

Using models and remote sensing to support a warning system: diagnosing climate and land use changes in Nahouri, Burkina Faso

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Abstract

Purpose – The study aims to diagnose climate and land use changes in Nahouri province (Burkina Faso) over the past 40 years. It seeks to explore the impacts of climatic and anthropogenic changes on local livelihoods and identify trends in climate variables, water availability variables land cover and aerosol concentrations, to inform climate change mitigation strategies and support a warning system.

Design/methodology/approach – The study uses multiple models and remote-sensing data sources, including TerraClimate, Landsat images and Moderate-Resolution Imaging Spectroradiometer Aerosol Optical Dust (MODIS-AOD) data over the past 40 years. The analysis was conducted across three seasonal periods: dry season (October to March), transition season (April and May) and wet season (June to September).

Findings – The results indicate a general warming trend, with more acute changes during the transition season, characterized by increased temperatures and decreased precipitation. Land cover and vegetation data show an overall increase in the Normalized Difference Vegetation Index (NDVI), likely related to land use changes in a landscape dominated by agro-forested areas and the shift from grassy to shrub savannas. In addition, MODIS-AOD data revealed higher aerosol concentrations in urbanized areas with an increase in the last 20 years, mostly during the transition seasons.

Originality/value – The findings confirm local observations of prolonged dry seasons and emphasize the importance of region-specific studies to guide conservation efforts and inform the development of tools to mitigate climate change.

Keywords Climate change, Burkina Faso, Nahouri, TerraClimate, Landsat images, MODIS Aerosol Optical Depth (AOD)

Paper type Research paper



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1. Introduction

The Sahel region of West Africa is highly vulnerable to anthropogenic climate change, with direct consequences for local livelihoods. Research conducted in this region has highlighted how variations in the amount, intensity and timing of precipitation, increases in temperatures and changes in wind patterns are affecting people's everyday lives and subsistence practices (Epule *et al.*, 2014, 2017; Niang *et al.*, 2014). In response, local communities are adopting a range of adaptive and coping strategies, such as crop diversification, water conservation, mobility, livelihood diversification and migration (Epule *et al.*, 2017; Mertz *et al.*, 2009; Nyong *et al.*, 2007). These local strategies to cope with climate change are often short-term and inconsistent, partly because of the unpredictable nature of these events.

Droughts and land degradation in the Sahel have already led pastoralists to shift from a cattle-based mobile lifestyle to a sedentary agro-pastoralist lifestyle (Brottem and Mcdonnell, 2020). Extreme droughts have decreased good pastures and increased tensions over such scarce resources. As a result, many people have been forced to sell part of their livestock and settle as farmers to sustain their livelihoods (Ouédraogo *et al.*, 2021). However, droughts also impact crop yields, leading to less food availability for both humans and livestock. This reduction in food weakens communities' ability to cope with climatic changes (Traore and Owiyo, 2013). Research conducted in various West African countries suggests that changes in precipitation may also impact people's mobility patterns. The decrease in rainfall may contribute to both short- and long-distance migrations, including circular migration, seasonal and sometimes permanent movements (Adjei and Schraven, 2025; Golovko, 2022; Henry *et al.*, 2003). Moreover, analyses on mobility in the Sahel show that these displacements are often temporary: people often move inside their own country or to nearby countries for short times to earn money and then return home (Adjei and Schraven, 2025). As highlighted by Freeman (2017), climate change and the decrease of resources caused by this phenomenon may "trap" people, who lack the financial means to migrate, reducing their options to adapt to such changes and therefore worsening current inequalities and amplifying vulnerabilities. In addition, movements of people caused by climate change may lead to land degradation and substantial changes in land use, which have been observed especially in areas that receive many migrants (West *et al.*, 2014).

Within Western African communities, women are usually the most affected by climate change due to their role in the family. Lower agricultural yields and land degradation force women to spend more time on productive activities while also retaining their household responsibilities, substantially increasing their workload. This impacts their health and their offspring's livelihood and ability to participate in community activities (Romero *et al.*, 2011). In the Sahel, many women report that climate change worsens their daily lives, and they are more affected by insecurity and health problems (Itriago, 2025). For example, droughts force them to travel long distances to collect water and firewood, which puts them at risk and reduces their time for education or paid work (McOmber, 2020).

Climate change may also trigger a variety of conflicts among groups of people. For instance, conflicts between farmers and pastoralists often happen because they compete for limited resources like water and land, especially during droughts and changing rainfall (Seter *et al.*, 2018). These tensions typically intensify during periods of resource scarcity, when grazing needs, agricultural expansion and unclear land rights intersect (Brottem and Mcdonnell, 2020). Such conflicts are complex, involving not only resource competition but also crop damage by stray or poorly managed livestock, obstruction of traditional pastoral migration routes and overlapping or unclear land tenure rights (Benjaminsen *et al.*, 2012; Sanfo *et al.*, 2015). In addition, the expansion of farmland into grazing areas and the lack of recognition for traditional pastoral rights also add to the problem (Benjaminsen *et al.*, 2012; Sanfo *et al.*, 2015). While

climate change isn't the direct cause, it makes the situation worse by putting more pressure on already limited resources (Sanfo *et al.*, 2015). Similar issues happen when more migrants arrive and compete with local communities for limited land and water (West *et al.*, 2020). Furthermore, the stresses on the local population caused by climate change, such as resource scarcity, livelihood disruptions and social tensions, create favorable conditions for the emergence and growth of armed groups, which fill the void left by the state (Hamdy, 2020).

Among the many countries in West Africa affected by the changing climate is Burkina Faso, a landlocked nation covering about 273,000 km² with a population of 21.49 million people (UN-data, 2023). The country features a semi-arid tropical climate with distinct dry and wet seasons. The dry season, from mid-September to mid-March, is characterized by the Harmattan wind and the near absence of precipitation, while the wet season, from mid-May to mid-September, with humid winds and substantial rainfall. This strong seasonal contrast is a defining feature of the climate system and shapes both ecological processes and human activities (Knauer *et al.*, 2017). Burkina Faso territory can be divided into three main climatic and ecological zones (Abdoulaye *et al.*, 2017):

- Sahelian zone, located north of 14°00'N, is the driest climatic zone, with 300 and 600 mm of annual rainfall, dominated by steppe vegetation; the driest zone in the country.
- Sudano-Sahelian zone, lies between 11°30'N and 14°00'N, receives 800–900 mm of annual rainfall and features a denser herbaceous and woody vegetation; serves as a transitional rainfall zone.
- South Sudanese zone, located south of 11°30'N, receives 900 and 1,200 mm of annual rainfall and features gallery forests along the water bodies, the wettest zone in the country.

A substantial share (24.7%) of the population is employed in agriculture, making the country particularly vulnerable to climate change. These heightened vulnerabilities come at a time when Burkina Faso is already facing social, economic and political struggles (UN-data, 2023). According to the United Nations Development Programme (UNDP, 2023), Burkina Faso ranks 186th out of 193 countries on the Human Development Index, reflecting low levels of health, education and income.

In Nahouri province, a small administrative region in south-central Burkina Faso bordering Ghana, the lack of monitoring infrastructure makes it difficult to draw a reliable assessment of the changes in the last decades related to climate change and human activities. This lack of information limits the capacity to develop effective early warning systems and hinders timely interventions. Several studies have looked at the impact of climate change and land use in Africa, and more specifically in Burkina Faso, looking at climate projections and their possible impact on the population (Wigna, 2019; Hamid, 2021; Roudier *et al.*, 2011). For example, Hamid (2021) reviewed 62 studies on how climate change affects the four dimensions of food security (availability, access, utilization and stability) in Burkina Faso, highlighting that most focus on projected impacts on crop yields and climate suitability for key staples such as maize, millet and sorghum, with potential consequences for population livelihoods and well-being. Yet, due to high spatial variability in Africa and even within the Sahel, large-scale studies often fail to capture the local nuances needed for adaptation planning in regions such as Nahouri. The strong contrast between wet and dry seasons is also a central component of the Nahouri climate systems that impacts all the ecological and human aspects of the region; thus, it is important to consider seasonal variability to fully understand the impact of these changes.

This study aims to diagnose climate and land use changes in the Nahouri province, Burkina Faso, using models and remote sensing information. Our project also aims to demonstrate the potential of these resources to inform communities with limited monitoring infrastructure, such as those in the Nahouri region. Such strategies may improve understanding of climate variability in their territory and help develop accurate mitigation strategies. The methodology developed in this framework can thus be adapted to other regions, but in this study, it is specifically tailored to support the Information and Early Warning System for Nahouri or *Système d'Information et d'Alerte Précoce pour le Nahouri* (SINAP-N), currently in place <https://sinap-n.info/>. This platform produces and disseminates climatic, ecological and hydrological information to the local population, providing them with a helpful tool to mitigate the impacts of climate change. Our analysis of nine central variables related to the people, climate, land use and land cover in the Nahouri province feeds directly into SINAP-N's database, making it more accurate and useful for local adaptation and resilience.

2. Methods

2.1 Study area

The study area is the Nahouri province, located in southern Burkina Faso and bordering the north of Ghana (Figure 1). The province covers over 388 504 hectares within the South Sudanese zone, where natural vegetation is characterized by unique dry forest and savanna ecosystems. According to the Geographical Institute of Burkina Faso (GIB), using national land cover maps from remote sensing classification validated by field surveys, the main landscapes in Nahouri province are Riparian habitat (7 590 hectares), Shrub Savanna (64 580 hectares), Grassy Savana (117 037 hectares) and agro-forested lands (187 365 hectares). These diverse landscapes sustain a rich biodiversity as well as a range of ecosystem services, from food and fuel wood to grazing areas, essential to local communities. The agricultural practices in the province are predominantly traditional subsistence farming of cereals (such



Figure 1. Location of Nahouri province in Burkina Faso, West Africa

as sorghum, millet and maize), legumes (peanut and cowpea), tubers (yams and potatoes) and livestock rearing (Azoupe, 1997; Bictogo, 2010). In addition, the agricultural areas support harvesting of fuelwood and non-timber forests, and recently, in the last years, cash crop production (e.g. cotton, sesame and mango plantations), which are important for both household use and local markets (Bictogo, 2010; Touré, 2021).

The climate in Nahouri province is tropical, with a mean annual temperature of about 28° Celsius (°C) and an average rainfall of approximately 933 mm. Seasonal patterns are shaped by two alternating and contrasting seasons influenced by the movement of the Intertropical Convergence Zone (ITCZ), where the humid wind coming from the Atlantic Ocean in the south (Monsoon) meets the warm, dry wind coming from the Sahara in the north (Harmattan) (Ibrahim *et al.*, 2014). The long dry season lasts from October to May, while the short rainy season occurs from June to September, with peak rainfall in August. Rainfall in the province varies greatly from year to year, with shorter rainy seasons and more intense storms (Bictogo, 2010). These changes affect farming, pushing farmers to adopt faster-growing crops and making lowland cultivation riskier due to flooding (Bictogo, 2010). Seasonal and yearly rainfall shifts strongly influence vegetation, water availability and land cover, making them key for interpreting environmental change.

In this study, according to monthly temperatures and precipitation (Figure 2), the analysis was performed over three seasons: dry, transition and wet. The dry season (October to March) is characterized by low precipitation, ranging from a minimum of 0.7 mm to a maximum of 49.1 mm, alongside high temperatures, with average minimum and maximum temperatures of 24.6°C and 38.7°C, respectively. Conversely, the wet season (June to September) has high precipitation with values ranging from 122.5 to 255.5 mm, and relatively lower temperatures, with average minimum and maximum temperatures of 22.2°C and 32.1°C, respectively. The transition season (an additional season created for this study), occurring in April and May, reflects a shift from dry to wet conditions. It shows a moderate

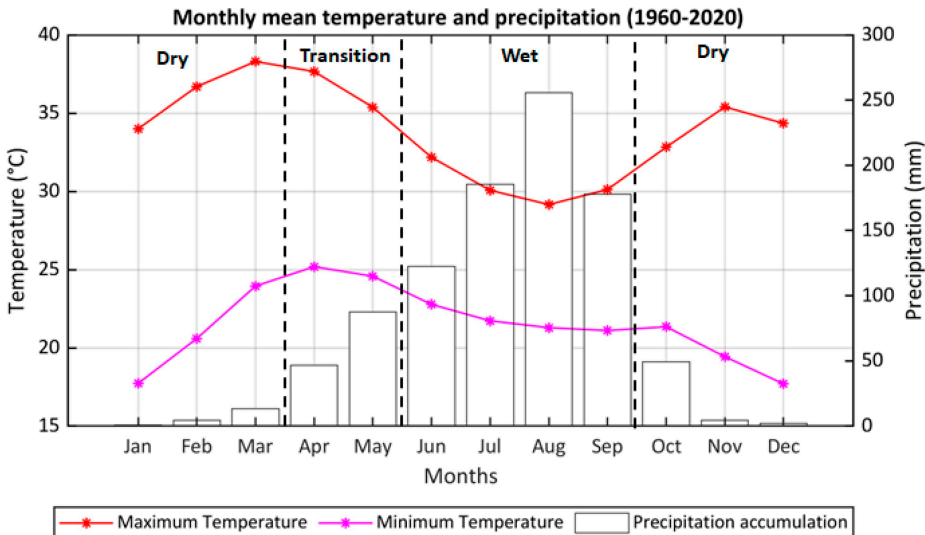


Figure 2. Identification of dry, transition and wet seasons in the Nahouri province based on monthly TerraClimate precipitation and temperature data (see Section 2.2.1)

increase in precipitation (average 67.1 mm). It is characterized by a slightly lower decrease in temperatures (and an increase in precipitation, with average minimum and maximum temperatures of 24.8°C and 36.5°C, respectively), and an average precipitation of 67.1 mm. This season is crucial for agriculture in the Nahouri province and across the southern and central areas in Burkina Faso. It marks the start of the preparation and planting activities for many staple crops, such as millet, sorghum and maize. Although the rainy season begins in April–May, delays in its onset can disrupt planting, hinder germination and necessitate replanting (FAO, 2024). Therefore, isolating the transition season in the analysis allows for better monitoring of climate signals, assessing their impacts on early vegetation and crop cycles and enhancing the relevance of early warning systems and adaptive agricultural planning for the Nahouri region.

2.2 Data set

Several data sets derived from modeling and remote sensing were used to diagnose changes in climate from 1960 to 2020, land use and land cover from 1985 to 2020 and dust from 2000 to 2020 in the Nahouri province (Figure 3). The climate variables (temperature, precipitation, wind, evapotranspiration, water deficit and soil moisture) were extracted from the TerraClimate data set. NDVI and land cover metrics were derived from Landsat products, while dust-related indicators, such as Aerosol Optical Depth (AOD) and the Angstrom Exponent (AE), were obtained from MODIS aerosol products.

To capture seasonal patterns, all variables were grouped into three key periods based on agricultural seasons: dry (October–March), transition (April–May) and wet (June–September). For each variable, seasonal mean values were calculated for each year from 1985 to 2020. Temporal trends were then analyzed using simple linear regression to estimate the slope per decade and assess long-term trends. This approach was applied consistently across all variables, including NDVI, climate indicators and aerosol data. For most variables, the mean values for each of the three seasons were calculated annually. Trends over time were calculated based on simple linear regressions on these temporal series. The primary objective of this work is to provide information to support the development of a warning information system in Nahouri.

2.2.1 TerraClimate. TerraClimate is a global climate data set for global terrestrial surfaces that offers monthly climate variables such as precipitation, maximum and minimum temperature and wind speed (Abatzoglou et al., 2018). It also includes additional variables extracted from the soil water balance model, such as evapotranspiration, surface water

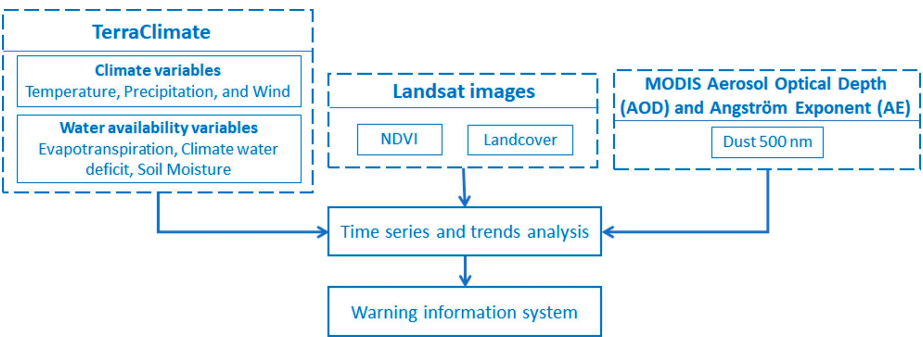


Figure 3. Flowchart of the proposed methodology

runoff, soil moisture and climate water deficit (CWD). This data set has a relatively high spatial resolution of 4×4 km ($1 / 24^\circ$) covering all global land surfaces (Abatzoglou *et al.*, 2018). The TerraClimate monthly temporal resolution covers a period from 1958 to 2023 and is regularly updated. Multiple data sets, including WorldClim Version 2 (Fick and Hijmans, 2017), WorldClim Version 1.4 (Hijmans *et al.*, 2005), Climate Research Unit (CRU) time series data version 4.0 (Harris *et al.*, 2014), Japanese 55-year Reanalysis (JRA-55) and Root Zone Storage Capacity (Wang-Erlandsson *et al.*, 2016), were used to develop TerraClimate.

The historical climate variables of TerraClimate from 1960 to 2020 were used in this study to analyze the climate change in the Nahouri province. The gridded spatial information of precipitation (mm), maximum and minimum temperature ($^\circ\text{C}$), wind speed (m/s), actual evapotranspiration (mm), soil moisture (mm) and CWD (mm) were extracted from TerraClimate. The precipitation variable corresponds to the total monthly precipitation derived from CRU Ts 4.0 at a grid resolution of 0.5° . The maximum and minimum temperatures derived from CRU Ts 4.0 at the same grid resolution correspond to the average highest and lowest temperatures for each month. The wind speed is the monthly average of 10-meter wind speed derived from JRA-55 at a grid resolution of 1.25° . Actual evapotranspiration and soil moisture are monthly accumulated variables derived from a one-dimensional climatic water balance model at a 0.5° grid resolution. The monthly climatic water deficit is determined as the difference between the monthly reference evapotranspiration (ET_0) calculated from the Penman-Monteith approach (Allan *et al.*, 1998) and the actual evapotranspiration. The evapotranspiration is computed as liquid water supply (precipitation and snowmelt) plus the soil water utilized. For more details regarding these climate variables, see Abatzoglou *et al.* (2018).

In this study, the TerraClimate collection in Google Earth Engine was filtered to 1960–2020 and clipped to the Nahouri region. For each month, the spatial average of each climate variable was calculated across all 4×4 km grid cells using the mean reducer function to produce regional time series. These series were divided into three seasonal periods for each year: dry season (October to March), transition season (April and May) and wet season (June to September). Seasonal means were then calculated. The trends were estimated in MATLAB using simple linear regression, with slopes expressed as changes per decade, and 95% confidence intervals were calculated to assess statistical significance.

2.2.2 Landsat satellite Normalized Difference Vegetation Index. The NDVI was used to monitor the yearly vegetation changes at the scale of Nahouri from 1985 to 2020. NDVI is defined as the ratio of the near-infrared and red reflectance, with a range between -1 and 1 , and is generally correlated to the photosynthetic activity (Tucker *et al.*, 1986). Values between 0.05 and 0.6 indicate sparse vegetation, while values between 0.6 and 1.0 represent healthy vegetation (Myneni *et al.*, 1997). Values less than 0.05 provide information about other types of surfaces, such as water, desert and exposed soil (Tucker *et al.*, 1986).

We used Tier 1 data surface reflectance from Landsat Collection 2 for the Nahouri from 1985 to 2020 in Landsat Collection 2 to create a temporal series of annual maps based on the method of (Bayle *et al.*, 2022). Image processing and analysis were conducted using the Google Earth Engine (GEE) cloud platform. The data set includes Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI), all at a 30×30 m spatial resolution per pixel. To ensure consistency across sensors, we adapted cross-sector radiometric calibration based on the methods and coefficients provided by Berner *et al.* (2023), minimizing systematic differences in NDVI values between collections.

Cloud-affected pixels were excluded using the quality assessment (QA) bands in GEE, and Bidirectional Reflectance Distribution Function (BRDF) was applied to correct for

angular reflectance effects. The NDVI was calculated using red and near-infrared bands from BRDF-corrected reflectance values. For each year and season (dry, transition and wet) from 1985 to 2020, we extracted the maximum NDVI (NDVImax) at the province scale. NDVImax is commonly used to represent peak vegetation activity, as it reflects the highest photosynthetic performance in a season (Tian *et al.*, 2013). To avoid discrepancies in data, we shortened the period of the dry season from December to March, which is more climatically homogenous, but the definition of the other two seasons remained unchanged.

2.2.3 Landsat satellite land cover. Satellite imagery from Landsat 5 M Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper + (ETM+) and Landsat 8 Operational Land Imager (OLI) were used to create annual landscape maps and study land cover changes in Nahouri from 1985 to 2020. A pixel-based classification model was developed using the 2012 land cover map provided by local stakeholders as a reference. Spectral indexes such as the Normalized Difference Water Index (NDWI), see McFeeters (2013), and the Modified Normalized Difference Water Index (MNDWI), see Xu (2006), were added to the median reflectance value of the optical bands for classification. These spectral indices help distinguish moist areas, improving the separation of the “riparian habitat” class from other land cover types. Supervised classification with the smileRandomForest algorithm was conducted in GEE based on the four main land cover areas of Nahouri, namely: Riparian habitat, shrub savanna, grassy savanna and agro-forested land. Due to spectral and spatial similarities observed during the interpretation of training sites, urban areas were aggregated with agro-forested land, as the spatial resolution of the imagery did not allow for a clear distinction between the two. Thus, the land cover analysis is an estimation of an ideal repartition of pristine land cover despite the increase in population over the decades. Land cover dynamics were analyzed by calculating the annual percentage of area covered by each class from 1985 to 2020. To reduce bias in trend analysis for each land cover type, we eliminated years with insufficient pixels from images and focused on 388 400 hectares. As a result, yearly maps with fewer pixels were removed since they covered a smaller region.

2.2.4 Atmospheric aerosol. Atmospheric aerosol was analyzed in this study to get a better insight into Nahouri’s air quality. Atmospheric aerosol is defined as a mixture of different particle species from specific natural and anthropogenic sources (e.g. sea salt, mineral dust, biological particles and soot) (Gui *et al.*, 2022; Tegen and Schepanski, 2018). The concentration and distribution of atmospheric aerosols are controlled by factors like changes in precipitation, atmospheric mixing and ventilation due to circulation changes and emissions from natural and anthropogenic sources. These aerosols are classified according to their origin (anthropogenic and natural sources) and can mix and interact with each other (Boucher, 2015). Regional differences in aerosol concentrations and types are attributed to a combination of factors, such as geographic location, topography, surface properties, population density, proximity of pollution sources and meteorological conditions (Gui *et al.*, 2022). In our study, we aim to understand the contribution of the different aerosol types to air quality in Nahouri province.

AOD and AE are key indicators of aerosol presence in the atmosphere (Salinas *et al.*, 2013). AOD is a columnar measure of aerosol loading, while AE is a measure of aerosol size distribution. Higher AOD values indicate greater aerosol concentrations in the atmosphere, and higher AE values correspond to finer aerosol particles and vice versa (Rupakheti *et al.*, 2019). As both AOD and AE are functions of visible wavelengths, their relationship has been used in many studies to distinguish between aerosol types (Rupakheti *et al.*, 2019). For example, Kaskaoutis *et al.* (2007) and Rupakheti *et al.* (2019) defined major aerosol types based on the relationship between AOD and AE: Clean Marine (AOD < 0.1 and AE < 1.0), Clean Continental (AOD < 0.1 and AE > 1.0), Biomass Burning/Urban Industrial (AOD > 0.2 and AE > 1.0), Desert Dust (AOD > 0.3 and AE < 0.7) and remaining cases that are not falling in any

of these categories were characterized as mixed aerosols. In this study, we analyze AOD and AE thresholds to determine the types of aerosols affecting Nahouri province.

Two Science Data Sets (SDS) from MOD04_L2 and MYD04_L2 products of Collection 6.1 named Aerosol Optical Depth at 550 nm (MODIS parameter name: AOD_550_Dark_Target_Deep_Blue_Combined) and Ångström Exponent (MODIS parameter name: Deep_Blue_Angstrom_Exponent_Land) were retrieved daily from MODIS instrument sensor onboard both the Terra and Aqua satellites with data covering 2000 (2002 for Aqua) to 2020 (www.ladsweb.modaps.eosdis.nasa.gov). Daily AOD and AE for the period 2000–2020 in Nahouri were analyzed.

3. Results

3.1 Climate variables

3.1.1 Air temperature. Figure 4 presents the seasonal time series of maximum and minimum air temperatures in the Nahouri province from 1960 to 2020, along with their decadal slopes and 95% confidence intervals derived from TerraClimate data. Both maximum and minimum temperatures in the Nahouri province show an increasing trend across all seasons, with averages of 34.29°C and 21.96°C, respectively. The transition season is the warmest and shows the most pronounced warming over time. In contrast, the wet and dry seasons had lower warming during the same period. However, both minimum and maximum temperatures have increased in the past decade for each season. The greater increase in maximum temperature is observed during the transition season, with a slope of 0.22°C per decade [0.12, 0.32], followed by the wet season at 0.15°C per decade [0.10, 0.20] and the dry season at 0.09°C per decade [0.02, 0.16]. Minimum temperature also rises most during the transition season, with a slope of 0.31°C per decade [0.24, 0.37], followed by the dry season, with a slope of 0.24°C per decade [0.19, 0.29] and the wet season, with a slope of 0.20°C per decade [0.17, 0.24].

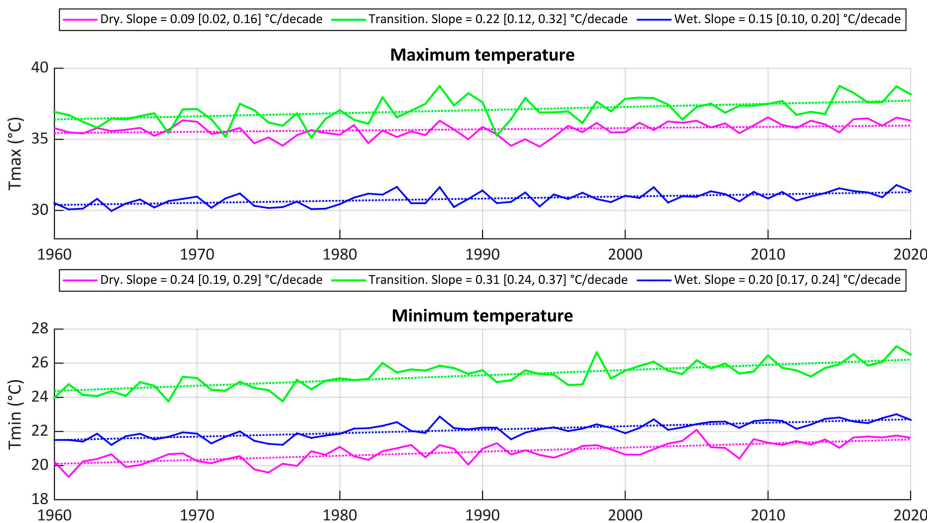


Figure 4. Regional average air temperature and trends per decade (1960–2020) with 95% confidence intervals for dry, transition and wet seasons, in the Nahouri province, based on TerraClimate data

decade [0.17, 0.24]. In all cases, the 95% confidence intervals do not cross zero, indicating that the warming trends are statistically significant.

3.1.2 Precipitation. Figure 5 shows the precipitation trends for the dry, transition and wet seasons from 1960 to 2020, with decadal trends and 95% confidence intervals. While temperatures have increased, precipitation data reveal a decline during the transition season, with a slope of - 2.97 mm per decade [-6.14, 0.19], followed by the dry season, with 0.19 mm/decade [-1.08, 0.70]. In contrast, the wet season shows a slight positive trend of 1.10 mm/decade [-2.40, 4.61]. In all cases, the 95% confidence intervals cross zero, indicating that these trends are not statistically significant.

3.1.3 Wind speed. Figure 6 shows the time series of wind speed at 10 meters elevation (10 m wind speed) for all seasons (dry, transition and wet) from 1960 to 2020, along with their decadal trends and 95% confidence intervals. The 10 m wind speed values were higher during the transition season (about 2.0–2.8 m/s) and lower during the dry (about 1.5–2.3 m/s) and wet (about 1.6–2.7 m/s) seasons, with noticeable annual fluctuations. The dry season shows a significant decline of -0.09 m/s per decade [-0.12, -0.06], while the wet season also declines significantly by -0.04 m/s per decade [-0.07, -0.01]. In contrast, the transition season trend is a smaller, non-significant decrease of -0.03 m/s per decade [-0.07, 0.01]. These reductions in wind speed may slow evapotranspiration, reduce dust in the air and affect local air circulation patterns (precipitation and temperature).

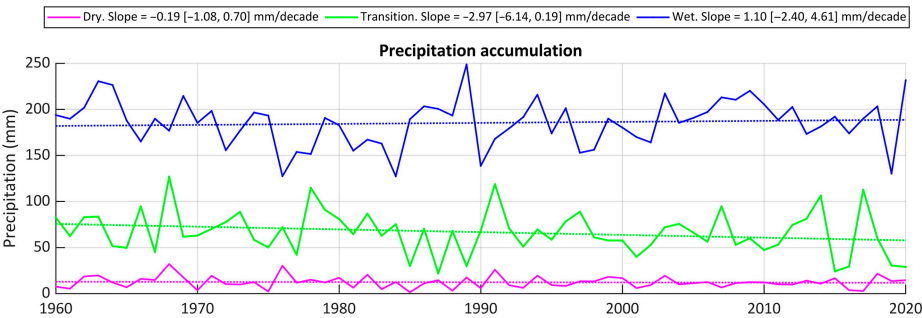


Figure 5. Regional average precipitation and trends per decade (1960–2020) with 95% confidence intervals for dry, transition and wet seasons, in the Nahouri province, based on TerraClimate data

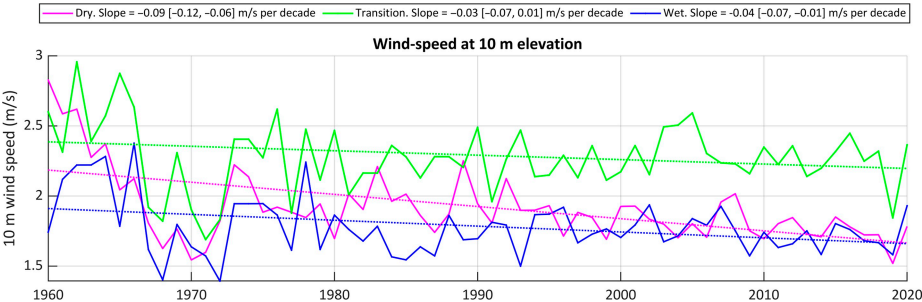


Figure 6. Regional average wind speed and trends per decade (1960–2020) with 95% confidence intervals for dry, transition and wet seasons, in the Nahouri province, based on TerraClimate data

3.2 Water availability variables

3.2.1 Evapotranspiration. Figure 7 shows seasonal evapotranspiration (ET_0) from 1960 to 2020, with decadal trends and 95% confidence intervals. ET_0 reaches its maximal value during the transition season, likely influenced by higher temperatures (see Figure 4) and strong solar radiation, which enhances evaporation from water bodies and soil. In the transition season, ET_0 increases by 0.78 mm/decade $[-0.55, 2.10]$, but this trend is not statistically significant. During the wet season, ET_0 significantly increases by 3.05 mm per decade $[2.26, 3.84]$ following the same trend as the maximum temperature (see Figure 4). In contrast, ET_0 shows a significant decline during the dry season, with a trend of -1.61 mm per decade $[-2.69, -0.53]$, possibly due to limited water availability and reduced vegetation cover.

3.2.2 Climate water deficit. CWD is the difference between potential evapotranspiration (ET_0) and actual evapotranspiration. A higher CWD value indicates that evapotranspiration exceeds the available liquid water supply and soil water utilization, suggesting that demand surpasses supply. From 1950 to 2020, CWD values were higher during the transition and dry seasons due to higher temperatures and evapotranspiration (see Figures 4 and 7) and lower precipitation (see Figure 5), as shown in Figure 8. The transition season shows a significant increase of 3.80 mm/decade $[0.24, 7.36]$, while the dry season shows a non-significant decline of -1.40 mm/decade $[-3.07, 0.27]$. The wet season has the lowest CWD values, with a small, non-significant increase of 0.95 mm/decade $[-0.10, 2.00]$. Elevated CWD, especially during the transition season, can limit water availability for crops and increase pressure on land resources, potentially driving changes in land cover and agricultural productivity.

3.2.3 Soil moisture. According to TerraClimate data, soil moisture was highest during the wet season but showed a non-significant decreasing trend of -1.15 mm/decade $[-4.78, 2.47]$ between 1960 and 2020 (Figure 9). The annual fluctuations in soil moisture during this season were highly variable. During the dry season, soil moisture increased slightly by 0.31 mm/decade $[-0.81, 1.42]$, but this trend was also not statistically significant. However, during the transition season, soil moisture remained relatively stable at lower values (~ 20 mm), with a non-significant trend of 0.21 mm/decade $[-0.16, 0.58]$.

3.3 Vegetation and land cover

3.3.1 Normalized Difference Vegetation Index. Landsat-based NDVI values have shown an increase since 1985 across all seasons, but only the dry and transition seasons exhibit a

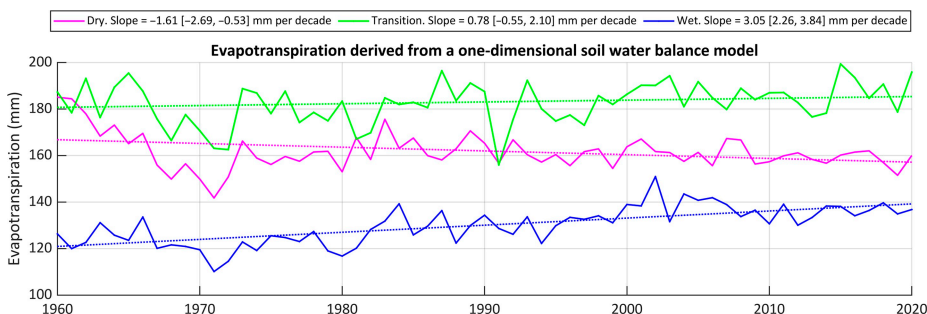


Figure 7. Regional average evapotranspiration and trends per decade (1960–2020) with 95% confidence intervals for dry, transition and wet seasons, in the Nahouri province, based on TerraClimate data

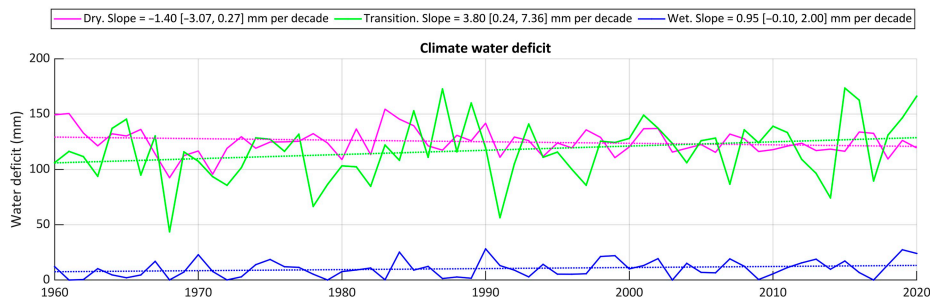


Figure 8. Regional average water deficit and trends per decade (1960–2020) with 95% confidence intervals for dry, transition and wet seasons, in the Nahouri province, based on TerraClimate data

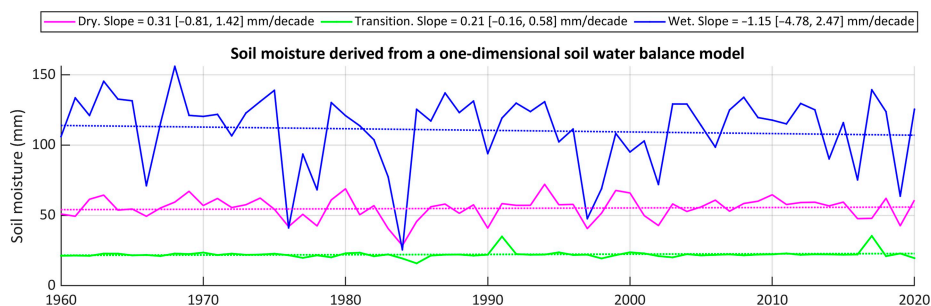


Figure 9. Regional average soil moisture and trends per decade (1960–2020) with 95% confidence intervals for dry, transition and wet seasons, in the Nahouri province, based on TerraClimate data

statistically significant trend (Fig 10). The NDVI for the dry season has gradually increased from 1985 to 2020, with a strong positive trend of 0.04 per decade [0.017, 0.059]. In contrast, the transition season shows a trend of 0.02 per decade [-0.007, 0.036]. The NDVI values during the wet season are higher than in the dry and transition seasons. However, the trend is reported as 0.02 per decade [-0.015, 0.062], indicating no statistically significant long-term change in the vegetation index during the wet season. The data from wet and transition seasons demonstrate a pronounced variability from year to year compared to the dry season. Decadal analysis reveals that trends before 2000 appear flatter due to the limited availability of data for that period.

3.3.2 Land cover. Four main land cover types dominate the landscape in Nahouri province: riparian habitat, shrub savanna, grassy savanna and agro-forested land. Over time, the distribution of each landscape remains relatively constant, with a modest amount of riparian habitat and a predominance of agro-forested areas. Even if the savannah's area cover varies throughout time, the impact on the distribution of the landscapes is small. Trends and general changes in land cover provide valuable indicators despite some outlier data. Over the period from 1985 to 2020, the trend suggests an increase in riparian vegetation and grassy savanna, while shrub savanna has decreased, and agro-forested land remained relatively stable, as shown in Figure 11. Grassy savanna shows the strongest and statistically significant increase, rising by 0.96% per decade [0.418, 1.501]. Riparian habitat has also increased

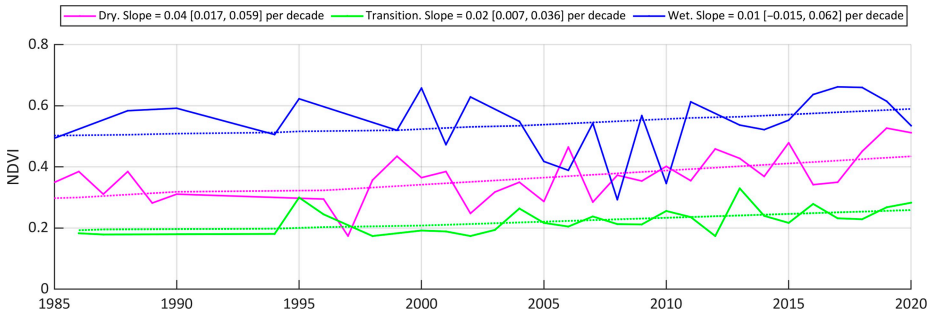


Figure 10. Regional average of NDVI and trends per decade with 95% confidence intervals for dry, transition and wet seasons from 1960 to 2020, in the Nahouri province, as calculated from Landsat images

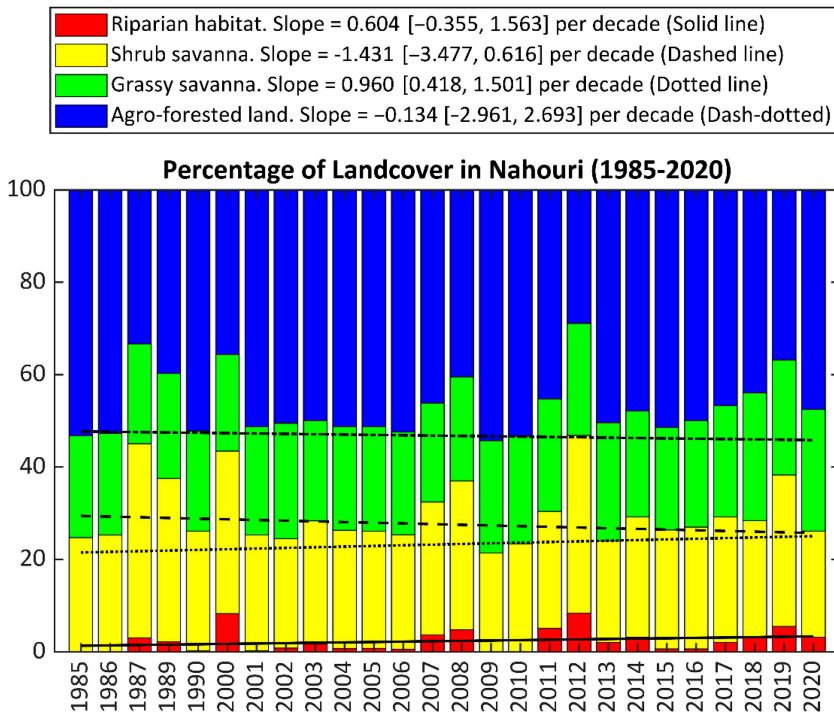


Figure 11. Percentage change in land cover per decade, with 95% confidence intervals, in the Nahouri province from 1985 to 2020, as obtained from land cover classification using Landsat images

0.60% per decade [-0.355, 1.563], though this trend is not statistically significant. In contrast, shrub savanna declined by -1.43% per decade [-3.477, 0.616], and agro-forested land decreased slightly by -0.13% per decade [-2.961, 2.693]; both declines are not statistically significant.

3.4 Dust aerosol optical depth

Figure 12 presents the spatial variability of the average AOD in the Nahouri province from 2000 to 2020, which aligns with the AOD values reported in a relevant study for northwestern Africa by Gupta *et al.* (2022). The higher values of AOD were observed in the eastern part of Nahouri, dominated by high anthropogenic activities, and the lower values were in the northwest part of Nahouri, dominated by natural cover. To estimate aerosol types, we analyze AOD and AE values, where AOD reflects overall aerosol concentration and AE indicates particle size. By categorizing aerosols based on threshold values, we find that mixed aerosols dominate at 44% of the total, suggesting a complex blend of sources. Desert dust contributes 20.7%, influenced by nearby deserts, while clean marine aerosols account for 13.5%, underscoring marine impacts on the aerosol profile in Nahouri. Figure 13 shows the temporal trend of dust AOD from 2000 to 2020. AOD concentrations increased during the transition season at a rate of 0.060 per decade $[-0.023, 0.142]$, while slight decreases were observed during the dry season $(-0.006 \text{ per decade } [-0.063, 0.050])$ and the wet season $(-0.006 \text{ per decade } [-0.032, 0.019])$. In all cases, the 95% confidence intervals cross zero, indicating that none of these trends are statistically significant.

4. Discussion

The results indicate a general warming trend, consistent with findings from numerous studies on the Sahel region (Tesfaye, 2022; Trisos *et al.*, 2023). These results align with studies on Burkina Faso’s environmental conditions, which also indicate an increase in temperature across the country (Alvar-Beltrán *et al.*, 2020; Niang *et al.*, 2014; Sorgho *et al.*, 2021). Specifically, there has been a global warming of 0.2°C in Gaoua, located in the southern

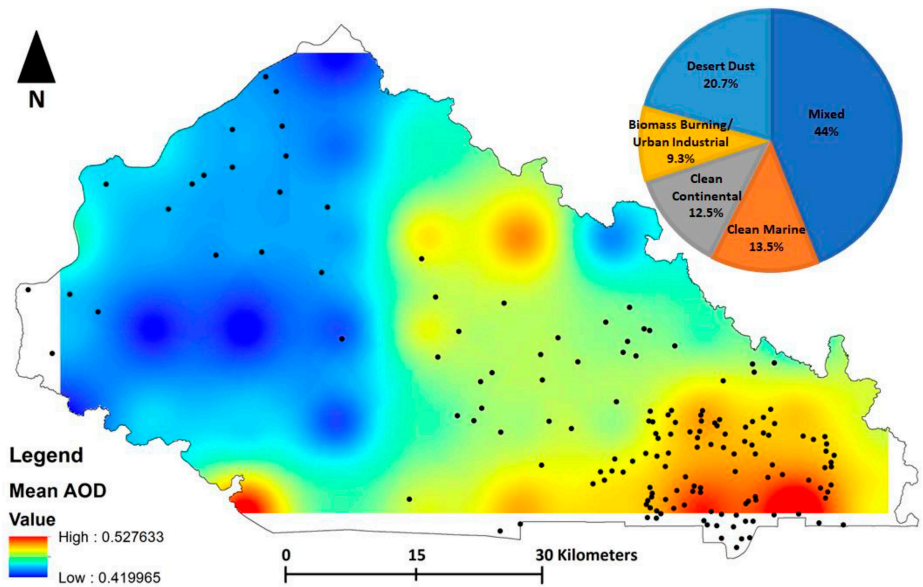


Figure 12. Spatial variability and types of AOD in the Nahouri province from 2000 to 2020. The black dots on the map represent the locations of residential areas. The average AOD values in the Nahouri province range from 0.42 to 0.53

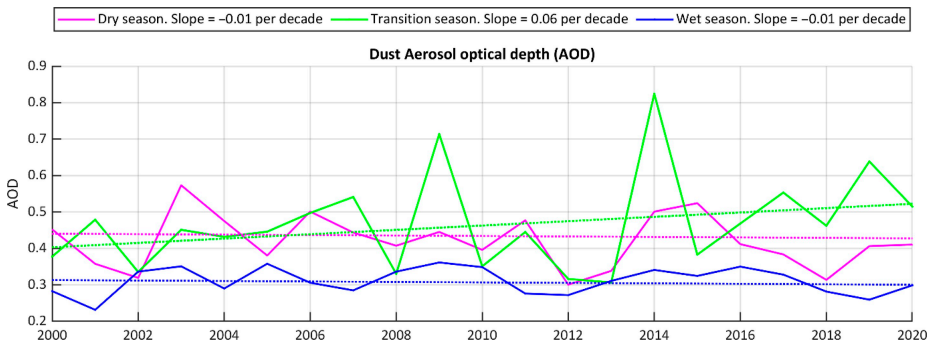


Figure 13. Regional average AOD and trends per decade with 95% confidence intervals for dry, transition and wet seasons from 2000 to 2020, in the Nahouri province

Sudanian zone, 1°C in Ouagadougou, in the Sudanian-Sahelian zone and 1.35°C in Dori, located in the Sahelian zone, during the period from 1961 to 2000 (SP/CONEDD, 2010). On the other hand, an important aspect of the study is the demonstration of accentuated phenomena during the transition season, between the dry season and the beginning of the wet season, a critical period for the start of agricultural activities in the Nahouri province. Our results demonstrate that increases in temperatures and decreases in precipitation during the transition season contributed to a significant increase in water deficit, with a trend of 3.80 mm per decade [0.24, 7.36] over the last 40 years (Figures 4, 5 and 8). This warming also coincides with the highest seasonal evapotranspiration rates (Figure 7) and the lowest soil moisture levels of the year (Figure 9), amplifying agricultural water stress. Dust AOD also peaks during the transition season (Figure 13), affecting air quality and crop productivity. Confidence interval analysis shows that the warming trends for both maximum and minimum temperatures are statistically significant across all seasons, reinforcing the robustness of these findings (see Figure 4). For precipitation, wind speed, evapotranspiration, soil moisture and AOD trends, the 95% confidence intervals cross zero during the transition season, meaning the results are uncertain and may reflect natural climate variability rather than a consistent long-term change (Figures 5, 6, 7, 9 and 13).

The marked deficits during the transition season can significantly impact agricultural activities and food security in the Nahouri province (Aguirre-Unceta, 2023), and align with the perception of residents regarding the impact of climate change (Epule *et al.*, 2017). According to a study conducted by the Ga Mo Wigna Association in 2018 in the Nahouri province, changes in rainfall patterns are the primary element in the perception of climate change by producers (Wigna, 2019; Léon *et al.*, 2023). In general, an analysis of 30-year cumulative rainfall in Burkina Faso shows a southward migration of 600 and 900 mm isohyets by approximately 100 to 150 km from 1930 to 2010 (Mamadou Onadja, 2014). Our analysis of TerraClimate data indicates a general decrease in wind speed, which contrasts with certain studies, such as Mertz *et al.* (2009) that report an increase in extreme wind events in rural Sahel. This result must be put into perspective. TerraClimate data offering monthly averages does not allow extreme events to be captured and powerful winds to be identified, underscoring the need for more localized climatic-hydrological analyses. Nonetheless, these findings highlight the importance of conducting region-specific studies to better understand climate impacts.

Data related to land cover shows a generalized increase in NDVI, which seems to confirm the hypothesis of a greening of the Sahel (Fensholt *et al.*, 2012). Increases in NDVI are

strongest during dry and transitional seasons (see [Figure 10](#)). The increase in NDVI during the dry season could be explained by slightly advantageous climatic characteristics, such as the decrease in the water deficit for this season. However, there is still an increase in NDVI during the transition season, even though this period is particularly affected by an increase in water deficit. This suggests that additional factors beyond climate alone are contributing to increased vegetation cover in the region. The expansion of tree crops, such as mango, which are planted during the dry season, may contribute to increased NDVI ([Bictogo, 2010](#); [Knauer et al., 2017](#); [Touré, 2021](#)). These plantations have spectral reflectance characteristics similar to degraded forests and may therefore artificially elevate NDVI values ([Tong et al., 2017](#)). However, at the resolution of Landsat imagery (30 × 30m), it is difficult to accurately assess the extent of their contribution, as small or mixed land uses may not be distinguishable. In addition, land cover changes, such as the conversion of natural vegetation to subsistence and perennial cropland or urban vegetation, can increase surface greenness, further influencing NDVI measurements. Thus, as observed in the Sudanese zone of Burkina Faso, part of the greening could be linked to the observed new practices and developments that have increased plant cover ([Ouedraogo et al., 2014](#)). Some drought-resistant species, including millet and cowpea, maintain photosynthetic activity even during the dry season, contributing to NDVI levels ([Lawin and Lota, 2019](#)). In many regions in the Sahel, dry-season irrigation practices may support active vegetation growth and further enhance NDVI signals ([Brandt et al., 2014](#)).

Indeed, at both the national and local levels, significant efforts are being made by communities whose attitudes are shifting toward environmental protection and the sustainable management of natural resources, with the support of technical and financial partners. Several government strategies reinforce these efforts. For example, the Sectoral Policy on Agro-Sylvo-Pastoral Production, under the National Economic and Social Development Plan (or *Plan national de développement économique et social (PNDES-II)*) 2021–2025, promotes sustainable and productive agricultural practices ([MARAH, 2021](#)). The National Plan for Adaptation to Climate Change (or *Plan National d'Adaptation aux changements climatiques (PNA)*) by 2050 aims to enhance adaptation and resilience in vulnerable sectors, including agriculture, livestock, water resources, health, energy and infrastructure ([Bikienga, 2014](#)). Similarly, the National Plan for the Planning and Sustainable Development of the Territory (or *National d'Aménagement et du Développement Durable du Territoire (SNADDT)*) by 2040 focuses on reducing spatial disparities while integrating sustainability into territorial planning and development management ([MINEFID, 2017](#)). These policies promote reforestation, land restoration and sustainable land use, all of which may also contribute to the observed trend of greening. Although our study does not assess the direct impact of these policies, their implementation may help explain the greening trends observed through NDVI analysis.

Our land cover analysis generally reveals a landscape predominantly composed of distribution dominated by agro-forested areas, interspersed with urban areas and natural vegetation types. The main land cover classes include riparian habitats, shrub savannas, grassy savannas and agroforestry. While small-scale increases in riparian habitats and grassy savannas have been observed, the overall trend between 1986 and 2021 shows a significant expansion of agroforestry territories, accompanied by a decline in forest cover and both tree and shrub savannas. These shifts reflect broader national patterns, as agricultural land in Burkina Faso increased by over 35% between 1983 and 2014, driven by population growth, land conversion for agriculture and socio-economic pressures ([Wigna, 2019](#); [Léon et al., 2023](#)). Despite land tenure reforms since 1984, institutional capacity to manage land sustainably remains limited, especially in rural areas where customary and formal systems

often conflict. Although annual classification values are subject to uncertainties due to methodological limitations, the broader patterns remain meaningful and point to substantial and policy-relevant land transformation in the Nahouri province.

For aerosols, our analysis reveals a slight decreasing trend in AOD values over Nahouri, aligning with findings from a recent study by [Gupta et al. \(2022\)](#), which reported a similar AOD decline across Western North Africa. [Gupta et al. \(2022\)](#) attributed this trend to reduced surface wind speeds in dust-prone areas, likely driven by large-scale atmospheric circulation changes over the Sahel region ([MEA, 2022](#)). In Burkina Faso, and particularly in the southern region, including Nahouri, the aerosol concentrations are shaped by multiple interacting sources. These include long-range transport of Sahara and Sahel dust, intense biomass burning from the Gulf of Guinea and local sources such as agricultural fires and road dust resuspension ([Bado et al., 2024, 2025](#)). During the dry season (November–March), northeasterly Harmattan winds transport mineral dust into the region, while combustion aerosols from land clearing and biomass burning become prominent in both local and regional air masses ([Bado et al., 2024](#)). Satellite-based studies, including MODIS AOD and AE, indicate that autumn and early winter are periods of elevated AOD in the south, including Nahouri, with evidence of fine particles in spring and summer likely tied to long-range transport from coastal fires ([Bado et al., 2024](#)). Urban emissions and soil dust resuspension also contribute significantly during the dry and transition seasons, when rainfall is limited and atmospheric conditions favor aerosol accumulation ([Bado et al., 2024, 2025](#)). Despite the general decreasing trend, these seasonal and multi-source dynamics highlight the complexity of aerosol behavior in Nahouri, underscoring the need for continued monitoring to assess both environmental and health-related impacts.

This study presents a comprehensive analysis of key variables related to climate change and land use, primarily based on TerraClimate for climate-hydrological data and remote sensing products for land cover and aerosol assessments. The research focuses on identifying trends in the temporal variations of vegetation, land cover and aerosols through the analysis of monthly-scale variables. While TerraClimate and remote sensing data serve as the primary data sources, we acknowledge the existence of several other models, with their strengths and limitations ([Bell et al., 2021](#)). For example, ERA-5 data could offer similar information but at more precise time scales, i.e. on a time step of 6 h. Such data would make it possible to further identify the effect of climate change on extremes, which are often the most damaging events for communities and ecosystems. However, it remains recognized that models generally tend to underestimate the extremes ([Schewe et al., 2019](#)).

In our study, TerraClimate data were used to simplify the analysis and offer an initial general diagnosis for the Nahouri province, based on its high (~4 km) spatial resolution and extensive temporal coverage. It should also be noted that the reliability of analysis models implemented in TerraClimate depends on the quality and quantity of the input data ([Abatzoglou et al., 2018](#)). In the case of Nahouri province, TerraClimate incorporates an adequate quantity of data points, ensuring a reasonable level of accuracy for the region. However, several limitations must be considered when using the TerraClimate product to assess climate trends, including its inability to capture sub-monthly variability and short-lived extreme events, the use of a static land-cover map in its water-balance model that does not account for vegetation heterogeneity and reduced reliability in areas with sparse ground-station coverage ([Abatzoglou et al., 2018](#)). In Nahouri province, where adaptation policies need local data to manage variable water resources and protect vulnerable communities, TerraClimate is a useful starting point but should be complemented with in-situ observations to improve the relevance and effectiveness of adaptation measures. Also, when using our method in other areas, researchers should be careful to assess whether TerraClimate data is suitable and understand its limitations for their study region.

Ground truth data remains a major limitation in the Nahouri province due to multiple structural and logistical constraints. The region faces limited accessibility, a lack of financial and technical resources and an underdeveloped infrastructure for data collection and processing (INSD, 2023). There is only one weather station in the city of Pô (11.1667° N and -1.15° E), which has limited coverage and outdated records. For vegetation analysis, no regular field surveys were available to verify NDVI values or monitor land use changes. Aerosol concentration data are exclusively derived from MODIS observations, as no ground-based monitoring stations in the area. In the absence of a comprehensive ground-based monitoring for aerosol optical depth network in Nahouri province, we relied on MODIS-derived aerosol products, which have been shown to provide reliable and representative estimates over Burkina Faso (see Figure 12). According to Bado *et al.* (2024), MODIS exhibited the strongest correlation with AERONET (AErosol RObotic NETwork) ground measurements among several satellite sensors tested, with a correlation of $R = 0.84$, supporting its use as a trustworthy alternative when *in situ* observations are unavailable. These challenges are made worse by poor accessibility, limited equipment and the absence of a centralized data-sharing system. Although new tools like SINAP-N are beginning to improve data collection, long-term field data remain scarce. Despite these limitations, the framework presented in Figure 3 provides a reliable method for monitoring environmental changes and supporting early warning efforts in the Nahouri province. One strong point of this study is using satellite data to provide helpful information when there are few measurements taken on the ground. By utilizing common remote-sensing and climate data, this method can provide information to systems like SINAP-N and operate in other areas with limited data, enabling local leaders to monitor climate changes and prepare for potential problems.

This study underlines some worrying effects of climate change on the Nahouri province. The results confirm the observations made by the Nahouri communities, who have noticed the dry season stretching over recent years (Wigna, 2019). Such prolonged dry seasons contribute to increased water stress, which critically affects agricultural productivity in a region where over 80% of the population depends on rainfed farming (Wigna, 2019). Furthermore, higher temperatures and unpredictable rainfall also add to problems like land damage and resource competition. These changes match wider trends in the Sahel, where extreme heat and drought happen more often, threatening local food and the environment (Epule *et al.*, 2014, 2017). To address these challenges, the implementation of the obtained results into the SINAP-N warning system enables more timely decisions and targeted conservation strategies. For example, by providing detailed information on vegetation (NDVI) and land-use change, the system can highlight areas experiencing greening trends, improve resource allocation and promote more sustainable land management practices. This integration has already begun: the findings of this research have been shared with the GA Mo Wigna Association, which manages the SINAP-N warning system, and are now integrated into its database and monitoring activities. Going forward, it will be important to evaluate how the obtained results are applied in practice and to assess their social, ecological and economic impact, while also exploring ways to enhance SINAP-N with advanced monitoring tools and socio-environmental impact assessments.

While this study focused on historical changes over the past 40 years, these tools could also be used for near real-time monitoring of key variables, supporting more effective land management. For example, the SMAP L4 global daily product 9 km EASE-Grid Carbon Net Ecosystem Exchange product (SPL4CMDL) (see Jones *et al.*, 2017) enables global quantification of carbon fluxes. This tool could help assess the effect of conservation efforts on CO₂ fluxes and track variations related to climate. Analysis of this product over Nahouri province shows that the region acts as a carbon sink (negative Net Ecosystem Exchange or

NEE) during wet seasons, while dry and transition seasons contribute to CO₂ emissions (Figure 14). The SPL4CMDL product indicates that Nahouri is generally a net source of CO₂ in the atmosphere. However, spatial analyses could identify ecosystems or land management practices that optimize carbon storage.

Other operational products, such as soil moisture products from Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP), could help in identifying risks related to short-term water stress, while the MODIS fire product could help locate active fire zones. However, implementing these approaches in near-real-time mode requires advanced operational computing systems and expertise for development and management.

5. Conclusion

This study provides a comprehensive diagnostic of climate, hydrology and atmospheric changes in Nahouri province of Burkina Faso using an integrated approach that combines modeling and remote sensing data. Key scientific contributions of our work include: 1) revealing the pronounced sensitivity of the regional climate system during the transition season, as an increase in temperatures, a decrease in precipitation and intensive water stress, all of which directly impacts agricultural productivity; 2) monitoring changes in ecosystem composition, notably the increase in grassy savannas at the expense of shrub savannas, confirming the “greening” in the Sahel through robust NDVI analysis and 3) identifying the link between aerosol loads and patterns of land use and human activity, with higher aerosol concentrations observed in areas dominated by intense anthropogenic activities (such as agriculture, biomass burning or urbanization), and lower concentrations in regions with more natural cover

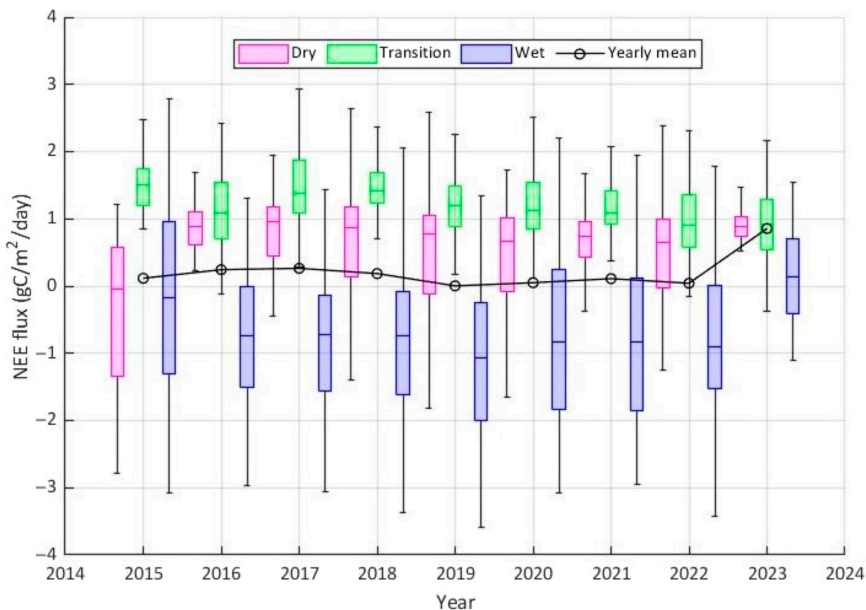


Figure 14. Net Ecosystem Exchange flux (NEE flux) over the Nahori province calculated from the SPL4CMDL product from 2015 to 2023 for the three seasons (wet, transition and dry)

These findings have direct practical implications for climate adaptation and land management. The results inform and strengthen the operational capacity of the Information and Early Warning System for Nahouri (SINAP-N or *Système d'Information et d'Alerte Précoce pour le Nahouri*) and can help stakeholders involved in climate change adaptation to acquire technical and scientific knowledge and understand the impacts of climate change on local ecosystems and livelihoods. This knowledge will support local producers in making informed seasonal decisions to optimize agricultural practices and provide policymakers with the tools necessary to develop effective programs and actions that enhance climate resilience.

Beyond the local context, the methodological framework developed here is scalable and applicable to other regions facing similar challenges of limited data and climate vulnerability. In addition, by bridging local knowledge and scientific evidence, this study strengthens the credibility and relevance of climate science for diverse audiences, fostering inclusive dialogue among communities, decision-makers and researchers.

Overall, this research makes a first step toward reconciling and building bridges between local perspectives and scientific knowledge by painting a scientific picture corresponding to climate perceptions. This bridge between traditional and technical/scientific knowledge greatly enhances the credibility of science among populations with a more limited level of scientific background, but whose experience and traditional knowledge are primary sources of information. The study educates communities, decision-makers, customary authorities and stakeholders about the climate change context while demonstrating the connections between scientific findings and local observations.

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