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Effects of Climate Variability on Vegetation Dynamics in Upper Guinea: An Approach Based on NDVI, Precipitation, and Temperature Indices

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Abstract

Upper Guinea, a transitional zone between the Sahelian climate and forest influences, is particularly exposed to the impacts of climate change, with an intensification of climatic extremes. This study aims to investigate the relationship between climate variability (temperature and precipitation) and vegetation response, as measured by the NDVI index, over the period from 2012 to 2021. The data were obtained from reliable satellite sources such as MODIS (NDVI), ERA5 (temperature), and CHIRPS (precipitation). The methods employed include monthly climatology, linear trend analysis, standardized anomaly assessment, and Pearson correlation analysis. The results reveal a pronounced seasonality of NDVI, peaking in September to October, reflecting a biological lag following rainfall. Temperature shows a significant upward trend (+0.091˚C/year), while precipitation remains highly variable without a clear trend. NDVI displays a moderate but significant positive trend (+0.009 NDVI/year), particularly marked after 2015. A strong correlation with temperature (r = 0.72) contrasts with the weak influence of precipitation (r = 0.03). The study highlights the key role of temperature in ecological dynamics and the relative resilience of vegetation, while emphasizing that this resilience remains dependent on sufficient water availability. It concludes by recommending rigorous climatic and ecological monitoring to support adaptation strategies, sustainable management, and food security in West Africa.

Keywords

Climate Variability, NDVI, Temperature, Vegetation Dynamics

1. Introduction

At the global scale, climate change is one of the most pressing challenges of the 21st century, profoundly affecting ecosystem balance and socio-economic systems. Rising temperatures, altered rainfall regimes, and the increasing frequency of extreme events have significant consequences for biodiversity, water resources, and ecosystem productivity [1] [2]. In this context, vegetation dynamics, as a direct response to climatic conditions, represent a key indicator for assessing the impacts of global change on terrestrial environments [3]-[5].

Although Africa contributes minimally to global greenhouse gas emissions, it is among the most vulnerable regions to climate change due to its strong reliance on rainfed agriculture and limited adaptive capacity [6] [7]. African ecosystems are already under multiple pressures, and growing climate variability exacerbates risks of land degradation, food insecurity, and population displacement. Remote sensing tools such as NDVI have proven particularly effective in monitoring vegetation dynamics across vast, poorly instrumented African landscapes [8]-[10].

In West Africa, a region characterized by high interannual rainfall variability and a warming trend, the Sudano-Sahelian zones are particularly affected. The migration of the Intertropical Convergence Zone (ITCZ), modulated by climatic teleconnections such as ENSO and the Atlantic Niño, largely controls the spatial and temporal distribution of rainfall [12] [13] [19]. The impacts of these climatic dynamics on vegetation are complex and heterogeneous, requiring fine-scale regional approaches to better understand ecosystem resilience and vulnerability mechanisms.

The Republic of Guinea, situated at the ecological crossroads between the Sahel and the humid Guinean forests, exemplifies this complexity. More specifically, Upper Guinea (characterized by vast grassland savannas and granitic plateaus) experiences a prolonged dry season, high temperatures, and increasing pressure on cultivable land. In this context, analyzing the effects of climate variability on vegetation dynamics using NDVI (MODIS), precipitation (CHIRPS), and temperature (ERA5) is a relevant approach to understanding ecosystem evolution and supporting adaptation policies. This study is therefore framed within the perspective of sustainable natural resource management. It aims to provide scientific insights to guide spatial planning, secure agricultural production, and enhance resilience to environmental change.

This study is structured as follows: Section 2 presents the data used, including precipitation, temperature, and NDVI indices, along with the adopted methodology. Section 3 reports the results of the climatic and ecological analysis in Upper Guinea, followed by an in-depth discussion. Finally, Section 4 provides the general conclusion of the study.

2. Data and Methods

2.1. Study Area

Upper Guinea, one of the four main natural regions of the Republic of Guinea, occupies the eastern part of the country. It is characterized by a vast, gently undulating savanna plain, well-suited to agro-pastoral activities. The region is bordered to the north by Mali, to the east by Côte d'Ivoire, to the west by Middle Guinea, and to the south by Forested Guinea (**Figure 1**).

Several strategically important rivers originate from or flow across the region. The most notable is the Niger River, one of the major hydrographic basins of West Africa, whose source lies in the Faranah area [14] [15]. These water resources are vital for domestic, agricultural, and pastoral uses.

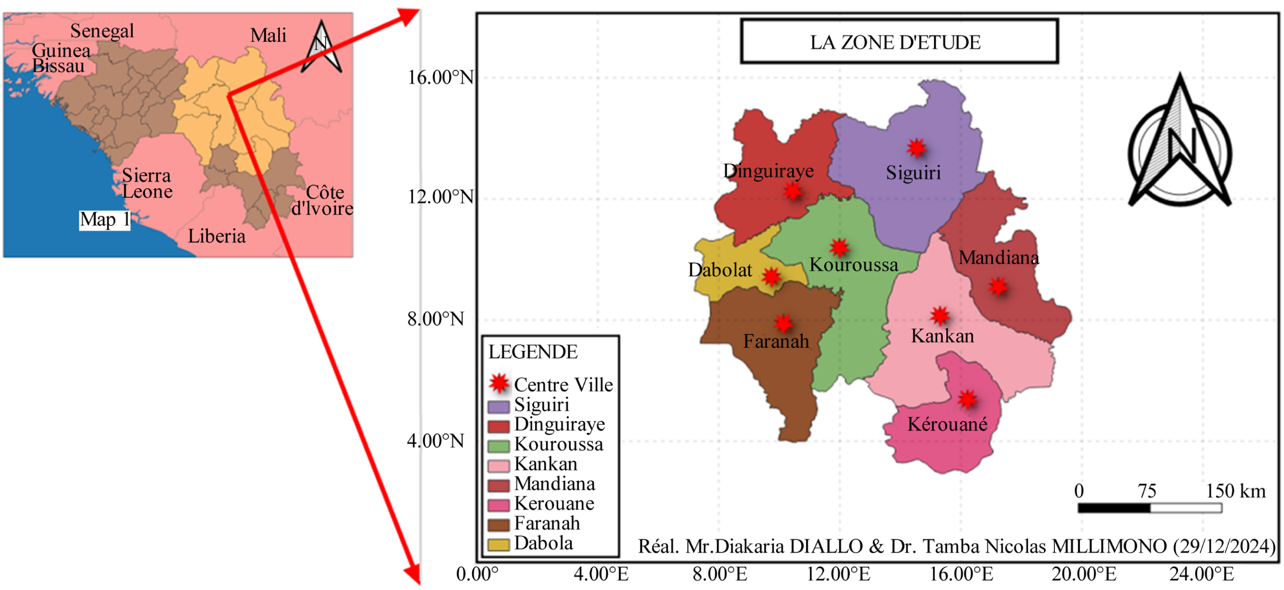

Figure 1. Map of the Upper Guinea region (Republic of Guinea).

The climate regime of Upper Guinea is typical of the Sudano-Sahelian zone, characterized by an alternation between a rainy season (May to October) and a prolonged dry season (November to April). Average annual rainfall ranges between 900 mm and 1200 mm, with a peak generally observed in July or August [16]. During the dry season, the Harmattan (a dry, dust-laden wind from the northeast) prevails, drastically reducing relative humidity and accentuating climatic aridity [16]. This regime is subject to strong interannual variability, largely driven by fluctuations in the West African monsoon system.

Temperatures are generally high, with an annual average exceeding 27˚C. The months of March, April, and May record the most extreme values, with maximum temperatures often exceeding 40˚C [17]. This combination of intense heat and irregular rainfall is further exacerbated by the impacts of global climate change, leading to an increased frequency of climatic extremes [18]. Consequently, the regional climate is becoming increasingly unstable, complex to model, and difficult to predict, with direct implications for ecosystems and livelihoods.

2.2. Data

This study is based on the use of climatic and environmental data covering the period 2012-2021, focused on the Upper Guinea region. Three types of variables were employed:

Normalized Difference Vegetation Index (NDVI): NDVI is a spectral indicator measuring chlorophyll activity and vegetation biomass. The NDVI data were obtained from MODIS satellite sensors (MOD13Q1 or equivalent), with a monthly temporal resolution and a spatial resolution of 250 m. NDVI values were spatially averaged over the study area to produce a representative time series.

Air Temperature: Monthly mean temperature data were derived from reanalysis datasets (ERA5, ECMWF), with a spatio-temporal resolution appropriate for regional-scale analysis. These data allow the identification of thermal trends and anomalies associated with specific climatic events.

Precipitation: Monthly cumulative precipitation data were extracted from calibrated satellite-based sources such as CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data), widely used for climatological analyses in West Africa. The dataset covers the same period as the other variables.

All datasets were preprocessed to ensure homogeneity through spatial interpolation (when necessary), monthly averaging, standardization, and removal of outliers or missing values. The period 2012-2021 was selected due to the simultaneous and continuous availability of these three variables across the study area.

2.3. Methodology

2.3.1. Monthly Climatology

The monthly climatology was obtained by averaging the data for each month m of the year, over the period $t = [2012, 2021]$, as follows:

$$\overline{X}_m = \frac{1}{n}\sum_{i=1}^{n} X_{m,i} \tag{1}$$

where:

- $X_{m,i}$ is the value of month m for year i.
- $n = 10$ is the number of years considered.

This analysis made it possible to characterize the seasonal cycles of climate and vegetation, and to identify lags between precipitation and vegetation response.

2.3.2. Analysis of Interannual Trends

For each variable, a linear trend was estimated using a simple regression model:

$$Y_t = at + b + \varepsilon_t \tag{2}$$

where:

- Y_t is the annual observed value (NDVI, Temperature, or Precipitation).
- t is the year (e.g., 2012-2021).
- a is the slope coefficient (trend).
- b is the intercept.
- ε_t is the random error term.

The significance of the slope was tested using a Student's *t*-test under the null hypothesis $H_0 : a = 0$, with a significance threshold set at $\alpha = 0.05$. A p-value < 0.05 indicates a significant trend.

2.3.3. Standardized Anomalies

To detect atypical years, standardized anomalies were computed using the formula:

$$Z_i = \frac{X_i - \mu}{\sigma} \tag{3}$$

where:

- X_i is the observed annual value for year i.
- μ is the mean over the entire study period.
- σ is the standard deviation.

Standardized anomalies allow for direct comparison of interannual variations across different variables, independently of their unit of measurement.

2.3.4. Correlation between Variables

The linear dependence between pairs of variables X and Y (such as NDVI-Temperature, NDVI-Precipitation) was estimated using the Pearson correlation coefficient, defined as:

$$r = \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}} \tag{4}$$

where:

- $\bar{X}$ and $\bar{Y}$ are the means of the X and Y series.
- n is the number of years.

The results were interpreted according to the strength of the correlation:

- $|r| > 0.7$: strong correlation.
- $0.5 < |\rho| \leq 0.7$: moderate correlation.
- $|\rho| \leq 0.5$: weak to very weak correlation.

The significance of r was assessed using a two-tailed Student's *t*-test with $n-2$ degrees of freedom.

This methodology provides a robust framework to examine the relationships between climate and vegetation dynamics in Upper Guinea, combining descriptive, statistical, and mathematical tools. It lays the groundwork for a better understanding of the impacts of climate change on local ecosystems and agricultural production systems.

3. Results & Discussion

3.1. Results

3.1.1. Monthly Climatology of Upper Guinea

The NDVI (Normalized Difference Vegetation Index), a reliable indicator of vegetation vigor, exhibits low values from January to May, a period characterized by reduced vegetative activity due to pronounced water deficit. From June onward, a gradual increase in NDVI is observed, peaking between September and October before declining progressively from November. This lag of approximately one to two months between the rainfall peak and the NDVI maximum reflects the biological response time of natural vegetation, which requires a certain threshold of accumulated soil moisture to initiate and sustain growth (**Figure 2**).

The seasonal distribution of rainfall in Upper Guinea is typical of a tropical climate with a well-defined dry season. Rainfall is almost absent between January and April, marking a long and harsh dry season (**Figure 2**). The first rains appear modestly in May, before intensifying to reach a distinct maximum in August. This phase is followed by a rapid decline in rainfall from September onward. Consequently, the rainy season extends mainly from June to September, with its intensity concentrated in mid-season. This dynamic directly reflects the influence of the meridional migration of the Intertropical Convergence Zone (ITCZ), whose position governs the temporal and spatial distribution of rainfall in inland West Africa.

The monthly thermal profile of Upper Guinea follows the characteristic evolution of the Sudano-Sahelian zone. Average temperatures increase progressively from January, reaching a peak between April and May, corresponding to the annual thermal maximum, as shown in **Figure 2**. Thereafter, a significant decline in temperatures occurs between June and August, driven by the onset of the rainy season, which is accompanied by increased cloud cover and a cooling effect induced by rainfall and evaporation. At the end of the season, between October and November, temperatures rise slightly again, marking the transition toward the new dry season.

A joint analysis of NDVI, rainfall, and temperature curves highlights the strong interdependence between climatic conditions and vegetation dynamics in Upper Guinea. Vegetative growth depends primarily on the amount and timing of rainfall, but is also influenced by temperature, which regulates processes such as evapotranspiration and species phenology. The temporal lag observed between the rainfall peak and the NDVI maximum illustrates this delayed ecological response. These interactions emphasize the need for an integrated monitoring of climatic and ecosystem variables to better understand the potential impacts of climate change on agro-ecological systems in Upper Guinea.

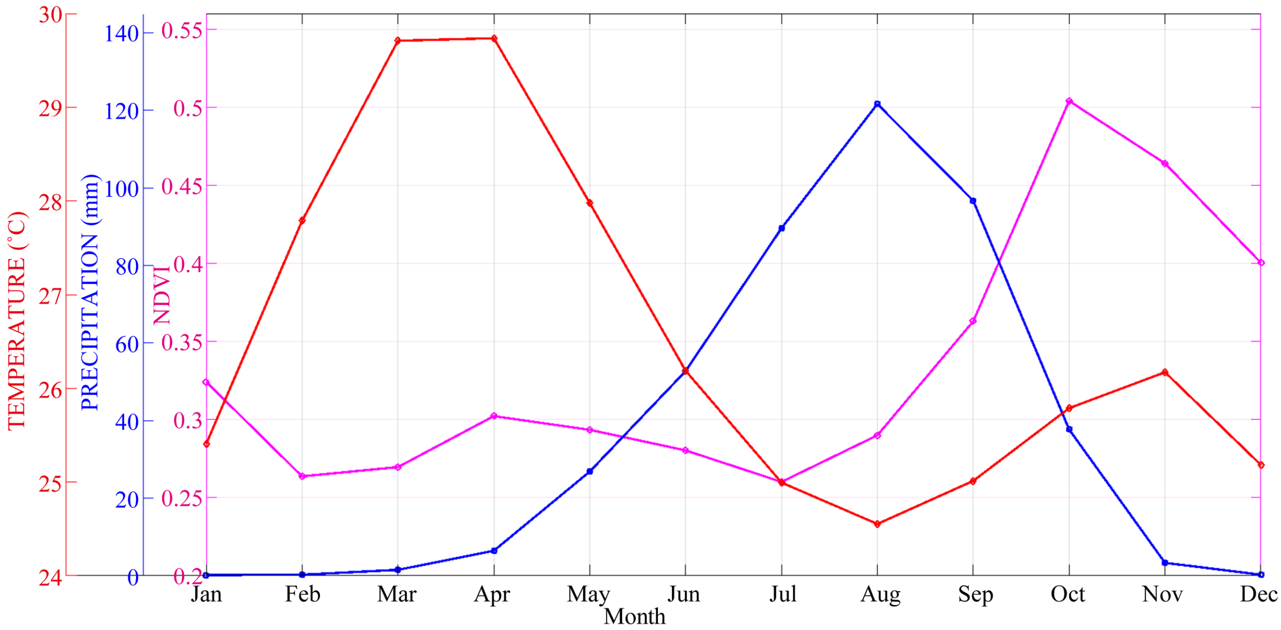

Figure 2. Monthly evolution of three climatic and environmental variables: mean temperature (red), precipitation (blue), and the NDVI vegetation index (magenta).

3.1.2. Interannual Trends in Upper Guinea: Temperature, Precipitation, and NDVI (2012-2020)

Figure 3 presents the interannual evolution of NDVI, precipitation, and mean annual temperature in Upper Guinea between 2012 and 2020. These variables are depicted with distinct curves and their respective linear trends, allowing an assessment of climatic and ecological dynamics at the interannual scale.

Mean annual temperature (red curve) exhibits a statistically significant upward trend (trend = 0.091˚C/year, p = 0.000), indicating a progressive warming of the region during the study period (**Figure 3**). This thermal signal, consistent with trends observed in the Sahel and inland West Africa, can be attributed to the global temperature rise associated with climate change. Such thermal increase may have notable effects on evapotranspiration, water availability, and plant heat stress.

Mean annual precipitation (blue curve) also shows a slight upward trend (trend = 0.234 mm/year), though it is not statistically significant (p = 0.512). This lack of significance suggests that, despite pronounced interannual fluctuations, no systematic change in rainfall occurred during the period under consideration (**Figure 3**). This instability may reflect the influence of climatic variability drivers such as the ITCZ, ENSO, or the Atlantic Niño, which modulate rainfall regimes at short- and medium-term scales in the region.

NDVI (magenta curve), as an indicator of vegetation productivity, displays a progressive increase with a trend of 0.009 NDVI/year, statistically significant (p = 0.018). This positive trend suggests a slow but tangible improvement in annual vegetation cover in the region (**Figure 3**). The increase in NDVI may result from a combination of factors: a slight rise in precipitation, improved agricultural practices (reforestation, soil conservation), or the adaptive response of certain plant species to emerging climatic conditions.

A comparison of the three variables highlights the complex interdependence between climate and ecological dynamics. Significant warming may, in some cases, stimulate vegetative growth at the beginning of the season through enhanced photosynthesis, provided that soil moisture is sufficient. However, excessive warming, if not offset by increased precipitation, may exacerbate water stress. NDVI appears to respond in a delayed and integrated manner to climatic variability, particularly to favorable rainfall episodes, even though rainfall itself does not display a significant long-term trend (**Figure 3**).

These results underscore the importance of monitoring both climatic and ecological trends simultaneously. In Upper Guinea, despite the absence of a significant change in rainfall, temperature is rising markedly, requiring close attention to its potential impacts on ecosystems, agriculture, and food security. The improvement in NDVI constitutes an encouraging signal, but its sustainability remains conditioned by the fragile balance between water availability, heat, and the resilience capacity of local ecosystems.

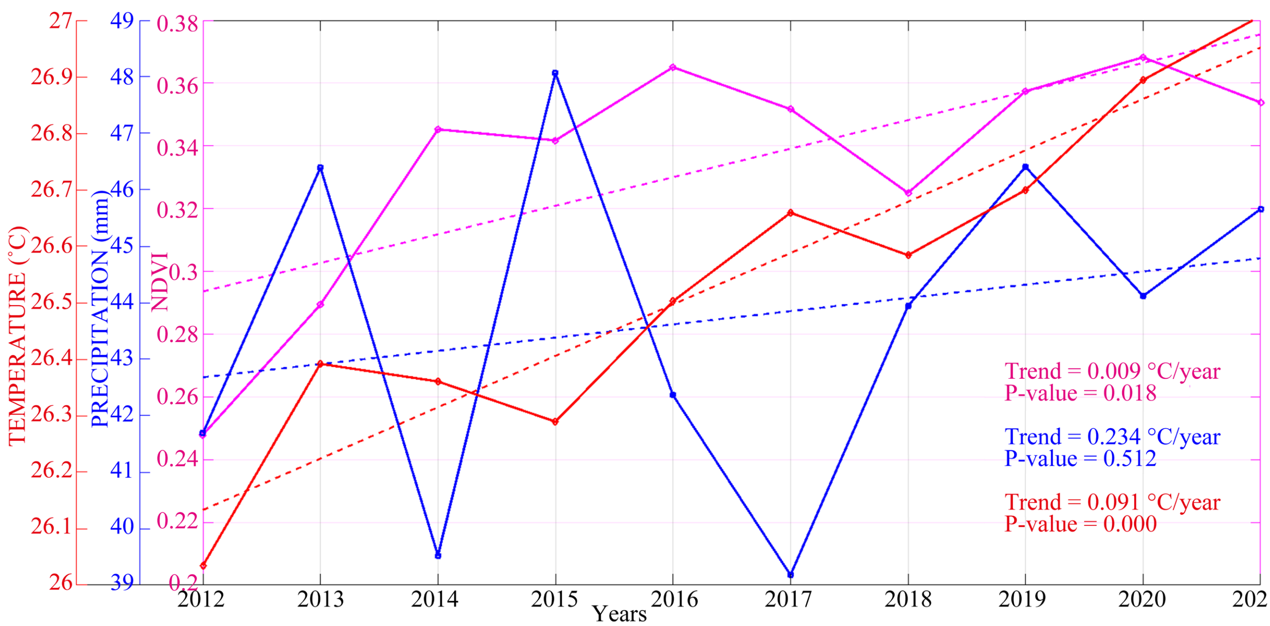

Figure 3. Interannual evolution of NDVI, precipitation, and mean annual temperature in Upper Guinea between 2012 and 2020.

3.1.3. Evolution of Standardized Climate and Vegetation Anomalies in Upper Guinea (2012-2021)

Figure 4(a) reveals a significant positive trend in NDVI anomalies, with a rate of 0.2391 NDVI/year and a p-value of 0.0318, indicating a progressive improvement in vegetation vigor over the past decade. Negative values (in pink) are concentrated at the beginning of the period (from 2012 to 2014), reflecting unfavorable ecological conditions, likely associated with water or heat stress. From 2015 onward, anomalies are predominantly positive (green bars), suggesting a recovery and increasing stability of vegetation cover in the region. This evolution may be linked to ecosystem adaptation, more resilient agricultural practices, or climatically favorable years.

In Figure 4(b), standardized precipitation anomalies display a slightly positive but statistically non-significant trend (0.0720 mm/year, p = 0.4743). This lack of statistical significance indicates pronounced interannual variability without a clear upward or downward tendency. Wet years (blue bars), such as 2013, 2015, and 2021, contrast with deficit years (pink bars), such as 2012, 2014, and 2017. This rainfall instability, characteristic of Sudano-Sahelian zones, is often associated with large-scale climate variability factors (ENSO, Atlantic oscillations, and the position of the ITCZ).

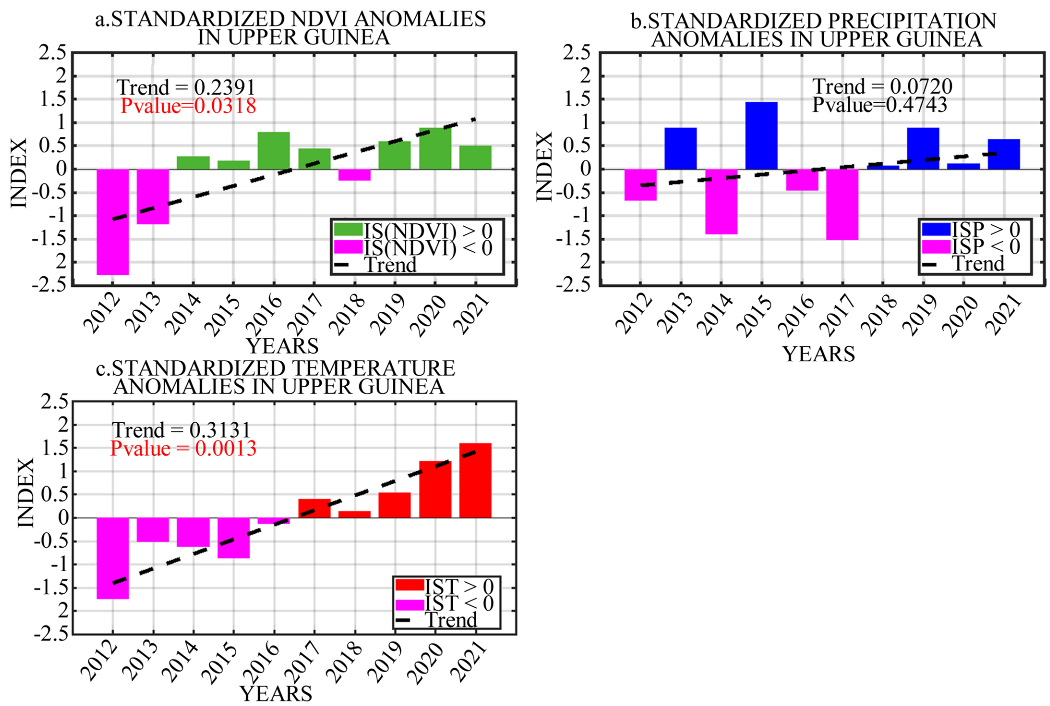

Figure 4. Standardized anomalies of (a) NDVI, (b) precipitation, and (c) temperature in Upper Guinea over the period 2012-2021, along with the associated linear trends.

Figure 4(c) highlights a clearly positive and highly significant trend in temperature anomalies, with a rate of 0.3131˚C/year and a p-value of 0.0013. This indicates accelerated warming in Upper Guinea over the study period. Since 2017, anomalies have been systematically positive (red bars), with marked thermal intensification in 2019, 2020, and 2021. Such warming may significantly impact ecosystem processes, particularly by reducing soil moisture, accelerating evapotranspiration, and altering vegetation phenology.

A joint analysis of the three series reveals a complex relationship between temperature, precipitation, and vegetation. While rainfall remains broadly stationary, temperature increases significantly, potentially exacerbating water stress conditions if evaporation is not compensated by sufficient rainfall inputs. Nevertheless, the positive NDVI response suggests an adaptive capacity of vegetation cover under growing climatic constraints, possibly supported by effective episodic rainfall or biological and anthropogenic resilience strategies.

This situation underscores the importance of integrated, multidimensional monitoring of climatic and ecological variables to better understand ecosystem dynamics in Upper Guinea under climate change. The contrast between significant warming and stationary rainfall highlights the determining role of temperature as a pressure factor, while the NDVI response reflects a nuanced ecological dynamic that warrants close monitoring.

3.1.4. Correlation Analysis between Vegetation Index, Temperature, and Precipitation

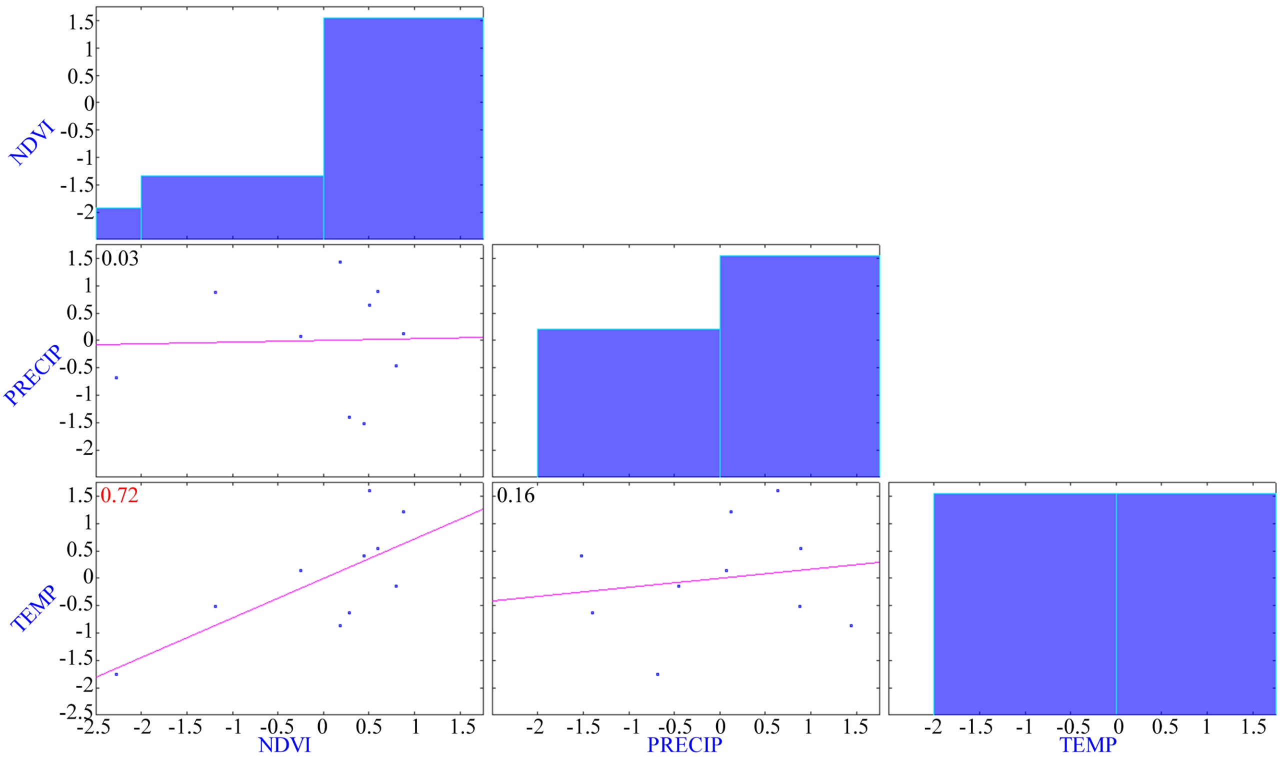

Figure 5. Correlation matrix of three standardized climate variables: NDVI (vegetation index), PRECIP (precipitation), and TEMP (temperature). Scatterplots with fitted linear regressions are shown in the off-diagonal panels, while the main diagonal displays histograms of standardized values. Pearson correlation coefficients are reported, with significant values highlighted in red.

The correlation coefficient between NDVI and TEMP is 0.72, indicating a strong and statistically significant positive correlation. This suggests that as temperature increases, the NDVI also tends to increase. Such a relationship may reflect a positive sensitivity of vegetation to heat in the study area, potentially associated with an active growing period or a warm season favorable to biomass development (**Figure 5**).

In contrast, the correlation between NDVI and PRECIP is very weak (0.03), suggesting virtually no linear relationship between precipitation and vegetation index in the analyzed dataset. This may be explained by several factors: precipitation might not be the limiting factor for vegetation growth in the region; the vegetation response could be delayed in time (lag between rainfall and plant growth); or the study period might be too short or not representative enough to capture this link (**Figure 5**).

Finally, the correlation between PRECIP and TEMP is moderately weak (0.16) and statistically non-significant (**Figure 5**). This points to a relative independence between temperature and precipitation within the dataset. Such a decoupling is common in regions where climatic regimes are governed by distinct atmospheric processes. Overall, these results highlight a strong interdependence between NDVI and TEMP, while the relationships between NDVI and PRECIP, as well as between PRECIP and TEMP, are weak or negligible. This underscores the importance of considering the variability of climatic factors separately in ecological or agro-meteorological analyses.

3.2. Discussion

The results highlight a complex climatic and ecological dynamic in Upper Guinea between 2012 and 2021. The strong seasonality observed in the monthly climatology, characterized by a long dry season and a short rainy season, is typical of Sudano-Sahelian regions [19]. The lag between the rainfall peak (August) and the vegetation maximum (September-October) reflects a delayed phenological response, driven by the prior accumulation of soil moisture required to trigger germination and growth processes [20]. The behavior of NDVI, a well-established indicator of vegetation productivity [21], confirms that vegetation vigor is more sensitive to the timing and effective availability of water than to the bulk amount of precipitation. Furthermore, the decline in temperatures observed during the rainy season can be explained by increased cloud cover and relative humidity, both of which reduce solar radiation and thus maximum temperatures [22].

At the interannual scale, the significant upward trend in mean annual temperatures (+0.091˚C/year) confirms the influence of regional climate warming, as documented in several recent studies in West Africa [2] [11]. This thermal evolution may disrupt hydrological balances and increase evapotranspiration, thereby intensifying soil and vegetation water stress. Paradoxically, despite this constraint, the results indicate a significant improvement in NDVI, suggesting a positive vegetation response. This phenomenon may be interpreted as a sign of resilience or ecological adaptation, potentially linked to more sustainable agricultural practices (reforestation, improved fallow) or shifts in floristic composition favoring stress-tolerant species [23] [24].

The weak correlation between NDVI and precipitation ($r = 0.03$) corroborates earlier studies showing that vegetation response to rainfall is often non-linear and temporally lagged [25], while the strong correlation between NDVI and temperature ($r = 0.72$) suggests that moderate temperatures can stimulate photosynthesis, provided that soil moisture is sufficient. This reinforces the idea that intra-seasonal variability, rather than annual means, exerts the strongest influence on vegetation productivity [26].

4. Conclusions

This study highlights the complex interactions between climatic variables and vegetation dynamics in Upper Guinea over the period 2012-2021. The findings reveal that, despite strong interannual variability in precipitation and the absence of a significant long-term trend for this variable, mean temperature exhibits a marked and continuous increase. This thermal rise, consistent with regional signals of climate warming, exerts a positive influence on NDVI—an indicator of vegetation productivity—which also displays a significant upward trend. The strong correlation observed between temperature and NDVI (r = 0.72) suggests that, within the ecological context of Upper Guinea, temperature is a key determinant of vegetation growth, whereas the relationship with precipitation remains marginal at the interannual scale.

These results point to a certain adaptive capacity of local ecosystems to increasing thermal constraints, potentially reinforced by agricultural or ecological resilience dynamics. However, such resilience could be undermined if warming intensifies without adequate hydrological compensation, thereby exacerbating stress on agro-ecological systems. In this context, the study underscores the need for integrated, continuous, and multidimensional monitoring of climatic and ecological variables to anticipate the impacts of climate change on natural resources, food security, and agricultural practices in Upper Guinea. This work provides a valuable foundation to inform adaptation policies, strengthen sustainable land management, and promote resilience strategies in the face of climate variability in this strategic region of West Africa.

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Conflicts of Interest

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

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