year 2010, the distribution of NDVI values is generally comparable to that observed in 2000. However, certain spatial variations are observed and may suggest localized changes or slight fragmentation of forest cover in some areas.

These spatial variations may be associated with local changes in land use and the intensification of agricultural activities, particularly in low-lying areas.

For the year 2024, the situation changed significantly, with a marked decline in

NDVI values, ranging from 0.1202 to 0.2517. This represents a significant decrease in the apparent density and condition of vegetation cover. The distribution of low NDVI values also highlights an increase in areas characterized by less dense vegetation or greater levels of disturbance.

3.2. Changes in the Vegetation Index

The Normalized Difference Vegetation Index (NDVI) shows that vegetation cover did not evolve uniformly across the three periods studied. An analysis of NDVI values between 2000 and 2024 reveals significant fluctuations, with a relatively stable trend until 2012. However, between 2012 and 2013, there was a sharp decline in the NDVI, followed by a gradual recovery through 2024 onward. A linear trend line was fitted to the entire data series (Figure 3).

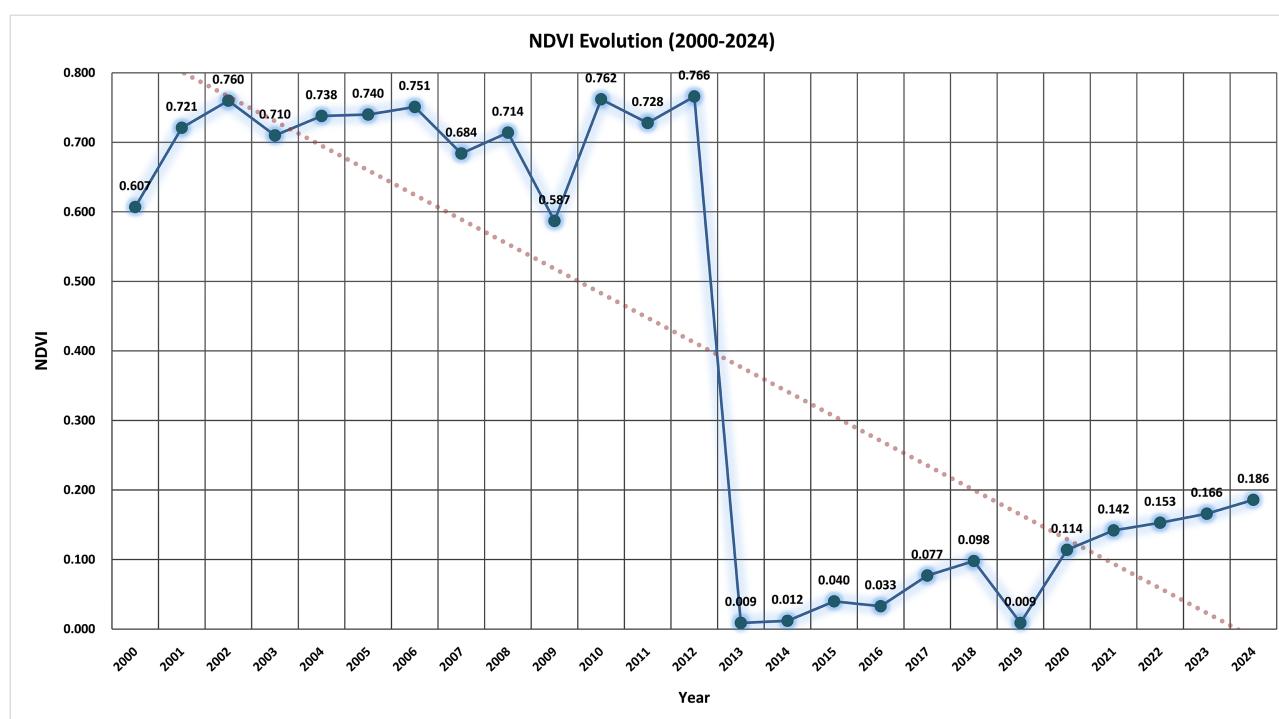


Figure 3. Rate of change of NDVI.

All annual NDVI values presented are averages for the entire reserve, calculated solely from valid pixels (free of clouds, shadows, or gaps) within the same reserve boundary mask for each year.

An analysis of the Landsat image log used for the study reveals a difference in quality between the scenes acquired in 2012 and those acquired in 2013. For some acquisitions, the 2013 scenes show a relatively low valid pixel coverage, ranging from 21 to 38 percent, as well as cloud cover reaching up to 44.9 percent for certain Landsat 8 scenes.

In contrast, the 2012 scenes show a higher and relatively constant valid pixel coverage, ranging from 66 to 71 percent, with low cloud cover. These differences

in quality were taken into account during the selection and preprocessing of the images in order to prioritize scenes offering the best spatial coverage and the least cloud contamination for land-use analyses.

An analysis of the average NDVI values reveals a very significant apparent decrease, from 0.766 in 2012 to 0.009 in 2013. However, this variation does not reflect an actual ecological change in vegetation within the study area. It is primarily due to a difference in how invalid and masked pixels were handled when calculating the average NDVI for 2013.

In fact, in the initial processing, pixels that were masked or lacked valid data were assigned an NDVI value of zero (0) instead of being excluded from the calculation. However, the 2013 imagery contained a relatively high proportion of invalid pixels and had higher cloud cover than the 2012 imagery. The inclusion of these zero values in the calculation of the average across the entire Ziama Biosphere Reserve. This led to a significant dilution of the average NDVI value in 2013.

Consequently, the value of 0.009 obtained for 2013 should be considered an artifact resulting from data processing rather than an indicator of a sudden deterioration in vegetation cover. Masked and invalid pixels were therefore excluded from the calculation in order to obtain a more representative estimate of the vegetation actually observed.

During the period from 2000 to 2012, NDVI values were relatively high (between 0.67 and 0.78), with slight year-to-year variation indicating relative stability in vegetation condition. In 2013, there was a sharp drop (0.009), corresponding to the lowest value in the series. From 2014 to 2024, NDVI values gradually increased, rising from 0.03 in 2014 to 0.06 in 2015 and reaching approximately 0.19 in 2024. Similarly, the linear trend shows a continuous decline in the NDVI across all periods from 2000 to 2024, despite the gradual recovery toward the end of the time series.

3.3. Correlation Matrix on the Vitality and Diversity of the Flora of Ziama

The relationship between vegetation condition in the Ziama Biosphere Reserve and various variables and land-use categories was studied using temperature, precipitation, NDVI, and the main land-use categories (fallow land, low-lying areas, and bare soil) over a 25-year period from 2000 to 2024. The purpose of this analysis was to examine the linear relationships between these variables and the dynamics of vegetation cover (**Figure 4**). This figure illustrates correlation coefficients ranging from -1 (strong negative correlation) to $+1$ (strong positive correlation), where negative values indicate an inverse relationship and positive values indicate a direct relationship between the variables.

The relationship between temperature and NDVI ($r = -0.614$) shows a strong negative correlation, indicating that an increase in temperature is associated with a decrease in NDVI values; However, the correlation between precipitation and

NDVI indicates a weak positive linear correlation with $r = 0.238$. Temperature and fallow land, as well as temperature and low-lying areas, showed strong positive correlation ($r = 0.750$ and 0.716 , respectively).

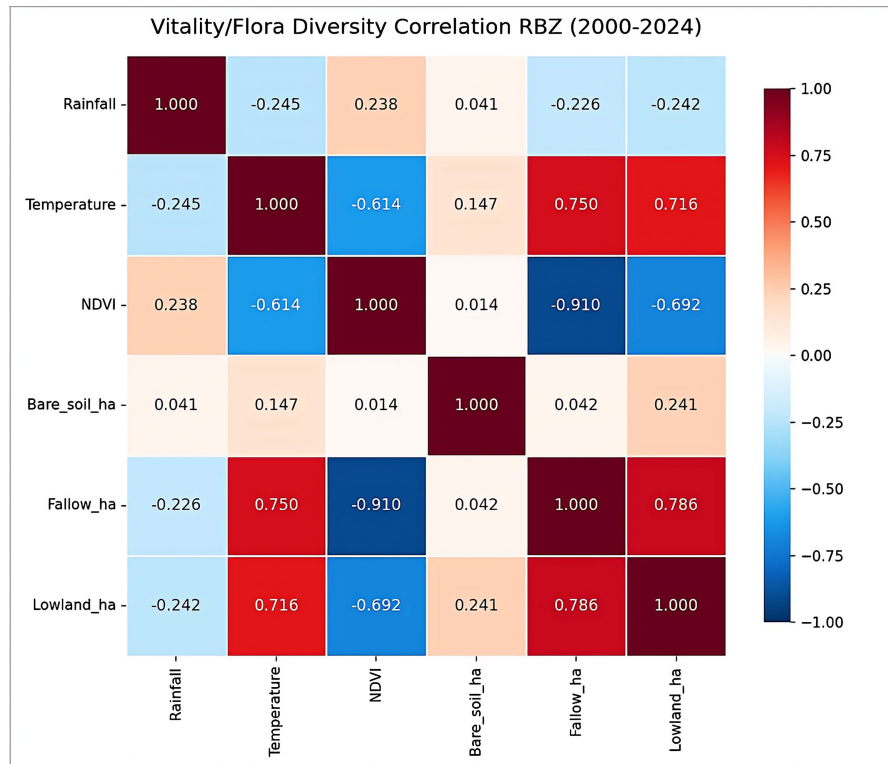


Figure 4. Correlation with vegetation vitality in the ZBR.

The relationships between NDVI and Fallow Land and between NDVI and low-lying area, showed a very strong negative correlation, with linear correlation coefficients (r) ranging from -0.910 to -0.692 . These results indicate that an increase in extent of these land-use categories is associated with a decrease in NDVI values.

The relationship between fallow land and low-lying areas showed a strong positive correlation with $r = 0.786$, indicating that the trends for these two land-use categories follow a relatively similar pattern over the study period. Finally, the variable relating bare soil to NDVI shows a very weak correlation, with $r = 0.014$.

4. Discussion

The average values (0.60695, 0.58655, 0.18595) obtained from the Normalized Difference Vegetation Index (NDVI) maps show that the RBZ is undergoing a process of vegetation degradation which may reflect a gradual decline in the condition of vegetation cover, potentially associated with various environmental and anthropogenic pressures. To ensure the consistency of the NDVI time series, the values used in the analysis correspond to the average calculated across the entire Ziama Biosphere Reserve, considering only pixels with valid data. An inconsistency was noted between the value of 0.58655 mentioned in the discussion for

the year 2010 and the value of 0.762 presented in **Figure 3**. This difference stemmed from the use of statistics derived from an intermediate stage of processing. The value selected for 2010 is therefore 0.762, corresponding to the average calculated from the valid pixels across the entire reserve.

When comparing the years 2012 and 2013, it is also necessary to take into account the change in sensor used for the Landsat data. The 2012 data come from Landsat 7 ETM+, while the 2013 data come from Landsat 8 OLI. Since the spectral responses of these two sensors are not strictly identical, a direct comparison of NDVI values may introduce a bias. This difference in sensors is also associated with a different observation quality in 2013, characterized by a higher proportion of invalid pixels and greater cloud cover in certain scenes.

To minimize these effects, the images underwent quality control, and masked or invalid pixels were excluded from the calculation of averages. The NDVI values from the Landsat 7 ETM+ and Landsat 8 OLI sensors were also harmonized prior to the time-series analysis. The rules for scene selection, pixel masking, and statistical calculation were applied consistently throughout the entire study period.

Consequently, variations in the NDVI between different years are interpreted with caution, taking into account both vegetation dynamics and differences related to acquisition conditions and the sensors used. The final time series presented in **Figure 3** corresponds to the corrected and harmonized values obtained after these various processing steps.

Consequently, this situation could be related to increasing anthropogenic pressure associated with agricultural expansion, leading to a reduction in forest cover and potentially exacerbating the effects of climate change. These results corroborate those observed by [22] in the Diécké Classified Forest. These authors found that plant species are often cleared to make way for agricultural activities.

An analysis of trends in NDVI and land cover shows that changes in vegetation cover occur in parallel with certain changes in land cover within the Zياما Biosphere Reserve. Periods during which NDVI values decrease correspond, in particular, to an increase in the areas occupied by croplands, fallow lands, and low-lying agricultural areas. Conversely, periods characterized by higher or relatively stable NDVI values generally correspond to a greater presence of natural vegetation.

These results therefore show an association between vegetation dynamics and the observed changes in land cover. However, since the data used in this study are observational in nature and the analysis is based on correlational relationships, it is not possible to assert that a change in land cover directly causes a variation in NDVI. The results suggest instead that the two phenomena evolved in tandem during the period under study.

In this study, vegetation analysis relies primarily on the use of the NDVI, which makes it possible to assess greenness and the overall condition of vegetation cover based on satellite data. The observed variations in the NDVI are thus interpreted in terms of vegetation dynamics, greenness, or condition, rather than as a direct

measure of floristic diversity.

In fact, no field data on species richness, floristic composition, or botanical surveys were collected as part of this study. It would therefore not be appropriate to use variations in the NDVI to directly conclude that there has been an increase or decrease in floristic diversity in the Ziama Biosphere Reserve.

In terms of changes in the NDVI, the curve shows relatively slight variation, with values ranging from 0.67 and 0.78 over the period from 2000 to 2012. This relative stability may indicate limited changes in vegetation cover during this period, allowing for relatively stable ecological functioning and the maintenance of forest cover. Thus, a period of decline was observed between 2012 and 2013, with values dropping from 0.76 to 0.003, which could be explained by human-induced disturbances associated with accelerated deforestation, wildfires, agricultural expansion, climate change, or mining activities, as noted by Kouakou *et al.* (2018), who reported that abrupt changes in the NDVI West African forests are generally associated with increased landscape degradation.

The observation of a gradual increase in NDVI values from 2013 to 2024 from 0.03 in 2014 to 0.06 in 2015, reaching 0.19 in 2024 indicates a gradual recovery of vegetation cover, potentially reflecting natural regeneration in previously degraded or bare areas. These results are consistent with the observations made by [23] in several protected areas in West and Central Africa.

Regarding the linear trend, it indicates a continuous decline in the NDVI over the entire periods from 2000 to 2024, despite a partial recovery observed toward the end of the time series. This trend suggests that the improvement observed in recent years has not been sufficient to reverse the overall downward trend in NDVI. This result is consistent with the observations of [24], who reported that the combination of deforestation, fragmentation, and climate stress can result in a declining NDVI trend even if positive fluctuations occur over shorter periods. The results of the correlation matrix show a negative correlation between temperature and NDVI ($r = -0.614$), suggesting that an increase in temperature is associated with a decrease in vegetation cover vitality. This relationship could be linked, in particular, to increased water stress, but other environmental and anthropogenic factors may also play a role. Thus, the strong negative correlation between NDVI and low-lying areas (-0.692) indicates a decrease in vegetation and an increase in low-lying areas linked to deforestation for agricultural practices. These results corroborate those of [20], who noted in his study on “The Impact of Climate Change and Human Activities on Variations in Vegetation Cover in China” that rising temperatures in tropical regions can increase water stress and negatively affect vegetation cover.

In fact, the strongest negative correlation in this matrix is that between the NDVI and fallow land (-0.910), indicating a very strong association between an increase in fallow land area and a decrease in NDVI. This significant decrease in forest cover suggests that land set aside for fallow is being used for only a short period, reflecting strong anthropogenic pressure. This situation could

contribute to the fragmentation of natural plant habitats, as observed by [24] in South Africa.

However, the strong positive correlation observed between fallow land and low-lying areas ($r = 0.786$) indicates that local communities are adapting to rising temperatures, a strategy that may allow farmers to migrate to low-lying areas to secure moisture favorable for crop production. Thus, this migration may lead to degradation of the flora due to anthropogenic pressure. This finding is consistent with the observations reported by [25] in areas characterized by vegetation cover and lowlands in West Africa.

5. Conclusions

The NDVI values recorded show that vegetation condition remained relatively stable between 2000 and 2012, with values ranging from 0.607 to 0.766. However, a sharp decline was observed in 2013, with a value of 0.003. A slight improvement in the NDVI was then observed between 2014 and 2024, but the linear trend remained downward over the period.

Furthermore, the linear correlation analysis (r) calculated for the period 2000–2024 reveals strong to very strong negative correlations between NDVI and fallow land, as well as between NDVI and low-lying areas, with correlation coefficients (r) ranging from -0.910 to -0.692 . These results suggest that an increase in the extent of these land-use categories is associated with a decline in vegetation condition in the Zياما Biosphere Reserve (ZBR). The results obtained in this study also highlight a gradual decline in the condition of vegetation cover in the Zياما Biosphere Reserve over the study period, which may be associated with changes in land-use categories and increasing anthropogenic pressures.

It therefore appears necessary to strengthen awareness and engagement among local communities, while improving the management of low-lying areas and implementing measures to conserve and restore degraded habitats, thereby contributing to the sustainable management of the Zياما Biosphere Reserve.

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Author Contributions

ZS contributed to the design of this manuscript. ZS and PM contributed to the collection, analysis, and processing of the data for this manuscript. ZS, PM, and NAA contributed to the preparation of the manuscript. NAA, DAS, and AC contributed to the editing and proofreading of the manuscript. All authors reviewed and approved the final version of the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest related to this work.

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