

Biophysical indicator-based assessment of climate change severity in the Upper East Region, Ghana

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ABSTRACT

Climate change has continued to be a pressing concern, particularly for climate-vulnerable regions around the world, including Sub-Saharan Africa. While climate change is occurring at a rapid rate, its impact increases in severity. This article examines the biophysical assessment of climate change severity in the Upper East Region (UER) of Ghana. The study's methodology combines satellite remote sensing data, field surveys, participatory mapping, and policy analysis. A year-long mean, Normalised Differential Vegetation Index (NDVI), rainfall pattern, evapotranspiration (ETa), and Land Surface Temperature (LST) were generated for four different years from Google Earth Engine. A survey involving 200 respondents was also conducted to complement the satellite-based imagery. The findings of the study showed a decline in the mean annual NDVI from 0.40 in 1990 to 0.35 in 2024, thus indicating a decline of 14% in vegetation health. The NDVI decline reveals a transition in vegetation from Sudan to Sahel savannah, suggesting an increasing climate change impact in the region. Rainfall also indicated a downward trend, thus reducing from 1216 mm/yr in 1990 to 1089 mm/yr in 2024. Also, we discovered an upward trend in LST, with mean maximum LST increasing from 39 °C in 2013 to 45 °C in 2024 and mean minimum LST increasing from 31 °C to 33 °C. In the same trend, ETa results suggest increasing evapotranspiration from a mean maximum of 113 mm/yr in 2000 to 178 mm/yr in 2024. While satellite-based data has revealed worsening climatic conditions in the UER, smallholder farmers acknowledge this and lament that its impact threatens their livelihoods and food security in the region. To address the situation, proactive climate action through collective effort, institutional commitment, and long-term localised adaptation strategies has been recommended.

1. Background

Global climate change is unfolding rapidly than at any other epoch in human history. These unfolding changes, without doubt, are caused by anthropogenic activities. According to Summerhayes et al. (2024), the intensification of human-forced climate change may have begun as early as the 1960s and 1970s. Scientific consensus posits that the primary causes of climate change are human-induced activities, including the burning of fossil fuels, deforestation and industrialisation (Intergovernmental Panel on Climate [IPCC], 2021). In contemporary times, climate change has remained one of the major pressing environmental

challenges that has attracted the focus of the scientific community. This stems from the fact that its impact is catastrophic and has major effects on the earth's ecosystems, weather patterns and challenges the very existence of humanity. In essence, climate change is a threat multiplier (WHO, 2023; Dodson et al., 2020) and remains the biggest threat to global health, development and wellbeing of the current and future generations (Cuartas et al., 2025).

Across many fronts, the impacts of climate change are already evident. These occur in the form of extreme weather events, melting ice caps, disruptions to agriculture, and disproportionately affect vulnerable populations (Dodson et al., 2020; World Bank, 2022). The

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combined effect of these evolving impacts reveals that Earth's natural systems are under siege, as shown by rapid shifts in global rainfall patterns, rising average surface temperatures, and widespread land and environmental degradation. For instance, according to IPCC (2021), the global average temperature has risen by approximately 1.1°C, surpassing the pre-industrial era and contributing to more frequent and intense heatwaves. Following this, precipitation patterns are also fluctuating across and within regions, with some regions now experiencing severe rainfall and flooding, while others face prolonged and persistent drought conditions (IPCC, 2023). Other global bodies, such as the United Nations Convention to Combat Desertification [UNCCD] (2022), assert that land degradation caused by desertification, soil erosion, and deforestation is reducing agricultural productivity and threatening biodiversity. This synergy of intertwined global challenges poses a considerable risk to the Earth's ecosystem (Malhi et al., 2020; Kasperson et al., 2022).

Although climate change is a global phenomenon, some studies suggest that its impact is unevenly distributed (e.g. Choongik, 2025; Odeku, 2022). Low-income countries and arid and semi-arid regions face elevated risks due to economic constraints and geographic vulnerabilities. According to Rantanen et al. (2022), the Arctic region, for instance, is warming almost four times faster than the global average, resulting in considerable ice melt and ecosystem disruptions. Some studies have equally revealed that small island nations in the Pacific and Caribbean seas are threatened by a continuous rise in sea level and tropical storms (e.g., Stephenson and Jones, 2017; IPCC, 2022), while most parts of Asia grapple with extreme monsoon storms (Yadav, 2022; Phongpaichit, 2024; World Bank, 2021).

Interestingly, Sub-Saharan Africa (SSA) contributes only about 7% of global emissions to climate change, yet SSA suffers the highest burden of global climate change impact (Nyinyari and Gweyi-Onyango, 2020). In SSA, the effects of climate change are particularly pronounced, impacting biodiversity at all levels, from genetic diversity to entire ecosystems (Sintayehu, 2018; Iyiola et al., 2022) and accelerating the risk of extinction of certain flora and fauna species (Iyiola et al., 2022). The continent, according to Sintayehu (2018), is experiencing increasing warming, resulting in frequent and severe weather disturbances that threaten biodiversity and certain sensitive ecosystem services. For instance, Dallas and Rivers-Moore (2014) have indicated that freshwater systems in South Africa are experiencing significant declines in quality and availability, with a ripple effect for aquatic biodiversity.

Ghana is not immune to climate change. Like other countries, Ghana is also experiencing rising surface temperatures, fluctuations in rainfall patterns and other extreme weather events. Reports indicate that Ghana ranks 109 out of 181 countries in global climate change vulnerability (Notre Dame Global Adaptation Initiative, 2020). Regionally, Ghana's northern-most regions are at extreme risk to climate change, with some studies documenting rapid temperature increases (Klutse et al., 2020; Abbam et al., 2018), fluctuations in rainfall patterns (Klutse et al., 2021; Owusu, 2018) and other extreme weather events, including drought (Adonadaga et al., 2022; Antwi-Agyei et al., 2013). These changes disproportionately affect communities that are highly dependent on rain-fed agriculture, where less than 1% of cropland is irrigated (World Bank, 2021).

The Upper East Region of Ghana has remained one of the major food basket areas in the country. While this is the case, increasing climate change in an already climate-fragile region raises concerns of future food security threats and their implications on agrarian livelihoods. This growing threat of climate change in an already climate-deteriorating region mandates the choice of the UER as the study area. Although a plethora of studies have been conducted on climate change at UER (e.g. Atitsogbey et al., 2018; Apuri et al., 2018; Baffour-Ata et al., 2021; Kumasi et al., 2019; Owusu et al., 2024; Ampadu et al., 2018; Tangonyire and Akuriba, 2021), yet most of these studies overly focused on household climate change adaptation (e.g. Ampadu et al., 2018; Apuri et al., 2018; Baffour-Ata et al., 2021; Kumasi et al., 2019), gender dimensions of climate change vulnerability (Nuhu and Matsui, 2022;

Alhassan et al., 2019), and spatiotemporal dynamics in weather and climate variabilities (Issahaku et al., 2016; Ampadu et al., 2019; Quaye-Ballard et al., 2020). Other studies also explored the issue of food insecurity (Gifty et al., 2024; Atitsogbey et al., 2018). Overall, these studies have deepened our understanding of climate change vulnerability, adaptation strategies, gender-based vulnerability and dynamics in regional climatic conditions. Notwithstanding this, the extent of climate change severity and its implications on farming in the UER remains a grey area that needs to be explored. Against this backdrop in research, this current study seeks to fill the void by examining the biophysical assessment of climate change severity in the UER of Ghana.

This study plays a crucial role in comprehending the severity and/or the spatial extent of climate change through a combination of multiple biophysical assessments and local knowledge. The combination of satellite data and field surveys is fundamental in leveraging the strengths of both data sources. According to Bento et al. (2020), the adoption of quantifiable biophysical indicators such as vegetation health, rainfall, and land surface temperature allows researchers to objectively assess spatio-environmental changes. Similarly, Quaye-Ballard et al. (2020) have argued that the adoption of biophysical analysis, especially for vulnerable regions such as the UER, provides insight while combining with local knowledge. The success of this approach will enable targeted adaptation strategies for better resilience to climate change. To that end, localised assessments become a rich source of data for integrated assessments that are vital for informing targeted interventions, guiding policy, and strengthening the resilience of communities already facing the harsh realities of climate change.

The study also adds to the literature on assessment of climate change severity in a number of methodological ways. Integrating socio-economic validation data with satellite data is one significant innovation that enhances the precision and local applicability of geospatial findings (). By fusing multigenerational community narratives with 34 years of remote sensing data, the study also adds temporal depth, providing a nuanced understanding of long-term change (Berkes, 2004).

The incorporation of scientific discoveries into practical policy frameworks is another contribution. Through the integration of stakeholder dialogues and field data, the research produces actionable insights for adaptation-focused local governments and non-governmental organisations (LSE, 2024). This interface between research and policy helps guarantee that results are converted into workable adaptation strategies.

2. Study area and methodology

2.1. Profile of study area

The Upper East Region (UER) is located in the northeastern corner of Ghana. It is bordered to the North by Burkina Faso, to the East by Togo, to the West by Sissala East District and to the South by the Northeast Region (Fig. 1). The UER lies between latitudes 10°30'N and 11°10'N and longitudes 0°00'W and 1°30'W. Its capital is Bolgatanga, with other major towns including Tongo, Garu, Bawku and Navrongo. The region spans an area of approximately 8842 km², accounting for 4% of Ghana's total land area (GSS, 2021). Topographically, the region is fairly low-lying with gentle undulations, with topographical heights of up to 300 m above sea level (Agyekum and Dapaah-Siakwan, 2008). The latitudinal position of the UER places it within the influence of the Intertropical Convergence Zone (ITCZ), contributing to its distinct climatic patterns. The climate is characterised as Sudan Savannah, with a unimodal rainy season occurring between May/June and peaking in October/November. Mean annual rainfall ranges from 900 mm to 1150 mm, and average temperatures typically range between 28°C and 34°C (Yiran and Stringer, 2016). Over the years, the region has experienced increasing rainfall variability, including prolonged dry spells and intense, short-duration storms (Quaye-Ballard et al., 2020).



Fig. 1. Map of UER
Source: [Owusu et al. \(2024\)](#).

2.2. Vegetation, soil, and hydrology

Vegetation in UER is predominantly Sudan Savannah, featuring open grasslands with drought-resistant trees such as shea and baobab. However, there has been a steady decline in vegetative cover due to human activity and environmental stress ([Liu et al., 2016](#)). Soils in the area are predominantly Lixisols, which are generally poor in nutrients and highly susceptible to erosion, especially under continuous cultivation and severe thunderstorms. The UER is drained by parts of the White Volta basin and its tributaries, and its flow is influenced by seasonal flow and spillage from the Bagre Dam in Burkina Faso ([Abanyie et al., 2020](#)). According to the 2021 census statistics, the population of UER is 1.31 million and represents 4.2% of Ghana's population. The region is predominantly rural, with about 79% of the population residing in rural areas (GSS, 2021).

2.3. Socio-economic activity

Agriculture is the primary economic activity, employing over 90% of the workforce. The region's farming system is mostly rainfed, with the vast majority of households producing basic crops such as maize, millet, and sorghum. Farm sizes are often small, usually less than 2 ha, limiting production and the adoption of modern farming technologies. An alternative source of income and food security is the rearing of livestock, such as cattle, goats, and chickens. The region was chosen for this study because the region's socioeconomic weaknesses and reliance on climate-sensitive agriculture highlight how urgent it is to advance sustainable, climate-resilient development solutions.

2.4. Methods of data collection and analysis

To thoroughly assess the severity of climate change and its effects in Ghana's UER, this study used a triangulation of methods. The

methodology combined satellite remote sensing, field surveys, participatory mapping, and policy analysis (O'Brien, 2006). This was to help provide a thorough and localised understanding of climate change vulnerabilities and adaptation strategies in the UER. The validity and reliability of the results were improved by the triangulation of data from several sources made possible by this integrated approach (Bryman, 2016).

3. Data source

To capture the many facets of the severity of climate change, the study makes use of a variety of complementary data sources. An essential part of the biophysical evaluation is satellite data. Accessible through Google Earth Engine, time-series data (1990–2024) obtained from Landsat (LST, NDVI, CHIRPS) and MODIS (Evapotranspiration) imagery offer information on important environmental variables. According to Limon (2024), the Normalised Difference Vegetation Index (NDVI) is used to evaluate the health of the vegetation and identify patterns in the change of the land cover, which can reveal processes like desertification and land degradation. To find hotspots suffering from heat stress and temperature anomalies, land surface temperature (LST) is tracked (Limon, 2024). While evapotranspiration data is analysed to assess drought conditions and water balance (Ampadu et al., 2020), rainfall patterns are analysed using long-term rainfall data to identify variability and trends over time (Senay et al., 2016).

Fieldwork in April and May of 2025 provided the study with data on local knowledge of climate change variability. This mark the period when farmers prepare their lands for planting. As a result, the farmers were available to respond to the questionnaires. The study surveyed 200 long-term residents who had lived in their communities for at least 35 years. This criterion was chosen based on the premise that one needed to live long enough in the community to have noticed changes in climatic conditions and their severity on local people. The recruitment of the survey respondents was conducted using the simple random sampling technique. This technique was employed to give a fair chance of inclusion in the sample population. The sample size of 200 survey responses was maintained because the region was plunged into an insurgency at the time of data collection, thus disrupting data collection activity.

In the same trend, several of the surveyed population participated in a structured interview session. This was to add quality data to the quantitative data gathered through surveys. According to Nyong et al. (2007), these interviews produced in-depth accounts of the perceived effects of climate change, coping mechanisms, and modifications to livelihood practices. Using GPS-based field reconnaissance, participatory mapping was carried out in ten selected districts. Areas that residents believe are susceptible to the effects of climate change were asked to be identified and mapped. This activity produced locally grounded spatial data by combining indigenous knowledge with geospatial validation (Corbett et al., 2005). The local observation through surveys and interviews were presented alongside the satellite for validation during the presentation of the study findings and discussions.

Transcripts of stakeholder discussions conducted in April 2025 were used to gather policy-level data. Twelve key informants from district assemblies, non-governmental organisations, and climate-related agencies participated in these. Policy frameworks, implementation obstacles, and chances to assist local adaptation efforts were the main topics of discussion (Biesbroek, 2021).

Fieldwork was strategically timed during the dry-to-wet season transition (April–May 2025), capturing seasonal variations in environmental conditions. Participatory mapping employed GPS units with an accuracy of less than 5 m, ensuring spatial precision. Sampling for interviews and FGDs was stratified by age, gender, and livelihood group, capturing a wide spectrum of experiences and vulnerabilities. These steps collectively enhance the credibility, reliability, and representativeness of the findings.

4. Data analysis

4.1. Biophysical assessment

To assess the severity of climate change in the UER, four primary indicators (Normalised Differential Vegetation Index (NDVI), Evapotranspiration (ETa), Land Surface Temperature (LST) and Climate Hazards Infrared Precipitation with Station data (CHIRPS)) were used. This choice was based on the premise that the convergence of multiple evidence guarantees a high level of accuracy of results. The analysis was conducted over a 34-year period, from 1990 to 2024, a timeframe that coincides with shifts in regional weather patterns and a marked decline in agricultural productivity (Sidibé et al., 2016; Yiran and Stringer, 2017). The study utilised the Google Earth Engine platform to compute the mean annual Normalised Difference Vegetation Index (NDVI) using Landsat satellite imagery. Spatial extent and annual mean NDVI were defined using the standard formula:

$$NDVI = (\text{float}(b1 - b2)) / (\text{float}(b1 + b2)) \quad \text{Eqn (1)}$$

This method of calculating mean annual NDVI helped minimise the influence of short-term seasonal fluctuations and cloud interference. NDVI values theoretically range from -1 to $+1$, with higher values indicating healthier, denser vegetation. In practice, values for healthy green vegetation typically fall between 0.2 and 0.8 (Owusu, 2018; 2013a; 2013b). Years with complete and high-quality NDVI imagery were selected to assess temporal trends and document any decline in vegetative cover as a proxy for land degradation.

In a related methodological approach, another study applied Theil-Sen slope analysis—a non-parametric statistical method that is resistant to outliers—to detect long-term NDVI trends (Eastman, 2009). This analysis revealed statistically significant patterns of vegetation decline, which were then validated through a combination of field-based techniques. Soil profile inspections and vegetation surveys offered direct ground-truthing for the satellite-derived data, ensuring that observed trends were not merely remote-sensed anomalies but reflected actual ecological conditions (Thomas and Middleton, 1994). In addition to ecological observations, local knowledge was incorporated through community interviews to further contextualise and confirm the accuracy of satellite-detected land degradation.

Also, the Land Surface Temperature (LST) of the study area for the years 2013, 2015, 2017, 2019, 2022 and 2024 was retrieved from Google Earth Engine (GEE) using three steps and three formulas:

In step 1, the digital numbers of the thermal bands were converted to spectral radiance using the formula:

$$L\lambda = L_{\min} + (L_{\max} - L_{\min}) \times \frac{DN}{255} \quad \text{Eqn(2)}$$

According to Kafy et al. (2021), $L\lambda$ is the spectral radiance. For Landsat 5, $L_{\min} = 1.238$; $L_{\max} = 15.30$; for Landsat 7, $L_{\min} = 0.0$; $L_{\max} = 17.04$; For Landsat 8, $L_{\min} = 0.10033$; $L_{\max} = 22.00180$.

In step 2, the spectral radiance was then converted to atmospheric brightness temperature using the formula:

$$T_B = \frac{K_2}{\ln \left(\left(\frac{K_1}{L\lambda} \right) + 1 \right)} \quad \text{Eqn (3)}$$

where K_1 is the Calibration constant 1; K_2 Calibration constant 2; For Landsat 4, $K_1 = 671.62$; $K_2 = 1284.30$; For Landsat 7, $K_1 = 666.09$; $K_2 = 1260.56$; For Landsat 8, $K_1 = 480.88$; $K_2 = 1201.14$ (Kafy et al., 2021).

In step 3, the measured LST is then converted to degrees Celsius ($^{\circ}\text{C}$) using the formula:

$$T_B (^{\circ}\text{C}) = T_B (K) - 273.15. \quad \text{Eqn (4)}$$

5. Socioeconomic validation

Interview and FGD transcripts were analysed thematically to extract dominant perceptions of climate change, such as changing rainfall patterns, increased temperatures, and soil degradation (Braun and Clarke, 2006). Also, the 200 responses through the surveys were coded and analysed using IBM SPSS (Version 27). These local socio-economic narratives were cross-referenced with satellite data to assess alignment and identify areas of mismatch. In doing so, the study triangulates remote sensing findings with community insights, adding depth and credibility to the analysis.

Adaptation strategies were categorised based on field responses and then analysed to identify common practices. These included diversified cropping, tree planting, and seasonal migration. The strategies were then reviewed alongside insights from stakeholder policy dialogues to explore the potential for policy integration (Smit and Wandel, 2006; NAP Global Network, 2024). Special attention was given to how local adaptation practices could be scaled up or supported by formal governance frameworks.

The results were displayed using a mix of qualitative syntheses, temporal charts, and spatial visualisations. By combining satellite data and local knowledge, spatial maps identify areas with varying severities of climate change. Temporal charts provide a historical summary of environmental change by displaying 34-year trends in important climate variables like temperature, vegetation health, evapotranspiration and rainfall. Gaps in policy implementation are examined, along with suggestions for enhancing local governance and adaptation planning. A non-parametric statistical test, particularly the Mann-Kendall trend test

was computed to examine the trends in the biophysical indices employed.

6. Results and discussion

The findings of the data collected and analysed are presented to provide evidence of climate change severity in the Upper East Region (UER) of Ghana. The biophysical indicators NDVI, CHIRPS, LST, and ETa employed in this regard were presented and discussed in tandem to highlight the synergy between the factors.

7. Evidence of perceived vegetation decline in the UER

Declining quantity and health of vegetation is the earliest and most noticeable evidence of climate change (Hartmann et al., 2022; Owusu et al., 2024). Vegetation dynamics are significantly influenced by changes in climate patterns. The most influential factors in enhancing plant and vegetation coverage are rainfall and temperature (Chang et al., 2011). In this study, NDVI-based evidence was employed to examine the health of vegetation over the period spanning 34 years in the study area (1990–2024). The satellite-based NDVI data revealed a rapid diminish in vegetation health across the UER (Fig. 2). For example, the mean maximum NDVI for the initial year (1990) recorded a value of 0.4. This value fluctuated throughout the study period reaching 0.35 in 2024 (Fig. 2). The mean minimum NDVI values, on the other hand, fluctuated between -0.13 and -0.2 . This trend of NDVI values suggests a gradual transition of the UER from a Sudan Savannah vegetation to a more Sahel vegetation area. Spatially, vegetation decline is

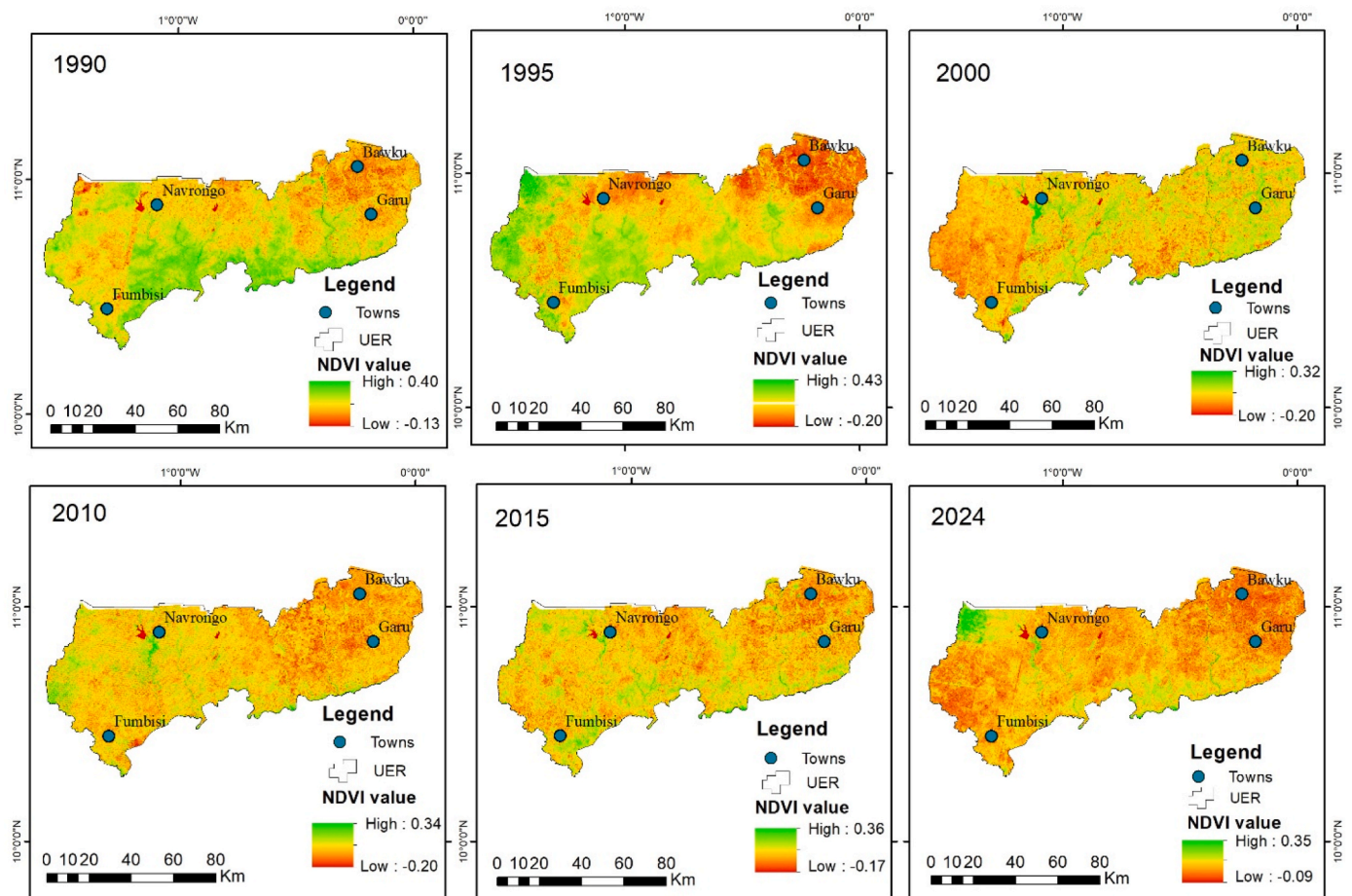


Fig. 2. Evidence of declining vegetation.
Source: Authors' construct (2025)

more prevalent in the eastern sections of the UER, specifically in agriculture-dominated areas including Bawku and Garu. Studies by other authors (e.g. Owusu et al., 2024; Quaye-Ballard et al., 2020; Owusu et al., 2013) have discovered similar findings in the UER. For instance, using the multi-resolution analysis to examine NDVI from 1982 to 2015, Quaye-Ballard et al. (2020) discovered that vegetation in the UER is eroding at a rapid rate, with the degraded areas located in the northeast towards the middle of the UER. Similarly, Owusu et al. (2024) examined desertification conditions in the UER between 1986–2022. The study revealed that vegetation in the UER has been rapidly dwindling relative to past years, where the mean maximum NDVI declined from 0.5 in 1986 to -0.12 in 2022. The findings of this current study converge with those of the above-cited studies, and reaffirm the fact that climate change is fast unfolding and rapidly depleting vegetation resources - signalling that the Sahelian aridity of neighbouring countries, including Burkina Faso and Niger, is rapidly gravitating towards the UER and reshaping the area's ecology.

The satellite NDVI data was triangulated with fieldwork validation through personal observation, interviews and open-ended questionnaires. It was revealed through observation that districts such as Garu-Tenpane and Bawku now exhibit expansive bare soils, scattered vegetation species and fragmented grassland. Some respondents attributed these recent biophysical changes to several factors, including erratic rainfalls, cattle overgrazing of the vegetation by the Fulani herdsmen from Burkina Faso and Niger. Some local farmers have, however, expressed concern about the rate of vegetation decline. In response to an open-ended questionnaire, a respondent indicated,

"I think climate change is real. In previous years, we used to have a lot of vegetation with different species of trees for both food and medicinal purposes. But these days, most of these trees have died. What we have left are a few patches of scattered trees and light grasses. You can hardly even get a full-grown tree that will serve as shelter". [A male respondent, personal interview]

The continuous decline in vegetation in the UER is both a consequence and a major driver of climate change. This disrupts biophysical and ecological balance and presents an urgent call for sustainable actions such as reforestation, pasture rehabilitation and sustainable land management initiatives. Without these interventions, the UER risks losing not only its biodiversity but also the natural systems that sustain the economic livelihoods of the people.

8. Evidence of perceived rainfall changes in the UER

Cultivation of crops in India is largely rainfed since the irrigation networks are not available in all the parts of the country. Therefore, it is vital to assess the changes and spatiotemporal pattern of the rainfall for the better crop production. Given that, a disruption in the rainfall pattern becomes a major challenge to farmers. To that end, satellite data on Climate Hazards Centre InfraRed Precipitation with Station data (CHIRPS) was employed to examine the intensity or fluctuation in rainfall in the UER over a period of 34 years. It gives a comprehensive assessment of how rainfall conditions have changed over the period spanning 34 years. The findings revealed a fluctuation and a drastic decline in rainfall throughout the study. (Fig. 3). For instance, at the

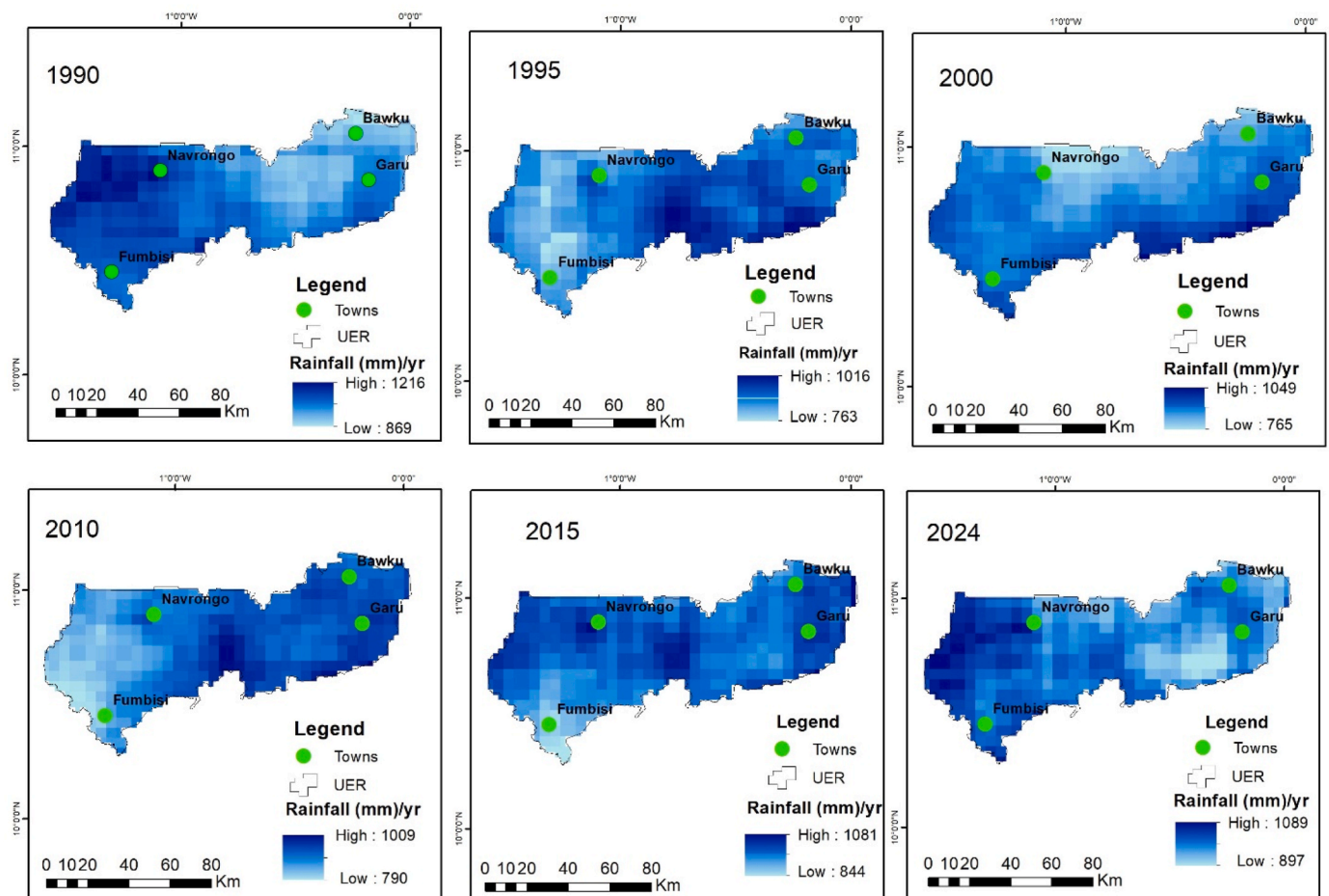


Fig. 3. Evidence of changes in rainfall in the UER.
Source: Authors' construct (2025)

initial stage of the study in 1990, the mean maximum annual rainfall in the UER was roughly 1216 mm. This quantity fluctuated thoroughly, but often reduced, reaching 1089 mm in the final stage (see Fig. 3).

The observations from the analysis indicated that certain weather conditions are favorable for the increases in NDVI. The values of NDVI is at a maximum twice a year due to the two seasons witnessed in the area (dry and wet seasons). The values of NDVI have decreasing trend during the hot weather (January–May). However, the values of the NDVI have a maximum in July to September during wet season. This study confirms a report by Awasthi et al. (2023) when they discovered similar findings in their study in India.

Spatially, the eastern sections of the UER tend to receive much higher rainfall than the western sections, with areas around Bawku and Garu receiving the highest rainfall (Fig. 3). This rainfall phenomenon is dictated by the proximity of the eastern section to the Gambaga escarpment that stimulates high relief rainfall in the windward areas, such as Bawku and Garu and dry conditions in the leeward areas, such as Navrongo and Fumbisi. While satellite data revealed an overall dwindling in rainfall intensity across the UER, survey respondents have noticed a swift shift in the traditional April–October unimodal rainfall season to a delayed onset in June or July and ends abruptly in September. However, the pattern of rainfall tends to vary every alternate year, with the highest intensity being recorded during the period of August and September, and the lowest during the months which fall within the dry season. Similar findings by Akolgo et al. (2025) and Ansah-Mensah and Asamoah (2023) concurred with this finding and added that the dry seasons in the UER are prolonging, relative to many decades ago. Triangulating survey data revealed that 86% of respondents indicated having noticed rapid shifts and a decline in rainfall (Fig. 4A). On the nature of changes in rainfall patterns, the vast majority of respondents (65%) indicated a decrease in rainfall (Fig. 4B).

While both satellite data and surveys revealed a decline in rainfall, there are reported cases of flooding in the UER. Some respondents have lamented that the rains are unreliable, short, severe and often associated with occasional flash floods. The occasional flash floods cause severe damage to crops, farmlands, and infrastructure. By way of survey, 47% of respondents indicated that floods have become severe in the UER (see Fig. 5). The lack of adequate water harvesting or drainage infrastructure has further exacerbated the impacts, particularly in flood-prone areas like Bawku and Garu. According to a respondent in an open-ended questionnaire:

“... ..the length of the rains has shortened and the dry seasons prolonged. But in most cases, they are severe and often cause flooding in many parts of the region. This washes away many years of efforts in farming and other agriculture-related activities”.

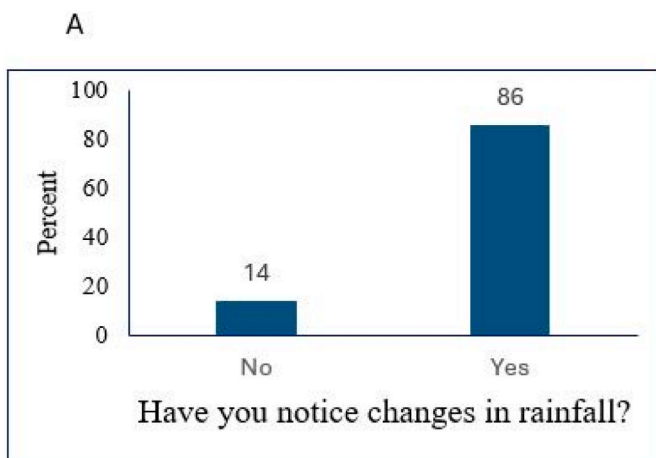


Fig. 4A. Changes in rainfall patterns.

B

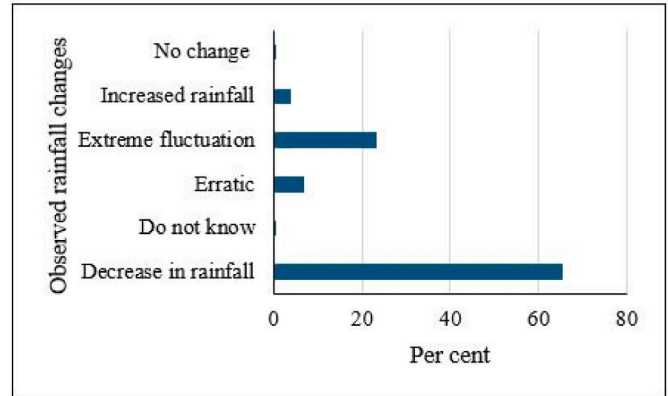


Fig. 4B. Type of Observed rainfall changes.
Source: Fieldwork (2025).

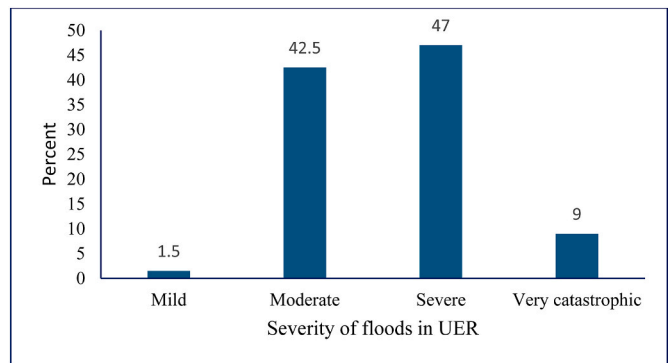


Fig. 5. Severity of floods in the UER.
Source: Fieldwork (2025)

9. Evidence of increasing temperatures in the UER

Across the UER, the results of the Land Surface Temperature (LST) analysis revealed a consistent increase in ambient temperatures (Fig. 6). The highest mean maximum LST was recorded in 2024 (45°C), indicating an upward trend in LST from 39°C in 2013. In general, this showed that the average LST across the UER had increased by 6°C (13.3%) over the decade. Regionally, the western sections tend to record lower temperatures than the eastern sections. This stems from the fact that these areas are predominantly rural. Alternatively, the eastern sections are predominantly urban and peri-urban communities and cushion the conditions of urban heat islands. Increasing LST, as discovered by this study, concurs with other studies, including Atitsogbey et al. (2018), Issahaku et al. (2016) and Klutse et al. (2020). In summary, all the studies revealed an increasing trend in average ambient temperatures across the UER. Survey data validates this satellite-based finding, as most respondents (80%) indicated having noticed increasing LST over the decades. Some farmers and community members have also indicated that the heat experienced during the dry season, especially between February and April, has become more intense and prolonged, often described as “unbearable” and “life-threatening.” Even during the rainy season, they observed that temperatures remain unusually high, affecting both crops and human comfort. In previous years, according to a respondent, “areas once characterised by cooler land surfaces now face frequent and intensified heat stress and often become extreme during the dry season. [Community respondent, personal interview].

Health wise, elevating LST in the UER is exacerbating issues of public health crises. According to findings by Arhin et al. (2016), increasing dry

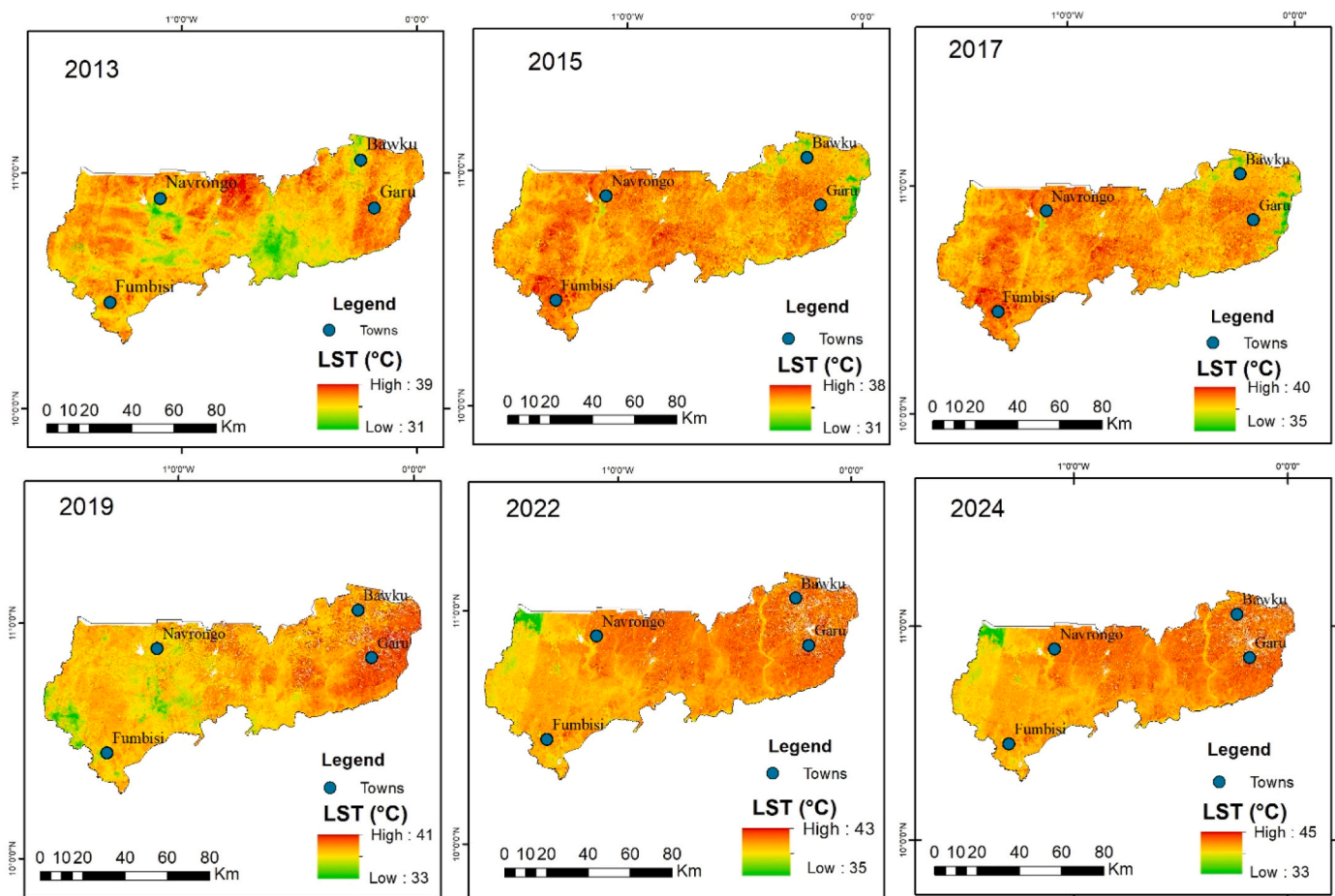


Fig. 6. Land surface temperatures in the UER.
Source: Authors' construct

periods and temperatures affect the groundwater regime by affecting the recharge and thereby compelling inhabitants to drink contaminated water, which explains the increasing cases of diarrhoea in the UER. A similar study by Adjei et al. (2025) has demonstrated that extreme heat is rapidly escalating public health concerns, particularly in the Sudan and Guinea Savannah zones of Ghana. In that regard, public health issues, including heatstroke, skin infections, and Cerebrospinal Meningitis (CSM), have been reported by some authors, including Benmarhnia et al. (2015). With the increasing severity of the heatstroke, many farmers explained that they are now forced to begin work earlier in the morning and end before noon due to the intensity of the sun.

This has negatively affected productivity and the amount of time spent on key farm activities like weeding, planting, and harvesting. Livestock suffer from weight loss, lower milk production, and increased mortality due to earlier drying of water sources. Increasing LST in the UER has emerged as a major stressor, deepening the vulnerabilities of rural livelihoods already struggling with poor soil nutrients, soil degradation and other climatic variabilities. This is evidence based climate change, and without targeted adaptation interventions, the compounding effects of rising temperatures could further worsen land degradation and undermine food security.

10. Evidence of increasing evapotranspiration in the UER

Actual Evapotranspiration (ETa) data (Fig. 7) of the UER revealed an increase in evapotranspiration. Fig. 7 revealed that ETa increased from 2000 to 2010, and plummeted slightly in 2015. ETa values began rising again from 2020 onwards. The highest mean maximum ETa was

recorded in 2024 (178 mm/yr), up from 113 mm/yr in 2000. Rising temperatures may have increased ETa rates, soil moisture and intensified dry spells. This condition is cushioned as warmer air through rising LST has the potential to hold more water, allowing the atmosphere to absorb water from soils and plants through the combined physical process of evapotranspiration. According to Gmet, ETa is very high across the entire Northern belt of Ghana. An additional increase in surface temperatures and a reduction in annual rainfall will therefore have a significant impact on agriculture (Klutse et al., 2020; Boamah et al., 2024).

11. Statistical trend and synergy between the biophysical indicators

Statistical trends, particularly the Mann-Kendall (MK) test and Sen's slope analysis, were computed to examine the trend in the four biophysical indices (see Figs. 8–11). In the LST index, the results revealed a highly significant upward monotonic trend. The MK statistics ($S = 13$), Kendall's tau ($\tau = 0.867$) and Z score ($Z = 2.44$) indicate a strong positive trend in LST (Table 1). The Sen's slope estimator showed an average annual LST increase of $0.667^\circ\text{C}/\text{year}$, highlighting an extreme and significant shift in localised climatic conditions. Together, the MK (Fig. 8) trend test and Sen's slope estimator provide a robust statistical confirmation of the worsening LST conditions in the UER. This finding is similar to a study by Boegh et al. (1999) when they analysed the slope in between land surface temperature (LST) and NDVI to evaluate the evapotranspiration rate. They found that the evapotranspiration increased with the temperature, and the NDVI and declining with the

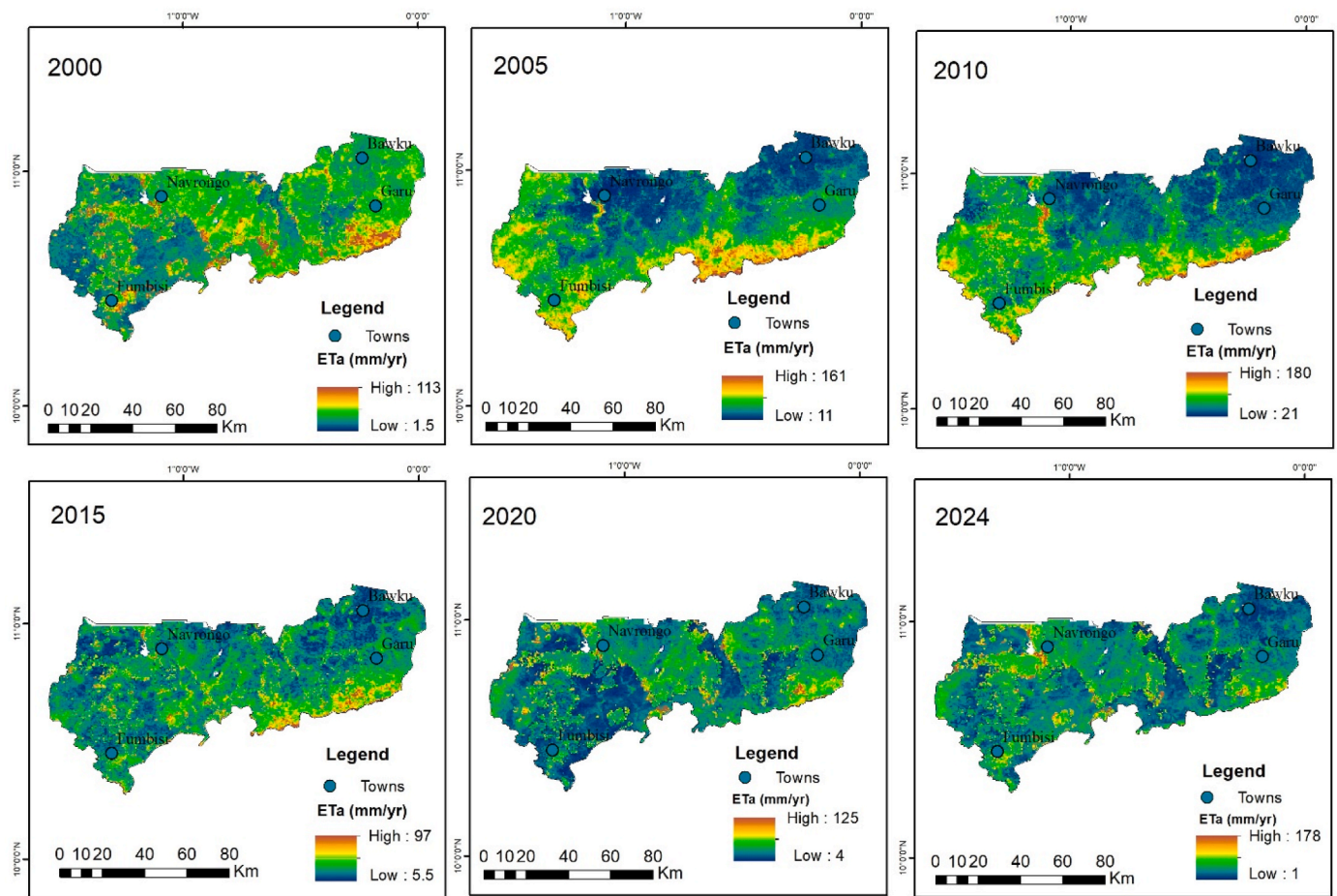


Fig. 7. Actual evapotranspiration (ETa) of the UER.
Source: Authors' construct

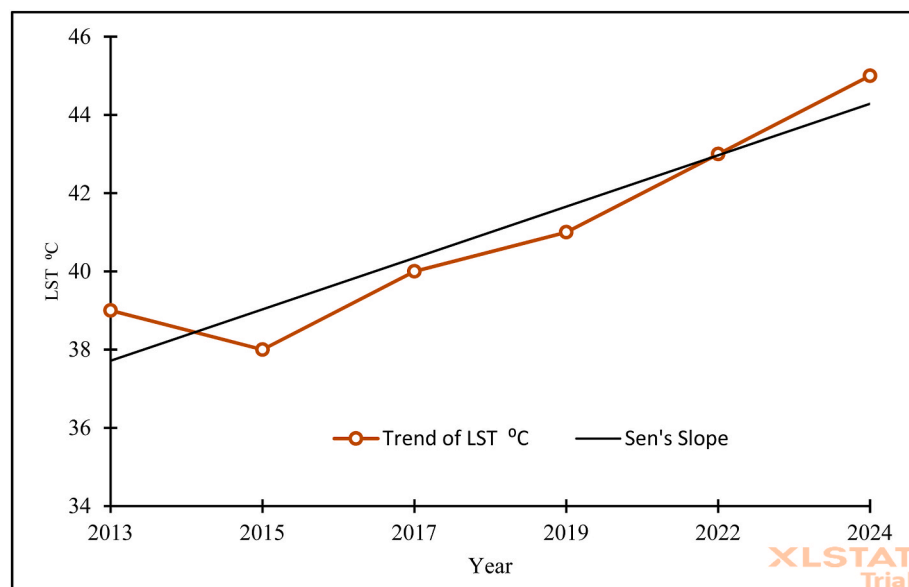


Fig. 8. Trend of LST with Sen's Slope estimator.
Source: Authors' construct

soil moisture levels. However, they also found that the higher vegetal zones induced higher evapotranspiration and lowering in LST.

For mean maximum rainfall, the study revealed a positive but

significantly weak upward trend in average rainfall in the UER (Fig. 9). The MK statistics ($S = 1$), Kendall's tau ($\tau = 0.07$) and Z score ($Z = 0.19$) indicate a statistically weak downward trend (Table 2). The Sen's slope

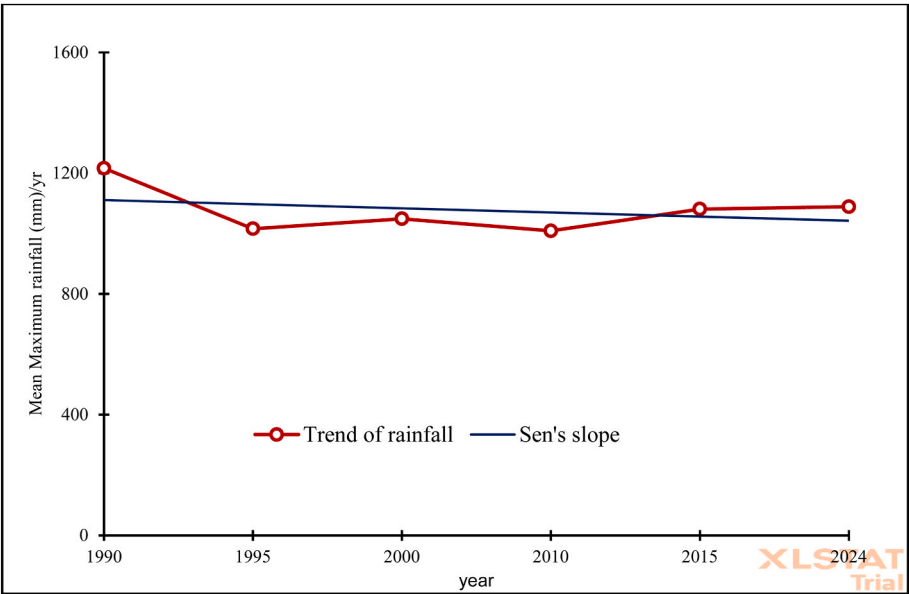


Fig. 9. Trend of Rainfall with Sen's Slope estimator.
Source: Authors' construct

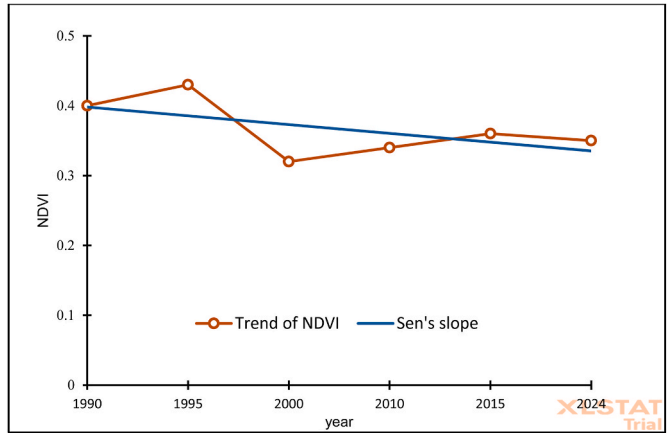


Fig. 10. Trend of NDVI with Sen's Slope estimator.
Source: Authors' construct

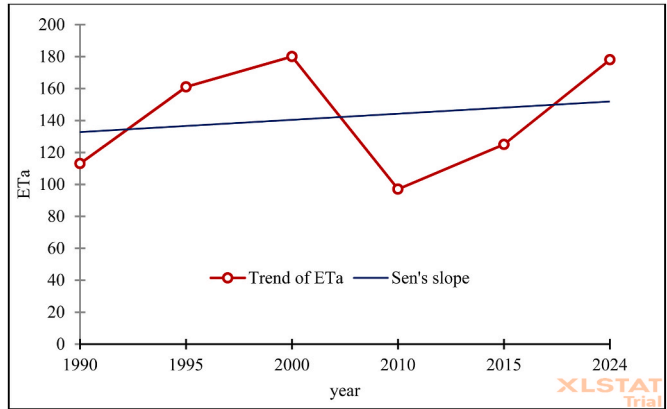


Fig. 11. Trend of ETa with Sen's Slope estimator.
Source: Authors' construct

estimator showed an increase in rainfall of 0.9 mm per annum.

Table 1
Mann-Kendall Trend Test results.

Statistic	Value
S statistic	13
Var(S)	28.33
Z score	2.44
Kendall's Tau	0.867
Sen's slope	0.667 °C/year

Table 2
Mann-Kendall Trend Test results.

Statistic	Value
S statistic	1
Var(S)	28.33
Z score	0.19
Kendall's Tau	0.07
Sen's slope	0.9 mm/year

Also, the Mann-Kendall trend test was conducted to determine the trend of the mean maximum NDVI (Fig. 10). The Z score of -0.56 and Kendall's Tau of -0.2 indicate a downward trend in vegetation greenness. The Sen's slope estimator showed a reduction in NDVI by 0.001 /per annum (Table 3). Significantly good correlation is found between vegetation and climate variables in this study, indicating the significant impact of climate variables.

Finally, the Mann-Kendall trend test for ETa was also conducted to reveal the trend of Evapotranspiration (Fig. 11). The Z score of 0.56 indicates an upward or increasing trend in evapotranspiration. A Kendall's Tau of 0.2 , however, indicates a positive but weak monotonic

Table 3
Mann-Kendall Trend Test results.

Statistic	Value
S statistic	-3
Var(S)	28.33
Z score	-0.56
Kendall's Tau	-0.20
Sen's slope	-0.001 /year

trend (Table 4). The Sen's slope estimator revealed that an average of 0.59 mm of water is lost through evapotranspiration per annum. In climate-fragile regions such as the UER, an average loss of 0.59 mm/year is a significant loss. The annual fluctuation in NDVI is primarily influenced by the planting, growth, and harvesting phases of the crop. Rainfall plays a role in shaping the timing of planting and crop development, indicating that rainfall indirectly affects NDVI trends (see Tiwar et al., 2024).

There exists an intricate and mutual relationship among the biophysical factors. The examination of this relationship is fundamental to understanding the increasing severity or otherwise of climate change in climate-fragile regions such as the UER. For example, the intricate relationship between ETa (Fig. 11) and NDVI (Fig. 10) is a cornerstone for comprehending the dynamics of water availability and how it serves the purpose of healthy vegetation in a climate-sensitive ecological environment such as the UER. This synergy is not a mere statistical relationship but a profound ecological synergy that reveals the vital signs of vegetation and explains the kind and type of vegetation classification in a particular geographic location. The vegetation classification of the UER under Sudan Savannah is characterised by relatively low rainfall (Fig. 9) and an increasing LST (Fig. 8). Increasing LST, therefore, suggest high evapotranspiration (Sadok et al., 2021; Zhang et al., 2013), resulting in vegetation decline (Fig. 10) as more water escapes through the combined process of evaporation and transpiration. This relationship is encapsulated by the Mann-Kendall trend test; thus, as surface temperatures skyrocket (see Fig. 8), evapotranspiration increases (see Fig. 11), resulting in the wilting of vegetation (Fig. 10).

Rising surface temperatures and rainfall cycles are a complex foreplay of a relationship. In theory, rising LST intensify the water cycle, causing heavier rainfalls and more drought conditions simultaneously. This creates extreme conditions where dry areas get drier, and wet areas get wetter (Mwabumba et al., 2022). Despite the fact that the trend analysis revealed a statistically insignificant but positive increase in rainfall (Fig. 9), yet evapotranspiration rates showed signs of a significant increase (Fig. 11). While these changes disrupt the water cycle, the increasing ETa to a larger extent is influenced by increasing LST in the UER. Some studies, including Owusu et al. (2024) and Sokode et al. (2025), have revealed that this annual rainfall cycle significantly affects vegetation greenness, leading to desertification conditions.

12. Implications of the severity of climate change for farmers

Smallholder farmers in the UER are experiencing profound challenges due to the combined effects of shifting rainfall patterns, rising temperatures, evapotranspiration and vegetation degradation. These farmers, who form the backbone of the regional agrarian economy, depend heavily on natural systems, and the biophysical changes are steadily eroding their capacity to sustain livelihoods. Previous studies have revealed decreasing rainfall intensity in the UER (Quaye-Ballard et al., 2020; Ampadu et al., 2019), and it is often attributed to prolonged dry seasons (Ampadu et al., 2019). This undermines traditional knowledge systems for planting and harvesting. Many farmers have reported a decline in agricultural productivity due to unpredictability and deviation of rains from the traditional planting periods. In response to an open-ended questionnaire, a farmer indicated that:

“The length of the rains has shortened, and the rainy seasons are moving away from the traditional seasons to a more delayed rainy period. So if you fail to accurately predict the rainfall pattern before planting, then you are going to run at a loss. And even in some cases when you accurately predict the start of the rains, the season sometimes ends abruptly.” [A male farmer, Garu community].

This unpredictability also complicates pest and disease control, as outbreaks are often linked to fluctuating moisture conditions, trapping farmers in a cycle of uncertainty and low productivity.

Rising temperatures add further strain by causing heat stress that adversely affects both crops and labour capacity. Crops such as maize, cowpea, and okra, once reliably cultivated, now show stunted growth and withering under intense sun exposure. It also causes illnesses such as Cerebrospinal meningitis (CSM) and stunted growth, as well as a decrease in revenue. CSM cases have increased in the various districts, especially during the dry season (EPA, 2023). Farmers adapt by working early mornings and late evenings, reducing overall labour time and productivity.

Concurrently, declining soil fertility worsens the situation. Continuous cropping without adequate inputs, limited access to fertilisers, and shifting cultivation to marginal lands are depleting soil nutrients, drastically lowering yields. For many households, what was once a surplus harvest is now barely sufficient for subsistence. This land shift disproportionately affects land-constrained groups, especially women and the elderly, who face difficulties securing new plots. Vegetation loss further eliminates essential safety nets, as trees and shrubs previously supplied emergency food, medicine, fuel, and income through firewood and charcoal. This aligns with the qualitative findings of Owusu et al. (2024), where respondents indicated that these trees were crucial to the local population in past years, significantly contributing to their economic well-being and health. With this safety net gone, livelihood options during lean periods are severely limited, intensifying vulnerability.

These environmental pressures have also triggered significant social consequences, particularly youth out-migration to southern Ghana and neighbouring Burkina Faso in search of employment. While remittances provide essential financial support, the labour drain during peak farming seasons weakens household agricultural capacity. The erosion of extended family support systems undermines community resilience to climate shocks. Taken together, these findings illustrate a multidimensional crisis where climate change and land degradation are deeply intertwined with social and economic instability, emphasising the urgent need for integrated policies addressing agricultural inputs, land access, soil rehabilitation, reforestation, and climate early warning systems to bolster rural resilience.

13. Enhancing livability and stability in the UER through adaptation strategies

Ensuring the Upper East Region remains livable and stable amid escalating climate change impacts requires a comprehensive approach beyond short-term relief. The region faces a compounding cycle of environmental degradation, economic vulnerability, and social fragility that, if left unaddressed, could deepen poverty, trigger increased youth migration, and collapse local livelihoods. Soil degradation, loss of vegetation, and declining water and pasture resources have reduced the land's capacity to support its population. This has led to food shortages, increased disease risks, and growing dependence on aid, ultimately weakening social cohesion and resilience, particularly in communities like Garu-Tempane and Bawku West, where communal support has traditionally been strong.

To reverse these trends, strategic investments in landscape restoration and infrastructure are essential. Reforestation, conservation agriculture, and sustainable land management can rehabilitate degraded land, improve water retention, and restore ecological balance. Farmers

Table 4
Mann-Kendall Trend Test results.

Statistic	Value
S statistic	3
Var(S)	28.33
Z score	0.56
Kendall's Tau	0.2
Sen's slope	0.59 mm/year

have changed their production methods and farm management practices; they have to spend more money to buy chemical fertiliser to apply on the farms before they can cultivate crops, a practice which is alien to the region. At the same time, improving infrastructure such as feeder roads, irrigation systems, health clinics, and storage facilities is critical, as their absence significantly limits farmers' ability to cope with climate variability. Small-scale irrigation using boreholes, dugouts, and drip systems enables dry-season farming and year-round food production, while enhanced market access and storage facilities can help reduce post-harvest losses and increase household incomes.

Numerous government and non-government programs aim to support smallholder adaptation. The Government of Ghana has rolled out initiatives, including the Root and Tuber Improvement and Marketing Program (RTIMP), National Fertiliser Subsidy Program, Northern Rural Growth Program, FAO Dry Season Support Program, Village Mango Program, Youth in Agriculture Block Farms, and Planting for Food and Jobs. These programs provide input subsidies, market linkages, and agricultural support. Complementing them are NGOs and development partners like the Association of Church-based Development NGOs (ACDEP), Esoko, and the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), which offer climate services, training, and technology solutions to strengthen resilience in the agricultural value chain.

Farmers in the region have adopted various adaptive strategies that reflect both resilience and constraints. Dry-season farming, especially along the White Volta River and near irrigation dams like Vea and Tono, is a vital livelihood strategy but remains inaccessible to many poorer households due to limited land and high irrigation costs.

Farmers in areas such as Bawku and Bolgatanga commonly adopt strategies such as crop diversification, intercropping, and the cultivation of drought-tolerant and flood-tolerant, early-maturing crop varieties, particularly maize, rice, and legumes. These practices are aimed at reducing the risk of crop failure under increasingly erratic weather conditions. Studies by some authors, including Antwi-Agyei and Nyantakyi-Frimpong (2021) and Kumasi et al. (2019), are examples of case studies on climate change adaptation strategies by smallholder farmers in the UER. To address declining soil fertility, many rely on subsidised chemical fertilisers, though there is a growing return to traditional practices such as composting and fallowing. Others have also relied on the traditional method of crop rotation to balance depleting soil nutrients. In that regard, a farmer lamented that *"in response to the rapid depletion of soil nutrients, we opt for crop rotation. Some of the crops replenish the depleting soil nutrients and enable us to continue planting in subsequent years"*. Livestock remains a key safety net, with a shift toward smaller animals like goats and poultry that are more climate-resilient. Social networks, remittances, and community-based initiatives in tree planting and water conservation, often supported by NGOs, also enhance local resilience.

Moving forward, scaling up successful local practices, strengthening extension and market infrastructure, and designing inclusive, community-driven climate resilience programs will be vital. Addressing youth migration through vocational training, entrepreneurship, and youth-targeted agricultural initiatives like "Youth in Agriculture" can revitalise rural economies and reduce demographic imbalances. Meanwhile, promoting equitable land access, strengthening local conflict resolution systems, and fostering peace-building efforts can reduce resource-related tensions. As a frontline region for desertification and climate migration, the Upper East Region offers a crucial testing ground for national climate adaptation strategies. By centering local knowledge, enhancing collaboration among stakeholders, and shifting from reactive responses to proactive governance, the region can chart a path toward a more resilient, equitable, and sustainable future.

14. Uncertainty analysis and limitations of the study

The use and application of satellite-based remote sensing data for

scientific studies has gained momentum over the past decade. Despite the growing plethora of studies using the applications of remote sensing data, there are inherent uncertainties. Many scientific studies have assessed these uncertainties in the area of NDVI (e.g. Khalesi et al., 2024; Borgogno-Mondino et al., 2016), land surface temperature analysis (e.g. Yamamoto et al., 2022; Zhao et al., 2024) and Climate Hazard Group Infrared Precipitation with Station Data (CHIRPS) (Kurnianingsih et al., 2025; Beyene et al., 2024). In essence, the uncertainty in satellite-based remote sensing data arises from different sources and in many cases becomes a significant limitation to scientific studies. In the application of NDVI, uncertainty arises primarily from atmospheric conditions, sensor limitations and spatio-environmental variability. According to Khalesi et al. (2024), the major contributor to NDVI uncertainty often results from atmospheric conditions, nominal wavelength tolerance of the sensor camera and the variability of the seasons. In this study, seasonal variability of the UER may affect NDVI assessment to some extent. For instance, while the data was sourced in the dry season, which is accompanied by high evapotranspiration and heat stress, leafy vegetation may begin to wilt. This will slightly affect the green nature of vegetation, hence some uncertainties in the NDVI analysis.

Similarly, uncertainty in LST stems from a combination of factors, including sensor noise, water vapour, surface emissivity variations and pixel-scale sampling challenges. The failure of traditional meteorological stations to provide enough data for LST assessment has made satellite images an invaluable tool (Dervisoglu, 2023). While satellite-based LST analysis has gained popularity, yet series of allowable error flaws limit its assessment. For instance, the allowable error for studies in vegetation monitoring is 1–2 K (Zhou et al., 2020), while it is 1 K for crucial climate research and urban heat island studies (Guillevis et al., 2014). However, current LST retrieval algorithms achieve accuracy of about 2 K (Hunga et al., 2023; Li et al., 2020) with inherent errors influenced by environmental conditions, including cloud cover, moisture and seasonal variations.

In contemporary studies, CHIRPS has replaced traditional methods such as gauges for measuring rainfall. According to Nawaz et al. (2021), the use of CHIRPS is widespread, especially in low and medium altitudes and areas with unreliable data. However, the applicability of CHIRPS needs investigation (Alejo and Alejandro, 2021) as it comes with uncertainties. For instance, CHIRPS data require careful consideration of its error characteristics at daily intervals and local scales. This is true given that geographical variations enable it to perform better in some regions than in others, thus exhibiting higher errors in high elevation due to mountain shadows and limitations in satellite detection. Also, the study was limited by challenges associated with the satellite data, especially cloud cover for the LST computation. This explains the differences in the date of data acquisition for the LST data from the other indices. This limitation was addressed by using satellite images that are cloud-free.

15. Conclusions and policy recommendations

The Upper East Region of Ghana faces mounting biophysical impacts from climate change—erratic rainfall, rising land surface temperatures, increasing evapotranspiration and dwindling vegetation—which undermine agricultural productivity and rural livelihoods. Local farmers have responded with adaptive strategies such as fertiliser application, crop diversification and mixed livestock systems. However, these efforts remain limited by high input costs, restricted land access, and inadequate support. The region's high climate variability demands adaptive farming systems built on cost-effective and sustainable practices. Yet, short-term coping alone is insufficient. A long-term adaptation agenda must be prioritised—one that includes reforestation, conservation agriculture, and improved infrastructure. Government programs like Planting for Food and Jobs, Youth in Agriculture, and the National Fertiliser Subsidy Programme, alongside NGO-led initiatives, should be expanded, better coordinated, and targeted to reach the most climate-

vulnerable communities.

Investment in irrigation systems, feeder roads, storage facilities, and affordable inputs can improve year-round production and reduce post-harvest losses. Simultaneously, institutional reforms must address land tenure insecurity, limited extension services, and fragmented governance to ensure inclusive and sustainable land use. Human security is also central to resilience. Rising youth migration reflects both environmental and economic strain. Vocational training and entrepreneurship programs can offer viable alternatives, reduce rural exodus and reinforce social cohesion.

The region's vulnerability to extremism and food insecurity further highlights the urgency of coordinated action. Addressing these threats requires sustained stakeholder collaboration, community empowerment, and strategic planning that integrates local knowledge with national policy goals. Climate resilience in the Upper East Region must not only protect the land but also safeguard the lives and futures of its people.

In sum, ensuring a sustainable future for the Upper East Region demands a shift from reactive relief to proactive, long-term solutions. Through collective effort, institutional commitment, and localised adaptation strategies, the region can overcome its climate challenges and build a stable, food-secure, and livable environment.

CRediT authorship contribution statement

Alex Barimah Owusu: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision. **Collins Adjei Mensah:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Kofi Adu-Boahen:** Data curation, Investigation, Methodology, Validation, Writing – review & editing. **Alhassan Mahama Kunda:** Data curation, Software, Validation, Visualization. **John Aloba Atubiga:** Formal analysis, Investigation, Methodology, Validation, Writing – review & editing.

Consent to participate

Consent to participate in the data collection option was provided in the instruments for the data collection which was followed strictly. Respondents who opted not to take part were respected. Surveys and other instruments would be made available upon request.

Data availability

Data will be made available upon request.

Ethics

The study sought opinions in the form of a questionnaire, policy dialogue, and focus group discussions from participants who have specialities in the field of study. Permission was obtained by way of invitation letters before conducting the study. Participants were assured of the confidentiality of their views, which was purely for academic purposes. This invitation letter would be made available upon request.

Consent to publish declaration

We hereby give consent for the publication of the manuscript, including any other data that may be made available during the course of the review process or included in the manuscript.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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